INVESTIGATIONS ON LOW FREQUENCY PIEZOFILM HYDROPHONES WITH IMPROVED PERFORMANCE

A THESIS SUBMITTED BY

J. JAGANNATH BHAT

IN PARTIAL FULFILMENT OF
THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

DEPARTMENT OF ELECTRONICS
FACULTY OF TECHNOLOGY
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY
COCHIN - 682 022, INDIA

DECEMBER 1994

"In every work of Genius, we recognise our own rejected thoughts; they come back to us with a certain alienate majesty"

- Ralph Waldo Emerson

CERTIFICATE

This is to certify that the thesis entitled "**Investigations on Low Frequency Piezofilm Hydrophones with Improved Performance**" is a bona fide record of the research work carried out by Mr. J. Jagannath Bhat under my supervision in the *Department of Electronics, Cochin University of Science & Technology*. The results embodied in this thesis or part of it have not been presented for any other degree.

(Dr. P.R. SASEENDRAN PILLAI)
(Supervising Teacher)
Professor
Dept. of Electronics
Cochin University of Sci & Tech.

COCHIN 682 022
29th December 1994

DECLARATION

I hereby declare that the work presented in the thesis entitled **"Investigations on Low Frequency Piezofilm Hydrophones with Improved Performance"** is based on the original work done by me under the supervision of Dr. P.R. Saseendran Pillai, in the *Department of Electronics, Cochin University of Science & Technology*, and that no part thereof has been presented for the award of any other degree.

J. Jagannath Bhat J

COCHIN 682 022
29th December 1994

(J. JAGANNATH BHAT)

ACKNOWLEDGEMENTS

First and foremost I would like to express my profound gratitude to my research guide Dr. P.R. Saseendran Pillai, Professor, Dept. of Electronics, Cochin University of Science & Technology (CUSAT), for his invaluable help in the course of this study. This thesis is the outcome of education, able guidance, encouragement and inspiration I received from him.

I am extremely grateful to Dr. K.G. Nair, Professor and Head, Dept. of Electronics, CUSAT, for the genuine interest he has shown in the progress of my work.

Sincere thanks are due to Dr. C.S. Sridar, Professor, Dept. of Electronics, for his invaluable suggestions and enlightening discussions during the course of this study. Dr. D. Srinivasan, Emeritus Scientist, DOD, IIT, Madras, Dr. V.K. Aatre, Former Director, NPOL, Cochin, Dr. V.N. Bindal, Deputy Director (Retd.), NPL, New Delhi, Dr. Rama Rao, Professor, IIT, Madras and Dr. Varaprasad, Director, C-MET, Kanpur, were helpful to me by way of fruitful discussions and inestimable suggestions during the different phase of my work. I express my extreme and sincere gratitude to them.

I am indebted to the Director, NPOL and Mr. H.R.S. Sastri, Head, Transducer Section, NPOL for permitting me to use various measurement facilities and infrastructure available with NPOL, without which it was impossible to carry out this work. Mr. Ralph Sebastain, Mr. Unnikrishnan, Mr. Gopalakrishnan, Mr. Vishnubatla and Mr. Jacob, Scientists of NPOL deserves special appreciation for their kind co-operation and estimable suggestions during the course my work. Thanks are also to Mr. Sudhakaran, Mr. Ummer and Mr. John, technical staff of NPOL for their assistance and help for the experimental

investigations.

My acknowledgement would be incomplete if a mention is not made of generous help, practical suggestions and whole hearted support I received from Mr. Gangadharan, Scientist, NPOL. I express my deep gratitude to him.

I owe special debt to Mr. A.J.P. Namboodiri, Guest Lecturer, Dept. of Ship Technology, CUSAT, who extended a helping hand by way of discussions on certain theoretical aspects of my work.

I gratefully thank my former colleagues, Dr. P.M. Joseph, Lecturer, Neumans College, Thodupuzha and Mr. P.P. Thomson, Project Associate, New South Wales University, Australia, for their immense help, inspiration and friendship, during their tenure as research scholars of this department.

I take this opportunity to express sincere thanks to all members of faculty, laboratory and non teaching staffs and research scholars of this department for their kind-hearted co-operation. I owe special debt to Miss. R. Sumangala, Mr. Paul V. John, research scholars and Mrs. Sani Francis of this department for their affection and encouragement during the period of my work. While expressing my gratefulness to all of them, I would also like to place on record the co-operation I received from my enjoyable colleagues, Mr. U. Raveendranath, Mr. Thomaskutty Mathew, Mr. Saji Stephan, Mr. Jacob George and Miss Mariamma, research scholars of this department.

I wish to acknowledge Dept. of Electronics, Govt. of India and CSIR, New Delhi for providing the financial assistance during the course of my research work.

INVESTIGATIONS ON LOW FREQUENCY PIEZOFILM HYDROPHONES WITH IMPROVED PERFORMANCE

Contents

Chapter 1 Introduction

Chapter 2 Review of past work

Chapter 3 Methodology

Chapter 4 Prototype design

Chapter 5 Refined design

Chapter 6 Multifilm design

Chapter 7 Conclusions

Chapter 1

Introduction

With over 70% of the surface of the planet Earth being covered by Seas and Oceans, they play a substantial role in the various facets of life on the Globe. The oceans are major store houses of vast living and non living resources compared to the land based ones which are becoming scarce day by day. The exploration and exploitation of oceans whether for scientific, commercial or military purposes face severe complications as the water medium is essentially opaque to visible light, infrared, radio or microwaves, which are the best means of communication and sensing in air and in space. Short range communication is possible with cables, but is impracticable for long ranges. Sea water being a good conductor of electricity, dissipates the energy of electromagnetic waves into heat, limiting their penetration, and hence electromagnetic waves are as such not suitable for long range communication or detection of objects in the sea [1]. As ocean waters are turbid, the optical visibility is limited to a very short range. Here comes the role of sound, a form of mechanical energy, emerging as the most suitable tool for detection and communication purposes in the saline, muddy water of the sea. The hostile and fluctuating nature of the water medium therefore makes the techniques for detection and ranging in water quite different from that in air.

Acoustic waves differ in some aspects from the electromagnetic waves. For a given frequency, the electromagnetic waves attenuate in water considerably more than acoustic waves. Electromagnetic waves are transverse whereas acoustic waves are longitudinal. Electromagnetic waves can be polarised unlike acoustic waves. Acoustic waves travels with a velocity of 1500 m/sec in water and with 340 m/sec in air, while the velocity of electromagnetic waves is 3×10^8 m/sec in air, and they propagate with much less velocity in water.

The systems employing sound for detection of objects underwater are known as sonar systems. SONAR is an acronym for SOund Navigation And Ranging, it is the most effective means for underwater detection and transmission using sound [2]. Porpoise and bats are examples of naturally occurring acoustic systems, which guide themselves with incredible precision and accuracy.

Sonar has two modes of operation - active and passive. In active sonar systems, the source of acoustic energy forms part of the system. This acoustic energy from the source travels through water and the echoes reflected from the targets are received by acoustic receivers known as hydrophones. The signal outputs are amplified and analyzed to obtain details of target range. Thus active sonar systems are said to be echo ranging on their targets.

In passive or listening sonar systems, the source of sound is that radiated by the targets themselves, which are independent sources of sound. These sources include various kinds of marine organisms, propellers of ships, boats *etc*. Here hydrophones are used to listen the target sounds and the hydrophone outputs are processed to give details of source location. The components of a typical sonar system are shown in Fig. 1.1 [3].

1.1 BRIEF HISTORY

Sonar has its origin deep in the past [4]. In 1490 Leonardo da Vinci wrote [5], *"If you cause your ship to stop, and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at great distance from you"*. This remarkable disclosure is perhaps the first one ever reported to indicate that it is possible to detect underwater sound. This simple example includes all the essential elements of a modern passive sonar system. The acute impedance mismatch between air and water degraded the performance of this passive sonar system, which also lacks in directionality and sensitivity. Even though in 1635, the French philosopher, Pierri Gessendi and a French scientist Marin Messeene [6] attempted to measure the velocity of sound in water, the Swiss physicists Daniel Colladon *et al.*[7] are being usually credited for the first accurate measurement of the speed of sound in water. In 1827, they used a flash of light coupled with sounding of an underwater bell to obtain the velocity of sound in Lake Geneva with a surprising degree of accuracy.

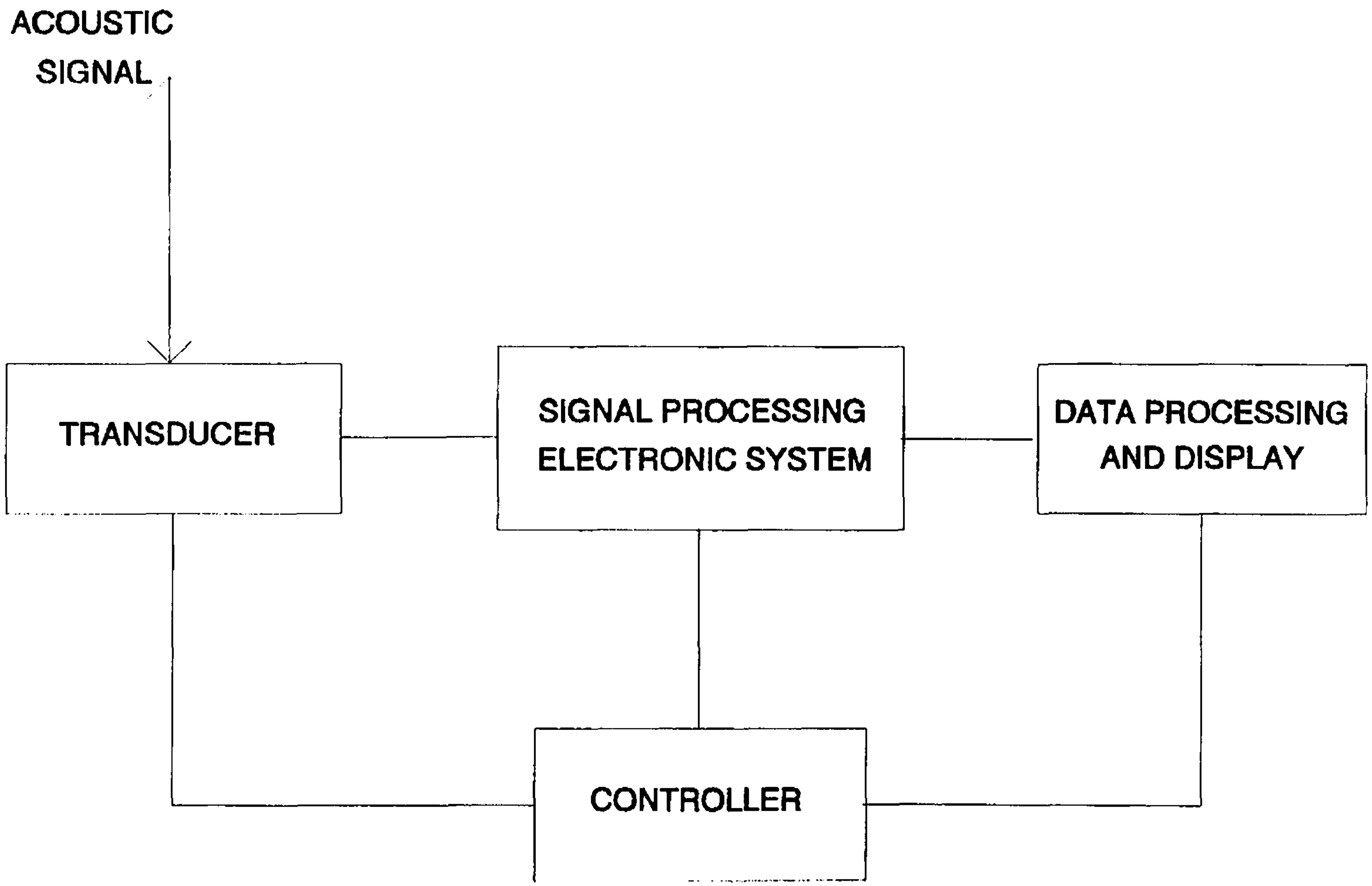


Fig 1.1 : A Typical Sonar System

With some notable exceptions, the development of underwater systems remained dormant for years due to the lack of devices for generation and reception of underwater acoustic signals. In 1840, James Joule [8] discovered magnetostriction in certain magnetic materials and carried out quantitative measurements on the change in dimensions under magnetic field, and is known as the discoverer of the magnetostrictive effect. One of the important 19th century invention was the telephone, for which A.G. Bell got patent in 1876. Edison's achievements such as the carbon microphone, the phonograph, and the bipolar moving armature telephone receiver were landmarks in the history of electroacoustic transducers. With the discovery of piezoelectricity in certain crystals by Jacques and Pierrie Curie in 1880, entrusted a big boost for the science and technology of underwater transducers.

In 1912, after the tragic incident of *"Titanic"*, L.F. Richardson came out with a device for echo ranging with air borne sound and later its underwater version. Even though these ideas were invaluable, they remained unimplemented. Meanwhile in United States, Fesseden developed the first high power underwater source known as Fesseden Oscillator. Operating at frequencies of 500 Hz and 1000Hz, these devices were able to detect ice bergs as far as 2 miles away. Simplicity and usefulness of these devices enabled them to find a suitable place in all the U.S. submarines during the World War I.

The first World War in 1914 gave a big boost to the development of underwater detecting devices for military applications. In 1915, due to the severe threat from the German submarines on shipping, active programmes were intensified for detecting the submerged submarines. Optical, thermal, magnetic and electromagnetic means were sought along with the acoustical means and it turned out that, acoustical means were best suited for detection. For this Leonardo's air tube was modified by adding two tubes for getting better directionality. This device was called SC device [9]. An extension to SC device was the MB tube. It has six rubber bulbs on each side of a rotatable tube. This tube provided better sensitivity and angular resolution than SC tube. A still improved version called MV tube was developed with flush mounted array of six bulbs on each side. The MV tube was then the most sophisticated non electrical listening device used in the World War I, and also this tube offered a longer range of 2000 yards for a ship travelling at 20 knots.

The self noise of the moving ship used to adversely affect the performance of the MV Tube. This effect was rectified to some extent by using towed hydrophone devices. In 1918 the first towed system known as U3 Tube was developed. It consisted of twelve equally spaced carbon button microphones enclosed in a flexible rubber tube. This line array of hydrophones was known as "*eel*". The entire U3 Tube system had two *eels* spaced 12ft apart. To improve the signal to noise ratio, the U3 Tube system was equipped with two electrical high pass filters.

Even though the passive systems such as SC, MV and U3 Tube were reasonably successful in detecting the submerged submarines, they lacked accuracy for weapon delivery. This led to the enhanced interest in echo ranging systems. The distinguished French physicist Paul Langevin applied echo ranging method to detect submarines, and in 1917, he developed a design incorporating piezoelectric crystals and vacuum tube amplifiers for underwater detection. With a projector of quartz - steel sandwich, he was able to detect echoes from submarines at distances of 1500 meters. During the World War I period these echo ranging devices were generally known by the name ASDIC (Allied Submarine Devices Investigation Committee) [2]. Among notable findings in the post World War I era was the emergence of Rochelle salt and ADP as suitable piezoelectric materials and increased use of electronics in underwater devices.

The years of peace that followed the war retarded the pace of research in the field of underwater sound. Magnetostrictive projectors started finding increased use for echo ranging in echo sounders.

Ultrasonic frequencies were being used for both listening and echo ranging, which enabled increased directionality for both projectors and hydrophones. By 1938, when the World War II commenced, a large number of U.S ships were equipped with echo ranging sonars. The acoustic homing torpedo, the acoustic mine and scanning sonar were some of the war time contributions. During the period of World War II, effective methods for calibration of projectors and hydrophones were developed and the factors that influence the performance of these devices were investigated and identified.

After the conclusion of World War II the pace of activity did not lower to the extent that happened after World War I. The underwater detection and ranging devices were started to be used increasingly, in civilian sectors like fishing industry, hydrographic surveying *etc*. This resulted in changing the name ASDIC, which has military implications to SONAR. Emergence of Electronics also helped a lot to develop better underwater systems.

Considerable field experiments and theoretical studies were undertaken to understand the propagation of sound waves in sea water. Woolard, Ewing and Wazel made investigations on the deep sound channel, through which acoustic waves can be propagated up to thousands of miles.

Yet another post world war development was the introduction of more sophisticated techniques in the field of sonar signal processing [10]. In 1960, Anderson introduced multibeam steering system. By late 1960s and 1970s digital signal processing systems were introduced. In 1946 with the discovery of high piezoelectric effects in ceramics like barium titanate led to the development of modern piezoelectric transducers for underwater use with improved performance. Barium titanate is a ferroelectric and becomes piezoelectric by poling. Later lead zirconate titanate (PZT), a mixture of lead zirconate and lead titanate has been developed, which still finds lot of applications as a transduction material. PZT is a ferroelectric with polycrystalline structure and shows better piezoelectric properties than barium titanate. Extremely high piezoelectricity exhibited by certain polarised polymers came to be known in 1969.

The increased interest in achieving longer ranges resulted in the use of lower frequencies, to avoid the high absorption loss at ultrasonic frequencies. In 1991 an experiment called Heard Island experiment was conducted by Walter Munk of Scripps Institute of Oceanography, involving low frequency sound (50-70Hz), for world wide transmission through sound channel to study the global warming and related effects.

Thus with the technology becoming more and more sophisticated, the interest in oceans and underwater devices is also gaining enhanced momentum, both for military and civilian applications.

1.2 TYPES OF UNDERWATER TRANSDUCERS

A transducer is a device which converts one form of energy to another. In underwater acoustics, the transducers mostly used are of electroacoustic type [11-14]. The electroacoustic transducer converts acoustic energy to electric energy and vice versa. Transducers used mainly for the generation of acoustic energy are called projectors and those used for reception are called hydrophones. There are transducers which perform the tasks of both reception and transmission of acoustic energy and are known as reversible or reciprocal transducers. This type of transducers are widely used for sonar and underwater communication systems.

1.2.1 Performance characteristics

For most of the applications, the electroacoustic transducers may satisfy the following performance criteria [15].

(i) Linearity : The output of the transducer should be essentially a linear function of the input.

(ii) Passivity : The output energy whether electrical or acoustical is to be obtained only from the input energy whether acoustical or electrical.

(iii) Reversibility : The device should be able to convert electrical energy to acoustical energy and vice versa.

1.2.2 Transduction techniques

Even though there are a number of transduction techniques, most of the transducers rely on one of the two categories of transduction process, those which employ electrical fields for conversion and those which make use of magnetic fields. Almost all the transduction materials are not as such linear. The linearity is inducted into them by polarisation.

The electroacoustic transducers employing electric fields and magnetic fields are given below [16].

Electric Field Types

1. Piezoelectric
2. Dielectric
3. Electrostrictive
4. Spark Source

Magnetic Field Types

1. Electrodynamic
2. Electromagnetic

3. Magnetostrictive
4. Dynamometric

Except piezoelectric, magnetostrictive and electrostrictive types, all others are finding their applications in specialised purposes only.

1.2.2.1 Piezoelectric transducers

Piezoelectricity or pressure electricity is a peculiar property shown by certain crystalline materials which change their dimensions when subjected to an electric field or conversely which produce electrical signals when mechanically deformed. This effect arises because of the asymmetry in the crystal structure that creates an electric dipole moment in the crystal lattice which is sensitive to both elastic strain and applied electric field. Quartz, Rochelle Salt, Lithium Sulphate and Ammonium di hydrogen phosphate are some of the highly polar piezoelectric crystals.

1.2.2.2 Electrostrictive transducers

Electrostriction is a phenomenon shown by certain class of dielectrics known as ferroelectrics. In these materials electric dipoles with preferred orientations are formed simultaneously within certain localised regions of the crystal. Ordinarily these domains are randomly distributed and the net electric dipole moment of the material is zero. However the application of an electric field causes the domains to become aligned with the field resulting in the variation of physical dimensions of the material. Electrostrictive materials are inherently non linear and must be polarised to exhibit the linear transducer action. The polarised electrostrictive materials have properties similar to that of piezoelectric materials and are often referred to as piezoelectric. Examples of electrostrictive materials are barium titanate and lead zirconate titanate.

1.2.2.3 Magnetostrictive transducers

Magnetostriction is the capability of certain dielectric materials, in which randomly oriented spontaneously generated magnetic domains are aligned regularly when an external magnetic field is applied. This effect is dominant in certain ferroelectric materials like iron, nickel, cobalt and polycrystalline non-metals called ferrites. As in electrostrictive materials, polarisation is essential for ensuring linearity and reversibility. Due to its similarity with piezoelectric effect, the magnetostrictive effect is also known as piezomagnetic effect.

1.3 CLASSIFICATION OF TRANSDUCERS

There are only five to six basically different physical mechanisms used to achieve most electroacoustic conversions. Transducers can be classified into different groups according to the basic design. Some of these are briefly mentioned below.

1.3.1 Ceramic flexural disc transducer

In this configuration as shown in Fig.1.2, a single ceramic disc or a number of discs are laminated in between inactive discs like steel or aluminium. When the discs are driven, a flexing motion is produced in the structure. To keep the size of the ceramic disc within reasonable limits, they are assembled in mosaic form instead of single large pieces. This type of configuration is useful for high power low frequency applications. The disadvantage of this design is the dominance of the internal cavity impedance in determining the sensitivity at resonant frequency.

1.3.2 Flextensional transducer

In its common form as shown in Fig.1.3, a flextensional transducer has an elliptically shaped housing or shell, with a longitudinally vibrating ceramic stack mounted along its major axis. The housing itself acts as the radiating face, and the ceramic stack is pre-stressed by the shell to ensure that the active material does not go into tension and fracture at high drive levels. A single large shell or several small shells may be stacked together in a line configuration. The flextensional transducers are highly efficient but they are resonant devices and have a high Q than most of the non ceramic designs. The primary disadvantage is the complexity of the design, especially for lower resonance frequencies.

1.3.3 Ceramic bender bar transducer

As shown in Fig.1.4, the ceramic bender bar transducer has multiple bars arranged in a barrel stave configuration around a cylindrical housing. Each bar consists of two segmented stacks of ceramic and are hinged at each end. When stacks are driven, a bending motion is produced in the bars. The central cavity formed in the above configuration is usually filled with oil to compensate the hydrostatic pressure. This transducer is capable of producing high output power levels over a frequency range of an octave at depths of several hundreds of metres.

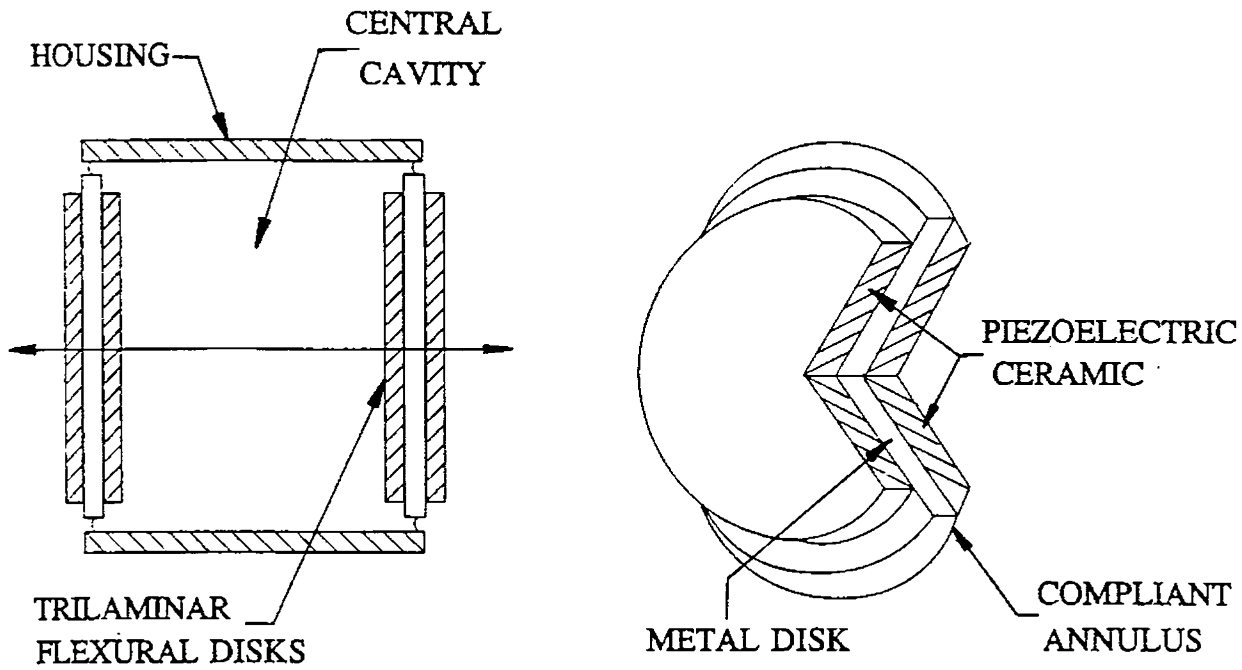


Fig. 1.2 : Flexural disk transducer

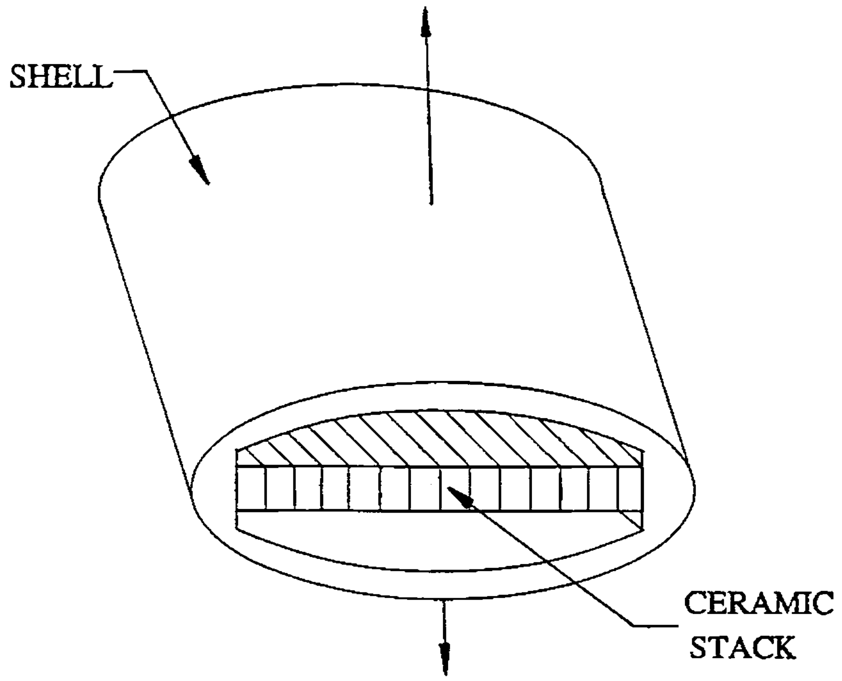


Fig. 1.3 : Flextensional transducer

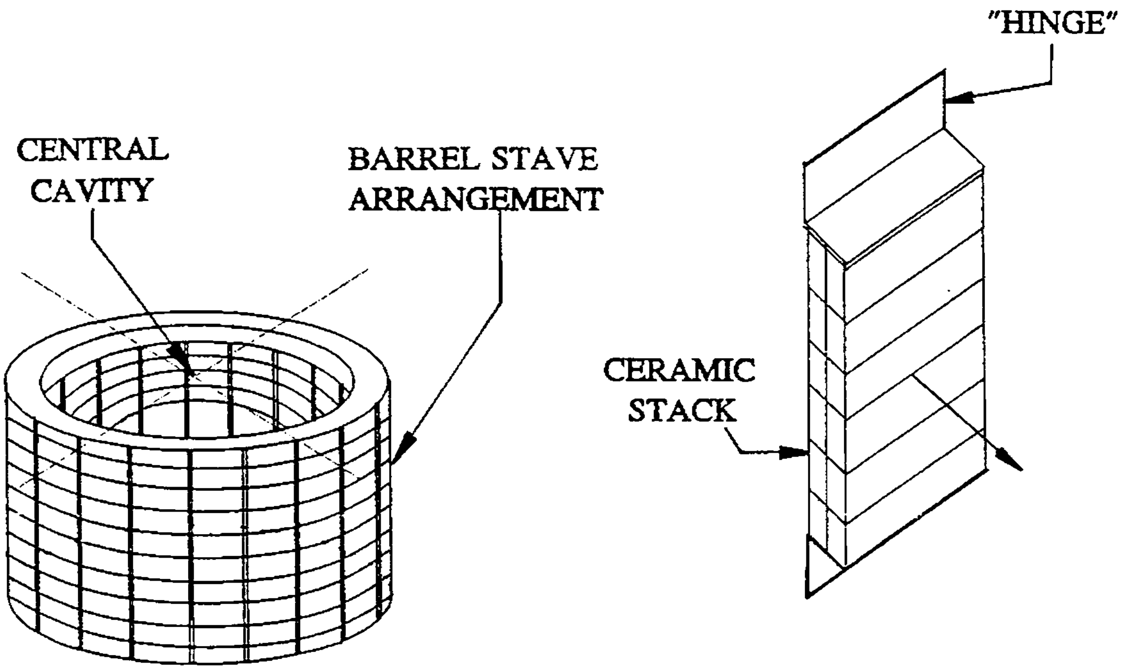


Fig. 1.4 : Bender bar transducer

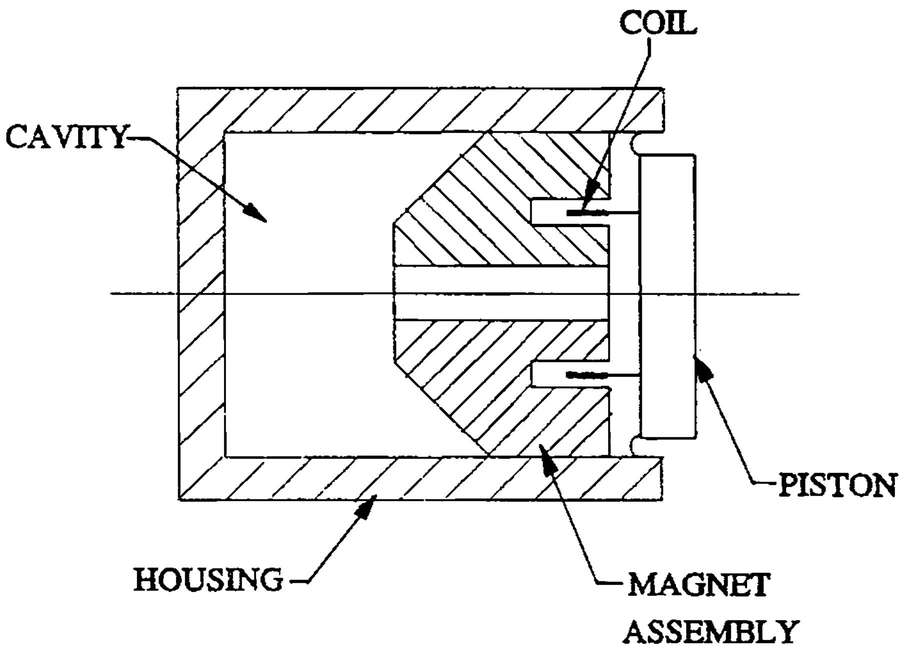


Fig. 1.5 : Moving coil transducer

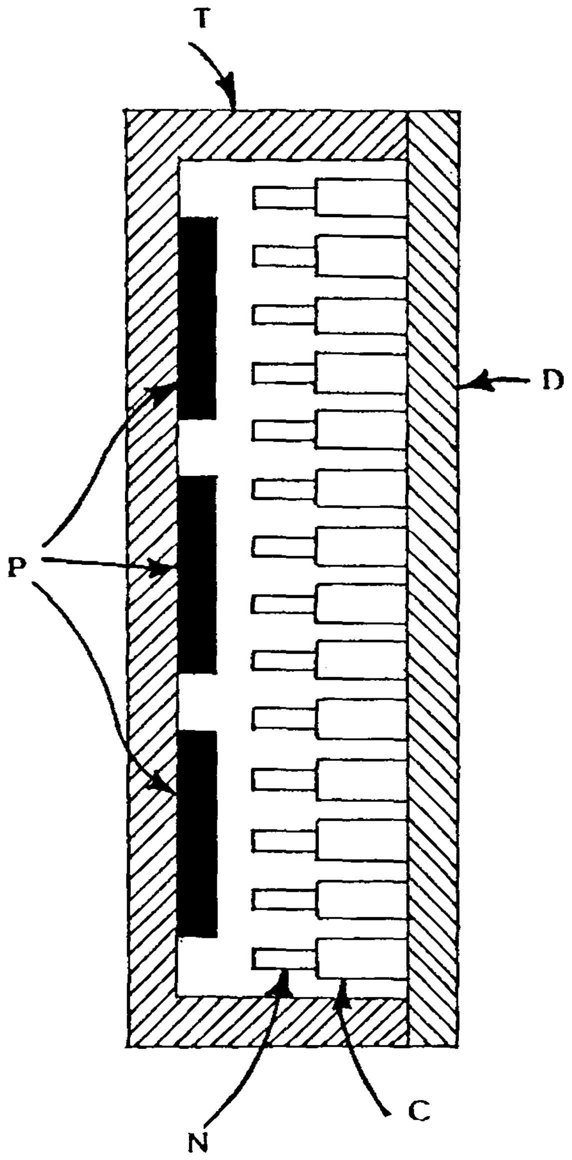
However its design is such that it uses a very large amount of ceramic and thus the transducer is heavy and expensive. As in the case of flexural disc transducer, the output power is limited by the electric field and the maximum stress that the ceramic can withstand.

1.3.4 Moving coil transducer

The electrodynamic or moving coil transducer shown in Fig.1.5, is one of the oldest designs still in use. The principle of working of this model is the interaction between an a.c. current moving in a conductor and a large magnetic field, which results in a driving force, and is used to drive a rigid piston radiator. The advantages of this type of transducers include, low resonant frequency, ability to accommodate large displacement and wide operating bandwidths. The disadvantages are inefficiency in transduction, relatively small output power and its variation with change in the depth of operation.

1.3.5 Magnetostrictive transducer

The most common type of magnetostrictive transducer is as shown in Fig.1.6. It is having a long thin ribbon of nickel rolled up in the form of a scroll and encapsulated with epoxy cement. The laminated ring thus formed is then wound with a toroidal winding of wire. A varying current in the winding produces a varying magnetic field in the circumferential direction of the ring, which changes the ring dimensions and causes it to radiate sound. The non-linearity between the variation in magnetic field and corresponding change in the material dimensions are thwarted by superposing a large external magnetic field with the smaller



T : TRANSDUCER HOUSING
P : PERMANENT MAGNETS
N : NICKEL TUBES
C : COILS
D : DRIVEN PLATE

Fig. 1.6 : Magnetostrictive transducer.

alternating magnetic field.

1.3.6 Non-linear acoustic transducer

Another different approach to the generation of sound in water is by the conversion of acoustic energy at two higher frequencies to acoustic energy at the difference frequency. This is usually accomplished by using a pair of transducers to transmit at two frequencies into the same volume of water. The non linear properties of the water causes the production of the difference frequency. The potential of such non-linear conversion is not much accepted as it depends on the environment of the water where the transformation occurs.

The transducer designs mentioned above are mainly described as projectors. Due to their reciprocal nature, most of these mechanisms have the capability to work as receivers also. Even though all the models are competently linear at the normal operating conditions, their linearity ceases once they are driven with sufficiently large forces. Surprisingly most of the transducers have efficiencies less than 50%.

1.4 MOTIVATION FOR THE PRESENT WORK

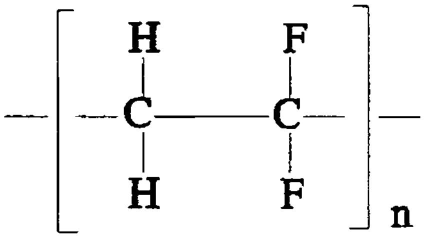
The increased range requirements in underwater detection and ranging resulted in the use of lower frequencies to avoid high absorption losses at ultrasonic frequencies. Acoustic waves propagate more through water with lesser attenuation, as the frequency decreases. If the sonar is to be used as a passive listening system, the receivers should be equipped with transducers having credible performance characteristics at low frequencies. Also there is a growing need in military for transducers that generate and receive low frequency underwater sounds to detect submerged targets located at far distances. However it is an arduous task to design a low frequency - high power transducer with high directionality and high efficiency, maintaining the device size, weight, reliability and cost to reasonable limits. Hence an attempt is made here to develop hydrophones operating at low frequencies with simple and cost effective design.

1.4.1 Piezopolymers as active materials

The performance of the transducer either as a receiver or as a transmitter is influenced by the property of the transducer material used. So great care should be taken to choose a particular material which simultaneously meets the various performance criteria, including that of the device and the medium in which the transducer has to operate.

Piezoelectric ceramics like lead zirconate titanate is a widely used active material. But it is brittle and stiff. Hence it is impossible to produce large sized transducers and difficult to machine in complex shapes. In 1969, Kawai discovered high piezoelectric effect shown by certain polarised polymers and since then these have been increasingly used in transducers replacing ceramics.

Polymers based on vinylidene fluoride show the highest piezo and pyroelectric effect. Among them the polyvinylidene fluoride shows high piezoelectric effect when poled. Polyvinylidene fluoride is a fluorocarbon resin with the following chemical constitution [17].



$$-\left[-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}-\overset{\displaystyle F}{\underset{\displaystyle F}{\overset{|}{\underset{|}{C}}}}-\right]_n-$$

The properties of the PVDF including its piezoelectricity, depend heavily on the type of its crystalline structure. The polymer can be crystalline in at least three distinct forms, known as α, β and γ phases or of forms II, I, III respectively. The most common phase is the non-polar alpha phase and results when polymer is cooled from its melt.

For significant piezoelectric activity in PVDF, the polymer must be poled. Poling process involves electroding both surfaces of the polymer film and subjecting the polymer to electric field of 1 MV/cm at high temperatures followed by cooling with the applied field. Resultant piezoelectric activities depend on the poling time, field and temperature. The activity saturates at high poling fields and long poling times. Recently new poling techniques have been developed such as carona poling, plasma poling and short time room temperature poling with high electric fields.

The piezofilm, a flexible light weight, tough, plastic film, is commercially available in a wide variety of thicknesses and with large cross-sectional areas. Some of the advantages of the piezofilm are,

- Wide frequency range - from 0 to 10^9 Hz.
- Vast dynamic range - sensitive to both minute and explosive forces.
- Low acoustic impedance - resulting impedance match to water, human tissue *etc.*
- High elastic compliance - faithfully reproducing input forces.
- High voltage output - 10 times higher than piezoceramic for the same force input.
- High dielectric strength - can withstand strong fields.
- High mechanical strength and impact resistance.
- High stability - resisting moisture, most chemicals, oxidants *etc.*
- Relatively low raw material and fabrication costs.

Along with these salient features, the film can be easily fabricated into unusual designs, and can be adhered to any complex structures. Table 1.1, is a comparison of the acoustic properties of some of the materials.

TABLE 1.1 : Acoustic properties of some materials

Material	Density (ρ) 10^3 kg/m^3	Velocity of sound (V) 10^3 m/s	Acoustic Impedance (Z) 10^6 kg/s-m^2
Water	1.0	1.5	1.5
PVDF	1.8	2.2	3.9
PZT	7.5	3.2	24
PMMA	1.2	2.7	3.2
Brass	8.5	4.4	37
Epoxy	1.2	2.5	3.0

1.5 BRIEF DESCRIPTION OF THE PRESENT WORK

A schematic of the work carried out in this thesis is as follows.

A review of the work done in the field of underwater electrostrictive transducers particularly using polarised ceramics and polymeric materials is presented in Chapter 2. More emphasis is given for designs with PZT and PVDF.

The methodology adopted and experimental facilities and techniques used for the present investigation are highlighted in Chapter 3. The design philosophy adopted for the development of a (3,1) drive piezofilm hydrophone are explained in this chapter. The different field facilities, methods and infrastructure used for the evaluation of the performance of the experimental hydrophones are also elaborated. This chapter also throws light on the procedure to determine the directional response of the hydrophone and the design details of the additional preamplifiers incorporated with the test hydrophone to increase its signal-to-noise ratio.

Chapter 4 describes the different (3,1) drive hydrophone designs attempted and their experimental results. An overall study of the influence of the various design parameters on the performance of the above hydrophone design are also included.

Chapter 5 is mainly devoted to the extensive design procedures and experimental results of a refined (3,1) drive hydrophone design. This chapter also presents the theoretical analysis leading to the determination of the resonant frequency of the hydrophone model described along with an investigation on the probable factors which influence the resonant frequency of the hydrophone. Studies on the directional response of the hydrophones are also included in this chapter.

Multifilm hydrophone designs with two piezopolymer films are described in Chapter 6. The performance characteristics of two multifilm designs are presented here.

Final conclusions drawn from the above investigations are the essence of Chapter 7. Scope for further work in this area is also dealt within this chapter.

Chapter 2

Review of past work

Literatures available on various design aspects of underwater transducers are manifold [15,16,18-20], most of them dealing with sonar transducers using polarised electrostrictive ceramics and polymers as transduction materials. Some of the important contributions reported, particularly in the field of electroacoustic transducers using polarised ceramics and polymers along with the various experimental and theoretical results obtained are reviewed in chronological order. The chapter mainly consists of two sections, the first section dealing with the productive designs using ceramics and composite materials, where as the second section on polymeric transducer configurations alone.

2.1 CERAMIC TRANSDUCERS

Edward G. Thruston [21] derived the theoretical sensitivity of three different types of rectangular bimorph transducer elements while operating below their resonance frequencies.

The low frequency acoustic sensitivity of cylindrical barium titanate ceramic tubes with different boundary conditions were reported by R.A. Langevin [22]. A support for the idea of using cylindrical ceramic tubes for underwater applications were shown by C.P. Germano [23].

A theory had been devised by C.V. Stephenson [24] for the vibrations of long thin rods of piezoelectric barium titanate, with the electric field parallel to the length. The theory also shows how the coupling coefficients and piezoelectric constants are related to the fundamental resonance and anti-resonance frequencies. Experimental support also proposed to verify the theoretical results.

An optical interference technique employing stroboscopically illuminated multiple beam Fizeau fringes had been used by E.A.G. Shaw [25] to study the surface motion of barium titanate disks. Stress distributions for three important modes in the thickness resonance region had been accurately measured experimentally and compared theoretically.

A bubble transducer with a conventional low impedance electrodynamic driver with an air filled rubber membrane of adjustable volume over the diaphragm was used by Claude S. Sims [26] for transmitting very low frequency acoustic waves into water with reasonable power output.

The transient response of piezoelectric transducer was analyzed by M. Redwood [27] for a plate transducer in compressional and thickness vibration and for a bar in compressional length vibration. The various results were compared.

Paul M. Kendig [28] examined the physical properties and dimensions that determine the equivalent noise pressures of several different shapes of piezoelectric transducers. Expressions were also given to determine the equivalent noise, pressure, free-field voltage response and electroacoustic efficiency of the transducers below their resonance, using easily measurable parameters. As an extension of this work, T.F. Hueter and P.H. Moose [29] gave optimum hydrophone design for low frequencies.

The importance of signal to noise ratio of the transducer rather than its efficiency is highlighted by Ralph. S. Woolett [30]. He also analyzed the different transducer parameters which used to influence the performance of the hydrophone receiving system in which amplifier noise is dominant.

H.F. Tiersten [31] investigated on the thickness vibrations of an infinite anisotropic plate with electrodes coated on both sides, using linear piezoelectric equations. This theory was applied to ferroelectric ceramics with plate polarised in thickness direction and also for the one with polarised along its plane.

The theory of vibration of longitudinally polarised, thin wall ferroelectric ceramic tubes was derived by Gordon E. Martin [32] using the tensor approach.

George Kossoff [33] analyzed the effects of backing and matching on the performance of transmitting and receiving PZT7A transducers working in water.

Considerable enhancement of bandwidth was obtained by quarter wave matching between the backing and the load.

A mathematical model was developed by L.H. Royster [34] to investigate into the working principle of flextensional underwater acoustic transducer. The effects of various design parameters on its performance were also evaluated.

Ralph A. Nelson Jr. and Lary H. Royster [35] developed a mathematical model for Class V flextensional underwater acoustic transducers. A comparison was also made with the results from the experiments.

A mathematical modelling of a sandwich transducer based on longitudinal variation of particle displacement was presented by R. Dominguez *et al.*[36]. A general equation was deduced in which physical and geometrical characteristics of three layers that form the transducer were included.

Piezoelectric ultrasonic transducers of the Langevin type were illustrated by A.P. Hulst [37]. The type of transducers which can be designed for any frequency between 15 to 150 kHz, and having capacity to handle a power intensity of more than 40 W/cm^2 were described.

A method for developing wide band (0.5 - 20 MHz) transducers for pulse-echo systems was suggested by A.F. Brown *et al.*[38]. Excitation of transducers was achieved by specially shaped electrical pulses while for the reception mode, high gain wide band amplifiers and gates were used.

A design technique for acoustic thin disk transducers with high efficiency, broad bandwidth and good impulse response was presented by Charles S. Desilets *et al.*[39]. The method was largely based on the use of quarter wave matching layers between piezoelectric material and the acoustic load. Several transducers were built to illustrate the design approach with excellent agreement between theory and experiment.

K.L. Narayana *et al.*[40] worked on the transcendental equations relating the dimensions of a sandwich transducer to its impedance. Experimental verifications were also provided for the theory.

Construction and testing of short pulse ultrasound transducers with several examples were discussed by F.S. Foster *et al.*[41]. With a novel approach, they developed equations for the prediction of radiation field of short pulse transducer. Good agreement was observed between the experimental and theoretical results.

Jeffrey H. Goll [42] investigated on the performance of thin disk transducers using acoustic impedance matching and backing.Design of fluid loaded ultrasound transducers with a low transducer loss and high bandwidth were also described.

A mathematical model for the Tonpilz piezoelectric transducer using non linear goal programming techniques were developed by Diana. F. Mc Cammon *et al.*[43]. The theory was applied on the design of a simple hypothetical design.

T.A. Henriquez and A.M. Young [44] discussed the use of Helmholtz resonator for low frequency underwater acoustic applications. Effect of various design parameters on its performance were also analyzed.

W. Werging [45] presented PZT ceramics, which were like $PbNb_2O_6$ and had low mechanical Q values. Such materials are widely being used for the construction of wide band transducers.

Susan M. Cohick and John. L. Butler [46] constructed a rare earth iron magnetostrictive transducer in the form of a square ring, to operate in dipole mode and in omni mode. Having about 16.5 cm diameter, it was found to be resonating at 2 kHz in the omni mode and 2.4 kHz in the dipole mode.

A piezoelectric acoustic emission transducer with almost flat transmitting response over the frequency range of 50 kHz to 1 MHz was designed and developed by Thomas M. Proctor [47]. This transducer consists of a conical active element and extended backing. The factors that influence the response such as backing geometry and aperture size have also been experimentally investigated.

J.J. Bernstein *et al.*[48] examined experimentally and theoretically electret transducers made of anodized aluminium and compared their response with other electret condenser and piezoelectric transducers.

A deeper understanding on the use of PZT polymer composites for ultrasonic medical diagnosis was attempted by T.R. Gururaja *et al.*[49]. The composites originally developed for low frequency hydrophone applications were suitably used for ultrasonic range. These composites were prepared with 5 to 30 volume percent of PZT using 0.28 mm and 0.45 mm thick rods.

Gordon Heyward *et al.*[50] presented a new three port model of thickness mode piezoelectric transducer employing linear systems theory. A number of experimental and simulation results were also included for comparison.

S.C. Shorter and B. Bridge [51] described the design, construction and performance of a set of immersion probes using lead zirconate titanate and quartz piezoelectric elements. These multiple frequency operation probes had useful frequency coverage from 3-170 MHz. A comparison of the two transducer materials and a comprehensive study of their output power as function of frequency were also presented.

The design of an improved wide band transducer was given by M.W. Godfrey *et al.*[52]. Additional techniques were also suggested to strengthen the structure further along with an increased sensitivity.

Ultrasonic micro-probe hydrophones with element dimensions of less than 1 mm had been constructed by B. Moffet *et al.*[53] using various piezoelectric materials. The best type consists of a single 0.8 mm × 0.8 mm × 0.4 mm slab of lead titanate supported by 0.08 mm wires and potted in ρc polyurethane. This hydrophone was found to be showing a sensitivity of -234 dB re: 1V/μPa and omnidirectional response up to 500 kHz.

A.E. Karpel'son [54] suggested methods for designing ultrasonic piezoelectric transducers with a specified directivity pattern. General formulae were also given for the design problem. The experimental results presented support the theoretical conclusions.

Acoustoelectric transducers with uniform and non-uniform distribution of piezoelectric coefficients were designed and developed by Francois Chapeau *et* *al.*[55]. The experimental results were compared with then available theoretical results.

A review of the basic characteristics and progress in the transducer properties of different types of piezoelectric ceramics were reported by J.A. Gallego - Juarez [56]. The application of these materials in the practical ultrasonic transducers were also suggested.

Feasibility of using 0-3 piezoelectric composites for large area hydrophones were studied by N.M. Shorrocks *et al.*[57]. They used polymers of 0-3 connectivity with ceramic powder dispersed in it. These low cost hydrophones were found to be showing figure merit of 8×10^{-12} $Pa^{1/2}$. The effects of processing variables and other parameters on composite properties were also discussed.

A method for designing piezoelectric transducers using one and two quarter wavelength matching layers was presented by R. Salaman [58]. Using this method the impedance values of matching layers could be determined, which facilitates in achieving the required bandwidth.

W.A. Smith *et al.*[59] described the trade offs in designing piezoelectric composites, so as to enhance the performance of the conventional ultrasonic transducers, and also to attempt new improved designs.

R.Y. Ting [60] developed hydrophones using porous PZT, '0-3' and '1-3' ceramic polymer composites and non-ferroelectric glass ceramic composites. The experimental results were also given, which confirms the potential of these materials for underwater acoustical applications.

A unidirectional magnetostrictive/ piezoelectric hybrid transducer was constructed by John L. Butler *et al.*[61]. In its simplest form this transducer consisted of a quarter wave length section of piezoelectric material joined to a quarter wave length section of Terfenol-D, a rare earth magnetostrictive material. A 3 kHz experimental transducer with a total length of approximately 18 inches was constructed.

Diverse developments in the field of flextensional transducers were discussed by Kenneth D. Rolt [62]. A review was also made on the history of flextensional transducers. Different class of flextensional transducers and their future design trends were also examined.

J.E. Blue [63] reported the idea of using hydrodynamically modulated resonant cavities for generating acoustic pressures in the lower frequencies of the order of 10 to 100 Hz with source levels of 200 dB re: 1μPa. Experimental results from such devices showed source levels of 182 dB at 50 Hz and 168 dB at 34.5 Hz.

R.W. Timme *et al.*[64] examined the growing need and the constraints associated with the design of low frequency projectors and receivers. Different design approaches and transducer types were discussed and compared.

P.J. Kielozynski *et al.*[65] designed and tested ring piezoelectric transducers generating ultrasonic energy in air. The experimental results were compared with the numerical ones. Resonance frequency of the transducer was also determined experimentally and verified theoretically.

The vibrational modes of axially symmetric piezoelectric ceramic disks had been calculated by H.A. Kunkel *et al.*[66] using finite element method. For different types of disks, series and parallel resonance frequencies for each mode were determined using eigen frequency analysis and effective electromechanical coupling constants were calculated. The ratio of diameter to thickness of the disk was optimised for better transducer performance.

M. Bandys *et al.*[67] proposed a method for characterisation of ceramics used as transducers clamped in the sandwich construction. The dielectric and mechanical losses, electroacoustic efficiency and dynamic stress in transducers as a function of electric field, for ultrasonic power applications were described.

J.N. Dacarpigny *et al.*[68] discussed the difficulties faced in the design of low frequency projectors for sonar and oceanographic applications. The problems mainly related to the size of the projector, its radiation resistance, acoustic interaction effects in arrays *etc*. Different low frequency projectors were described and compared along with the general trends associated with the transducer shapes, dimensions and active materials were reviewed. Different modelling approaches were discussed and an insight into the respective advantages and disadvantages of the classical equivalent circuit model and the numerical model were also surveyed.

2.2 PIEZOPOLYMER TRANSDUCERS

H. Kawai [69] discovered the piezoelectric effect in the elongated and polarised films of polymers, particularly in Polyvinylidene Fluoride (PVDF) films.

S. Edleman *et al.*[70] enhanced the piezoelectric activity of bulk polymers by improving the poling techniques. The measured value of piezoelectric strain constant d_{31} of polyvinyl chloride was 0.6×10^{-12} m/V and the electromechanical coupling factor k_{31} was 0.6%. A sensitivity of -112 dB re: 1V/μ bar was obtained for a transducer developed using the above material.

J.H. Mcfee *et al.*[71] made the polyvinylidene fluoride films highly pyroelectric and optically non linear by poling in a field of around 10^6 V/cm.

Different types of transducers like stereophonic headphones, tweeters, microphones and phonograph cartridges were developed by Masahiko Tamura *et al.*[72] using very thin piezoelectric high polymer films. All these transducers were made from polyvinylidene fluoride films having thickness between 8 μm to 30 μm.

The piezoelectricity in polymers, electrets *etc.* along with the various applications of piezoelectric polymer films were surveyed by N. Murayama *et al.*[73].

L. Bui *et al.*[74] adopted simple procedures for the development of broad band ultrasonic transducers using PVF_2 piezoelectric plastic film. Frequency spectra of impulsed transducers using films of 25 and 50 μm thickness. centred at 10 and 5 MHz were also shown.

The suitability of polyvinylidene fluoride as an underwater transducer material was examined by B. Woodward [75]. He also measured the piezoelectric constants like d_{33}, g_{33} and the dielectric constant, which together determined the transmitting and receiving performance of a transducer in the thickness direction.

Dependency of the receiving response on the poling fields and temperatures used in making PVDF transducers were also evaluated.

Len. Bui *et al.*[76] measured the acoustic loss factor and piezoelectric coupling coefficient of poled polyvinylidene fluoride films. A theory was also developed to determine piezoelectric resonance in unsupported films and compared these values with the measured ones.

A variable focus ultrasonic transducer which finds applications in medical imaging was described by S.D. Bennett *et al.*[77] using PVF_2 film. By controlled deformation of the stretched PVF_2 membrane, the focal point can be scanned axially. A theory was also proposed in support of the design.

N. Chaubachi and T. Sannonuiya [78] developed PVF_2 acoustic transducers for generating and detecting VHF ultrasonic waves in water. It consisted of PVF_2 transducer formed on a substrate with higher acoustic impedance. Two types of composite resonating mode transducers were described.

Feasibility of using piezopolymers as transduction materials for hydrophone construction were shown by T.D. Sullivan *et al.*[79]. In the design, the PVF_2 was mounted on a flexure circular disk and the pressure strains developed on the disk due to the incident acoustic pressure were used to excite the PVF_2 film. Different improvements in the original design were made to increase the sensitivity. Hydrophones which can withstand up to 4 MPa and with sensitivities of around - -200 dB re: $1V/\mu$ Pa were constructed.

G.R. Crane [80] demonstrated the usefulness of piezoelectric polymer polyvinylidene fluoride for sensors in coin operated devices. As polymers offers high sensitivity, low cost and ease of handling and processing, this material can be extremely attractive for these applications.

F. Micherson and C. Lemonon [81] constructed new types of piezoelectric polymer transducers by moulding the polymer in three dimensional surfaces like cones, portions of spheres, corrugations *etc.* and then were poled electrically. These type of transducers were used for high range loud speaker applications. The films were moulded in three dimensional surfaces such as curves, portions of spheres, corrugations *etc.* which were locally stretched and then electrically poled. Such transducers could be designed for particular acoustic characteristics (resonance modes, bandwidth, directivity), which could not be obtained with plane or curved films.

Design and construction of PVDF transducers with different backing materials were reported by N.C. Sasady and A. Hartig [82]. Advantageous features offered by the thickness mode of vibration of the film, for underwater applications, extending up to the MHz range were also analyzed.

Reinhard Lerçh [83] investigated theoretically and experimentally microphones with cylindrical and spherical diaphragms of polyvinylidene fluoride. The response of the microphones were calculated by using parameters like diaphragm geometry, acoustic impedance of the surrounding medium, coupling volume and excitation. A relationship was also established between the output voltage of the microphone at low frequencies and the position of its resonance frequency. A good agreement was observed between the theoretical and experimental frequency responses.

E. Carana *et al.*[84] used thin film PVF_2 polymer transducers operating in the thickness mode for the detection and generation of surface acoustic waves on ceramic substrate. Wide band acoustic pulses were generated using this assembly, and performance of the transducer was also evaluated.

D.T. Wilson *et al.*[85] described design and performance of a PVF_2 microprobe suitable for mapping pressure fields from arrays. Having a centre frequency of 3 MHz, this probe was made of a PVF_2 film of 1.5 mm diameter and $30\mu m$ thick. Its experimental performance was compared with the theoretical predictions, both acoustically and electrically.

J. Sussner [86] emphasized the unique advantages of PVF_2 as a transducer material, compared with other materials used in ultrasonic, audio and medical applications.

W.R. Scott [87] examined the problems faced by the conventional techniques used for lead attachment to PVDF transducers. The proposed lead attachment technique provided high mechanical stability, electrical power capacity and over all durability. Some of the transducers thus evolved using this technique and their applications were also described.

Piezoelectric microphones with rigidly supported curved polyvinylidene fluoride membranes were described by R. Lerch and G.M. Sessler [88]. These microphones were designed for a resonance frequency of 5 kHz, showed a sensitivity of -55 to -60 dB $V/N/m^2$. A well designed geometry of the membrane, good mechanical and thermal stability, possibility of varying the membrane tension *etc.* were some of the features of this design.

The acoustic response of rigidly backed PVF_2 to voltage and current source electrical drive was analyzed and broad band nature of the response to current source drive was demonstrated by Robert G. Swartz and James D. Plummer [89]. A multiple layer stack was used for increasing the available power output from the PVF_2 transducer. To verify the theory an experimental support was also included.

K.C. Shotton *et al.*[90] described a hydrophone for measuring the spatial and temporal distributions of pressure within the fields from medical equipment. The device consisted of an acoustically transparent plastic membrane with a small, central region activated to provide a freely suspended piezoelectric element. The response of this prototype hydrophone and some of its applications were also described.

S. Kovnovich and E. Harnik [91] proposed a simple method for the generation and detection of short duration stress pulses using poled PVDF films. This type pulses are used for high resolution ultrasonic applications.

M. Toda *et al.*[92] investigated experimentally and theoretically the bending properties of a double support PVF_2 bimorph cantilever structure. Using the analytical results, double support structures for specified conditions were designed. Typical properties of a $9\mu m$ thick double support bimorph were also given.

Theoretical and experimental studies of electroacoustic transducers using piezoelectric foil membrane supported in its centre by rigid support were described by R. Lerch [93]. These hydrophones showed sensitivities in the range of -55 to 60 dB V per N/ m^2 with electroacoustic transmission factors in the range of 70 to 90 dB SPL re: 1V input voltage. Solutions were also given for the static and dynamic deflections of the membrane.

Norman F. Foster [94] demonstrated experimentally and explained theoretically the structure and behaviour of piezoelectric thin films for both bulk and surface wave applications.

Michel A. Marcus [95] reviewed the physical properties of PVF_2 polymers and their applications were classified on the basis of transduction mechanism including electrical to mechanical, mechanical to electrical, thermal to mechanical, thermal to electrical, and optical to mechanical. Advantages and disadvantages of using these ferroelectric polymeric materials were compared with the conventional materials.

Miniature piezoelectric polymer hydrophones for ultrasonic field characterisation in the low megahertz region had been developed and tested by A.S. De Reggi *et al.*[96]. The principal advantages of these devices as regards to their uniform frequency response and minimal perturbation of the field were achieved by rendering a small central region of a thin sheet of polarised PVDF and then supporting the sheet in the field by holding it taut in a metal hoop having dimensions larger than the field being probed.

Piezoelectric Zinc Oxide films of about 10 μm thick were used by Richard M. White *et al.*[97] for the construction of transducers. The developed ultrasonic transducers used these films which were deposited in a planar magnetron radio frequency sputtering system on 50 μm thick stainless steel shim stack so as to make ultrasonic transducers for NDT and acoustic emission applications. A theoretical analysis based Mason equivalent circuit were also included.

Transient fields of pulsed ultrasonic sources radiating into water were investigated by Gerald. R. Harris *et al.*[98]. Dot and annular polyvinylidene fluoride spot poled membrane hydrophones with element dimensions ranging from 0.3 mm to 1 mm were used. The transient ultrasonic fields were generated using thick piezoelectric circular plates and broad band thickness resonant disks.

The experimental determination and theoretical evaluation of the frequency response, directivity and electrical characteristics of a membrane hydrophone were described by David. R. Bacon [99]. This hydrophone was found to be useful for studying acoustic waves in the frequency range of 1- 100 MHz and for investigating the properties of PVDF.

Broad band shock hardened hydrophone was developed by Theodore A. Henriquez [100] using PVDF piezopolymer in tubular form. This hydrophone displayed flat frequency response to over 5 kHz and a smooth usable response over 50 kHz, along with the capability to withstand explosive shocks greater than that specified for Naval use.

Gerald.R. Harris [101] studied the receiving sensitivities of piezoelectric polymer polyvinylidene fluoride hydrophones constructed using spot poled membrane design. Sensitivity variations within 1 dB from 1-10 MHz were achieved for hydrophones with active element diameters from 0.3 to 1.0 mm. Receiving sensitivities of -234 to -268 dB re: 1V/ μPa were obtained for different element sizes and amplifier configurations.

The design theory for a variety of piezoelectric polymer flexure mode devices like unimorph, bimorph and multimorph were presented by Michel A. Marcus [102]. Their resonance and deflection behaviour were discussed along with their output characteristics. The effects of electrodes and bonding layers were included in the analysis. Flexure mode devices were constructed from non uniformly polarised piezoelectric polymers.Experimental results for a variety of flexure mode devices were compared with the theory and application of these flexure mode devices were also surveyed.

The performance of miniature piezoelectric polymer ultrasonic hydrophones were described by Peter A. Lewin [103]. Their application as reference hydrophones and as probes in ultrasonic measurement of tissue properties were discussed along with the advantages of needle like construction. A novel calibration technique based on time delay spectrometry which allows the hydrophone probe free field parameters to be determined as a continuous function of frequency in reverberant environments, while keeping signal to noise ratio high.

A. A. Schoenberg *et al.*[104] developed small flexible tactile sensor for mounting on the thumb or fingers. This sensor used ultrasound to measure the amount of compression in a thin rubber layer. Its dynamic response up to 10 Hz was demonstrated and much higher rates up to 200 Hz were found to be possible. The construction was based on using piezoelectric plastic film to measure the amount of compression of 1.5 mm thick rubber array element by measuring the time of flight of an ultrasonic pressure pulse in the rubber. The sensor construction and the related electronics to generate and measure ultrasonic pulses were also described.

The suitability of different piezoelectric materials as generators of ultrasound for surgical, therapeutic and diagnostic purposes in medicine was discussed by A.N. Hadjicostis *et al.*[105]. PVF_2 had been preferred because of its low characteristic impedance which is comparatively nearer to that of the human tissue.

The design, construction and testing of polyvinylidene fluoride catheter tip transducer operating primarily in the extensional mode for the detection of inter-cavitary pressure and sound was described by P. Dario *et al.*[106]. They compared the capability of PVF_2 sensor to detect faithfully pressure wave forms and sounds than that with the commercial silicon strain gauge micro-transducer.

P.TH.A. Klaase [107] investigated variations in the piezoelectric, mechanical and dielectric properties of PVDF films along its plane and in the thickness direction, with the methods of its preparation. He optimised the film properties for specific applications like as a bimorph vibrator which made use of the in plane properties and ultrasonic transducer which utilised the thickness properties. A method was also suggested to enhance its performance by incorporating non piezoelectric backing material.

A substantial improvement in the image quality derived from a PVDF sensor compared to a half wave resonant x-cut quartz crystal, for ultrasonic imaging applications along with its performance in high vacuum were discussed by P.H. Brown [108], in terms of a detailed analysis of the way in which the acoustic wave enters the sensor plane and spread by the multiple reflection process.

A ρc hydrophone which is acoustically transparent in water was developed by Mark B. Moffet *et al.*[109]. They used voided PVDF and ρc window material for the construction of a ρc hydrophone, whose response was essentially free from resonance and diffraction effects.

PVDF membrane hydrophone was developed by H.R. Galeantree [110], which showed a flat frequency response and wide frequency range 0.5 to 15 MHz for calibrating ultrasonic transducers. The co-planar shielded device consists of a single layer of PVDF film, which was at the centre of the membrane.

D.A. Hutchins *et al.*[111] elaborated the transient pressure fields of pulsed polyvinylidene fluoride transducer experimentally and compared with the theory in three dimensions. The transducers were in the form of disks, cones or bowls, excited with a range of known transients in the form of gated sinusoidal voltages. A good agreement between theory and the experiment was observed. It was also shown that PVDF transducers may be manufactured so as to behave as plane piston radiators.

David R. Fox [112] used PVDF cable for the construction of a simple hydrophone design. Having a sensitivity of -183 dB V/ μPa, this hydrophone could be made in lengths from 4 cm to more than 1m, and diameters from 8 to 40 mm.

The design was centred on a helical structure which translates the hydrostatic pressure field into longitudinal compressive strain in the cable. Excellent pressure stability (0.04 dB/MPa) along with a flat frequency response was achieved from 1 Hz to several kHz and hence could be used in low frequency sonar applications.

S.P. Robinson [113] gave an account of needle probe and membrane PVDF hydrophones. A thin walled metal tube of about 1 mm diameter and a thin needle like structure supporting the active element constitutes the needle probe hydrophone. The membrane hydrophone is made of a thin sheet of PVDF film stretched over an annular ring with gold electrodes deposited on the membrane. The needle probe hydrophone showed better sensitivity than the membrane hydrophone, but its sensitivity exhibited considerable variations at lower frequencies. The membrane hydrophone had the advantage of allowing the sound beam to pass through the membrane with minimal disturbance. It had response which corresponds to that of an ideal hydrophone.

C.C. Hebegar *et al.*[114] made a study on the quality of acoustic coupling achieved by pressing neoprene faced PVDF transducers to a solid surface without an intervening couplant. Efficient coupling was realized with these transducers when they were operated within the prescribed ranges.

An ultrasonic contact transducer generating point focused Rayliegh waves along the flat surface of the specimen was developed by B.G. Kim *et al.*[115] using PVDF. This transducer displayed a beam width of 6 dB and high echo amplitude. This device could be used for detecting and imaging surface cracks and sub surface defects. A simplified model developed for echo amplitude showed good agreement with the measured results.

H.L.W. Chan *et al.*[116] fabricated hydrophones suitable for the characterisation of medical ultrasonic transducers using polyvinylidene fluoride trifluro ethylene (VF_2 - VF_3) co-polymer. Both needle type and line hydrophones were constructed and their experimental results were reported.

Lewis F. Brown and David L. Carson [117] presented a method for determining the piezoelectric constants and the frequency dependent dielectric properties of polymers from a five step algorithm based on the analysis of air loaded broad band impedance measurements. It was then shown to account for the frequency dependent lossy properties of these films in an equivalent impedance circuit model and a modified Masons model. Comparison between the models and actual film transducers showed excellent broad band simulation of both input electrical impedance and ultrasonic pulse echo performance.

C.C. Habeger and W.A. Wink [118] presented a simple way to construct multiple active element ultrasonic transducers using PVDF. This hydrophone finds applications in pulse echo measurements using separate transmitter and receiver.

PVDF transducers with sturdy constructions suitable for operating in industrial systems as well as for laboratory applications were described by M. Platte [119]. A comparative study on the basic constructions and other transducer parameters of ceramic as well as polymer transducers were also given.

A focused conical transducer had been developed by H. Hurmila *et al.*[120] using PVDF film. The specific application of these ultrasonic transducers include NDT and other similar applications.

Chapter 3

Methodology

In this chapter a detailed description is made on the design philosophy adopted, which led to the development of the (3,1) drive hydrophones, along with the test facilities, experimental set-up and methodology employed for validating their performance.

3.1 DESIGN PHILOSOPHY

Availability of piezofilms in different shapes and sizes opened new vistas in the vast field of transducers, particularly for underwater applications. Piezopolymers are more sensitive than quartz and far more sensitive than ceramics as a transformer of mechanical to electrical energy [17]. KYNAR piezofilm manufactured by Pennwalt Corporation is used in the present work. The basic resin used for Kynar piezofilm is Polyvinylidene Fluoride (PVDF), which exhibits good piezoelectric properties when poled. For collecting the charges developed on its surface, the piezofilm is usually provided with metallised coatings on its surfaces. Of several metallisation available, film with tin aluminium metallisation is used in this work. First some preliminary experiments were carried out on the film to study its transduction properties.

Like all other piezoelectric materials, the PVDF is also highly anisotropic. Hence the electrical and mechanical responses differ for electrical and mechanical excitations along different directions. The mechanical output produced for a particular electrical excitation is determined by the piezoelectric strain constant d, and the equivalent electrical output developed for a given pressure input is defined by piezoelectric stress constant g.

The film's axes or drives are identified by numerals shown in Fig. 3.1 [17].

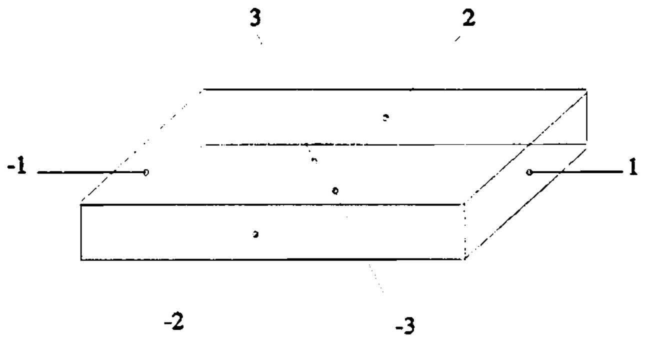


Fig. 3.1 : Numerical Classification of Axes.

$i = 1,2,3$ corresponds to length, breadth and thickness drive respectively. If an electric field E is applied, corresponding strain in the film is defined by,

$$S_i = d_{3i}E \tag{3.1}$$

S_i and d_{3i} are the strain developed and piezoelectric strain constant respectively in the i^{th} direction. In the Eq. (3.1) the first numerical subscript is the axis of polarisation or applied electric field and the second subscript denotes the mechanical stress or strain axis.

Similarly for a stress of X applied in the i^{th} direction, the resultant voltage output will be,

$$E = g_{3i}X_i \tag{3.2}$$

where E is the resultant output voltage and g_{3i} is the piezoelectric stress constant in the ith direction.

3.2 STRETCH DRIVE VIBRATION OF PVDF

Most conventional transducers utilise thickness or (3,3) drive of vibration. In this drive, the film is made to vibrate normal to its surface and the output is taken across the film.

During the process of poling, the film is subjected to a stretching process in a particular direction, while applying a high d.c. field. This direction is termed as the stretch direction. In the stretch drive, known as (3,1) drive, of vibration the film is intended to vibrate along the direction of stretching and the output is taken across its electroded surfaces.

Table 3.1 presents the piezoelectric constants and acoustic impedance of commonly used pressure transducer materials [17]. As can be inferred. the high piezoelectric stress constant and low piezoelectric strain constant makes the film highly voltage sensitive. The product of the stress and strain constants is a measure of the figure of merit of hydrophones, which for the piezofilm is 2.5 times greater than their counterparts like ceramics.

TABLE 3.1 : Some of the properties of the commonly used pressure transducer materials.

Material	d_{31} (10^{-12}) C/N	g_{31} (10^{-3}) Vm/N	k_{31} % at 1 kHz	Acoustic Impedance (10^6) kg/m^2- sec.
PVDF	23	216	12	2.7
PZT	110	10	30	30
$BaTiO_3$	76	5	21	30

As the electromechanical coupling constant k_{31} is comparatively low for piezopolymers, which means that the output acoustic power generated will be lesser for PVDF compared to PZT for the same electric input. Hence it is not usually recommended for projector applications. Other disadvantages of the polymeric ferroelectrics compared with ceramics include the thermal depolarisation when heated to temperatures above 100°C for long times, thus limiting the use of polymers below this temperature. Although the piezoelectric stress constant is comparatively higher for polymers, it is difficult to pole a thick piece of film, necessitating the use of multilayer stacks for high voltage outputs. Mechanical relaxation occurs when the polymers are subjected to a stress for long time, this will adversely affect the static measurements carried out with polymeric transducers.

The following calculations indicates the voltage output of the piezofilm for vibrations in both (3,3) and (3,1) directions. If a piezofilm of length l, width w and thickness t is subjected to a compressive stress of T Newton per square metres, then the voltage generated for,

(3,3) drive; $$V_3 = g_{33}\, T\, t \tag{3.3}$$

and for (3,1) drive; $$V_1 = g_{31}\, F/w \tag{3.4}$$

Where F is the force acting over the film and g_{33} and g_{31} are the corresponding voltage constants. The output voltages computed for (3,1) and (3,3) drives for a given stress input of 100 N/m^2 are shown in Table 3.2.

TABLE 3.2 : Voltages computed in (3,1) and (3,3) drives for a uniform stress of 100 N/m^2.

Film Dimensions $l \times w \times t$	Voltage computed in		The ratio of computed stress developed in the (3,1) drive to that in the (3,3) drive.
	(3,1) drive	(3,3) drive	
5 cm x 1 cm x 28 μm	1.08 V	0.95 mV	1785
4 cm x 2 cm x 28 μm	0.86 V	0.95 mV	1428
3 cm x 3 cm x 28 μm	0.65 V	0.95 mV	1071

Vast escalation in the voltage generated for (3,1) drive compared to that in (3,3) drive can be explained as due to the concentration of the given force input to a much smaller cross-sectional area of the film, which results in larger stress and a substantial increase in the output. This is the foremost and basic principle adopted for the development of hydrophones.

3.3 TERMINAL ELECTRODES

Polarised piezopolymers are usually available with metallised surfaces and with a marking of its stretch direction on the surface. According to the procedural requirements, the film can be cut in any shape as shown Fig. 3.2(a).

As the polymer has low melting point, it is not possible to solder the terminal electrodes directly to the film surface, as is done in the case of ceramics. Different techniques were therefore attempted. The first method adopted was to solder the cable leads to two very thin sheets of copper and these membranes of copper were then attached to the film surface with a conducting adhesive cement. This method was found to be unsatisfactory as it was not hard and sufficient to withstand the twisting as well as the weight of the cable. A better and more reliable technique used in the major part of the present work for lead attachment is shown in Fig. 3.2(b). It consist of two copper clads, which are etched and cut as shown. The leads of the output cable are soldered to the projected portion of these etched pieces. And they are attached to a 'L' shaped broad aluminium frame as shown, using nuts and bolts. The film is inserted in between these electrodes and is tightened properly using nuts and bolts. This arrangement ensures the electrodes always to be in contact with the film surface irrespective of the cable strains. Proper and careful etching of the copper clads is required so as to avoid contact between the two metal surfaces of the electrodes. This assembly is connected to the tail end of the film to lessen its interference in the vibration of the film.

3.4 METHODOLOGY

Before going into the design details of the hydrophones, a description is made on the methodology adopted for the calibration of the test hydrophones,

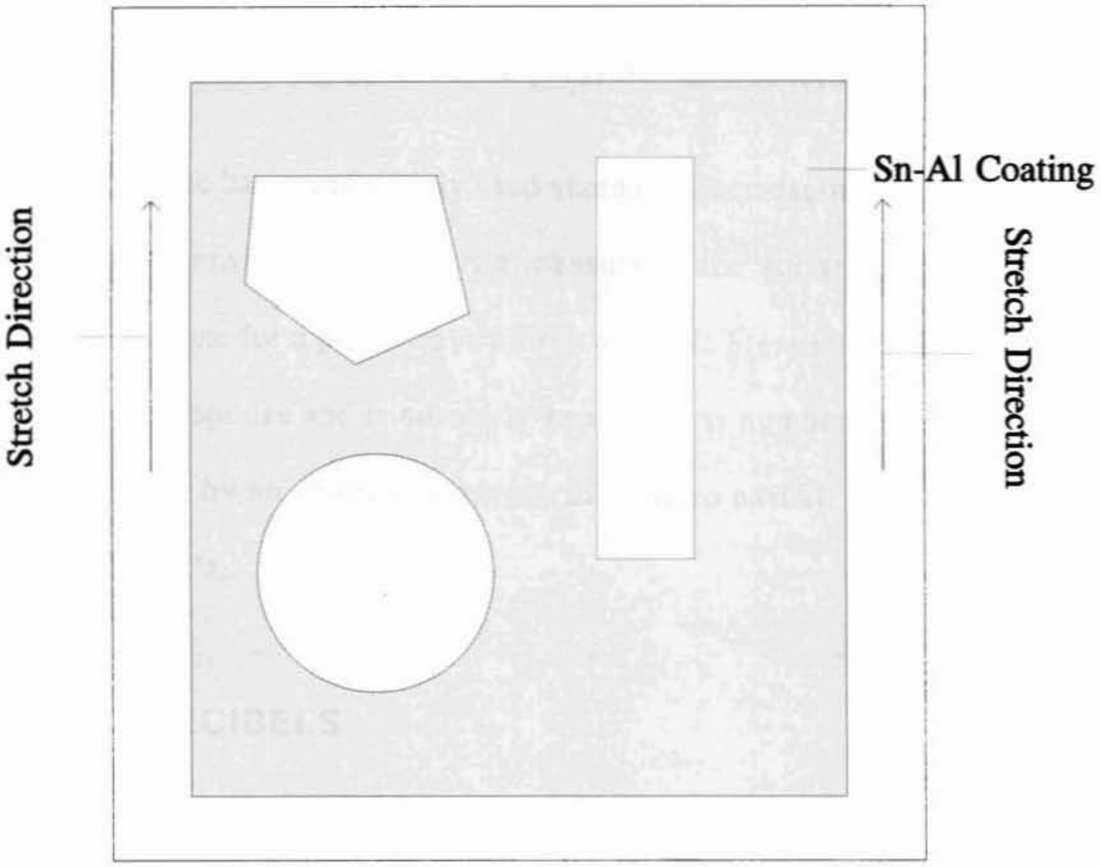


Fig 3.2(a) : A PVDF sheet with markings of stretch direction

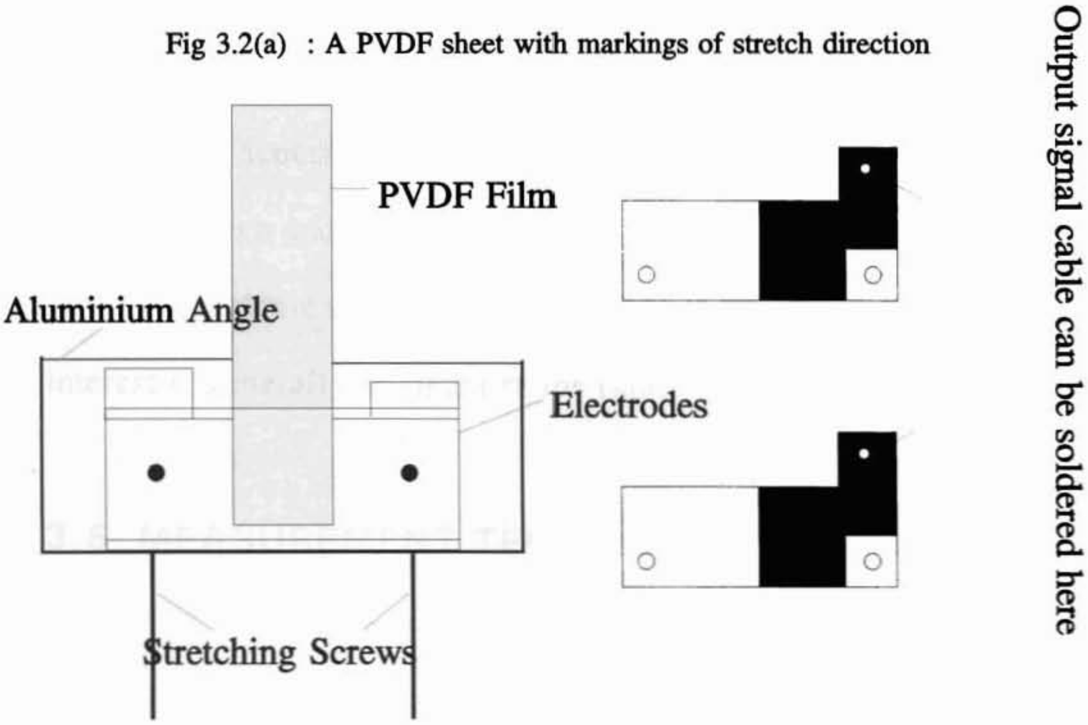


Fig 3.2(b) : Terminal electrodes used for extracting the film output.

which involves evaluation of the most significant electroacoustic parameter, the response (sensitivity) of the hydrophone, relating the generated voltage at its output to the incident acoustic pressure, as a function of frequency.

The basic and widely used standard electroacoustic response is the free field voltage sensitivity, which is a measure of the voltage across the terminals of the hydrophone for a plane wave of unit acoustic pressure. It is also known as the open circuit response and is normally expressed as number of decibels relative to 1 volt produced by an acoustic pressure of 1 micro pascal, and is usually denoted as dB re: $1V/\mu Pa$.

3.5 DECIBELS

The most suitable and widely used reference unit in underwater acoustic measurements is the decibel system, which gives a convenient measure of the ratio in comparison with a reference one. The reason for adopting this system is that generally in acoustic phenomena the range of the signal amplitude variations are extremely high and it is possible to accommodate these fluctuations conveniently with a logarithmic scale. In areas of acoustics and communication engineering, the interest is generally in signal ratios rather than its absolute values.

3.6 MEASUREMENT TECHNIQUES

The different methods [121-125] available to find the free field voltage sensitivity of the hydrophones, can be broadly divided into two groups as Primary and Secondary methods. The primary method is confined to the basic measurements like voltage, current, electrical and acoustical impedance, length, mass *etc.* of the transducer along with its operating frequency.

In the secondary method, the response of the transducer under test is compared with a reference transducer, which has already been calibrated using primary method. Even though the secondary methods in no way can compete with the primary calibration techniques, they are still convenient and popular as it requires fewer measurements and provides fewer sources of error than do primary methods. So for routine calibrations the secondary methods are increasingly popular. The measurement accuracy and reliability of the secondary methods can be improved by averaging the results obtained with two or more standard reference hydrophones.

Some of the widely used calibration techniques are given below [126],

- Comparison Method
- Reciprocity Method
- Two Projector Null Method
- Impedance Method
- Static Method
- Impulse Method
- Radiation Pressure Method

Of these, comparison method and reciprocity method are extensively used for the calibration of hydrophones.

In most of the measurement techniques, one of the pre-requisite is that the medium should be homogenous and infinite. Reflecting boundaries, temperature gradients, gas bubbles, marine life *etc.*, contribute adversely to the free field conditions.

3.6.1 Reciprocity method

Reciprocity method of calibration is a primary method and hence a reference standard transducer is not necessary, but it needs a series of measurements on several transducers. This method is based on electroacoustics reciprocity, equivalent to the electrical reciprocity for bilateral networks. One of the requirements of this method is the need for a reciprocal transducer. The peculiarity of a reciprocal transducer is that, its receiving sensitivity to the transmitting response will be a constant, termed as the reciprocity parameter. This parameter is largely influenced by the acoustic medium, the frequency of operation and the boundary conditions, but it is free from the design parameters of the hydrophone. Most of the piezoelectric and piezoceramic transducers are reciprocal at normal signal levels.

3.6.2 Comparison method

This is the most simple, reliable and straight forward method for calibration of hydrophones. This secondary method mainly consist of subjecting the unknown hydrophone and a previously calibrated reference hydrophone to the same free field pressure, and then comparing the output electrical voltages of the two. This method is also known as substitution method, as the test hydrophone is substituted for a standard hydrophone in the given measurement conditions.

In the comparison method the characteristics of the projector are irrelevant. The only requirement is that the pressure field should be homogenous throughout the medium surrounding the hydrophone. For this the test and the reference hydrophones are kept at considerable distances from the projector. If the standard reference hydrophone is not omnidirectional, it must be kept with the acoustic axis pointed towards the projector.

If the open circuit output voltage of the standard hydrophone is V_s and that of the unknown hydrophone for the same pressure is V_t, then the sensitivity of the test hydrophone can be calculated as follows [127].

$$M_t = M_s \frac{V_t}{V_s} \tag{3.5}$$

in decibels,

$$20\log M_t = 20\log M_s + 20\log V_t - 20\log V_s \tag{3.6}$$

$$i.e., \quad S_t = S_s + 20\log\frac{V_t}{V_s} \tag{3.7}$$

where M_t and M_s are the sensitivities of the test and standard hydrophones respectively, and S_t and S_s are their decibel equivalents.

The apparent factors which may jeopardise the reliability of the calibrations using this method include, the inability to measure the voltage under the true open circuit conditions, instability of the standard, absence of the true free field and insufficient signal to noise ratio.

Due to its lucid and faithful nature, comparison method is used throughout this work for validating the performance of the hydrophones.

3.7 CALIBRATION OF HYDROPHONES

The evaluation of the response of the hydrophones fall in the general category of free field, far field measurements. The ideal free field conditions assumed theoretically are difficult to accomplish practically. A true free field which is a uniform boundless medium, is one of the requirements for the standard measurements, is beyond the bounds of possibility. Yet another criteria for evaluation is that the measurement should be done in far field, and can be fulfilled to a certain extent by keeping sufficient separation between the projector and the hydrophone. A suitable means for measuring input current or voltage and open circuit voltage, is also having some influence on the measurements. Finally, the values of the parameters like distance between the projector and hydrophone, water density and frequency are also playing a role in determining the trust worthiness of the measurements.

The following facilities available with CUSAT / NPOL were used for the calibration of hydrophones,

1. Underwater Transducer Evaluation Facility (UTEF)
2. Acoustic Test Facility (ATF)
3. Underwater Acoustic Research Facility (UARF)

3.7.1 Underwater Transducer Evaluation Facility (UTEF)

This test facility forms a part of the Ocean Electronics Lab of Department of Electronics of the Cochin University of Science & Technology. UTEF is mainly devoted for the evaluation of hydrophones in water and air. The test tank of this set-up is of 600 cm x 355 cm x 215 cm, with a capacity of 15,000 gallons of water. This rectangularly shaped tank is having two moving platforms, which can be slide through the rails provided at the top of the tank. The platform I has three dimensional movement and is usually used for fixing the projector. The platform II is fitted with a B&K 3922 turn table, which can be remotely controlled using B&K 2307 level recorder. Usually hydrophone is fixed in a rod, and the rod is inserted into the turn table. Normally the platform II is fixed at one end of the tank and the platform I is adjusted for the desired distance. As the size of the tank is small, it is very difficult to take low frequency measurements free from the wall reflections. A moderately instrumented control room with the necessary set-ups will facilitate measurements in water and air using comparison method.

This tank was used for some preliminary calibration of hydrophones. Air calibrations of the hydrophones were carried out in the air measurement laboratory of UTEF.

3.7.2 Acoustic Test Facility (ATF)

This is a sophisticated test facility of Naval Physical Oceanographic Laboratory (NPOL), for the evaluation of various transducer parameters. This facility comprises of a test tank with slanted walls of size 1225 cm x 765 cm on top and 1070 cm x 610 cm at bottom, with a uniform depth of 610 cm, with a capacity of 4,80,000 litres of water and is designed for measurements above 4 kHz. It also consists of two moving platforms, each with a three dimensional movement, and can be remotely controlled from Instrumentation cabin near the tank. Both the platforms are equipped with turn tables. A transfer crane with a capacity of 3 tons, separately installed above the tank, facilitates immersion of large projectors and transducer arrays.

The instrumentation available as part of the facility includes an infrastructure for measuring various characteristics of hydrophones and projectors. The data acquisition for most of the measurements is through a computer.

Performance characteristics of certain sets of hydrophones were carried out in this tank. For getting a clear picture of the resonance frequency, signal-to-noise ratio *etc.* of the hydrophones, some preliminary measurements were carried out here, before meticulously calibrating them. The directivity pattern of the hydrophones was also taken in using this facility.

Even though the preliminary measurements were carried out in the above two facilities, increasing degree of accuracy is achieved by calibrating the test hydrophones in the Lake Facility of NPOL, which satisfies the free-field and far-field conditions up to certain limits.

3.7.3 Underwater Acoustic Research Facility (UARF)

All the final calibrations of the hydrophones were carried out at UARF, Kulamavu near Idukki. This Lake Facility of NPOL forms a part of the vast Idukki hydroelectric reservoir, having a total stretch of around 30 km. UARF mainly consists of two huge platforms - *M.V. Kolumban* and *F.P. Kuravan. M.V. Kolumban* is a barge of length 19 m and breadth 8 m, and is driven with two powerful engines, for propulsion. The barge comprises of an engine room, an instrument room along with a vast free deck space. Along the length of the barge the hydrophone and the projector can be suitably positioned. The barge can be anchored any where in the lake, depending on the water depth requirements.

F.P. Kuravan, a floating platform, is made up of small floats, over which a deck of 15.6 m x 10.8 m is fabricated. As the platform does not have any propulsion mechanism, it has to be towed for navigating in the lake. A 5 ton capacity mobile crane and a manually rotating turn table (capacity 2 tons) are some of the facilities available on the deck. An on board UPS serves for an uninterrupted and regulated power supply for the instruments. Besides this, a well equipped instrumentation cabin also forms part of the floating platform. There is a central well for positioning large transducer arrays in water without affecting the hydrodynamics of the platform. There is also a longitudinal channel for positioning hydrophones at different ranges from the projector.

Depending on the technical requirements and the logistic support available, either the floating platform or the barge, or both were used for the measurements on different sets of hydrophones. A watercraft *M.V. Jalaprayog*, which also forms a part of the facility was used for ferrying various instruments from shore to the platforms and back.

3.8 EXPERIMENTAL SET-UP

The hydrophones under test were evaluated in water using the Comparison method. Fig. 3.3 shows the experimental set-up used for the measurements. Even

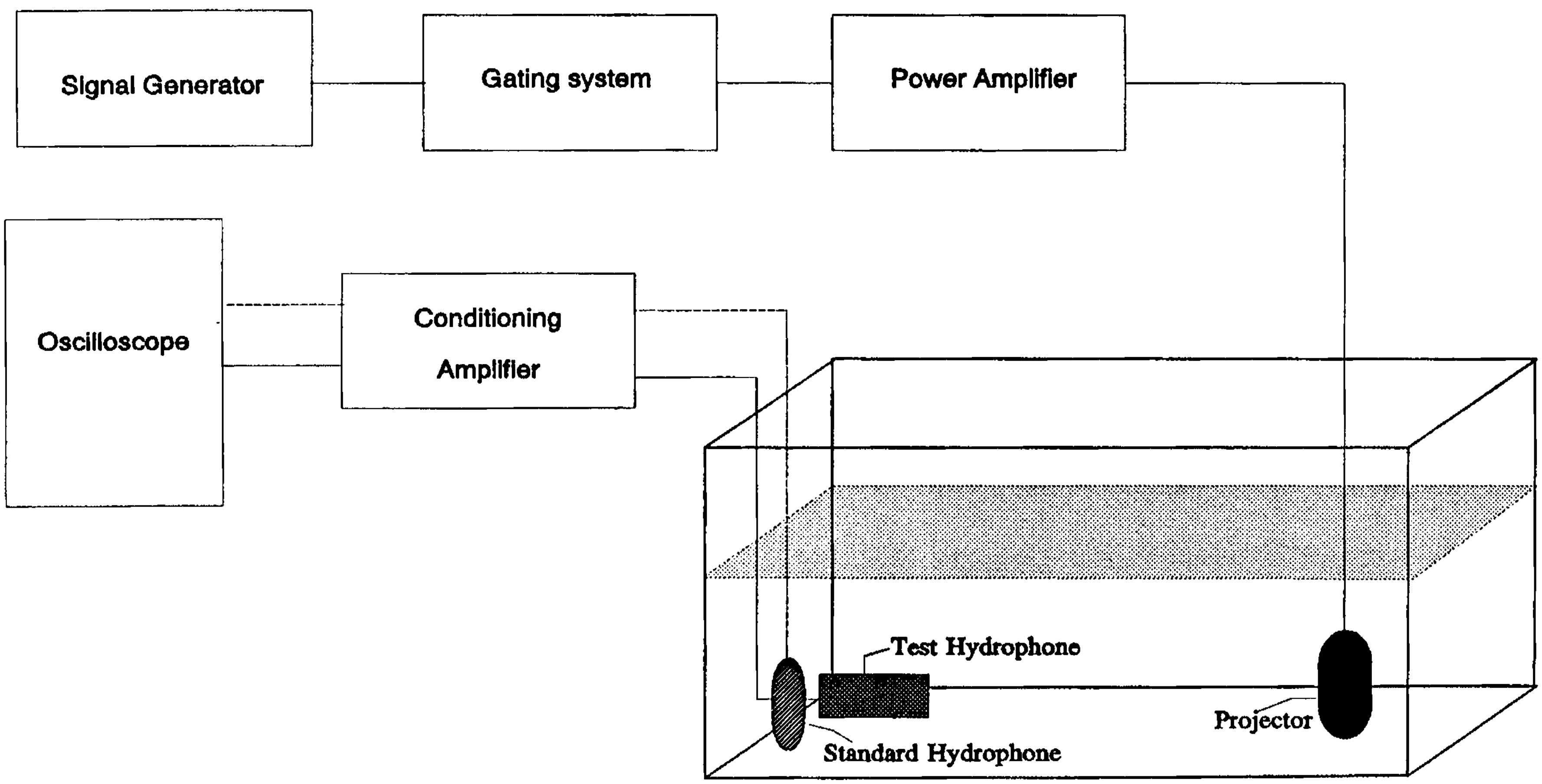


Fig 3.3 : Experimental set up for measuring the frequency response of the hydrophones in water.

though while carrying out measurements in different facilities described above, some additional instruments like extra preamplifiers, filters *etc.* were used, in accordance with the field requirements, the basic experimental set-up remained the same. It broadly consists of a signal generator, gating system, a power amplifier and of course a projector in the transmitting side, a conditioning amplifier and a source for measuring the output signal (usually a C.R.O) along with the standard and test hydrophone constitute the receiving part.

The sinusoidal signals from the signal generator are gated using gating system. These gated signals are amplified and fed to the projector. These transmitted acoustic signals received by the unknown hydrophone are amplified using conditioning amplifier and fed to a C.R.O for measuring the voltage levels. This is repeated for the desired frequency range. The experiment is repeated for the test hydrophone also. After compensating for extra gain provided either for the test or the standard hydrophone, the voltage outputs of both are compared and by knowing the sensitivity of the standard hydrophone, the sensitivity of the test hydrophone is computed using comparison method.

According to the availability of infrastructure in different measurement facilities, a variety signal generators and power amplifiers were used, but these instruments hardly had any influence in the final results. For all the measurements the conditioning preamplifier B&K 2650 was used at the receiving side so as to condition the input to the C.R.O. Gated signals were used for all measurements to distinguish the reflected echoes from the direct signals. This was done by triggering the C.R.O for every gated output, so that by adjusting the time base the direct signal can be extracted. The pulse width and repetition rate were also suitably minimised so as to avoid the superposition and time stretching of the direct signal from the reflected ones.

Different projectors and standard hydrophones were employed during the various phases of measurements. These include, underwater speakers UW-15 and UW-60 of Gearing & Watson, ITC TR 25, and MASA J-11 as the projectors and B&K 8100, B&K 8104 (both with a receiving sensitivity of -205.5 dB re 1V/ μPa in water) and ITC 1042 (with a sensitivity of -202 dB re 1V/ μPa in water) as the reference hydrophones.

For convenience, measurements on both the standard as well as test hydrophone were carried out together, by immersing them in water side by side and measuring their outputs simultaneously. It was assumed that the distance between them is sufficient to keep them as independent transducers. They were immersed to a depth of around 5-10 meters and the distance between them and projector was maintained in the range of 6-10 meters. The pulse width of the transmitted signals were kept in the range of 1-10 msec.

3.9 AIR CALIBRATION

If the acoustic impedance of the transducer is very high, so that the radiation impedance is negligibly small, and if the dimensions of the transducer are small enough so as to neglect the diffraction effect, then its receiving response will be same in air and water. Most of the conventional acoustical calibration methods can be used to calibrate the hydrophones in air.

Some of the test hydrophones were calibrated in air also so as to ascertain their response in air. The experimental set-up for air measurements is shown in Fig. 3.4. The only difference between the set-ups in air and water is the transmitter, which is a loud speaker in air. All the air calibrations were carried out at UTEF. Either B&k 8100 or B&K 8104 was used as the reference hydrophones and comparison method was used for the calculating the sensitivity of the test hydrophone. As the velocity of sound in air is only one fourth that in water, it is possible to reduce the distance between the transmitter and receivers considerably.

3.10 DIRECTIVITY PATTERN

Directivity pattern of a transducer is its response as a function of transmitted or received sound waves in a specified plane at a given frequency. The pattern provides an idea on the variation of sensitivity of the transducer with direction. It is also a free field far field parameter, used for computing the efficiency of energy conversion of the transducer. If the transducer is reciprocal, then its receiving and transmitting pattern will be similar. For convenience it is usually traced in polar charts.

The set-up shown in Fig. 3.5 can be used for plotting the directivity pattern of a hydrophone [126]. The test hydrophone is fixed to a turn table using a metal rod. The experimental set-up for comparison method can be used here, except that the output from the conditioning amplifier is fed to a level recorder. Keeping the projector fixed, it is energised for a particular frequency and the turn table accommodating the hydrophone is rotated remotely using level recorder B&K 2307.

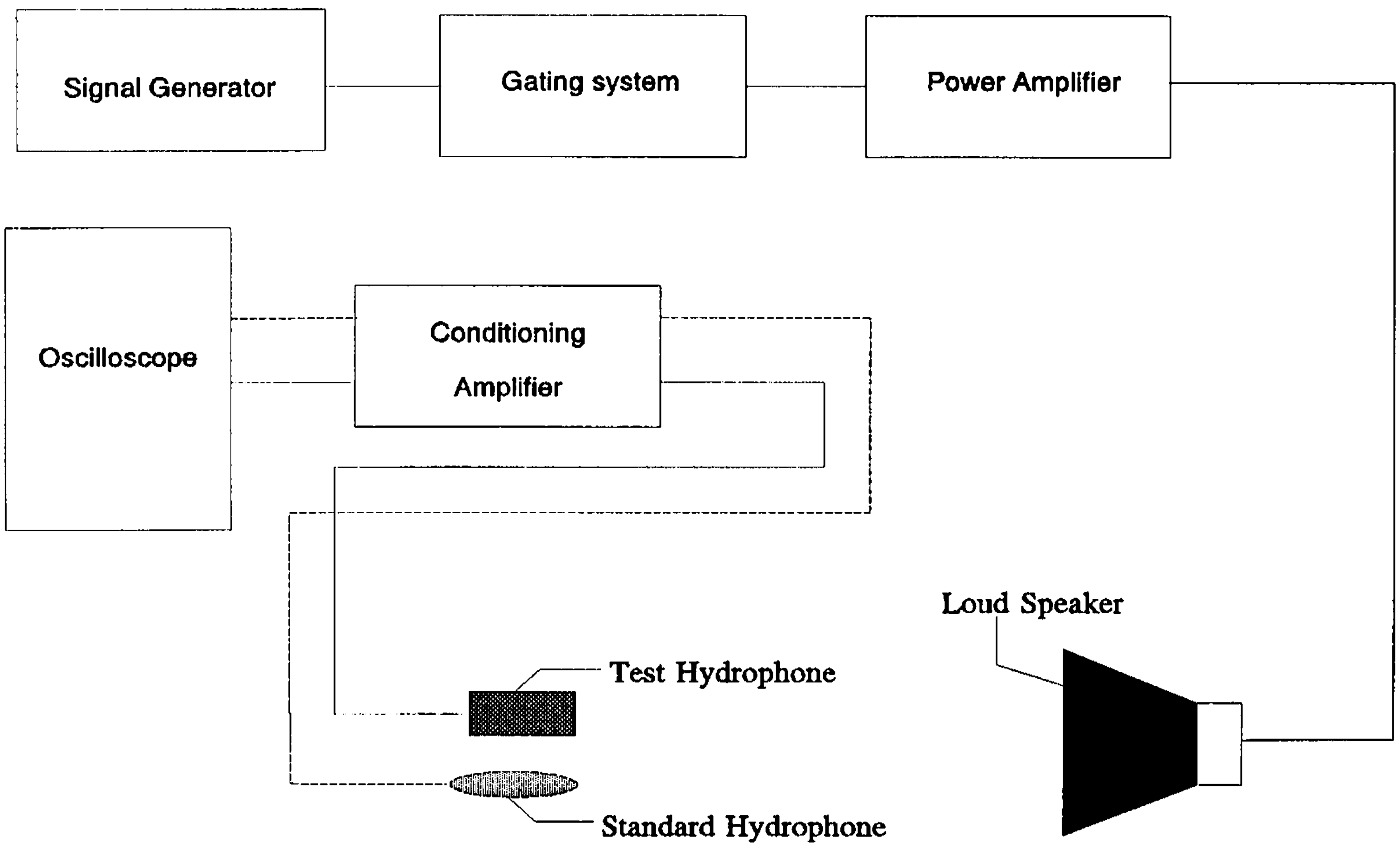


Fig 3.4 : Experimental set up for measuring the frequency response of the hydrophone in air.

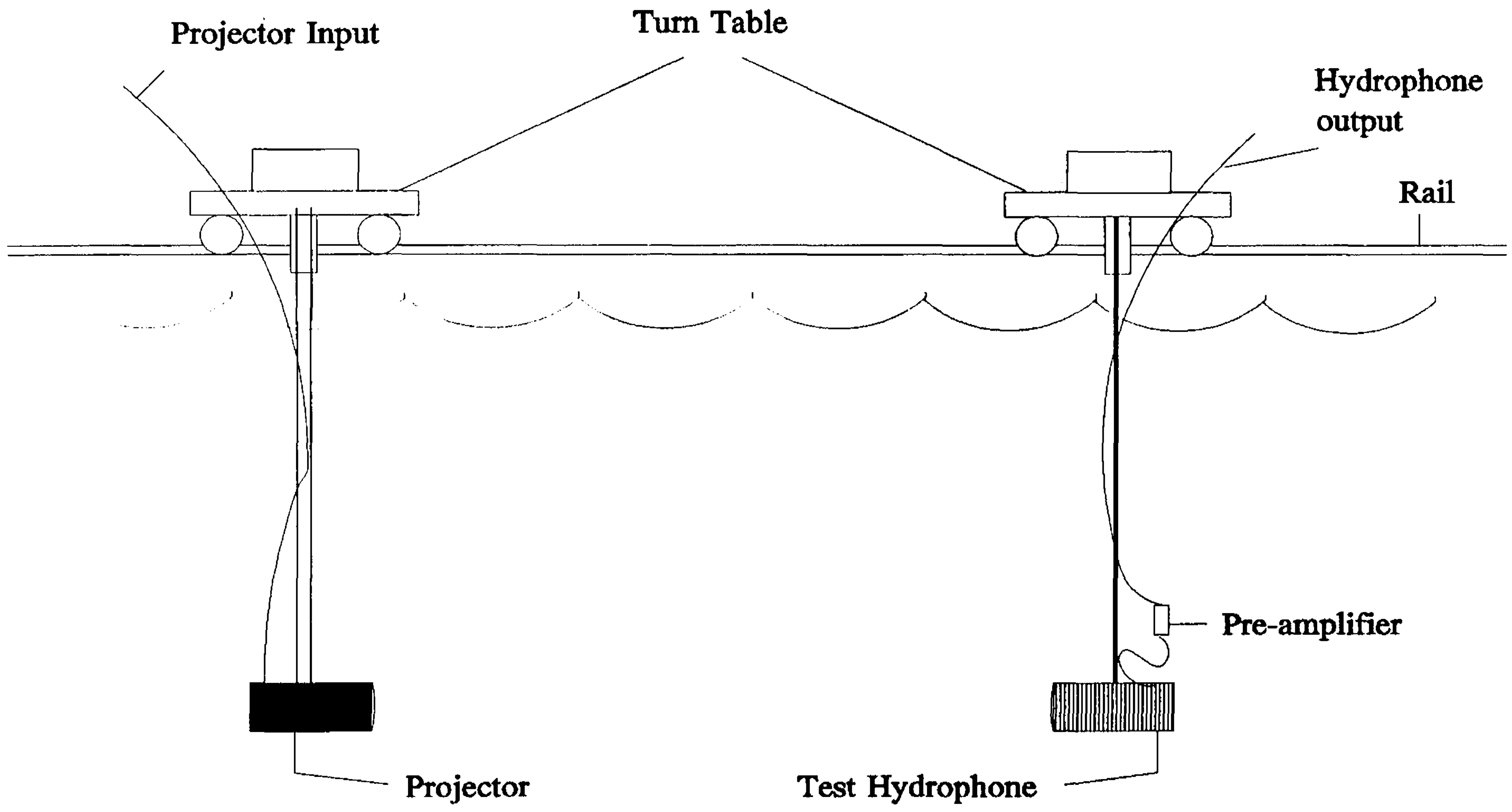


Fig. 3.5 : Field set-up for plotting the directional response of the hydrophone.

For a full rotation of 360° of the hydrophone, variation in its output are drawn on a polar chart of the level recorder. This gives the directivity pattern of the hydrophone for that particular frequency. The directivity pattern of the standard can also be drawn so as to compare it with that of the test hydrophone. As the directivity pattern is a function of frequency, the experiment can be repeated for different frequencies. The directivity patterns were measured at ATF.

3.11 ADDITIONAL PRE-AMPLIFIERS

Usually the hydrophones are equipped with built-in preamplifiers, which facilitate them to enhance the signal-to-noise ratio as well as to reduce the effective output impedance, which will cater the signal with a low impedance path. Usually signal output from the transducer are comparatively feeble and cables are used to carry this signal to the nearest instrument, probably a conditioning amplifier. Therefore the properties of the signal cable has much influence on the fate of the resultant output available at the conditioning amplifier. For normal measurements in water at least 25 m of cable is required for the proper positioning of the hydrophone. So the impedance of the cable as well as its cable noise will dwindle the signal-to-noise ratio [128]. This problem can be solved to a certain extent with the help of low capacitance cables. As this type of cables were not available in the open market, ordinary two core shielded cables were used with either of the following two types of preamplifiers.

1. AMP 4001
2. AMP 4002

AMP 4001 is a buffer amplifier where as AMP 4002 is a differential amplifier.

3.11.1 AMP 4001

This is a buffer amplifier [129], which is normally connected very near to the hydrophone. A buffer is an amplifier with unity gain, and is having a high input impedance and low output impedance. Hence by using this amplifier the signal path can be changed from a high impedance to a low impedance one, thereby reducing the damping of the signal due to high cable capacitance. As the output impedance of the hydrophone is usually very high a MOSFET op-amp CA 3140 is used. The circuit diagram of the amplifier is as shown in Fig. 3.6. It was wired in a PCB with input and output connections, and was moulded for making it water proof. For simultaneously taking the output signal from the preamplifier and to provide it with a proper d.c. power, a four core shielded cable was used.

3.11.2 AMP 4002

With the help of AMP 4001, the damping of the signal due to the cable capacitance was considerably reduced, still the cable noise used to creep in to the signal dwindling the signal-to-noise ratio. For eliminating this noise, the buffer amplifier was replaced with a differential amplifier AMP 4002.

The function of a differential amplifier [130] is to amplify the difference of the two input signals. Normally the differential amplifier will have high input impedance and high CMRR. It finds applications where a small signal voltage and

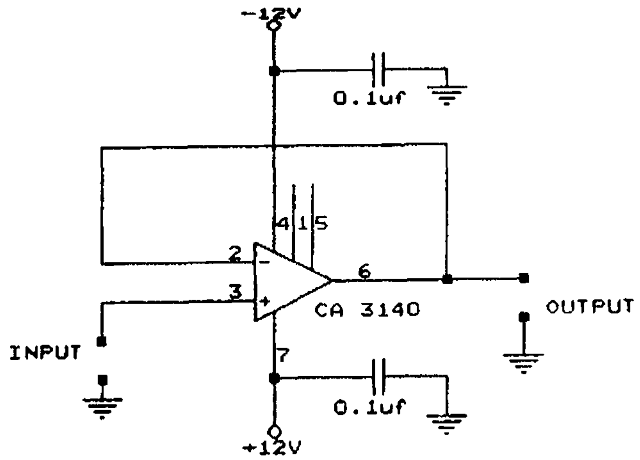


Fig. 3.6 : Circuit diagram of AMP 4001.

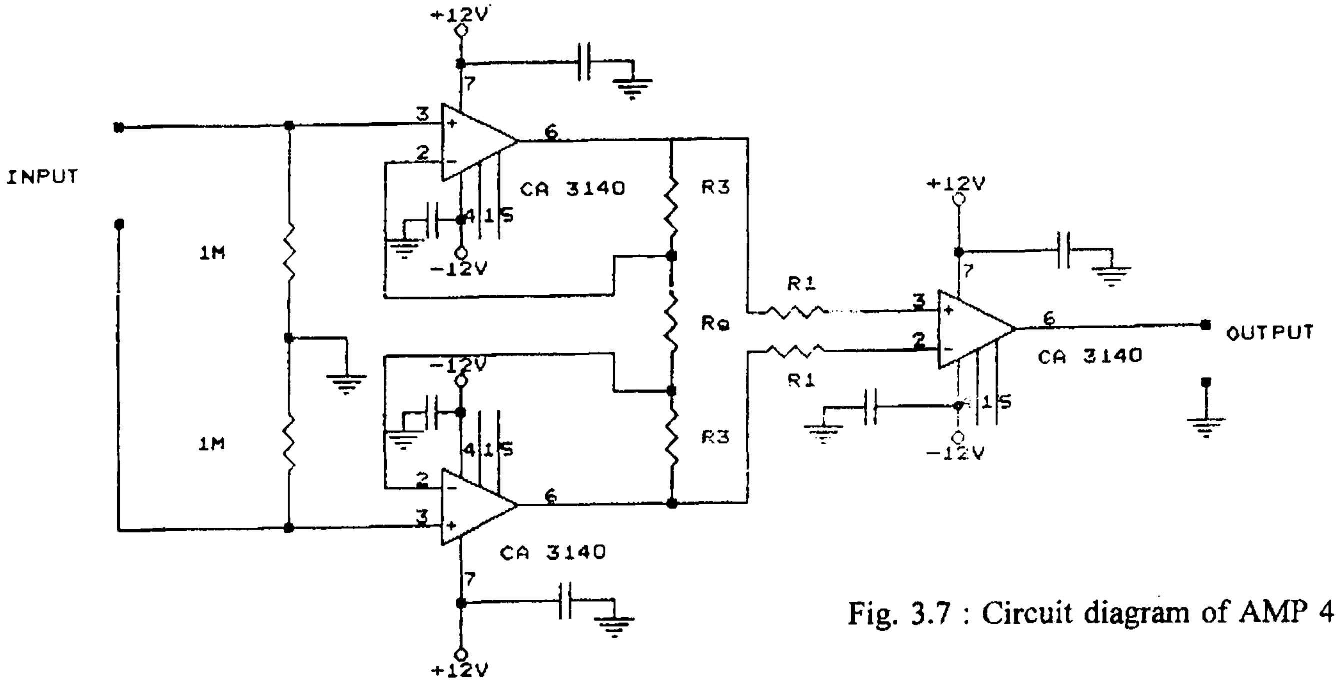


Fig. 3.7 : Circuit diagram of AMP 4002.

large common mode inputs are available. For an ideal differential amplifier the output V_0 is given by,

$$V_0 = A(V_1 - V_2) \tag{3.8}$$

Where A is the gain of the differential amplifier, and V_1 and V_2 are the difference inputs. Thus if the signal is common to both inputs, then output will be zero. However this is not completely true as the output not only depends on the difference inputs, but on the average of the two also, known as the common mode signal.

As the cable noise and other related noises are common to both the inputs, the noise level can be considerably reduced with this amplifier. The circuit of the differential amplifier (AMP 4002) is shown in Fig. 3.7. It is having two stages, the first one being a differential amplifier and the second a voltage amplifier. MOSFET op-amp CA 3140 was used here also. The overall gain A of the amplifier can be calculated using the following equation.

$$A = \left[1 + \frac{2R_3}{R_g}\right] \left[\frac{R_2}{R_1}\right] \tag{3.9}$$

Here R_1 = 1KΩ, R_2 = 10KΩ, R_3 = 4.7KΩ and R_g = 4.7KΩ were considered and hence the gain was set at 30 (29.7 dB). This gain was properly compensated in the calculations of hydrophone sensitivity. All capacitors were of 0.1μF, used for filtering high frequency noise. The amplifier was suitably enclosed for making it water-tight. A regulated D.C power supply of +12, 0, -12 was provided to the amplifier using positive and negative voltage regulators LM 7812 and LM 7912 respectively.

3.12 IMPEDANCE ANALYZER HP 4192 A

This is a fully automatic, high performance test instrument capable of measuring wide range of impedance parameters as well as gain, phase and group delay. Measurement range varies from 5 Hz to 13 MHz with a resolution of 1 mHz and oscillation level of 5 mv to 1.1 V r.m.s. Eleven impedance parameters can be measured using this instrument, including the absolute values of impedance and capacitance, which are useful parameters in the transducer design. The instrument can be remotely controlled through a built in HP-IB interface.

The impedance as well as the capacitance of the different transducers were measured using impedance analyzer. For the measurements the analyzer was interfaced with a computer through a GP-IB card. Measurements were taken and the data were stored in the computer using a software in BASIC.

Chapter 4

Prototype design

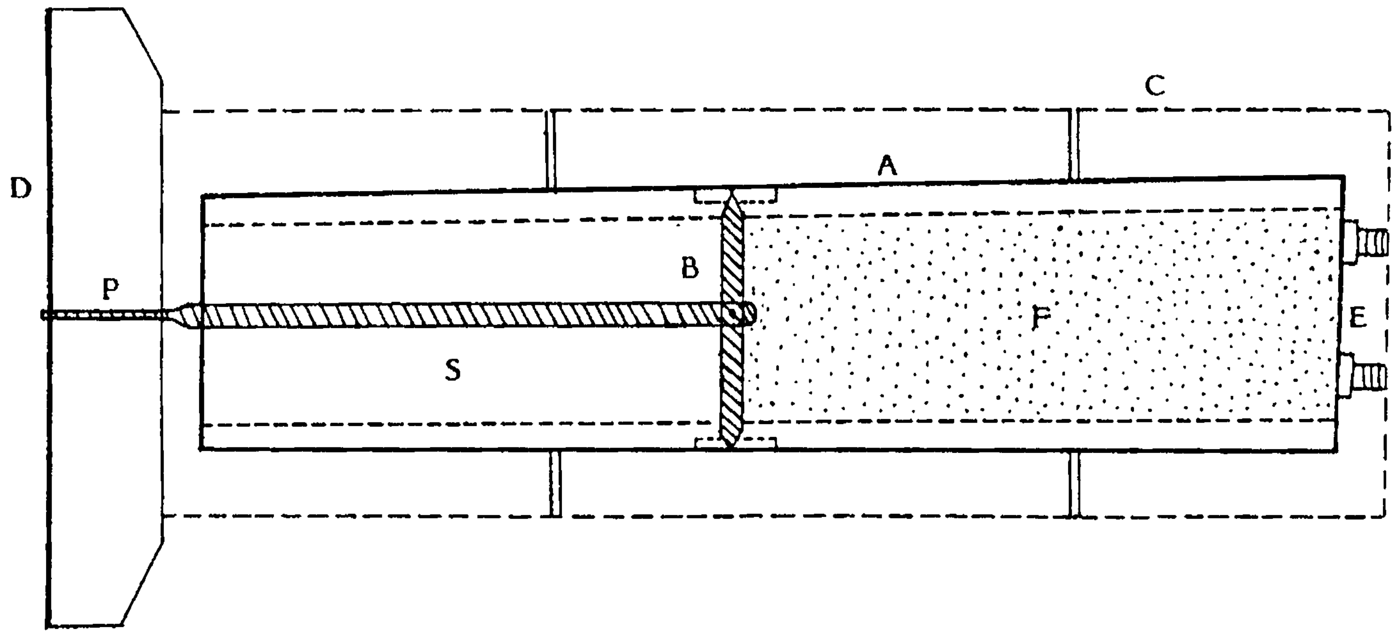
This chapter throws light on various design issues adopted for the formulation of (3,1) drive piezopolymer hydrophones along with the outcome of different experimental results. The following designs are described, along with an experimental analysis to determine the influence of various design parameters on the performance of the (3,1) drive design.

1. Exploratory Model
2. Improved Design
3. Prototype Version
4. Other Designs

In the preceding chapters descriptions were made on the design philosophy and adequacy of piezopolymers as a transduction material for underwater detection applications. A comparative study of voltage outputs developed for a given acoustic pressure, in a polymer film when it is made to vibrate in (3,1) and (3,3) drives, were also highlighted in Table 3.2 of Chapter 3. High values of voltage outputs in (3,1) drives led to their designs for higher sensitivities, by incorporating a modified structural assembly. Due to certain structural complexities associated with the stretch drive of vibrations, it is an arduous task to design a structure for making the film to vibrate in the (3,1) drive, as it involves proper holding of the film in the *1* direction and an appropriate mechanism to transfer the incident pressure field to the film. So a number of attempts were made before emerging into a satisfactory (3,1) drive design.

4.1 EXPLORATORY MODEL (T0)

To make certain the design feasibilities of (3,1) drive, an exploratory model as shown in Fig. 4.1 was attempted, which mainly consisted of a polymer film of 7.5 cm x 2.5 cm x 28 μm, to one end of which a plastic sheet was glued and the other end fixed to a rectangular aluminium frame as shown. The free end of the plastic film was attached to the upper part of the aluminium frame so as to stretch the film along its length. One end of a perspex rod of length 9 cm was attached to the junction between the film and the plastic sheet, and the other end at the centre of a diaphragm. A circular sheet of perspex of diameter 6 cm and thickness 0.5 mm was used as the diaphragm. The diaphragm was fixed over a cylindrical enclosure and the rest of the assembly was kept inside it. The principle of working of this model is that, any mechanical impulse on the diaphragm would flex it in



D : PERSPEX DIAPHRAGM
P : DRIVER PIN
S : PLASTIC SHEET
B : PERSPEX BAR
A : ALUMINUM FRAME
F : PVDF FILM
C : OUTER COVERING CYLINDER
E : FIXING SCREWS

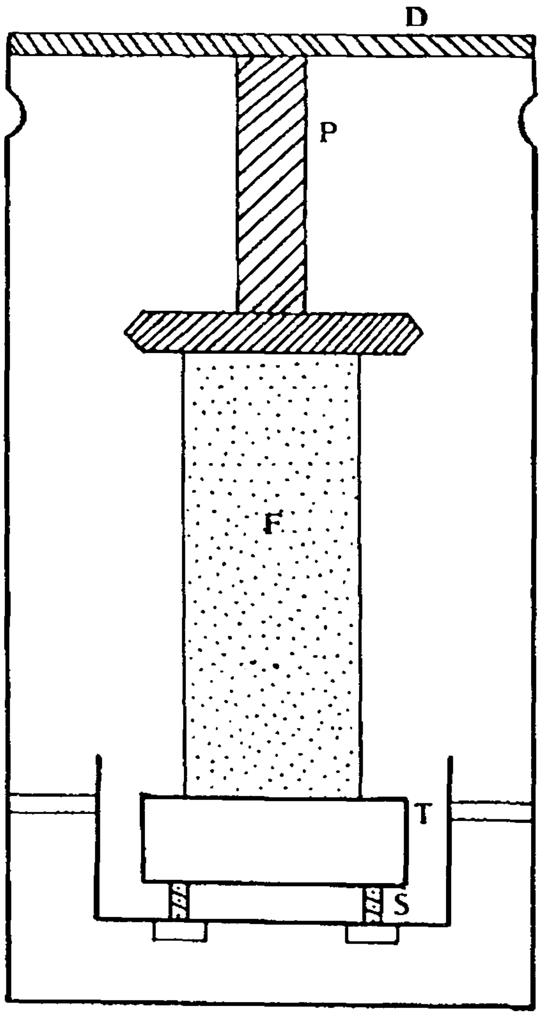
Fig. 4.1 : A cross-sectional view of T0.

accordance and these pressure pulses are transferred to the film through the perspex rod, which connects the diaphragm and the prestretched film. This perspex rod is termed as driver pin since it drives the film according to the diaphragm vibrations. With these arrangements the film will vibrate in the *1* direction, and due to the expansions and contractions of the film, charges will be developed across it. In order to take voltage output, two thin sheets of copper were adhered at the film surface using conducting cement, and the terminal leads were connected to these copper sheets.

This model performed satisfactorily in air. However as it was only a preliminary attempt, no detailed calibration was carried out.

4.2 IMPROVED DESIGN (T1)

Even though the design described above fulfilled the basic design criteria of (3,1) drive, it had certain disadvantages. The way of stretching the film was awkward and inefficient and also the procedure adopted for taking the output was unreliable. Therefore this intricate and complex design was modified by bringing certain changes. A cross-sectional view of the modified design is shown in Fig. 4.2. This improved design consists of a polymer film of 5.5 cm × 1.8 cm × 28 μm, bonded firmly to a small rectangular sheet of perspex. This sheet is fixed at one end of a perspex driver pin, whose other end is fixed at the centre of a diaphragm, again of perspex of diameter 5.5 cm and thickness 0.5 mm. The other end of the film is inserted in between two copper clads and the output electrodes are taken using the method described in Sec. 3.3 of Chapter 3. The film is properly



D : PERSPEX DIAPHRAGM
P : PERSPEX DRIVER PIN
F : PVDF FILM
T : TERMINAL ELECTRODES
S : SPRING LOADED SCREWS

Fig. 4.2 : A cross-sectional view of T1.

stretched using two spring loaded screws provided at the base of the terminal electrode assembly. In this design the mechanical oscillations caused by the incident acoustic waves on the diaphragm are transferred to the taut film through the driver pin. So the efficiency of transfer of oscillations to the film in this design is much higher, as it is almost directly coupled to the diaphragm, compared to the previous design in which the coupling between the diaphragm and the polymer film was incompetent.

The receiving sensitivity of the transducer in air was measured using comparison method, with B&K 8100 as the reference transducer and a loud speaker as the projector. Fig. 4.3 gives the response of the test model in the frequency range 500 Hz to 3 kHz.

4.3 PROTOTYPE VERSION (T2)

As expected, the above design performed better in air and a sensitivity of around -153 dB re: 1V/ μPa was obtained. In an attempt to develop a water tight working version, suitable to withstand hydrostatic pressure at considerable depths in water, some modifications were incorporated in T1. In T1, perspex sheet was used as the diaphragm. Perspex being a light material lacks strength to withstand the hydrostatic pressure even to moderate depths. To overcome this, if thin sheet is replaced by thick sheet, then the entire performance of the hydrophone was found to be affected. So it was decided to find another material for the diaphragm. The quest for a suitable material culminated in choosing phosphor bronze, also known as steel bronze, an alloy of copper, tin, lead and phosphorus. It is

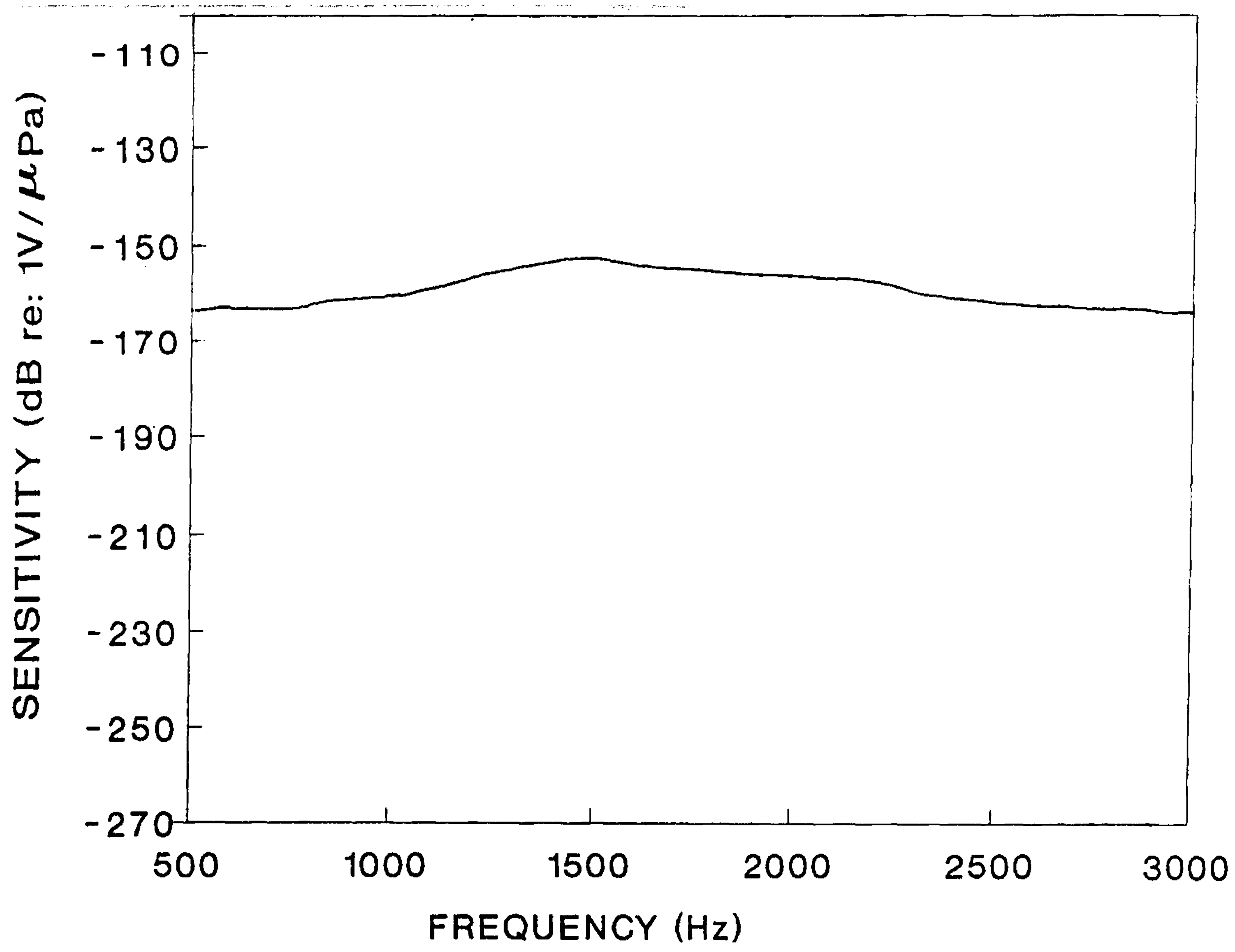


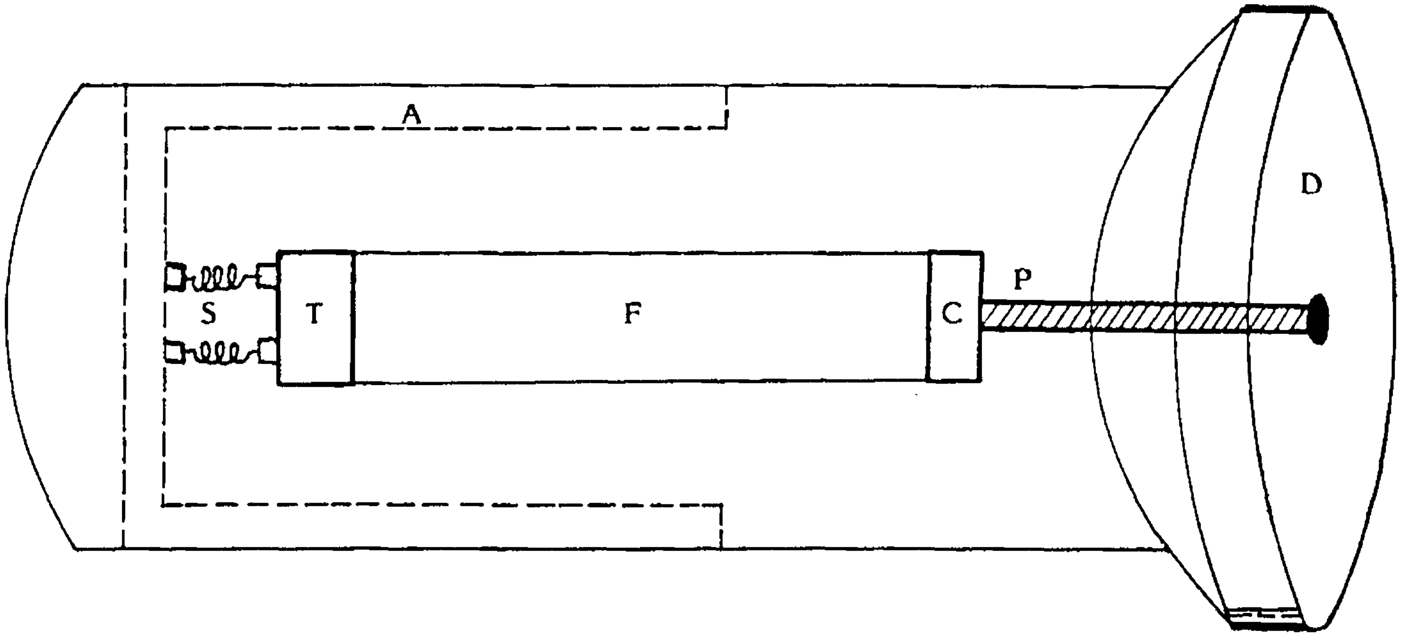
Fig. 4.3 : Frequency response of T1 in air.

comparatively a stiffer material with high spring constant.

Thus with a phosphor bronze diaphragm of diameter 5 cm and thickness 1.2 mm, a (3,1) drive model was evolved. A cross-sectional view of the design is shown in Fig. 4.4. The diaphragm is firmly fixed at the top of a thick cylindrical PVC enclosure, using adhesives. At its centre, a small hole is drilled for attaching the driver pin. A thin cylindrical brass driver pin of length 2.5 cm and thickness 1.5 mm is inserted and fixed at the hole provided at the centre of the diaphragm. At the other end of the driver pin a small rectangular sheet of copper is soldered as shown. One end of the PVDF film of 5 cm × 1 cm × 28 μm is adhered over this copper sheet. The terminal electrodes are connected at the other end of the film and it is stretched using spring loaded screws as in T1. The whole assembly is made water tight with only the diaphragm exposed to the outside.

For facilitating the evaluation of the hydrophone at greater depths in water and also to reduce the attenuation of the output signal due to the high capacitance of the signal cable, a unity gain MOSFET buffer amplifier (AMP 4001) is also connected very near to the hydrophone with an extension cable of 30 metres.

To examine the water tightness of the hydrophone assembly, it was continuously immersed in water for 3 days. For performance evaluation in water, B&K 8100 was used as the transmitter. B&K 8100 exhibits fairly good transmitting response from 2 kHz to 90 kHz and hence can be used as a projector in this range. It was driven using B&K 2713 power amplifier. The standard B&K 8104 and the test hydrophones were immersed to about 1.5m with the projector about 4m away at the same depth in the test tank of UTEF. The sensitivity of the test hydrophone



D : PHOSPHOR BRONZE DIAPHRAGM
P : BRASS DRIVER PIN
C : THIN COPPER SHEET
F : PVDF FILM
A : ALUMINIUM FRAME
T : TERMINAL ELECTRODES
S : SPRING LOADED SCREWS

Fig. 4.4 : A cross-sectional view of T2.

was computed in different frequencies using comparison method.

Rapid fluctuations in sensitivity was observed for the entire frequency range measured. For finding the impact of the field set-up on these fluctuations, the B&K 8104 was calibrated using another reference transducer B&K 8103 (receiving sensitivity of -211 dB re: 1V/μPa), and it was finally concluded that the wall reflections were responsible for these severe fluctuations in sensitivities. The low frequency reception of the signals was also very poor as the transmitting response of the B&K 8100 is restricted to above 2 kHz.

With a better level of accuracy, the measurements were carried out at the Lake Facility, UARF. UW 60 was used as the projector and B&K 8104 as the standard reference hydrophone. UW 60 is an electrodynamic projector known as underwater speaker, with a transmitting frequency range of 200 Hz to 7 kHz and can handle power up to 30 Watts r.m.s. The reference and the test hydrophones were immersed to about 3m in water and the projector about 6m away from them at the same depth. For a frequency range of 300 Hz to 2 kHz, the output of both the standard (V_s) and the test (V_t) transducers were compared and by knowing the sensitivity of the standard (S_s) that of the test hydrophone (S_t) was computed using,

$$S_t = S_s + 20\log\left[\frac{V_t}{V_s}\right] \quad dB\ re\colon 1V/\mu Pa \tag{4.1}$$

To investigate the variation of the response of the hydrophone with depth, the experiment was repeated by increasing the depth of immersion of the standard and experimental hydrophones along with that of the projector. Fig. 4.5 shows the response of the hydrophone from 300 Hz to 2 kHz for 3 and 5 metres of depths.

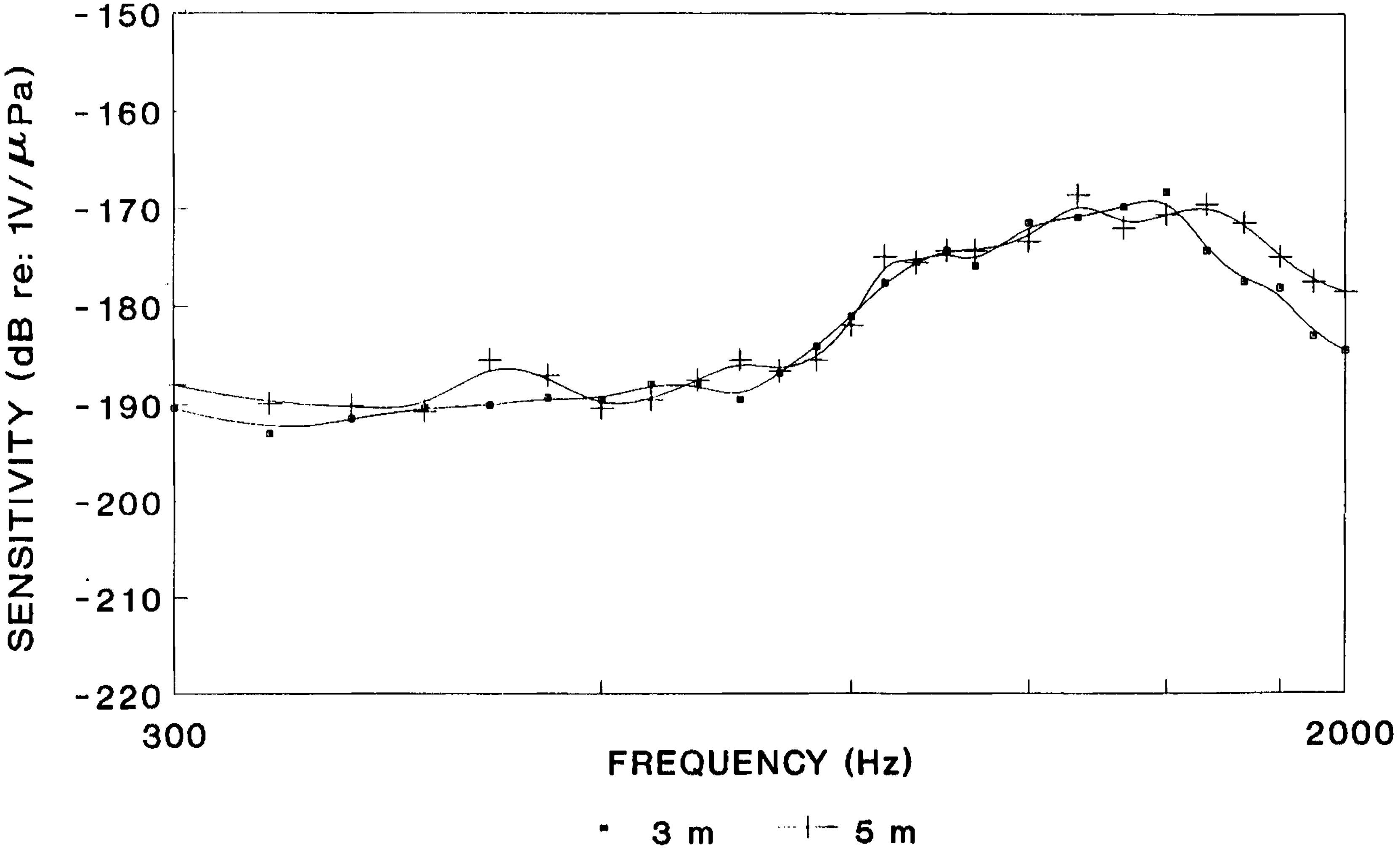


Fig. 4.5 : Frequency response of the hydrophone T2 for depths of 3 & 5 metres.

4.4 OTHER DESIGNS

Thus with the hydrophone model T2 a sensitivity of -170 dB re: 1V/μPa in water was obtained at certain frequencies along with a satisfactory performance in the range of 300 Hz to 2 kHz. This sensitivity is found to be around 30 dB better than the conventional designs which usually show sensitivities around -200 dB re: 1V/μPa. Thus T2 fulfilled the criteria like high sensitivity and lower frequency of operation to some extent.

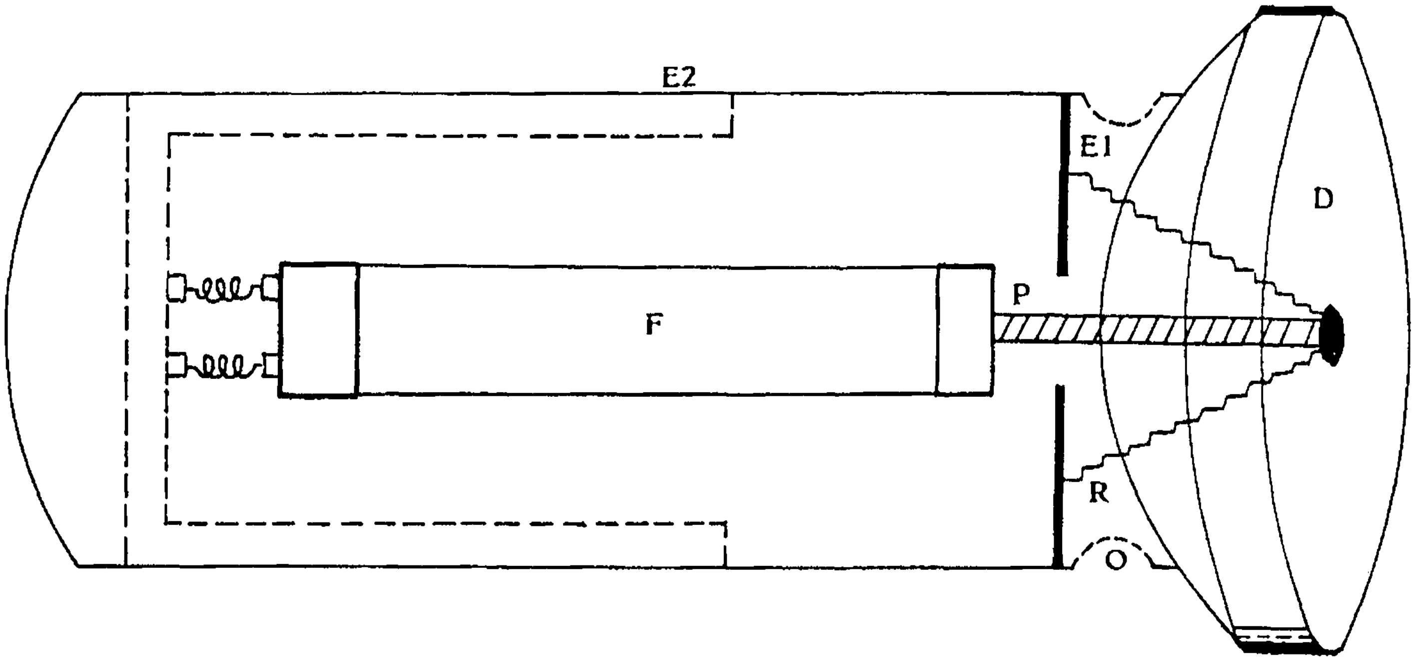
The following designs were also attempted, which are modified versions of T2.

1. Pressure Balance Type
2. Hydrophone with Convex diaphragm

4.4.1 Pressure balance type (T3)

While operating at greater depths, for T2 there is a possibility of encountering problems due to the ambient hydrostatic pressure, which may restrict the diaphragm movement, adversely affecting the performance of the hydrophone. Hence some modifications were made in T2, to overcome the adverse effects of ambient hydrostatic pressure on it, resulting in a model called T3.

A sketch of the T3 is in Fig. 4.6, which is a modified version of T2 with an added pressure balancing mechanism. This mechanism mainly envisages to make the diaphragm free from ambient hydrostatic pressure by allowing water to surround the diaphragm there by equalising the pressure on both sides of it. The design as such has two parts. Part I being the diaphragm assembly and part II or



D : PHOSPHOR BRONZE DIAPHRAGM
E1 : ENCLOSURE I
E2 : ENCLOSURE II
R : RUBBER BELLOW
P : DRIVER PIN
F : PVDF FILM
O : OPENINGS

Fig. 4.6 : A cross-sectional view of T3.

enclosure II is the film chamber.

The diaphragm assembly consists of a circular disc of phosphor bronze of diameter 5 cm and thickness 1.2 mm, which is adhered to a cylindrical enclosure using adhesives. Openings are provided on the walls of this enclosure for allowing water to enter into the diaphragm chamber. The bottom of the enclosure is closed using a circular perspex sheet. As in the T2, at the centre of the diaphragm a driver pin is fixed and over it a PVDF film of 5 cm × 1 cm × 28 μm is attached. The film is taken into the film chamber through a hole provided at the centre of the perspex disc, and is stretched using spring loaded screws. The lower part or enclosure II thus constitutes the film, along with the stretching and electroding mechanisms. Water is prevented from entering into the film chamber with the help of a thick conical hollow rubber bellow. The upper part of this cone is rigidly fixed at the centre of the diaphragm and the lower part to the perspex disc. Thus in effect it surrounds the driver pin, and protects the film chamber from water. This rubber bellow with thick walls is made of neoprene. Due to the flexible nature of the bellow, its restriction on the diaphragm vibrations will be nominal.

With this arrangement the diaphragm is free from the ambient hydrostatic pressure effect. The performance of T3 was evaluated in water. To examine the extent of influence of depth on the hydrophone performance, it was tested at different depths of 3, 5, 10, 15 and 25m. Fig. 4.7 presents a comparison of its response at different depths.

In this design also MOSFET buffer AMP 4001 was connected near the hydrophone, with an extension cable of 50 metres.

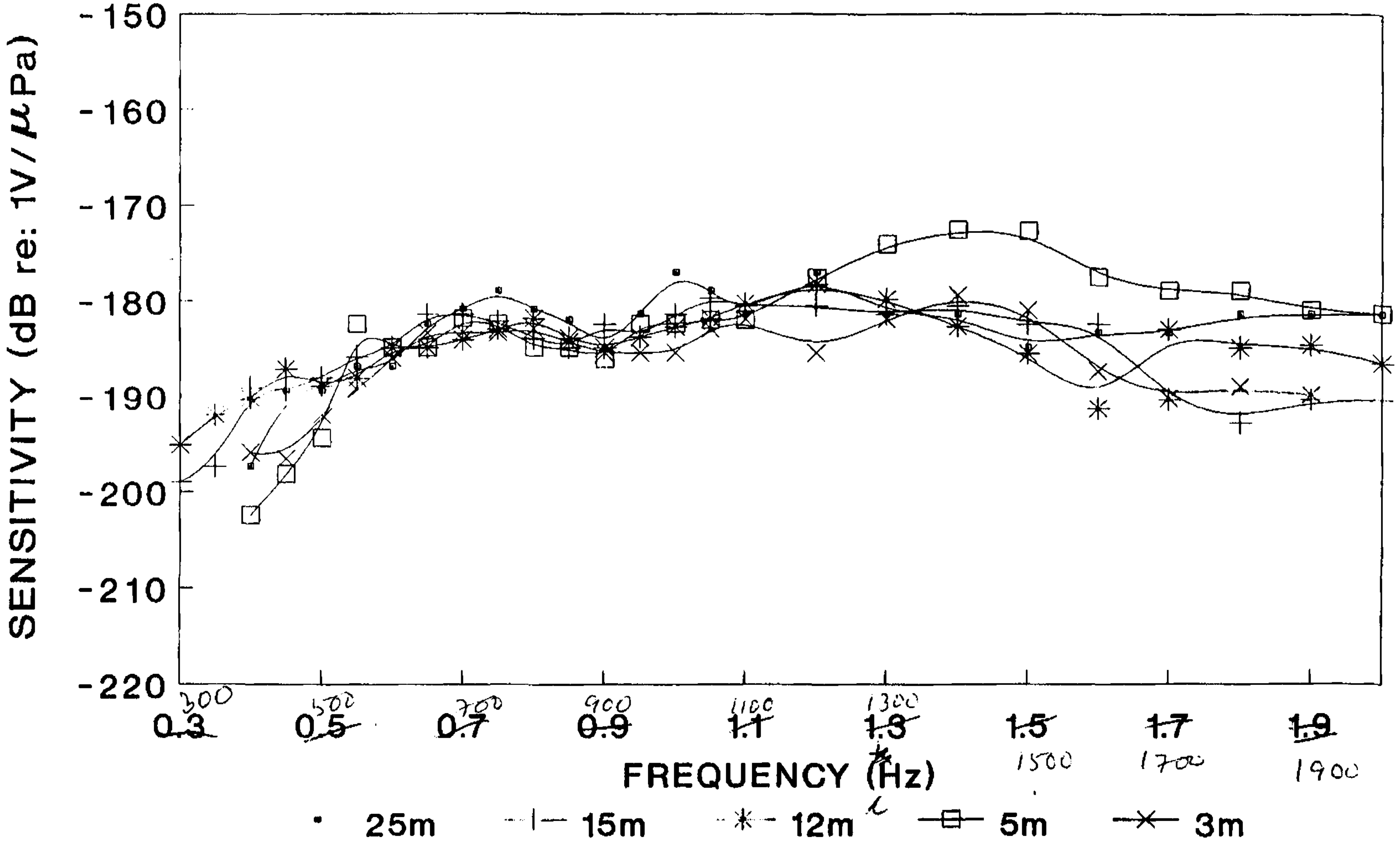


Fig. 4.7 : A comparison of the response of the hydrophone T3 for different depths in water.

As can be concluded from the response, even at 25m depth there is only a little variation in the sensitivity of T3, hence it can be assumed that the anticipated pressure balancing has been properly achieved. Decrease in its sensitivity by around 10 dB compared with that of T2 can be attributed to the additional load on the diaphragm, imposed by the bellow connected to it. Yet another disadvantage observed in this design is that, at greater depths the rubber bellow itself shrinks, hindering the movement of the driver pin.

4.4.2 Hydrophone with convex diaphragm (T4)

The idea to use convex diaphragm is to study the influence of its shape on the characteristics of the hydrophone. As the natural frequency and other mechanical parameters of a convex surface are entirely different from a plane circular disc, a shift in resonance frequency is anticipated. A phosphor bronze diaphragm of 5 cm × 1.2 mm was punched in such a way that its central portion bulges out to form a convex surface. Fig. 4.8 is the response of T4 in water. As expected, the resonance frequency is shifted from 1.5 kHz to 2.2 kHz, with a sharp resonance at 2.2 kHz.

A hydrophone with different enclosure material constitutes T5. The aim of T5 is to make out the role of the enclosure material on the hydrophone behaviour. T5 is similar to T2, except that the enclosure material is changed to brass instead of PVC in T2. Fig. 4.9 is the response of T5 in water, which is similar to that of T2.

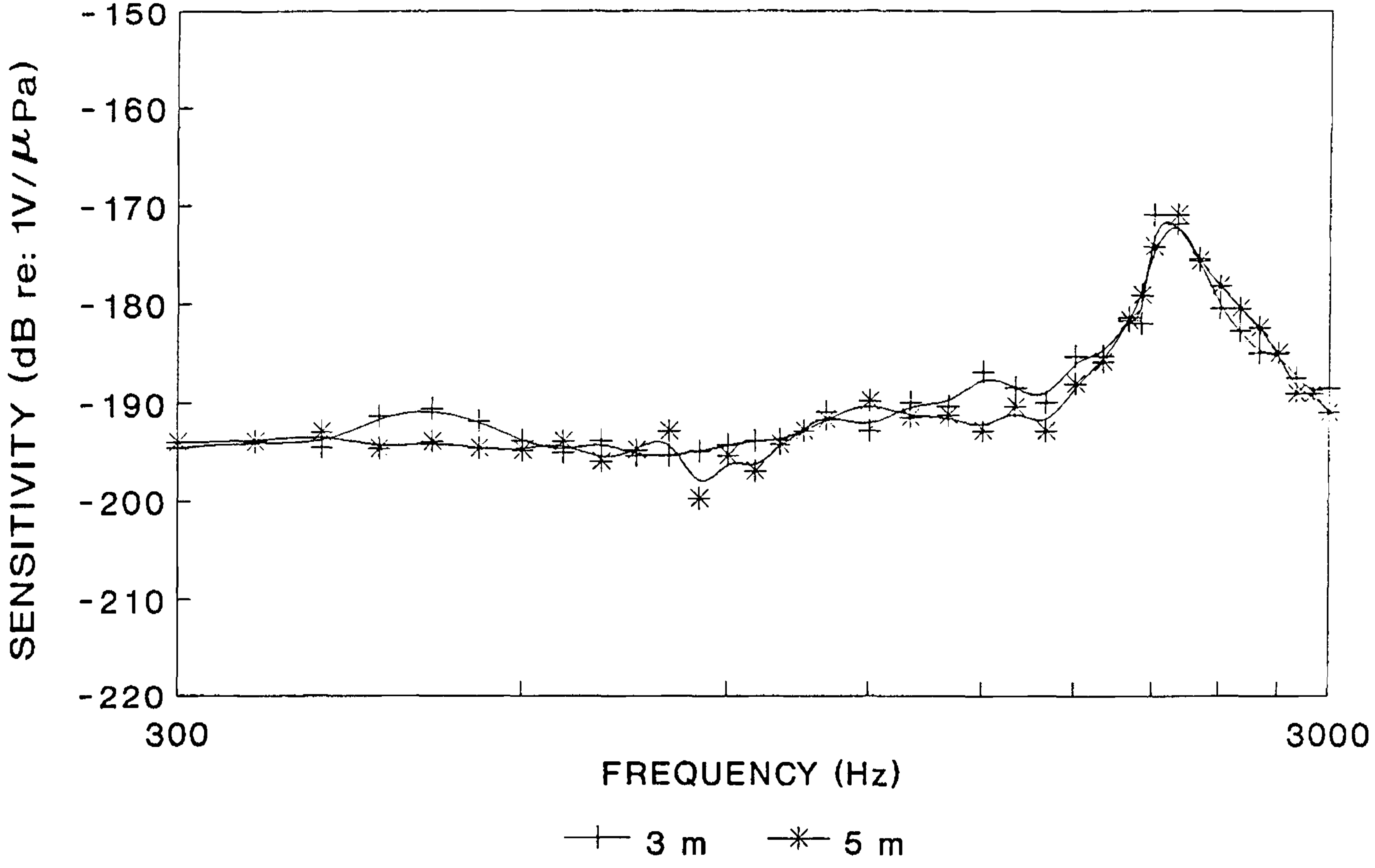


Fig. 4.8 : Frequency response of T4 in water.

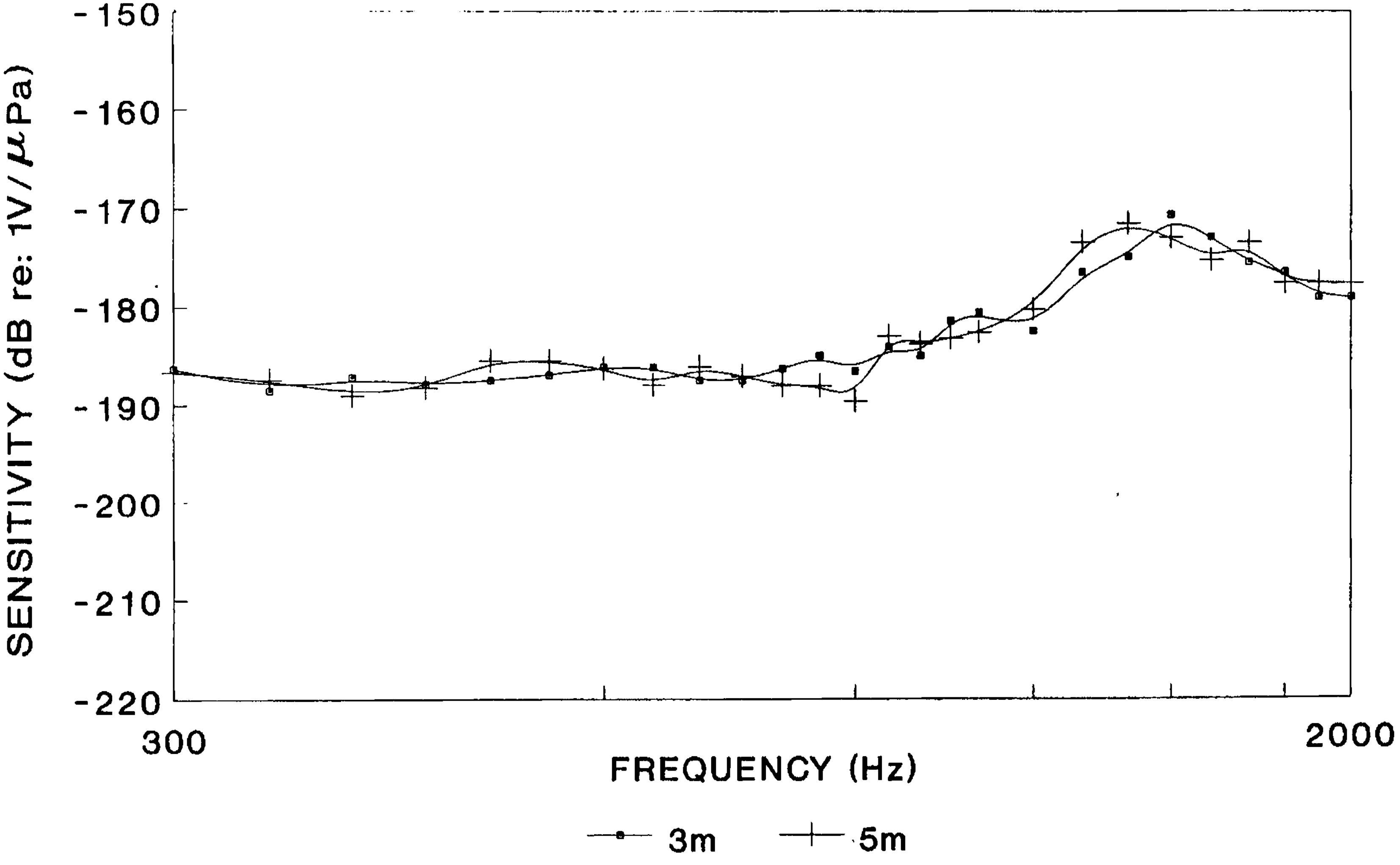


Fig. 4.9 : Response of T5 in water at depths of 3 & 5 meters

4.5 EXPERIMENTAL ANALYSIS OF DESIGN PARAMETERS

An experimental analysis is presented here to validate the influence of the various design parameters on the overall performance the (3,1) drive design. From the design of T2, it can be inferred that, the behaviour of the hydrophone is largely controlled by two factors. The first one being the properties of the active material, as it acts as a mechanism for converting the acoustic energy to electrical energy, and the second factor is the characteristics and dimensions of the diaphragm, which fulfils the task of transferring the impinging acoustic energy to the film. So an experimental analysis was carried out to take an account of the influence of these parameters on the response of the hydrophone. The investigation is divided into two parts,

1. Effect of film dimensions
2. Influence of diaphragm characteristics

4.5.1 Effect of film dimensions

The pressure variations on the diaphragm are transferred to the film, so the properties of the film are playing a vital role in converting the received acoustic energy to the equivalent electrical output. To examine the nature and extent of its influence, an investigation was carried out to analyze the performance of the hydrophone with change in dimensions of the film, *i.e.* either the length, breadth or thickness of the film was changed keeping the rest of the two parameters constant. This was repeated for all the three dimensional parameters of the film. So for a detailed analysis, following hydrophone series were fabricated.

1. LF series

2. BF series
3. TF series

Each series consisted of three similar type of hydrophones with a lone difference in their film dimensions. All the hydrophones carry phosphor bronze diaphragm of 5 cm diameter and 1 mm thickness.

TABLE 4.1 : Details of the dimensions of the films used for evaluating their influence on the hydrophone response.

Hydrophone Type		Film Dimensions $l \times w \times t$
LF series	LF 07	**7 cm** × 1 cm × 52 μm
	LF 05	**5 cm** × 1 cm × 52 μm
	LF 03	**3 cm** × 1 cm × 52 μm
BF series	BF 04	5 cm × **4 cm** × 52 μm
	BF 02	5 cm × **2 cm** × 52 μm
	BF 01	5 cm × **1 cm** × 52 μm
TF series	TF 110	5 cm × 1 cm × **110 μm**
	TF 52	5 cm × 1 cm × **52 μm**
	TF 28	5 cm × 1 cm × **28 μm**

4.5.1.1 LF series

The LF series substantiates the influence of the length of the film on the hydrophone performance. The LF family has three different types of hydrophones - LF 07, LF 05 and LF 03; all having a polymer film of same breadth and thickness. The design details are described in Table 4.1, and their performance in water is shown in Fig. 4.10 .

4.5.1.2 BF series

BF series were fabricated with a view to investigate the role of the breadth of the film on the hydrophone characteristics. BF 04, BF 02 and BF 01 each with a film of same length and thickness but of different breadth, constitute the BF series. Table 4.1 also highlights their design aspects, and Fig. 4.11 their frequency response in water.

4.5.1.3 TF series

Now the only remaining dimensional parameter to be varied is the thickness of the film, and the TF series is assigned to take care of it, while keeping the length and breadth constant. TF 110, TF 52, TF 28 form the TF series. The films with different thickness used in the above hydrophone types can be emphasised from Table 4.1 itself. The validation results obtained are shown in Fig. 4.12.

Conclusions drawn from the above investigation can be summarised as follows. When the film length and thickness increase, the sensitivity also increases, where as it is showing a reverse trend with increase in breadth. It can

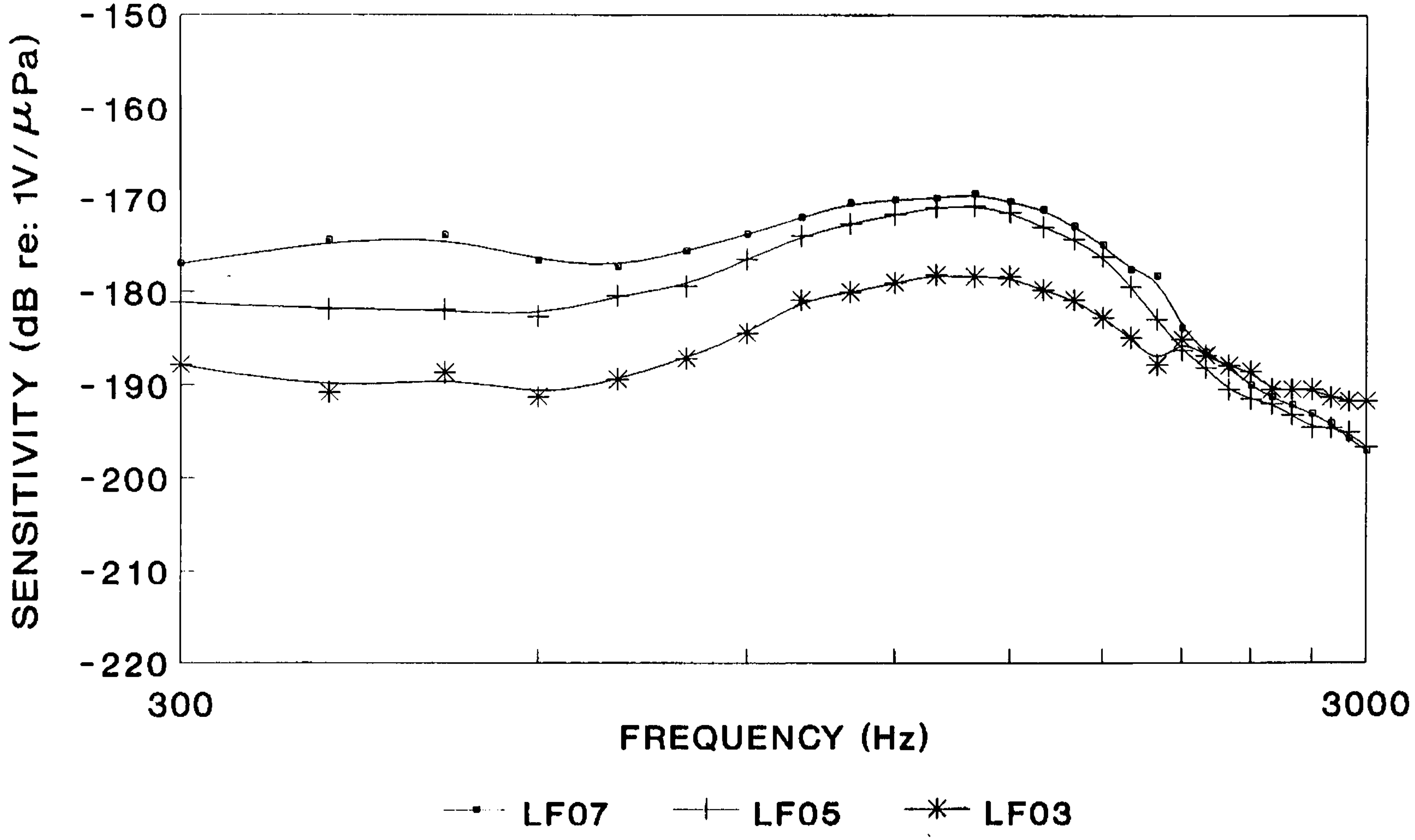


Fig. 4.10 : A comparison of the performance of the hydrophone with change in the film length.

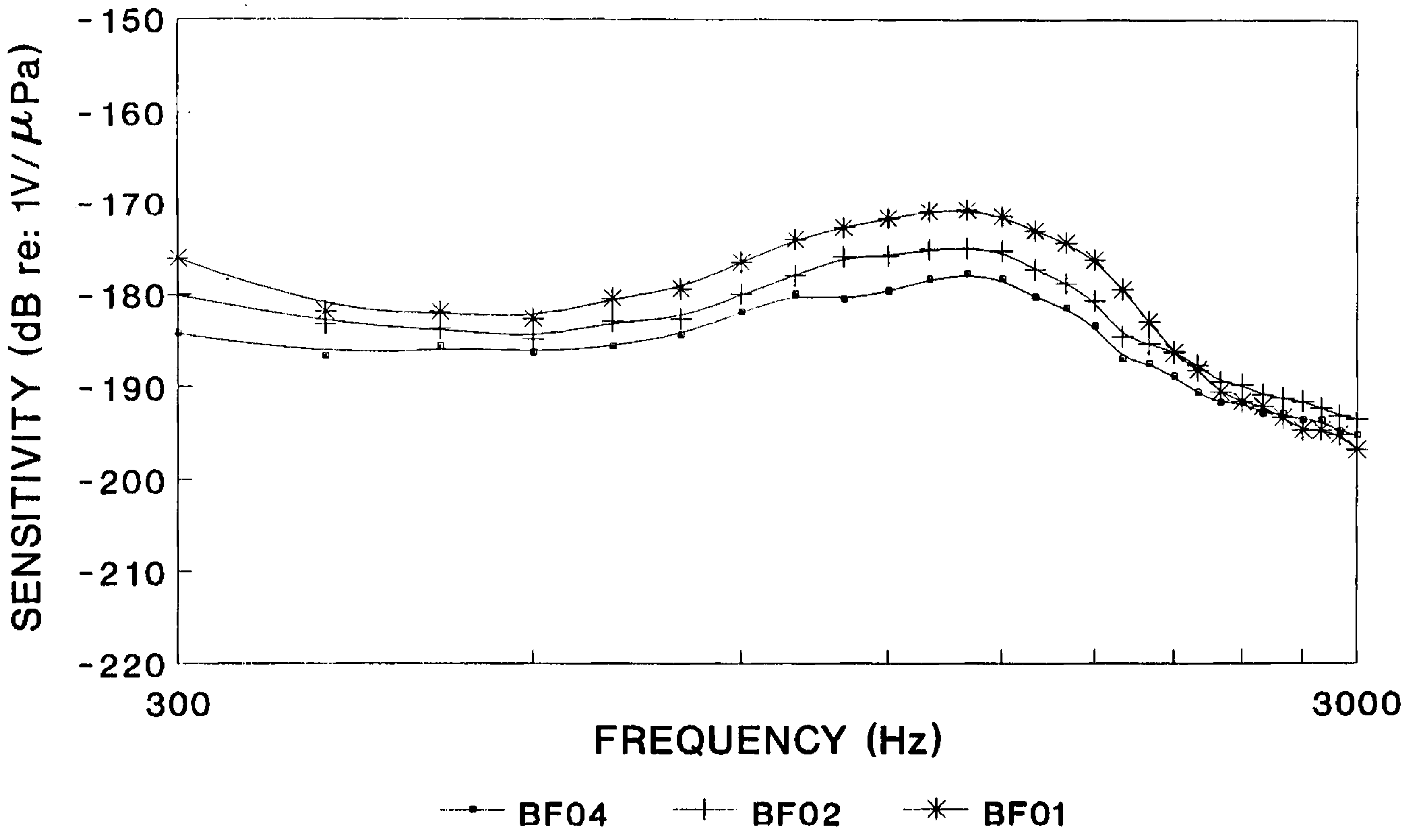


Fig. 4.11 : Variations in the response of the hydrophone with change in the film breadth.

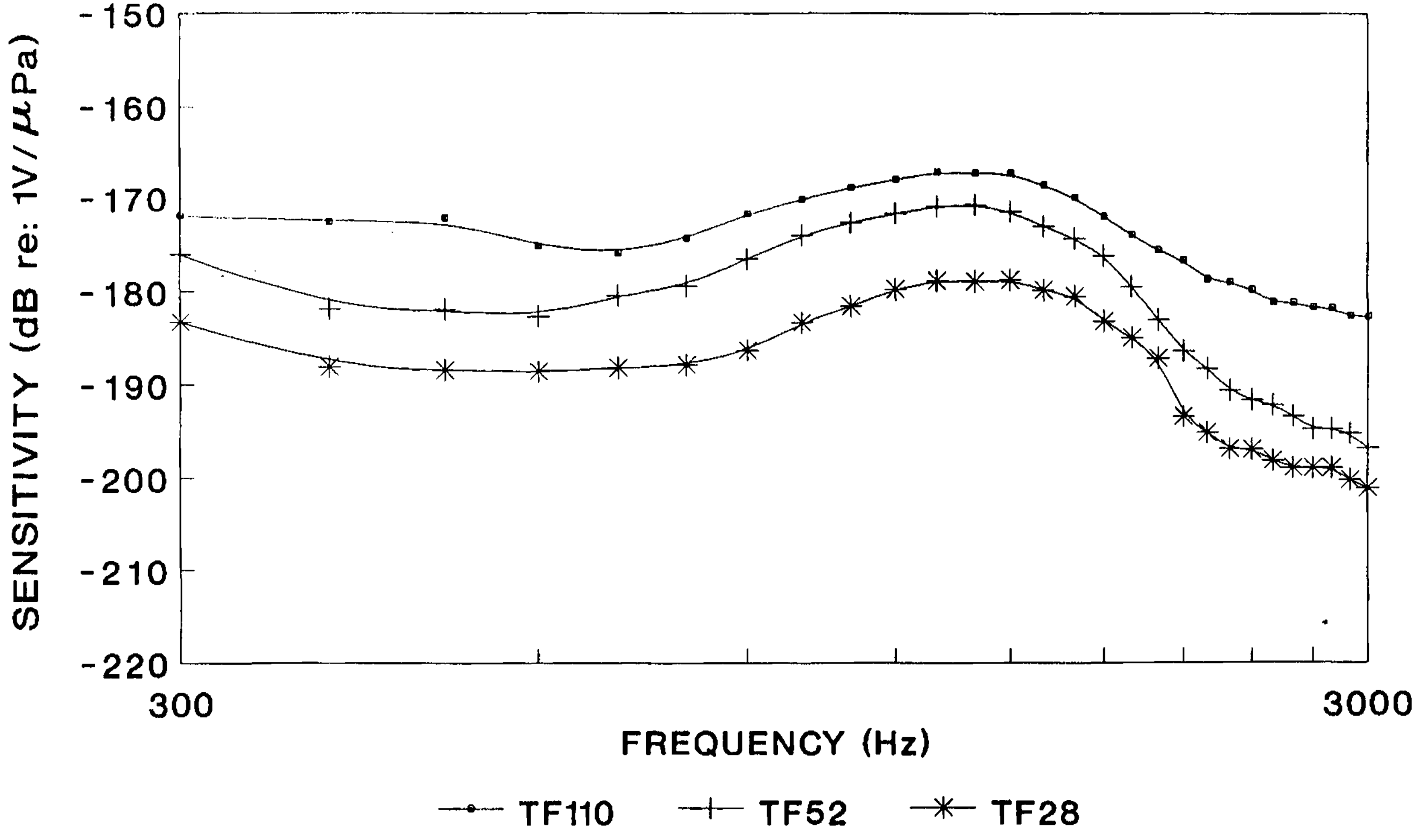


Fig. 4.12 : Change in the response of the hydrophone with variation in film thickness.

also be concluded that, the resonance frequency of the hydrophone is independent of film dimensions, as all the hydrophones in LF, BF, TF series displayed almost the same resonance frequency. From this investigation, the extent of domination of the piezofilm on the performance of the (3,1) drive hydrophone was estimated.

4.5.2 Influence of diaphragm characteristics

Following is an analysis to extract and explore the role played by the diaphragm. Due to the limited availability of phosphor bronze sheets, stainless steel was used in the major part of this investigation. As the inquisition was largely based on comparative studies rather than material study, the properties of the material had only nominal influence on the results.

The following five different groups of hydrophones were constructed with various types of diaphragms.

1. STL series
2. RAD series
3. TIK series
4. SQR series
5. CORE series

In all the above designs PVDF film of dimensions 5 cm × 1 cm × 52 μm was used.

4.5.2.1 STL series

STL series constitutes two hydrophones with different diaphragm materials, so as to study the influence of the diaphragm material on the characteristics of the hydrophone. STL 01 being a hydrophone with stainless steel diaphragm and STL 02 with phosphor bronze diaphragm. The diaphragm descriptions are given in Table 4.2 and their performance in water in Fig. 4.13.

TABLE 4.2 : Dimensions and materials of the diaphragms used for the evaluation of diaphragm characteristics on the performance of the hydrophone.

Hydrophone Type		Diaphragm Material & Dimensions *Diameter x Thickness*
STL series	STL 01	Stainless steel 5 cm × 1 mm
	STL 02	Phosphor bronze 5 cm × 1 mm
RAD series	RAD 02	Stainless steel 5 cm × 1 mm
	RAD 03	Stainless steel 6 cm × 1 mm
TIK series	TIK 08	Stainless steel 5 cm × 0.8 mm
	TIK 06	Stainless steel 5 cm × 0.6 mm
	TIK 01	Stainless steel 5 cm × 1 mm

4.5.2.2 RAD series

RAD 02 and RAD 03 form the part of RAD series, and this series mainly envisages to bring out the influence of the diaphragm diameter on the hydrophone performance. Both the hydrophones have stainless steel diaphragm with different

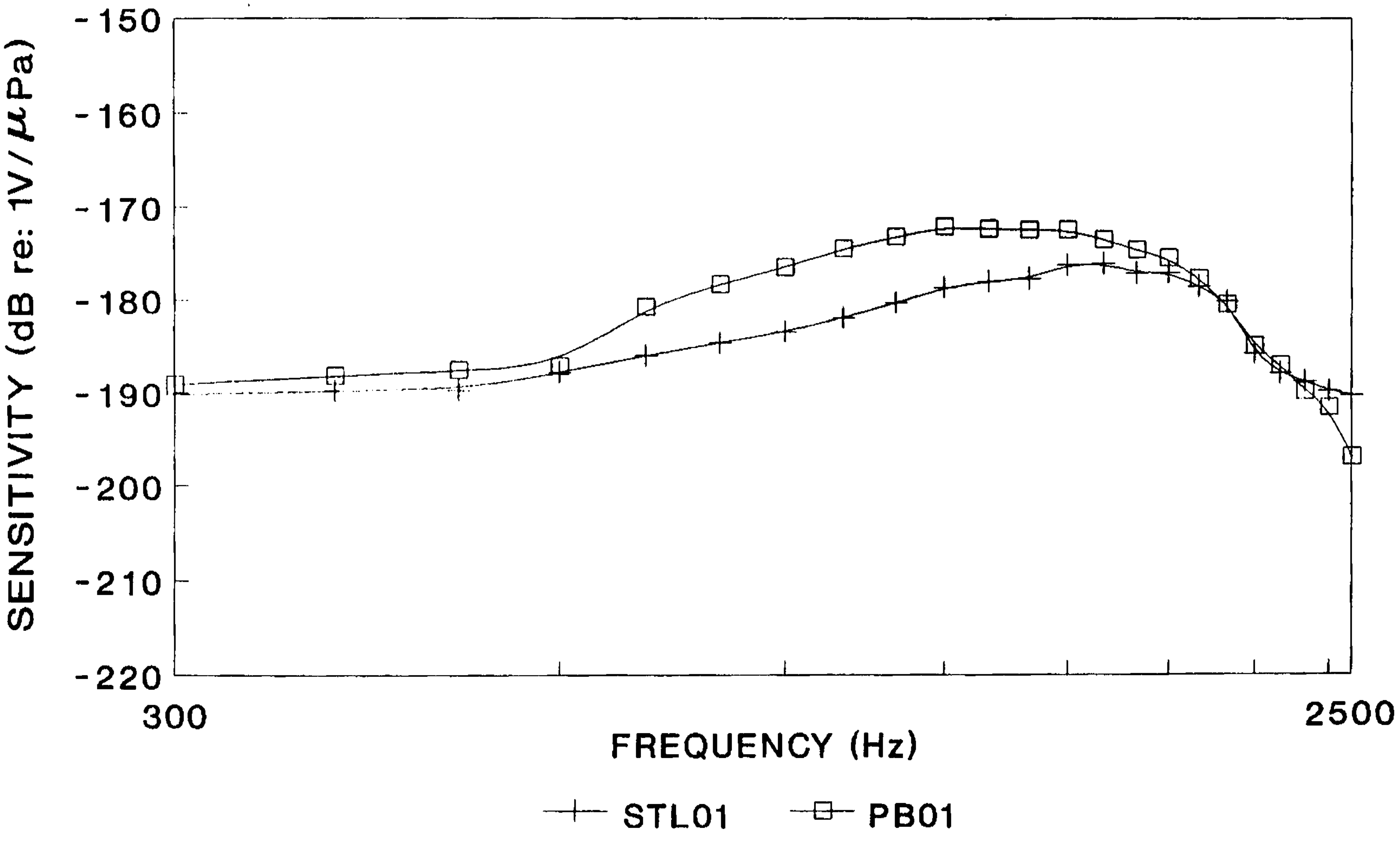


Fig. 4.13 : Frequency response of the hydrophone with different diaphragm materials.

diameters. In order to accommodate the larger diaphragm, the enclosure size of RAD 03 was suitably increased. Table 4.2 highlights their diaphragm dimensions and their in-water measurement results are shown in Fig. 4.14.

4.5.2.3 TIK series

As the diaphragm is the receiving part of the hydrophone, the thickness of the diaphragm will also control the functioning of the hydrophone. The aim of TIK series is to take an account of this influence. TIK 08, TIK 06 and TIK 10 forms the TIK family. The diaphragm dimensions are provided in the Table 4.2. Due to some technical reasons, they were not tested in water and were compared in air only. Fig. 4.15 gives a glimpse of the experimental results in air.

4.5.2.4 SQR series

In all the hydrophones described so far, the diaphragm used was of circular type. It is also possible to use rectangular and square diaphragms. So in SQR series a comparison was made between hydrophones with square and circular diaphragms. SQR 01 has square stainless steel diaphragm of sides 5 cm and CIR 01 has circular diaphragm of 5 cm diameter, and each with thickness of 1 mm. The experimental results in water are shown in Fig. 4.16.

4.5.2.5 CORE series

CORE series comprises of four hydrophones with different types of corrugated diaphragms. CORE 01, CORE 02, CORE 03 and CORE 04 constitute the CORE series. The shapes of the diaphragms used for the CORE hydrophones

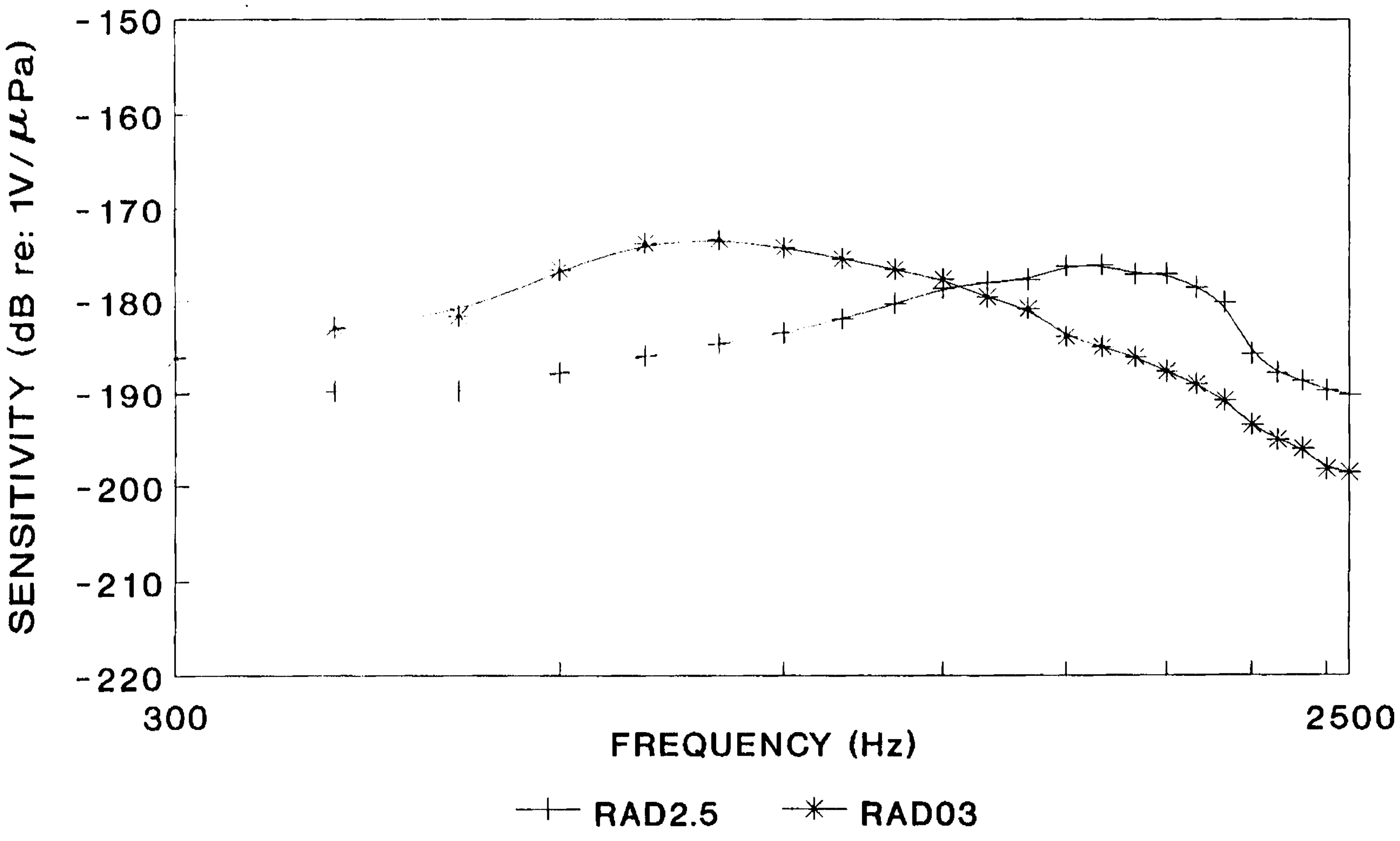


Fig. 4.14 Comparison of the responses of the hydrophones with varying diaphragm radius.

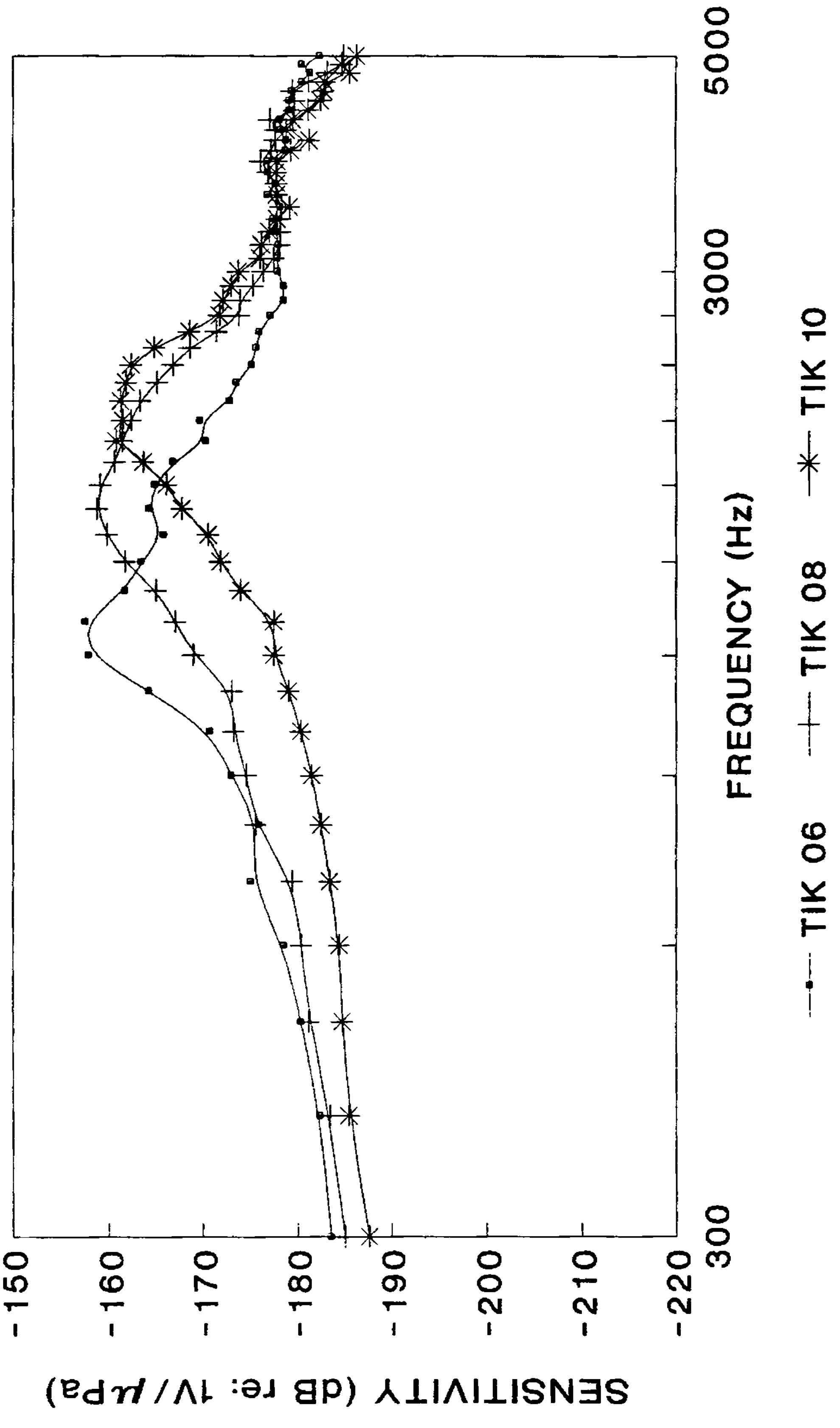


Fig. 4.15 : Hydrophone response with varying diaphragm thickness.

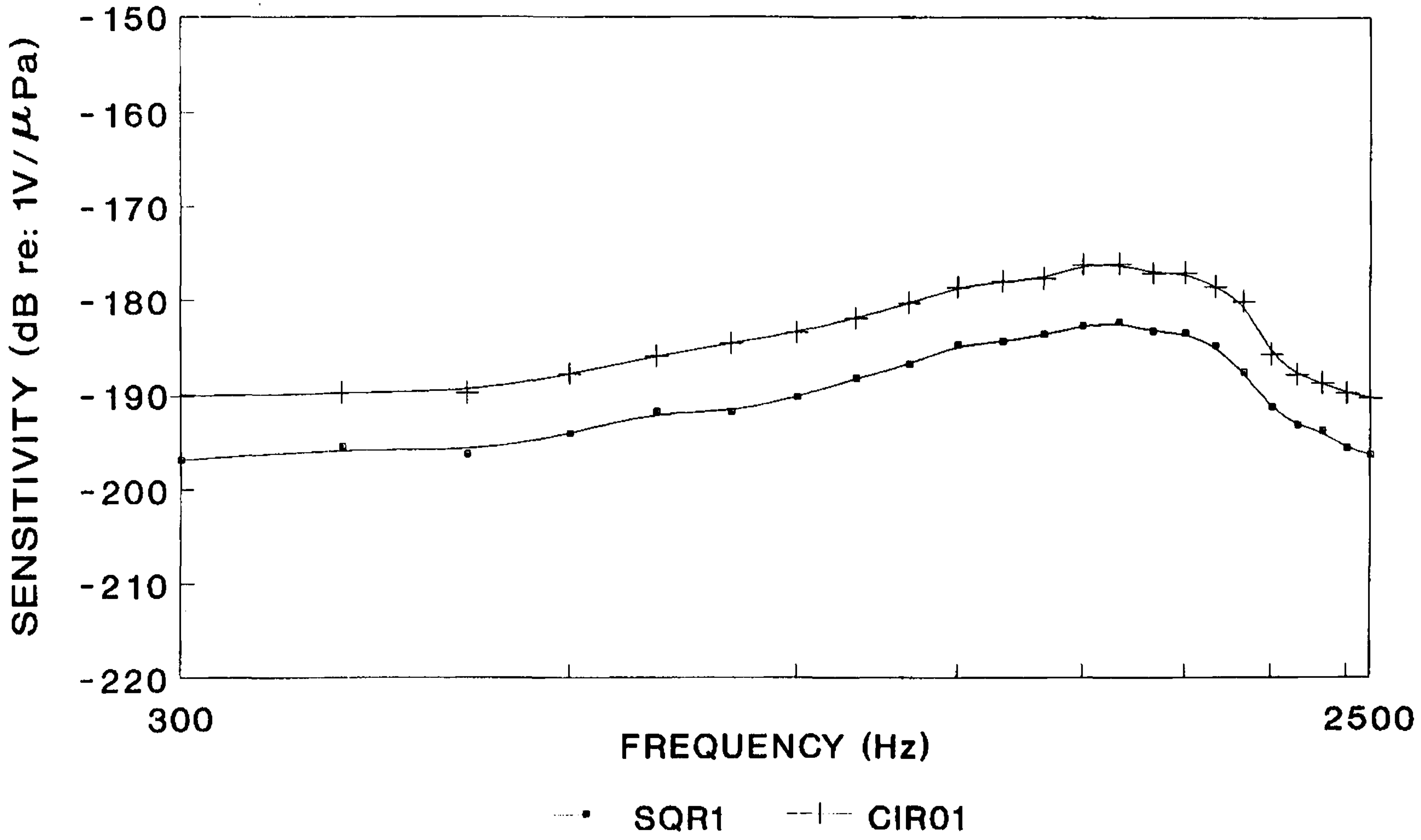
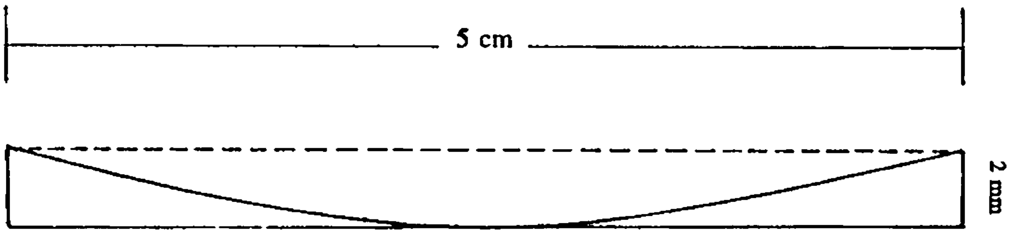


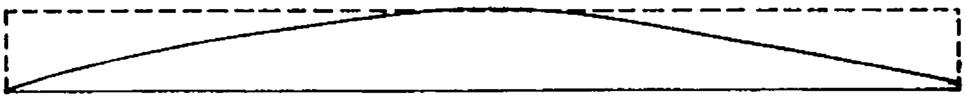
Fig.4.16 . Hydrophone response for square and circular diaphragms.

are shown in Fig. 4.17. All these diaphragms are fabricated from 2 mm thick stainless steel sheet and the required corrugations are machined over it. The idea of using corrugated diaphragms is to inquire their potential influence on the working of the hydrophones, particularly their resonance frequency. A collation of their performance in water is shown in Fig. 4.18.

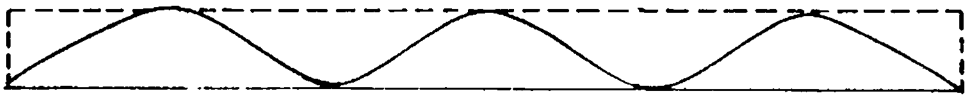
Thus in Fig. 4.13, the response of the hydrophones with stainless steel and phosphor bronze diaphragms are compared, and it is found that STL 02 has a slight upper hand in sensitivity over STL 01. In RAD series, with increase in radius of the diaphragm, the resonance frequency is found to be decreasing for RAD 03. But due to the larger surface area of the diaphragm, the sensitivity in RAD 03 is found to be increasing. In the case of TIK series, as can be inferred from Fig. 4.15, with increase in thickness, the resonance frequency is also found to be increasing. But the decrease in sensitivity observed can be explained as, when the thickness increases, the diaphragm becomes comparatively more stiff resulting in curtailment in its vibrations. SQR series consists of hydrophones with circular and square diaphragms. It is clear from its responses shown in Fig. 4.16 that, the response of SQR 01 and CIR 01 are almost similar with a slight improvement in sensitivity for CIR 01, with both of them showing the same resonance frequencies. The case of hydrophones with corrugated diaphragms is different. Contrary to the expectations, all of them behaved similarly, along with a decrease in sensitivity by around 10 dB than that of their counterparts. One of the reasons for this discrepancy may be that, all the corrugations were machined on a 2 mm thick stainless steel sheet and this thickness may be too stiff to produce any effects of corrugations on their performance. In other words, the diaphragm acts as if it is 2 mm thick.



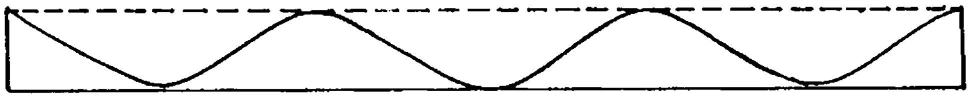
CORE 1



CORE 2



CORE 3



CORE 4

Fig. 4.17 : Shapes of the diaphragms used in CORE series.

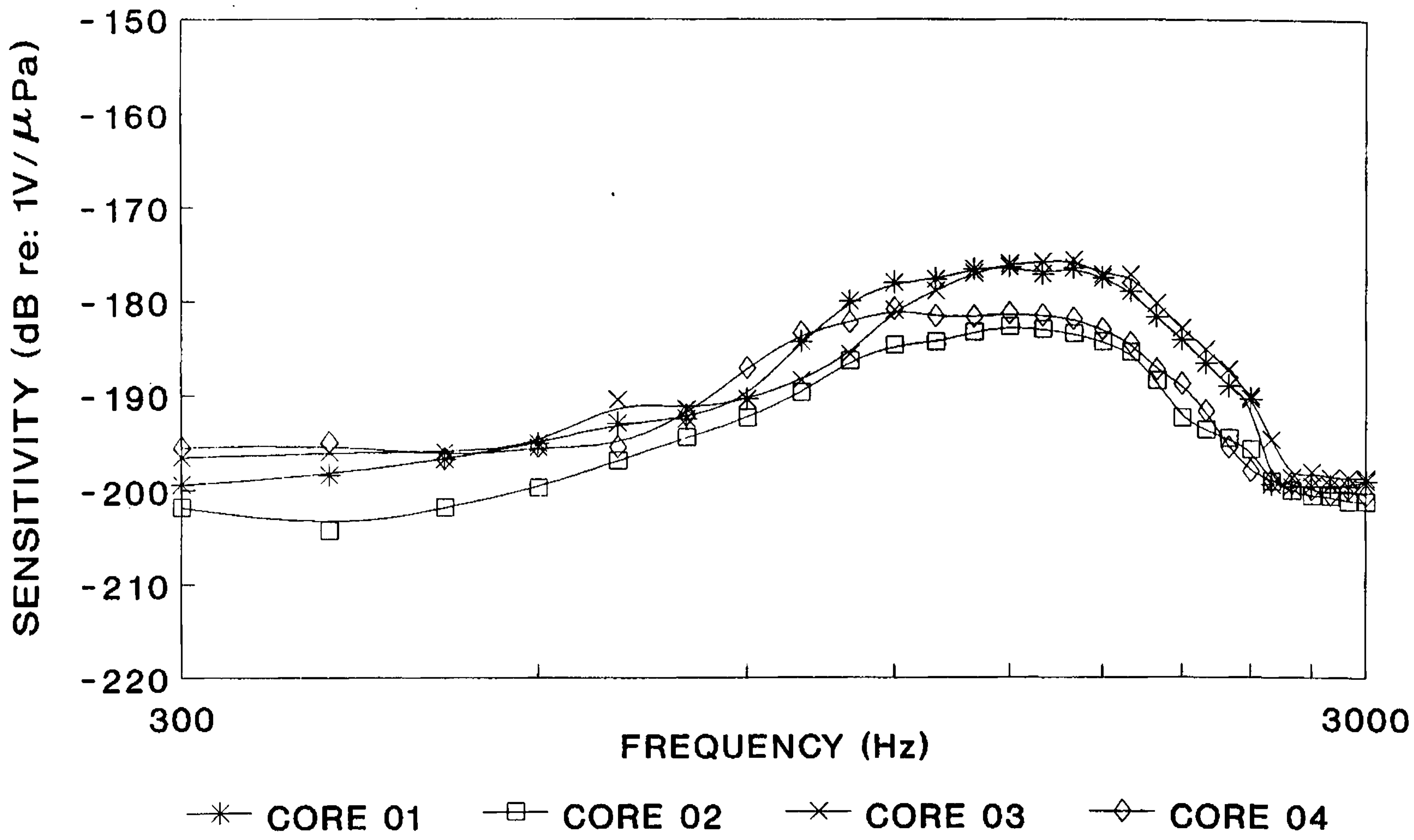


Fig. 4.18 Response of the hydrophones with various types of corrugated diaphragms.

It is evident from the design of T2, that along with the characteristics and dimensions of the diaphragm and film, another probable component that may influence the performance of the hydrophone is the stretching of the film, as it may act as additional load on the diaphragm affecting its flexing, changing the resonance frequency of the hydrophone. In order to study its influence, the film was fully released and stretched in steps of smaller intervals. For each interval, the resonance frequency was noted, and no marked difference was observed. Similarly the length of the driver pin was varied by ± 1 cm to evaluate its role in determining the hydrophone characteristics, no notable results were obtained.

4.6 CABLE CAPACITANCE

For the whole experimental analysis described above, the standard hydrophone used was ITC 1042 and the projector UW 15. All in-water measurements were carried out at the Lake Facility (UARF). As described in Sec. 3.11 of Chapter 3, a preamplifier is necessary to reduce damping of the hydrophone output due to capacitance of the cable. But connecting each hydrophone with a cable of around 30m and a preamplifier is not only uneconomical but difficult to handle as well. For simplicity and cost effectiveness, each hydrophone was provided with 5 metres of cable, so that when the hydrophones are immersed, the cable will reach just above the water level. From there onwards preamplifier and the extension cable can be suitably connected. With this arrangement, the same cable and preamplifier can be connected to all the test hydrophones, thus making its handling easy simultaneously reducing the over all cost considerably. But damping of the signal due to the cable capacitance has to be properly compensated for getting the actual hydrophone output. The following method was employed for computing the actual output voltage by deducting the cable loss.

Consider a hydrophone with electrical impedance Z_t, with a cable of impedance Z_c. Then this system can be represented as in Fig.4.19.

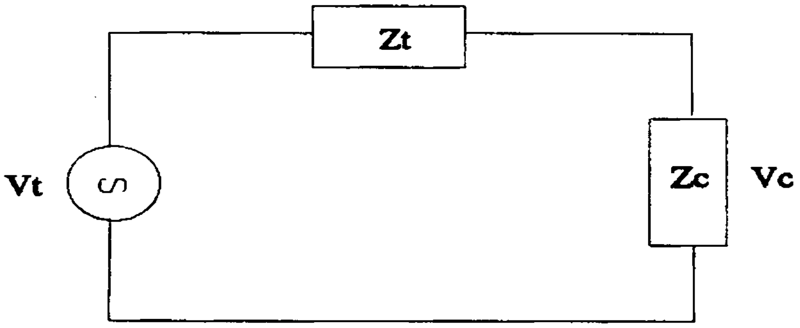


Fig. 4.19 : Electrical equivalent of a hydrophone connected with a cable.

V_t is the actual voltage generated by the hydrophone and V_c is the resultant output received at the cable terminals. So by knowing, V_t, Z_t and Z_c the generated voltage at the terminals of the hydrophone can be calculated as,

$$V_t = V_c \frac{(Z_t + Z_c)}{Z_c} \tag{4.2}$$

As all the hydrophones were thoroughly sealed with cables, for making them water tight, it was not possible to get the values of cable impedance and hydrophone impedance separately. So for measuring Z_t and Z_c, the resultant impedance of the combination was measured as Z and the average impedance of five different pieces of similar cable each with 5m length, was taken as Z_c. From Z_c and Z, the hydrophone impedance can be calculated as,

$$Z_t = \frac{Z_c Z}{Z_c - Z} \tag{4.3}$$

Here it was assumed that the cable and the hydrophone are connected electrically in parallel. To ensure the validity of this method, it was tested for two hydrophones in air. For this BF 04 and TF 110 were used, and their outputs were measured with and without the cables for different frequencies along with their resultant impedance. Table 4.3 provides a comparison between the experimental and numerical results obtained.

TABLE 4.3 : Comparison between the experimental and calculated outputs of BF 04 and TF 110 for different frequencies by compensating the cable loss.

Hydrophone Type	Frequency (Hz)	(V_c) Hydrophone output with cable (mv)	Impedance of the		Voltage output (V_o)	
			(Z) Hydrophone with cable (KΩ)	(Z_c) Cable alone (KΩ)	Without cable (mv)	Calculated (mv)
BF 04	500	22	67.60	325	28	27.77
	1000	36	34.43	175	45	44.81
	2000	240	17.56	94.5	300	294.8
	3000	190	11.82	66.07	230	231.4
	4000	100	8.96	51.23	120	121.2
TF 110	500	24	233	325	60	62
	1000	60	123	175	140	144.8
	2000	180	64.96	94.5	400	411.4
	3000	210	44.63	66.07	460	466
	4000	110	34.30	51.23	240	238.6

The numerical and experimental results agree, thus confirming the reliability of the approach. The impedance measurements were carried out using HP 4192A Impedance Analyzer.

Throughout the experimental analysis the pre-amplifier AMP 4002 was used. All the experimental results in Sec. 4.5 are with proper compensation for amplifier gain as well as for the cable impedance loss which arises out of the extended hydrophone cable.

4.7 FIL 14

FIL 14 is similar to T2 except that there is no air column inside. In T2 the film occupies only a limited space in the enclosure, resulting in a large free air column. As the air column itself resonates at certain frequencies, there is a possibility that these resonances may also appear in the resultant hydrophone response. The objective of FIL 14 is to get an idea of the role of this air column on the hydrophone performance. To eliminate the air column, the hydrophone was completely filled with Polyurethane, which shows good acoustic properties suitable for underwater applications. The responses of FIL 14 and FIL 15 in water are compared in Fig. 4.20. FIL 15 is similar to T2. In both FIL 14 and FIL 15 a phosphor bronze diaphragm of 5 cm × 1 mm and PVDF film of 5 cm × 1 cm × 52 μm were used.

From the response of FIL 14, it can be inferred that the sensitivity is found to be decreased considerably. This may be due to the restriction imposed on film vibration by the surrounding polyurethane, which is filled inside the enclosure.

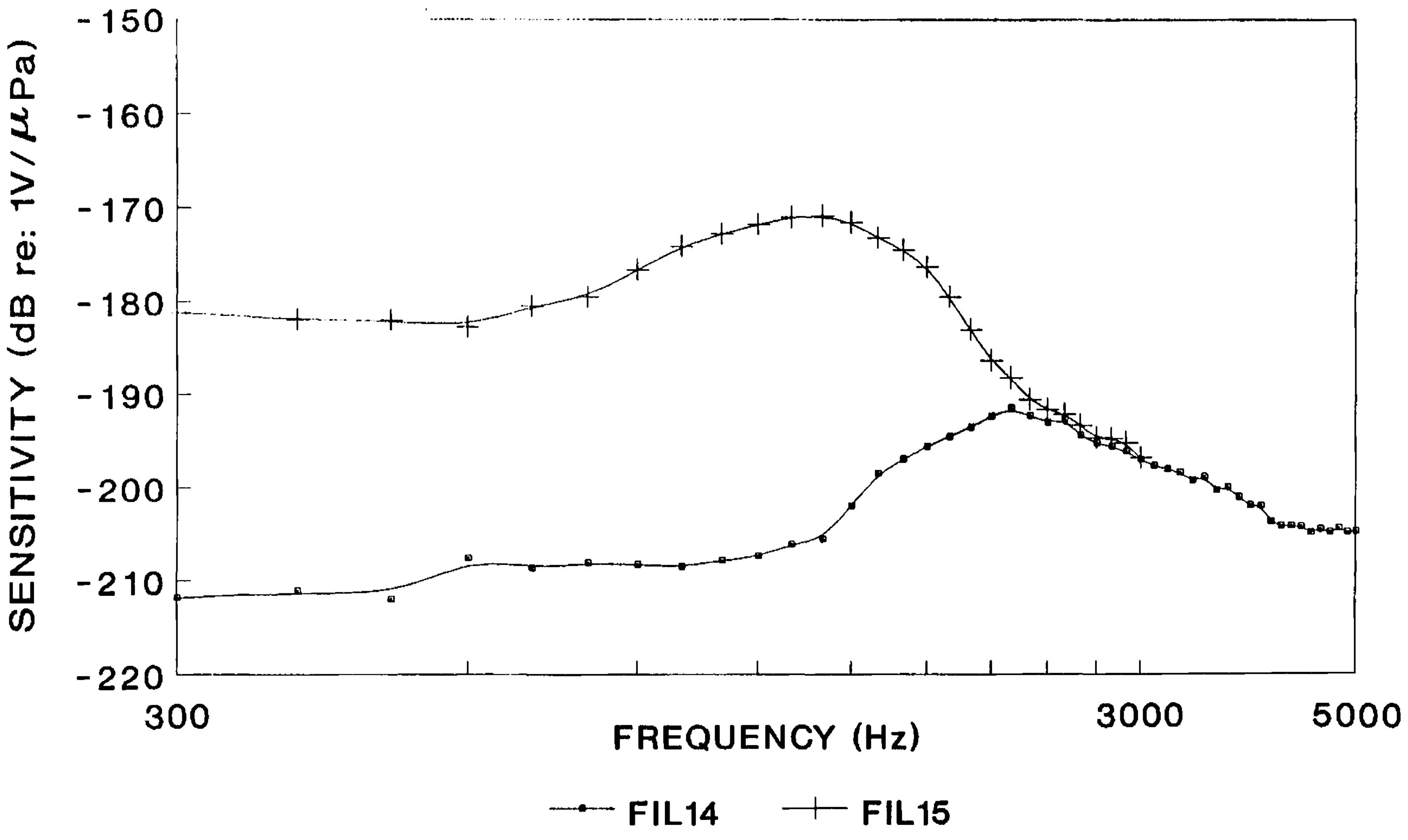


Fig. 4.20 : Influence of the air column on the hydrophone response.

Increase in resonance frequency is observed for FIL 14 compared to FIL 15. This may be the result of the increased stiffness of the hydrophone assembly, due to the filled material.

Chapter 5

Refined design

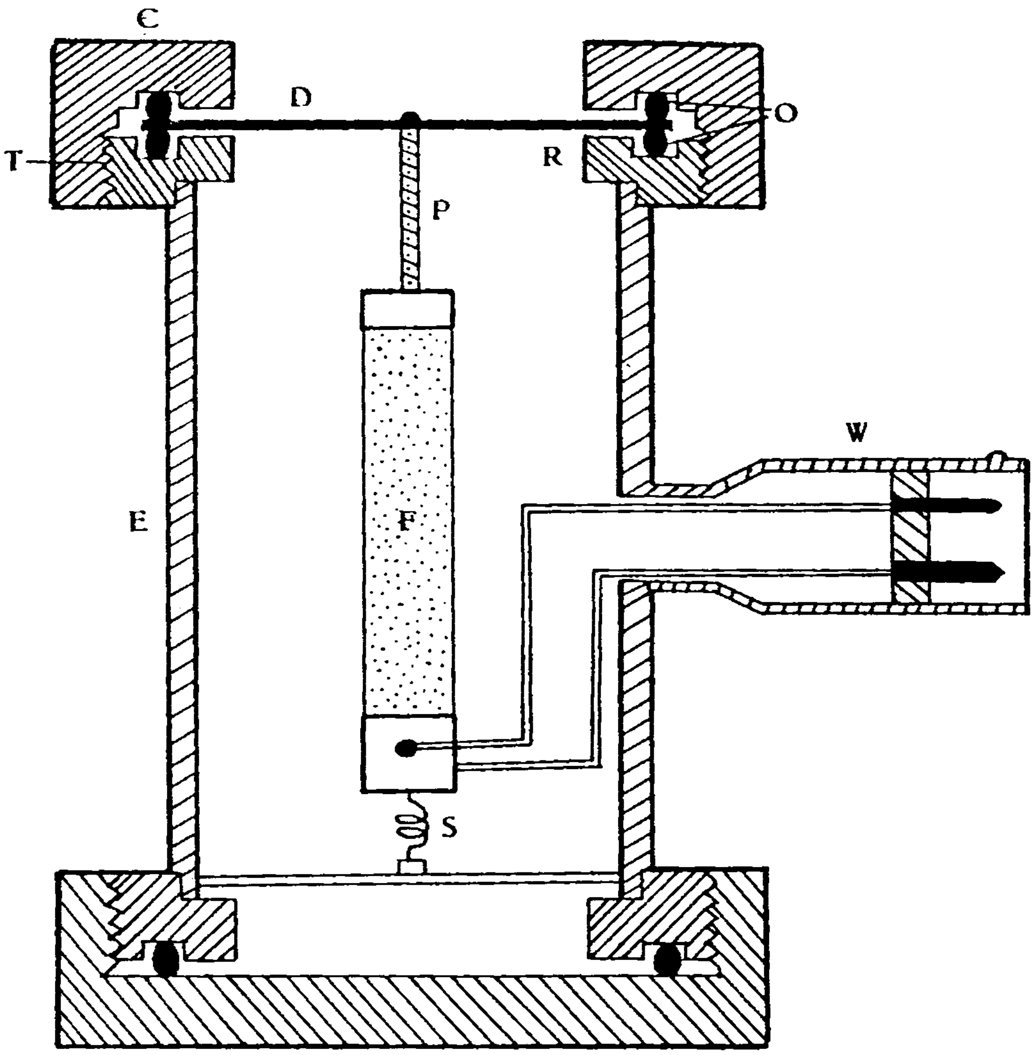
This chapter mainly concentrates on the formulation of the refined (3,1) drive hydrophone design along with a mathematical model, which facilitates the characterisation and design of the refined model. Various experimental outcomes of the refined design and its directional response are also highlighted here. This chapter has been configured as follows,

1. Formulation of a refined hydrophone design
2. Mathematical modelling of the (3,1) drive design

The principle of working of the hydrophone model T2 described in chapter 4 is that, any acoustic pressure variations on the diaphragm are transferred to the pre-stretched film resulting in the production of corresponding strains, which in turn develop charges on the film surfaces. As the diaphragm is the sole component exposed to the radiation, it contributes to the transfer of energy from the medium to the active element. Therefore the response of the hydrophone largely depends on the mode of vibration of the diaphragm, and for the consistent transfer of energy to the film, the diaphragm should be mounted uniformly. But in T2, the diaphragm is fixed with an adhesive and hence is very difficult to ensure a uniform mounting as well as a perfect sealing against water ingress. Diaphragm mountings with non uniform pressure at the edges results in inconsistent variations in hydrophone characteristics endangering the reproducibility of the design. Moreover this type of mountings are not reliable as their stiffness and rigidity may dwindle due to aging, resulting in the formation of cracks and flaws at the mounting surface. In the refined design a uniform pressure mounting as well as a good water sealing is provided by pressing the diaphragm in between two rubber O-rings.

5.1 DEVELOPMENT OF REFINED HYDROPHONE MODEL

A cross-sectional view of the improved model is shown in Fig. 5.1. It consists of a cylindrical enclosure over which a threaded perspex annular ring is attached. The width of the perspex ring is chosen to be approximately 1 cm, and a groove is provided on its top for proper seating of an O-ring. The diaphragm is placed over this O-ring and a cap again of perspex with its inner side threaded and with a groove at the bottom for the second O-ring, forms the head assembly. At the centre of this cap an opening of approximately 5 cm diameter is provided to expose the diaphragm to the medium. The head assembly is made perfectly water proof by tightening the cap properly, which makes the diaphragm to be squeezed in between



C : PERSPEX CAP
D : PHOSPHOR BRONZE DIAPHRAGM
O : RUBBER 'O' RINGS
R : PERSPEX ANNULAR RING
T : THREADINGS
P : DRIVER PIN
W : WATER TIGHT CONNECTOR
E : WATER TIGHT ENCLOSURE
S : SPRING LOADED SCREW
F : PVDF FILM

Fig. 5.1 : A cross-sectional view of the refined hydrophone model.

the O-rings there by providing it a uniform mounting. As in the previous designs, at the centre of the diaphragm one end of a driver pin is fixed and to the other end of which a PVDF film is attached. The film is stretched properly and the output is taken through the terminal electrodes.

To ascertain an acceptable level of reproducibility of the refined design, three different sets of three similar hydrophones in each set were constructed. Their film and diaphragm dimensions are given in Table 5.1. Out of the A, B and C series hydrophones, in A and B the diaphragm dimensions are kept the same while the length of the film is varied, where as in A and C the film lengths are the same with a change in diaphragm dimensions.

TABLE 5.1 : Film, Diaphragm and O-ring dimensions of the Hydrophones.

Transducer Type	Dimensions		
	Film *Length × Width × Thickness*	Diaphragm *Diameter × Thickness*	O-ring *Diameter × Thickness*
A Series	4.5 cm × 1 cm × 28 μm	6.0 cm × 1.2 mm	6.0 cm × 4 mm
B Series	6.0 cm × 1 cm × 28 μm	6.0 cm × 1.2 mm	6.0 cm × 4 mm
C Series	4.5 cm × 1 cm × 28 μm	3.0 cm × 1.2 mm	3.0 cm × 3 mm

All the hydrophones were terminated with underwater connectors so as to facilitate the use of the same preamplifier and cable for all of them. AMP 4001, the MOSFET buffer amplifier, with an extension cable of 30 metres was used throughout the measurements.

Response of these hydrophones was evaluated in water. ITC 1042 was used as the reference hydrophone and UW 60 as the projector. Both the standard and the test hydrophones were immersed to a depth of about 10 m and the projector at the same depth 10 m away from them. Using the comparison method the sensitivity of the hydrophones were calculated. Figs. 5.2, 5.3 and 5.4 show the variation of sensitivities with frequency. The hydrophones were calibrated in air also with B&K 8104 as the reference transducer. The air response is shown in Figs. 5.5, 5.6, 5.7.

From the responses of A, B and C series hydrophones, it is clear that all the three of the A series behaved similarly in the region below resonance with slight variations in their sensitivities above resonance, where as in the B series all but one responded similarly. The difference in its response can be explained as due to some structural inhomogenities. But in the case of the C series there is no clear resonance, and also all the three behaved similarly. The reduction in sensitivity of the C series may be due to the small capturing area of the diaphragm. However the operating frequency range of the C series has been found to be enhanced. These hydrophones were tested over a period of time to check their repeatability, and were found to be showing responses similar to their earlier ones. Thus the above hydrophones exhibit better levels of reproducibility as well as repeatability, which increases the adaptability of this design.

5.2 DIRECTIVITY PATTERN

Directional response of the hydrophones with refined design were evaluated in water. using the method described in chapter 3. A low frequency projector J 11 was used as the transmitter. The test hydrophone was fixed at the centre of a turn

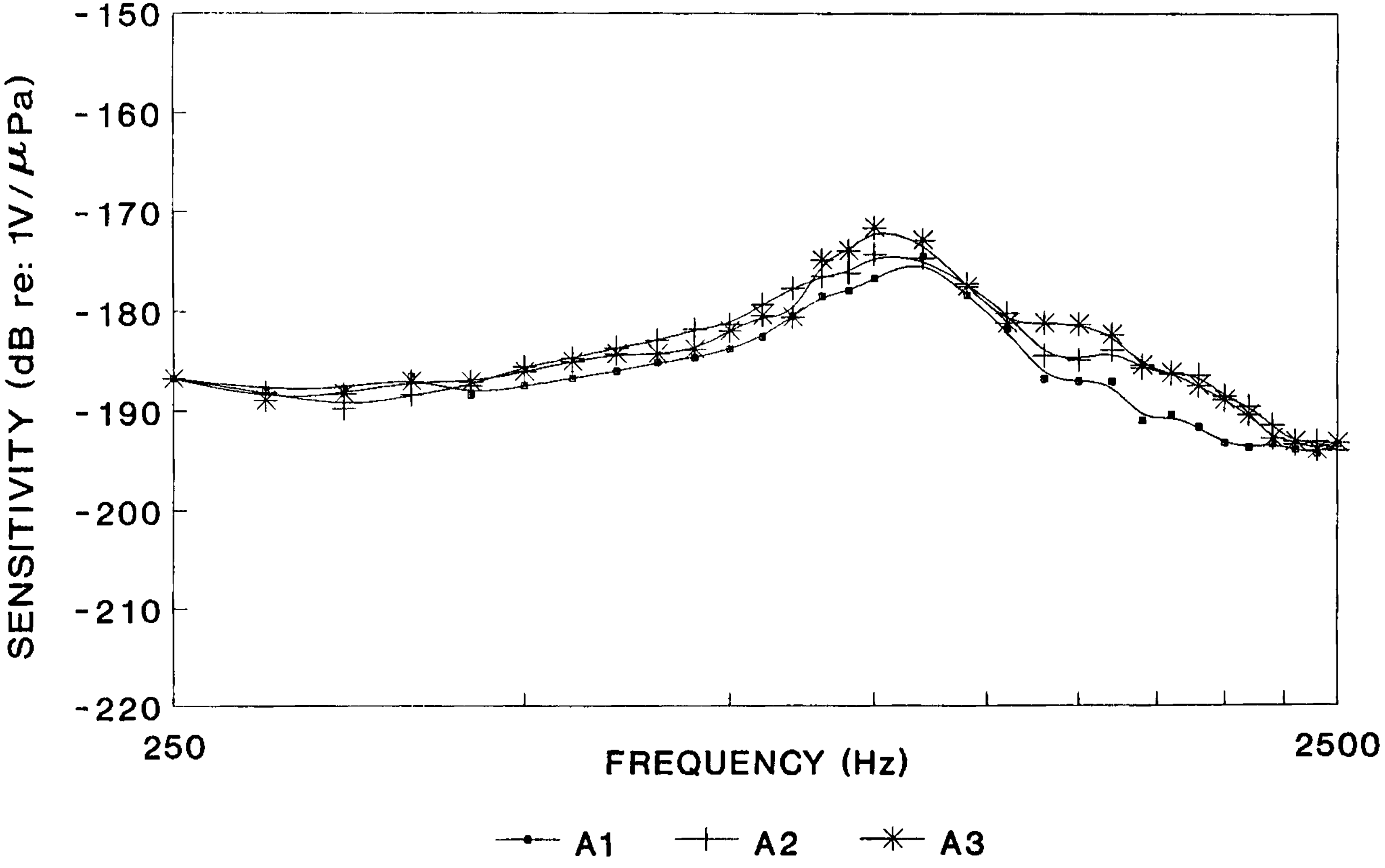


Fig. 5.2 : Frequency response of A series in water.

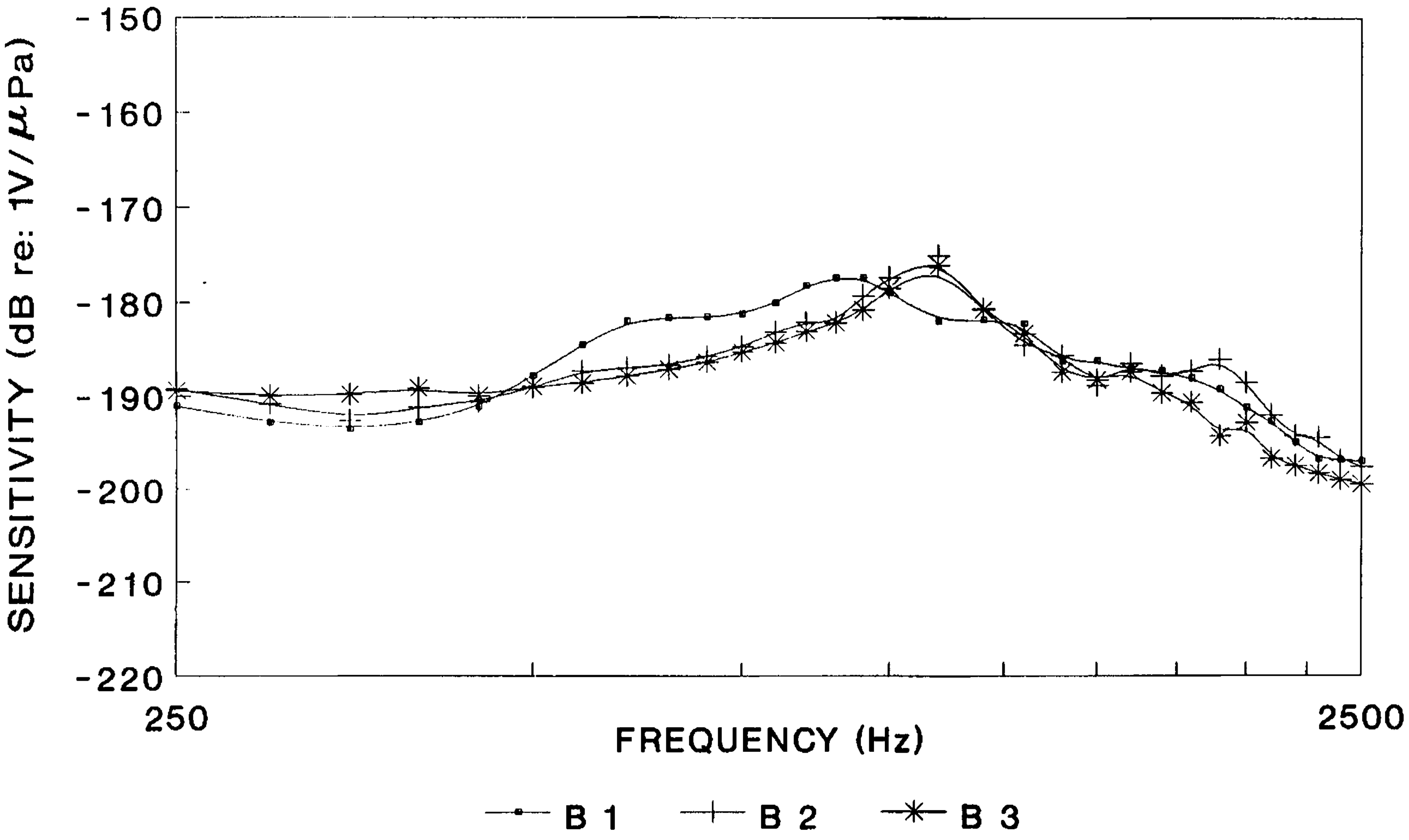


Fig.5.3 : Frequency response of B series hydrophones in water.

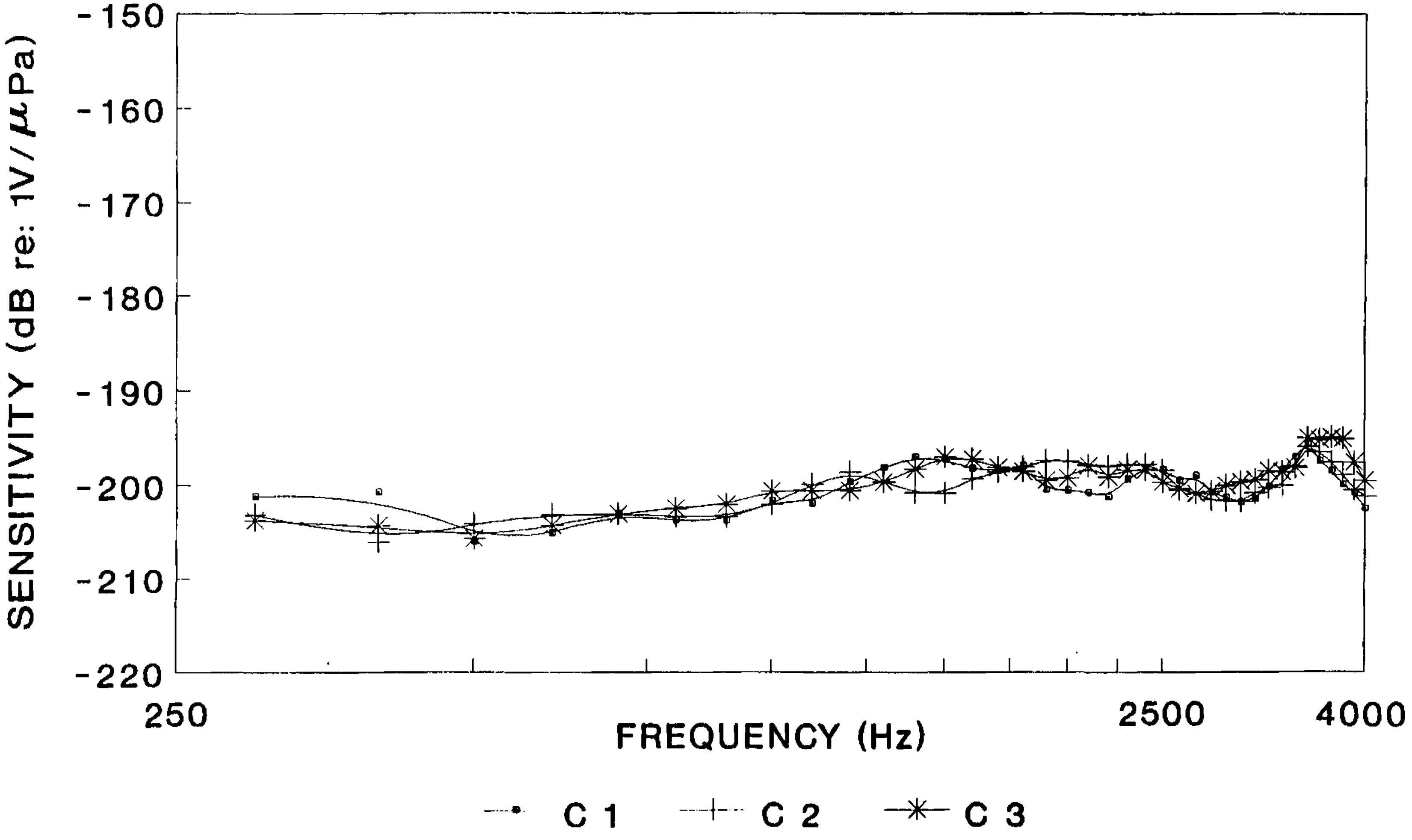


Fig 5.4 : Frequency response of C series hydrophones in water.

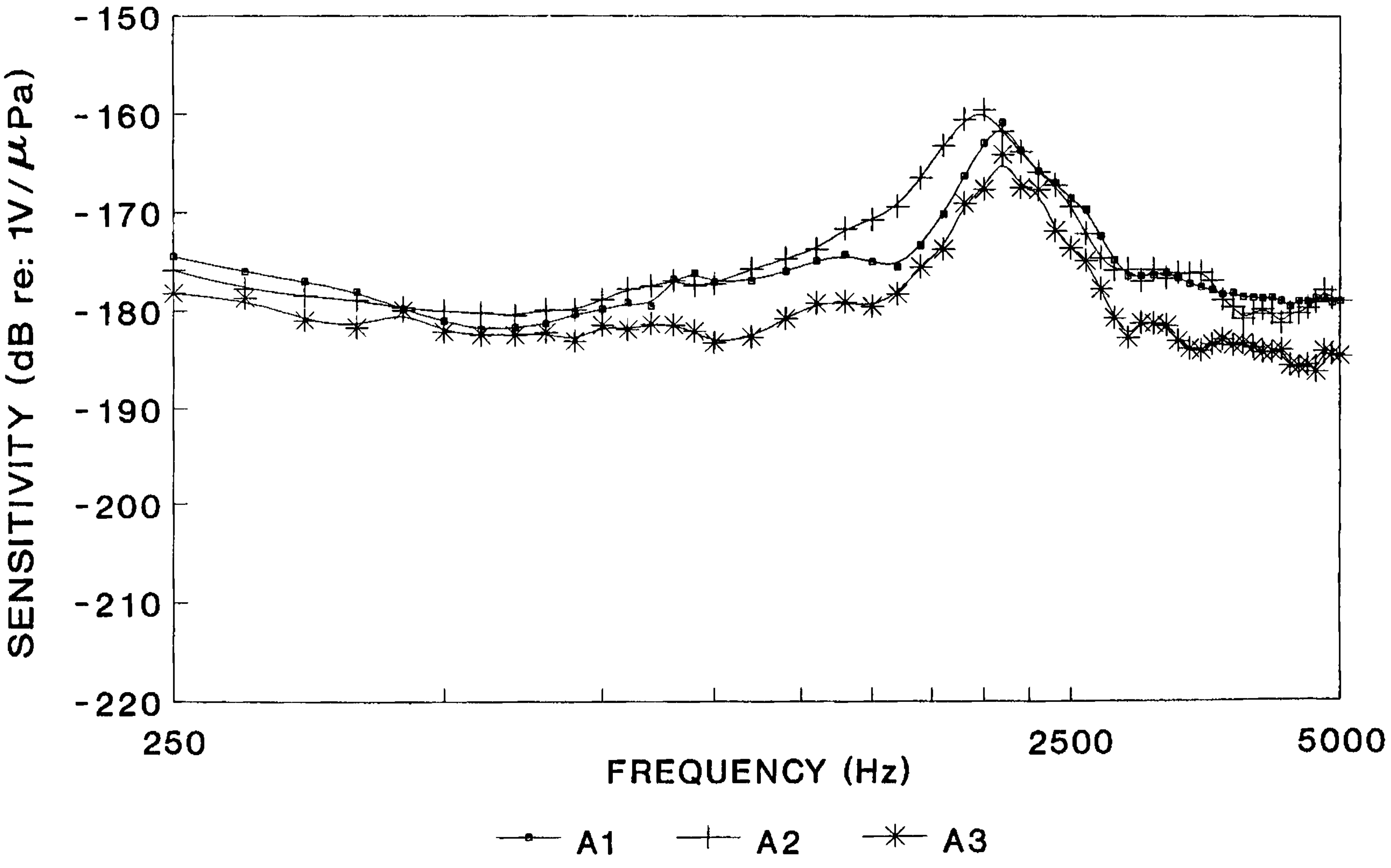


Fig. 5.5 : Frequency response of A series hydrophones in air

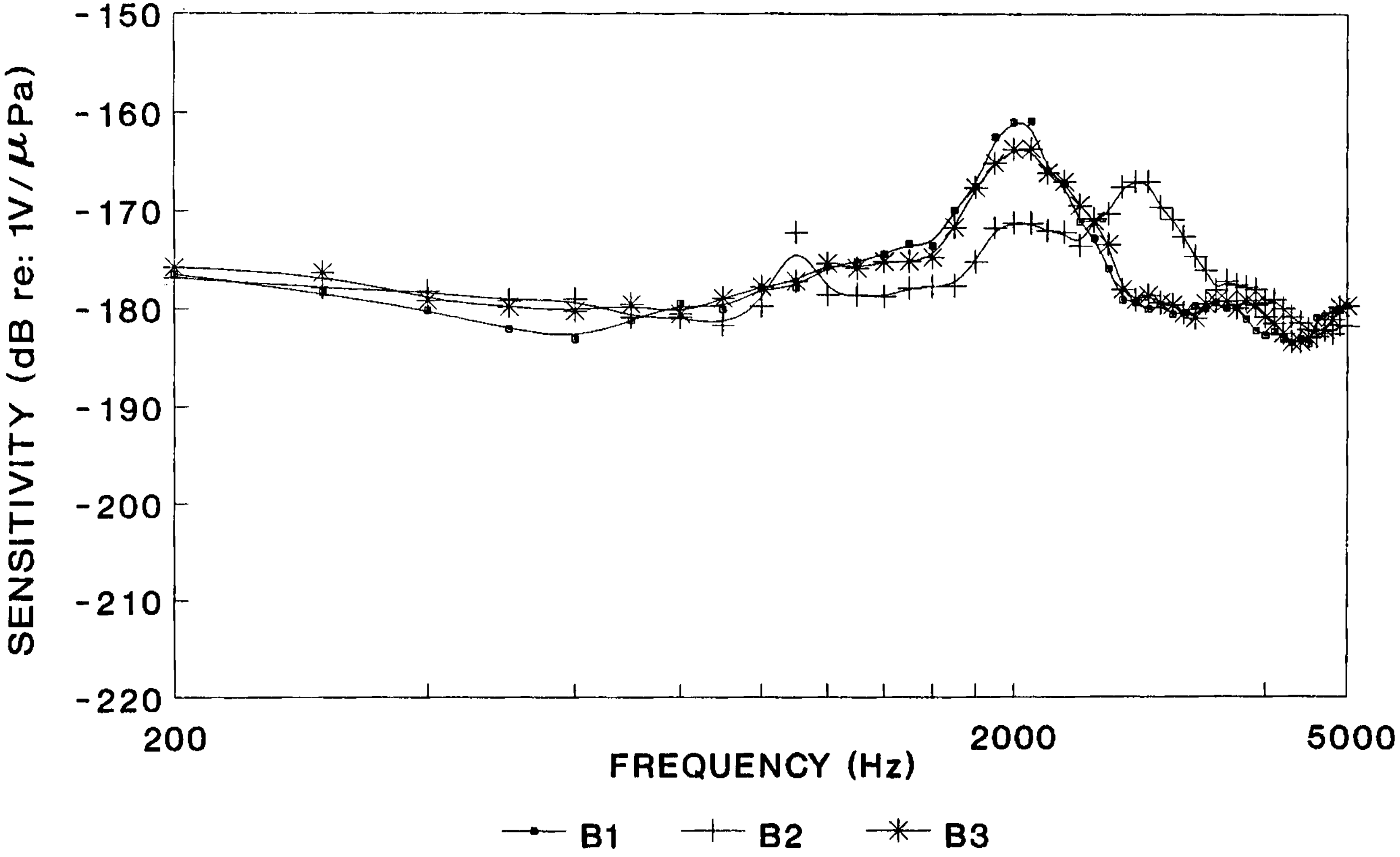


Fig. 5.6 : Frequency response of B series hydrophones in air

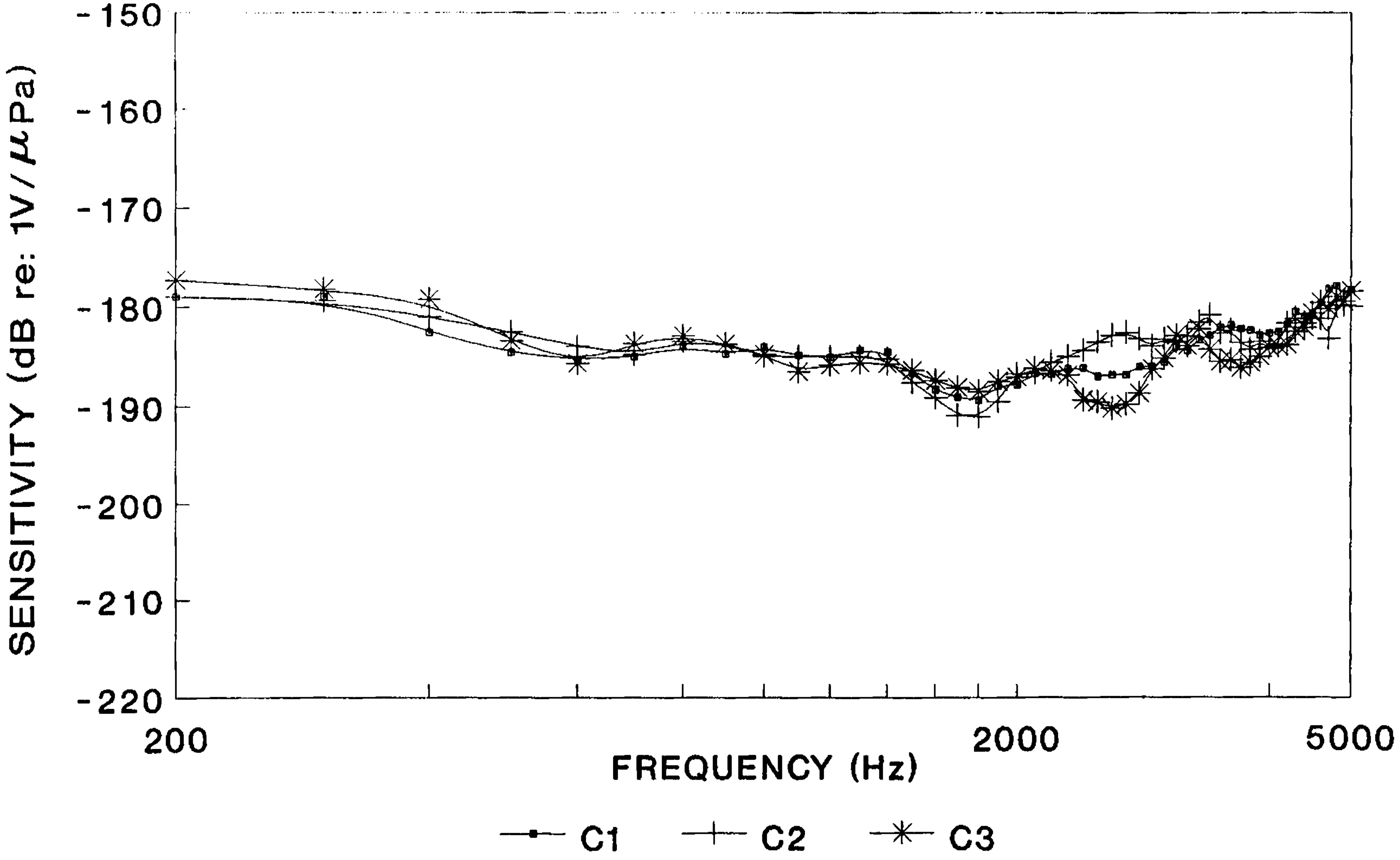


Fig. 5.7 : Frequency response of C series hydrophones in air

table. For a full rotation of 360°, the output of the hydrophone was measured and plotted in a polar chart. Figs 5.8, 5.9, 5.10 and 5.11 show the directional response of the different hydrophones. For the C series the response was studied for 3 kHz also. Due to severe reflections from the walls of the tank, the response was not plotted below 2 kHz.

As expected the experimental hydrophones are almost omnidirectional at the test frequency of 2 kHz.

5.3 ANALYSIS

The resonance frequency of the hydrophone has got a very significant role, as usually the useful band of operation of the hydrophone is restricted below this frequency. Above the resonance frequency, the sensitivity is seen to plunge drastically, hence the hydrophones are not usually operated above the resonance. By knowing the resonance frequency it is possible to establish the useful band of operation of the hydrophone. So an attempt is made here to formulate a mathematical formulation to determine the resonance frequency of the refined transducer models in air and water.

In most of the structures, the resonance frequency is controlled by the components having the least compliance. After analyzing the structure of the refined hydrophone design, it was assumed that the compliance of the diaphragm is smaller compared to the other components of the structure. Hence the diaphragm is considered to be playing a significant role in determining the resonance frequency of the hydrophone, and it is solely governed by the vibrational modes

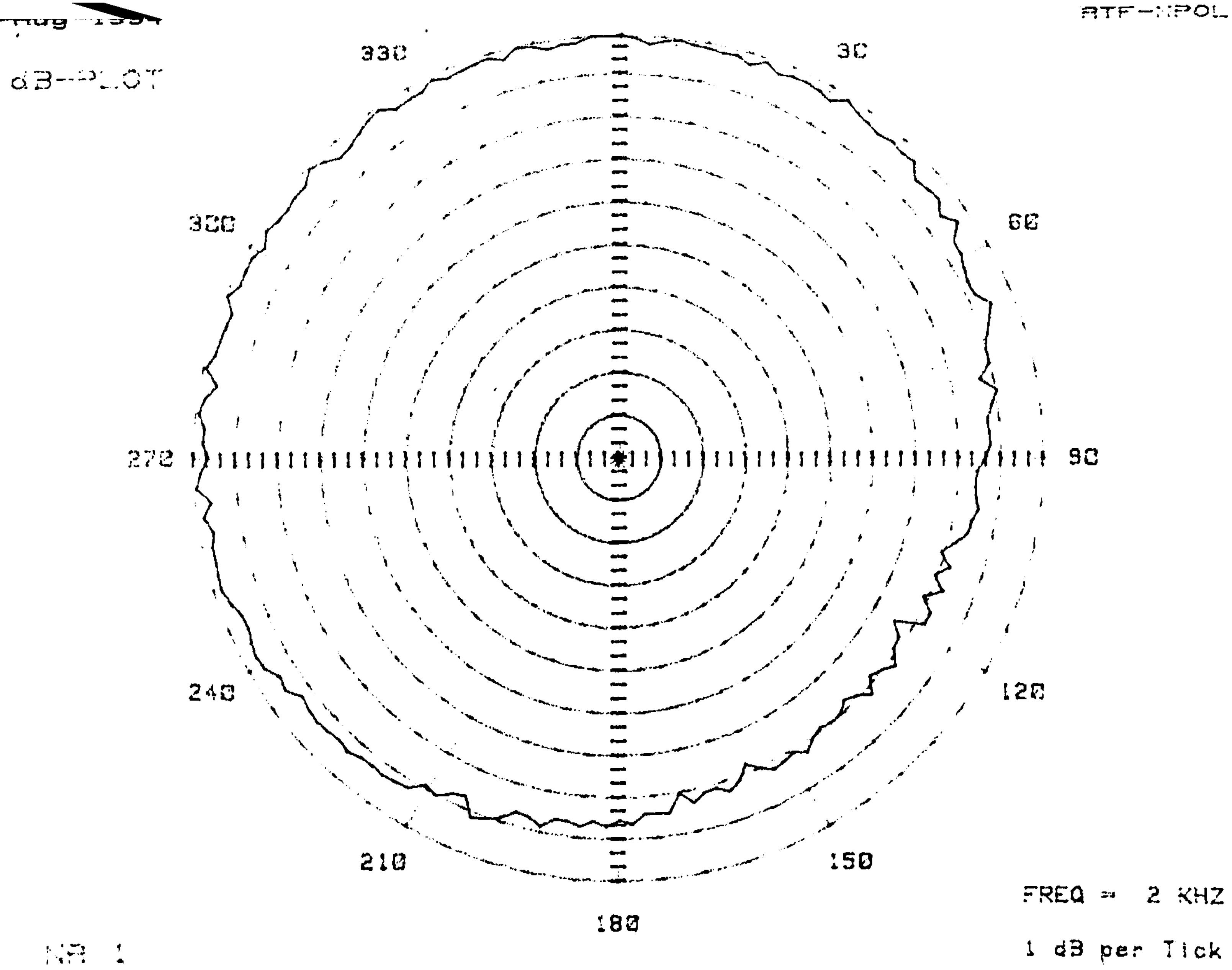


Fig. 5.8 : Directivity pattern of A1 at 2 kHz.

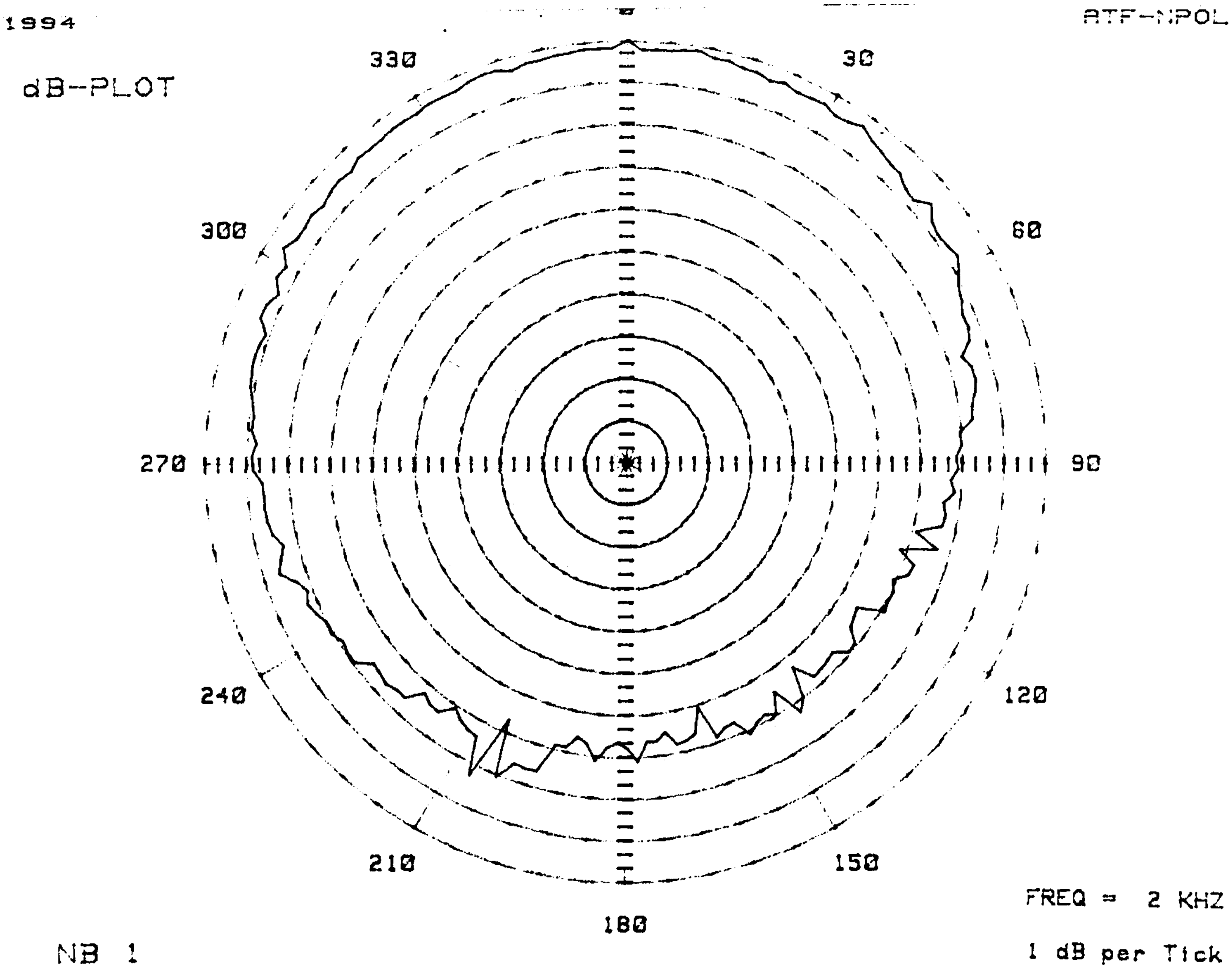


Fig. 5.9 : Directivity pattern of B1 at 2 kHz.

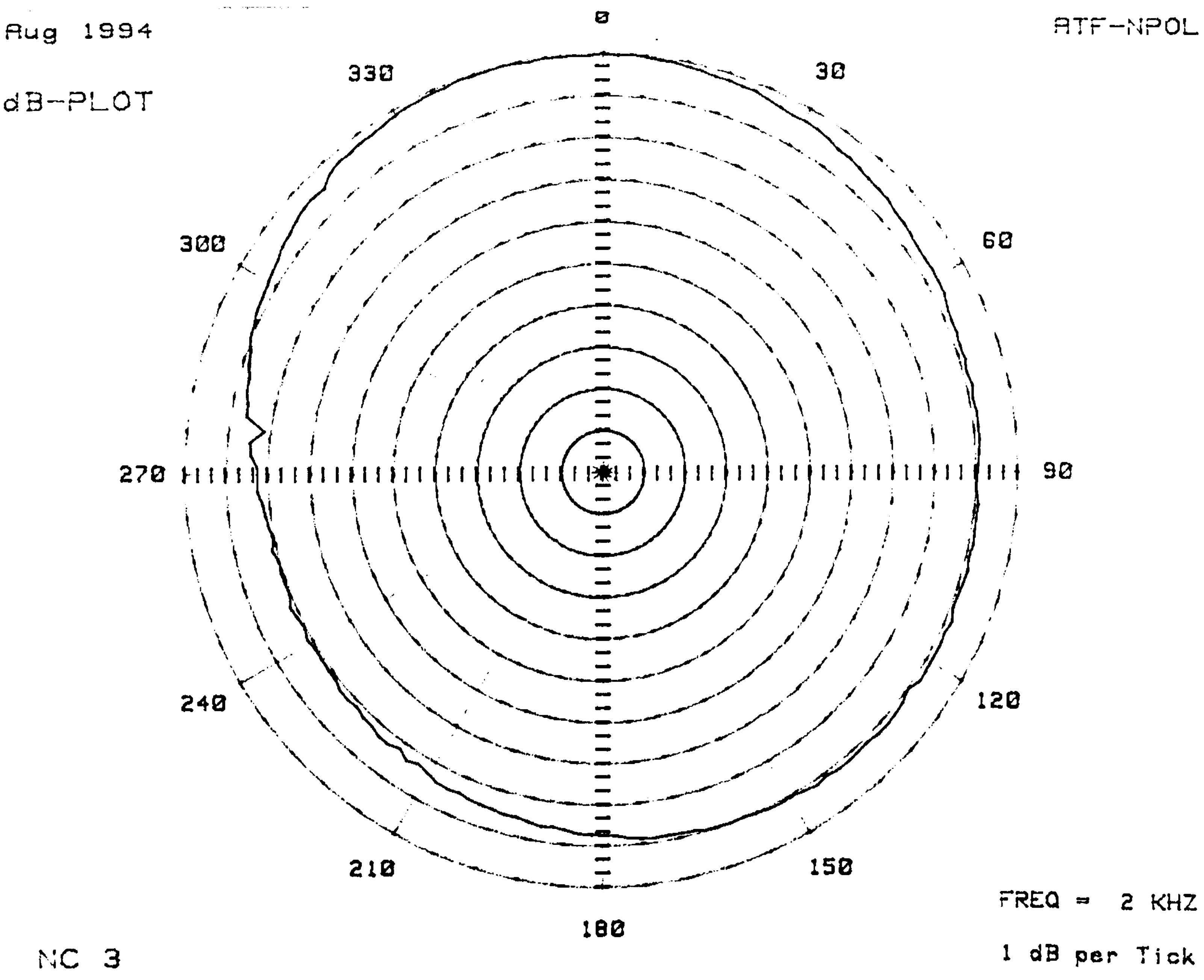


Fig. 5.10 : Directivity pattern of C3 at 2 kHz.

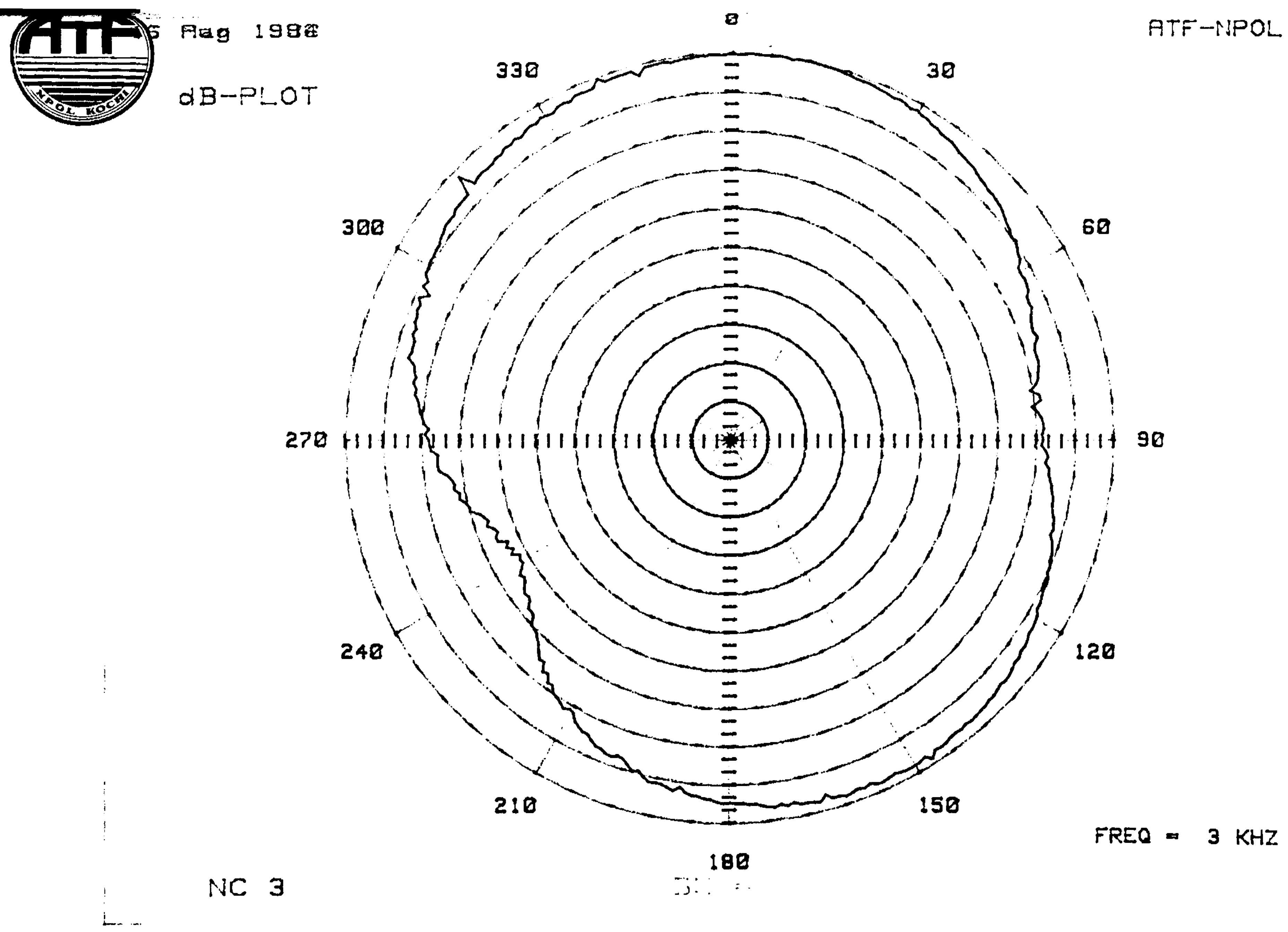


Fig. 5.11 : Directivity pattern of C3 at 3 kHz.

of the diaphragm. As the diaphragm is firmly clamped over the enclosure and the driver pin is fixed at its centre, the whole assembly can be considered as shown in Fig. 5.12, a circular plate with clamped edges and a point mass loaded at the centre.

5.3.1 Resonance frequency in air

The frequency of vibration of different modes of circular plates with free boundary was studied by G.R. Kirchhoff [131] using Poisson-Kirchhoff theory and for the clamped edges by Rayleigh [132] and Timoshenko [133] using an energy method. The exact solution for the problem of vibration of a circular plate involves the use of Bessel function. The Ritz method can be adopted for computing the fundamental mode of vibration of the plates with free or clamped edges with sufficient accuracy.

The deflection υ of a plate having thickness h and radius a, normal to its surface can be assumed as,

$$\upsilon = Z\cos(pt-\lambda_{i,j}) \tag{5.1}$$

Where Z is a function of polar co-ordinates r and θ, which approximates the shape of the deflected membrane *i.e.* mode of vibration, and p is the angular frequency with which the plate vibrates and λ, a dimensionless parameter, a function of the modes (i,j) of its vibration.

In general, the maximum potential energy U and kinetic energy T of the plate can be expressed as [133],

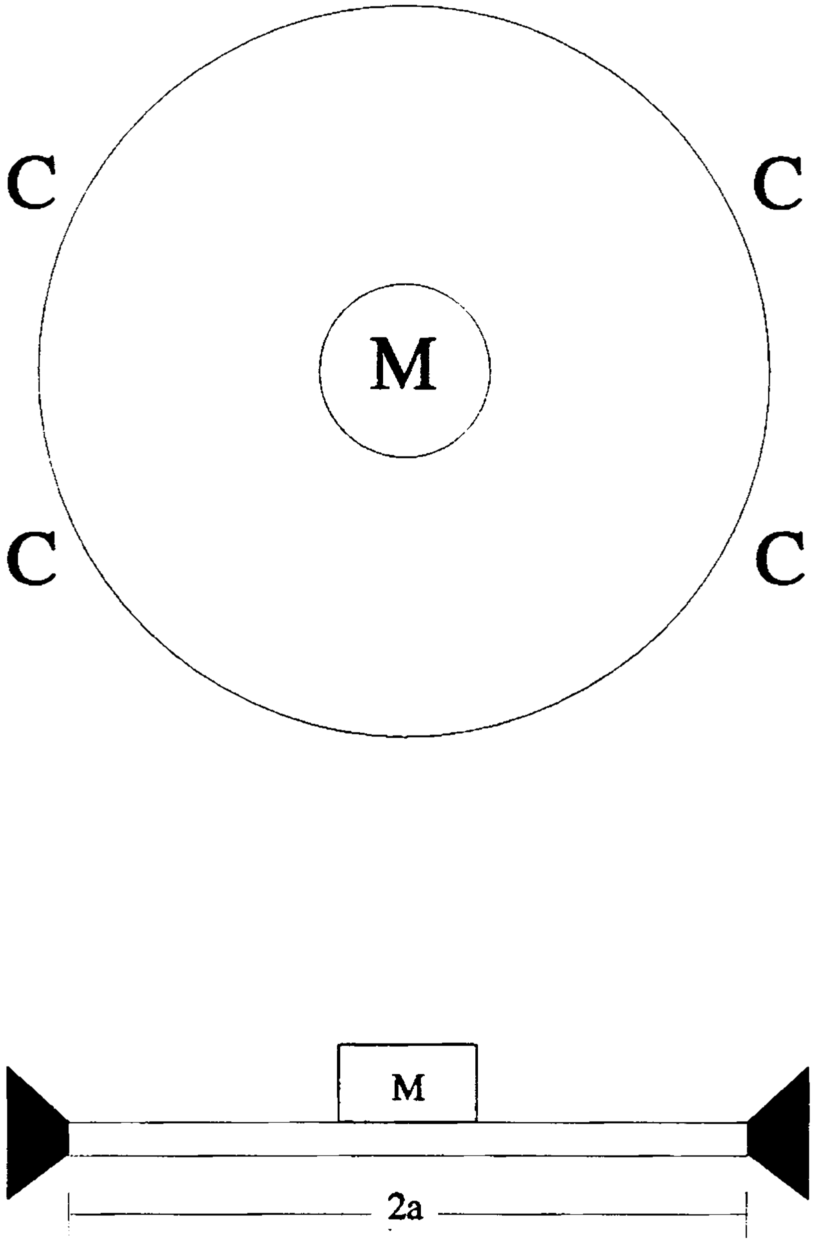


Fig. 5.12 : A circular plate with edges clamped and loaded at the centre.

$$U = \frac{D}{2}\int_0^{2\pi}\int_0^{a}\left[\left(\frac{\partial^2 Z}{\partial r^2}+\frac{1}{r}\frac{\partial Z}{\partial r}+\frac{1}{r^2}\frac{\partial^2 Z}{\partial \theta^2}\right)^2 - 2(1-\nu)\frac{\partial^2 Z}{\partial r^2}\left(\frac{1}{r}\frac{\partial Z}{\partial r}+\frac{1}{r^2}\frac{\partial^2 Z}{\partial \theta^2}\right) + 2(1-\nu)\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial Z}{\partial \theta}\right)\right]^2\right] r\,d\theta\,dr \qquad (5.2)$$

and

$$T = \frac{\rho h}{2}p^2\int_0^{2\pi}\int_0^{a} Z^2 r\,d\theta\,dr \qquad (5.3)$$

where $D = Eh^3/[12(1-\nu^2)]$ is the flexure rigidity of the plate.

Here E is the Youngs modulus of the plate and ν the Poisson's ratio.

In the case of a circular plate with edges clamped, the deflections are assumed to be symmetric about the centre, and the plate deforms only through flexural deformation, which are small compared with the thickness of the plate. The deflections parallel to the surface of the plate are neglected. With the above modifications, Eqs. (5.2) and (5.3) can be simplified as,

$$U = \pi D\int_0^{a}\left[\frac{d^2 Z}{dr^2}+\frac{1}{r}\frac{dZ}{dr}\right]^2 r\,dr \qquad (5.4)$$

$$T = \pi\rho h p^2\int_0^{a} Z^2 r\,dr \qquad (5.5)$$

Here Z can be expressed as a series to satisfy the condition of symmetry

$$Z = a_1\left(1-\frac{r^2}{a^2}\right)^2 + a_2\left(1-\frac{r^2}{a^2}\right)^3 + \ldots\ldots\ldots\ldots \qquad (5.6)$$

The coefficients a_1, a_2, a_3, ... can be expressed by equating Eqs.(5.4) and (5.5) and solving for minimum.

Then the resultant equation becomes,

$$\frac{\partial}{\partial a_n}\int_0^a\left[\left(\frac{d^2Z}{dr^2}+\frac{1}{r}\frac{dZ}{dr}\right)^2-p^2\frac{\rho h}{D}Z^2\right]rdr = 0 \tag{5.7}$$

Substituting the first two terms of Eq.(5.6) in Eq.(5.7), the resultant equation can be integrated as,

$$\int_0^a\left(\frac{d^2Z}{dr^2}+\frac{1}{r}\frac{dZ}{dr}\right)^2 rdr = \frac{96}{9a^2}\left[a_1^2+\frac{3}{2}a_1a_2+\frac{9}{10}a_2^2\right] \tag{5.8a}$$

and

$$\int_0^a Z^2 rdr = \frac{a^2}{10}\left[a_1^2+\frac{5}{3}a_1a_2+\frac{5}{7}a_2^2\right] \tag{5.8b}$$

Thus the Eq.(5.7) can be modified as,

$$\frac{\partial}{\partial a_n}\left[\frac{96}{9a^2}\left[a_1^2+\frac{3}{2}a_1a_2+\frac{9}{10}a_2^2\right]-\frac{p^2\rho h}{D}\frac{a^2}{10}\left[a_1^2+\frac{5}{3}a_1a_2+\frac{5}{7}a_2^2\right]\right] = 0 \tag{5.9}$$

Differentiating Eq.(5.9) partially yields,

$$a_1\left[\frac{192}{9}-\frac{\alpha^2}{5}\right] + a_2\left[\frac{144}{9}-\frac{\alpha^2}{6}\right] = 0 \tag{5.10a}$$

and

$$a_1\left[\frac{144}{9}-\frac{\alpha^2}{6}\right] + a_2\left[\frac{96}{5}-\frac{\alpha^2}{7}\right] = 0 \tag{5.10b}$$

where, $$\alpha^2 = a^4p^2\frac{\rho h}{D} \tag{5.11}$$

Solving for angular frequency p, the general equation for frequency becomes,

$$p = \frac{\alpha_{ij}}{a^2}\sqrt{\frac{D}{\rho h}} \tag{5.12}$$

For the fundamental mode of vibration, $i=0$ and $j=0$. So in general the natural frequency f of a circular plate with clamped edges can be expressed as

[134],

$$f = \frac{\lambda^2}{2\pi a^2}\sqrt{\frac{D}{\rho h}} \tag{5.13}$$

where λ^2 is a constant whose value is determined by the boundary conditions of the plate.

5.3.1.1 Value of λ^2

The proposed hydrophone assembly can be assumed to be a vibrational system having a centrally loaded circular plate with clamped edges. In the case of a plate loaded at the centre, the centre mass will also contribute in determining its fundamental frequency. The effect of the centre mass on the resonance frequency can be accounted by considering the values of λ^2 [135], which depends on the ratio of the sum of the masses of the driver pin and the film to the mass of the diaphragm. Table 5.2 gives the values of λ^2 for different fractions of mass at the

TABLE 5.2 : Values of λ^2 for different ratios of the centre mass and mass of the plate.

M/M'	λ^2
0.0	10.2
0.05	9.0
0.1	8.1
0.2	6.9
0.4	5.4
0.6	4.75
1.0	3.8
1.4	3.3

centre *M* to the mass of the diaphragm *M'*[136].Thus for a circular plate with edges clamped and without any centre mass the value of λ^2 is 10.2.

5.3.2 Resonance frequency in water

The effect of the surrounding medium on the natural frequencies of a structure has little influence for relatively compact structures, if the density of the medium is much less than the average density of the structure. That is why the surrounding air does not ordinarily affect the natural frequencies of most of the structures. However in the case of structures surrounded by water, the added mass of the fluid always decreases the natural frequency of the structures from that which would be measured in air. The importance of the added mass in the dynamic analysis of a particular structure can be estimated from the ratio of the density of the surrounding fluid to the average density of the structure. If a relatively compact structure is much denser than the surrounding fluid, added mass is not likely to have large influence on its natural frequency.

When the hydrophone is immersed in water, the water surrounding it will act as a load and this added mass would result in a decrease in the fundamental frequency of the hydrophone compared to that in air. In general the surrounding fluid will impose both added mass and damping forces on the plate. The added mass will lower the natural frequency of the plate and damping forces will restrict the free movement of the plate.

As the natural frequency of a circular plate is inversely proportional to the square root of the mass of the structure, the effect of the added mass on the natural frequency can be approximately expressed as [135],

$$\frac{f_{fluid}}{f_{air}} = \frac{1}{\sqrt{1 + (A_p/m_p)}} \tag{5.14}$$

Where m_p is the mass of the plate and A_p is the plate added mass, which is a function of the plate geometry, boundary conditions and mode number. In the case of the hydrophones described, only one side of the diaphragm being surrounded by water, Eq.(5.14) can be simplified as [137],

$$f_{water} = \frac{f_{air}}{\left[1 + 0.6689\frac{\rho_w a}{\rho h}\right]^{1/2}} \tag{5.15}$$

where, ρ_w is the density of water.

5.4 COMPARISON BETWEEN THE EXPERIMENTAL AND NUMERICAL RESULTS

The resonance frequencies of all the three series of hydrophones were calculated using Eq.(5.15), from a knowledge of their diaphragm and centre mass. Table 5.3 provides the mass of the diaphragm and centre mass, which is constituted by the driver pin and the film assembly, along with the corresponding values of λ^2.

By substituting these values in Eq.(5.15), the resonance frequency of all the three types of hydrophones are computed. The following values for the physical constants of phosphor bronze are considered, for these computations.

$$E = 11 \times 10^{10}\ \mathrm{N/m^2}$$

$$\rho = 8.85 \times 10^{3}\ \mathrm{kg/m^3}$$

$$\nu = 0.38$$

TABLE 5.3 : Mass of the plate, the centre mass and corresponding values of λ^2 for all the three series of hydrophones.

Transducer Type	Plate Mass	Centre Mass	λ^2
A Series	30 gm	3.0 gm	8.1
B Series	30 gm	3.0 gm	8.1
C Series	7.5 gm	2.6 gm	5.4

Table 5.4 is a collation of the experimental and numerical resonance frequencies for the three series of transducers.

TABLE 5.4 : Comparison of the Experimental and Theoretical resonance frequencies.

Transducer Type	Resonance Frequency (kHz)	
	Experimental	Theoretical
A Series	1.00	1.11
B Series	1.00	1.11
C Series	3.50	3.614

From the Table 5.4, it can be inferred that the experimental results agree well with the theoretical ones, within the limits of experimental errors and theoretical approximations. To validate the inferences gathered from the theoretical approach, a number of (3,1) drive hydrophones with different diaphragm diameters and materials were designed, including D and E series. The D series hydrophone has diaphragm similar to the A series, but with film dimensions 5 cm × 1.5 cm × 52 μm. Its frequency response in air and water are depicted in Figs. 5.13 and 5.14. For the E series the film dimensions are the same as that of the A series, with a

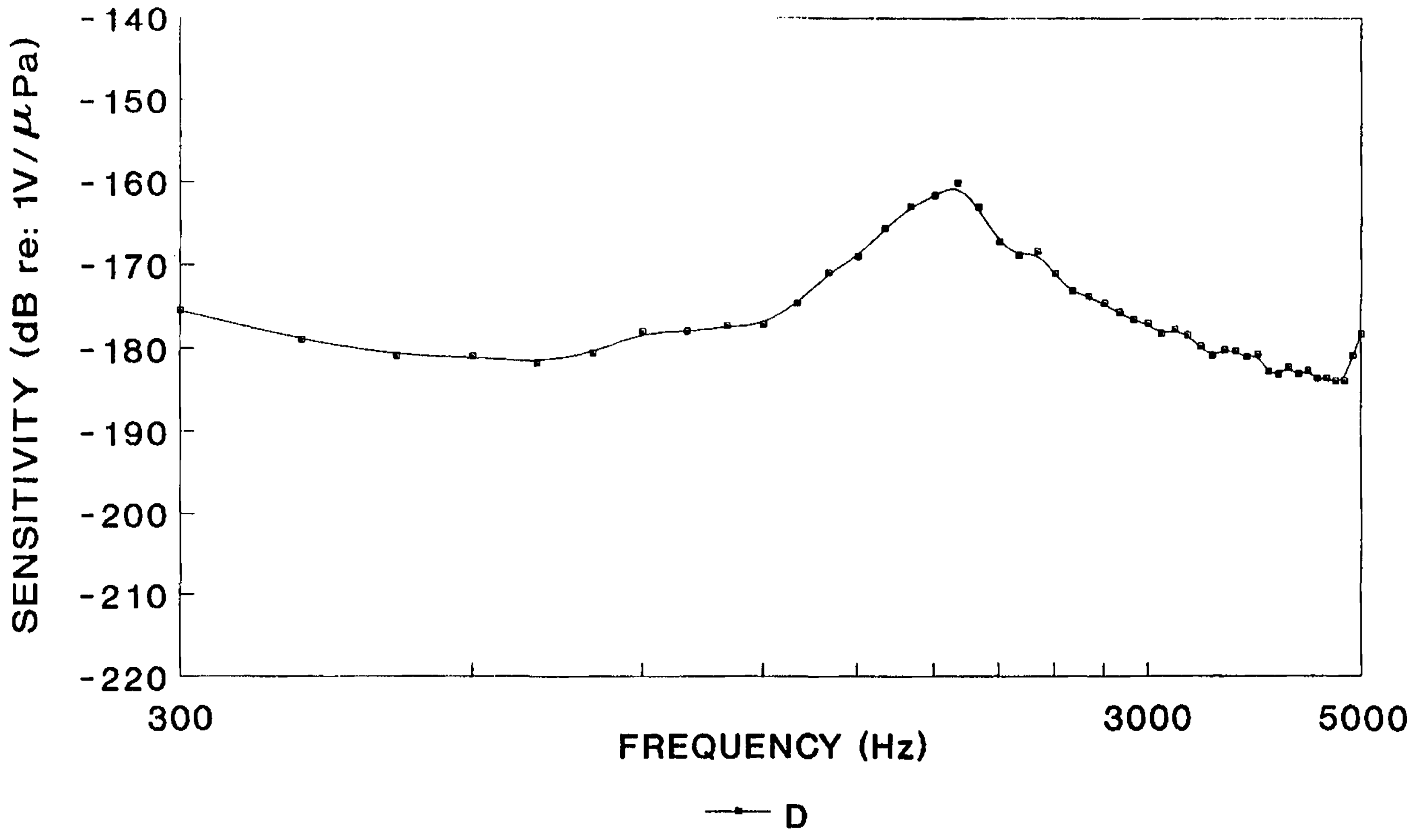


Fig. 5.13 : Frequency response of D series hydrophones in air.

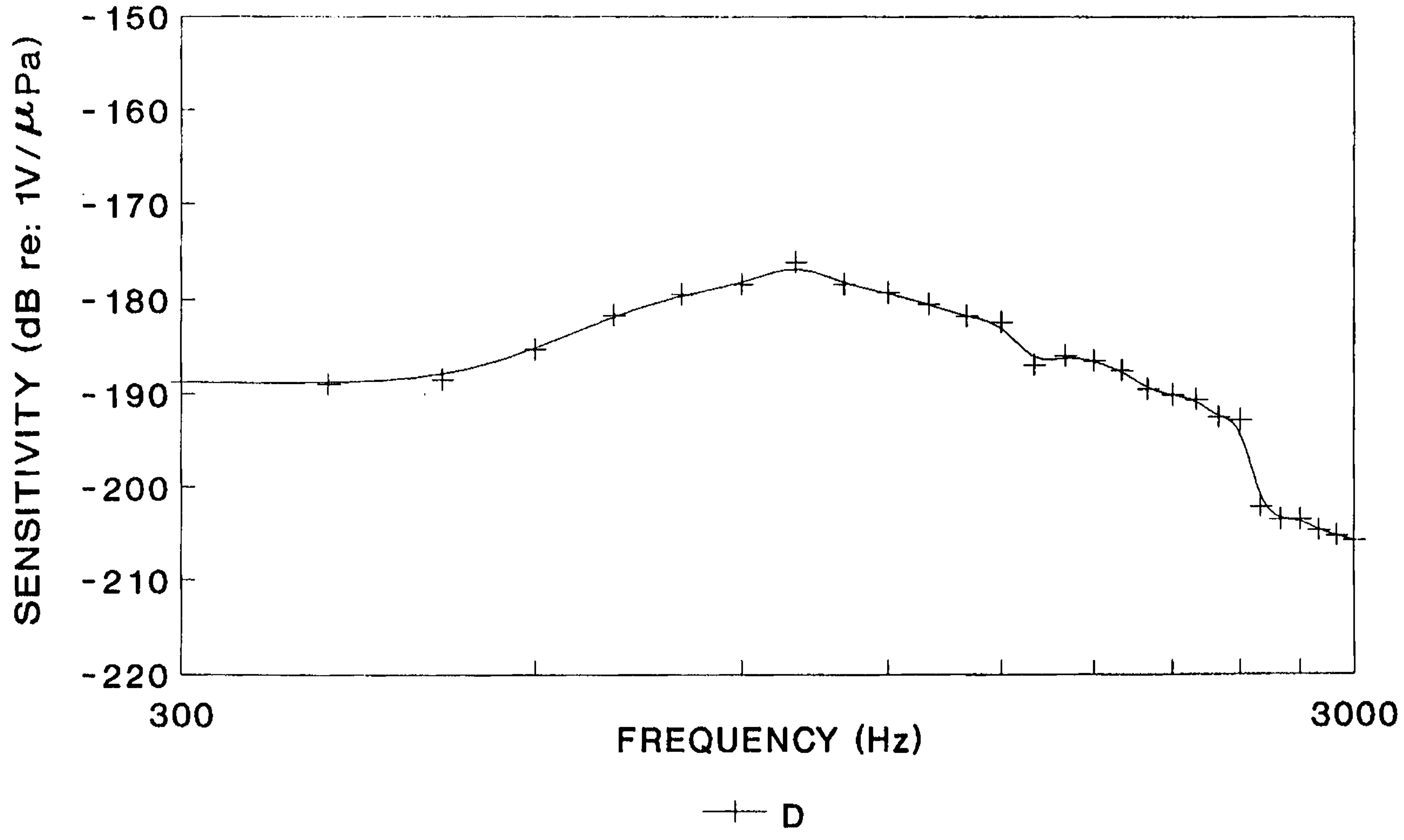


Fig. 5.14 : Frequency response of D series hydrophones in water.

phosphor bronze diaphragm of 10 cm × 1.2 mm and its response in air is shown in Fig. 5.15. As the resonance frequency computed for the E series was around 300 Hz in water, the same was not calibrated in water. Resonance frequency of the earlier models T2 and STL 01 were also computed with the theory, and found to be matching well with the experimental results.

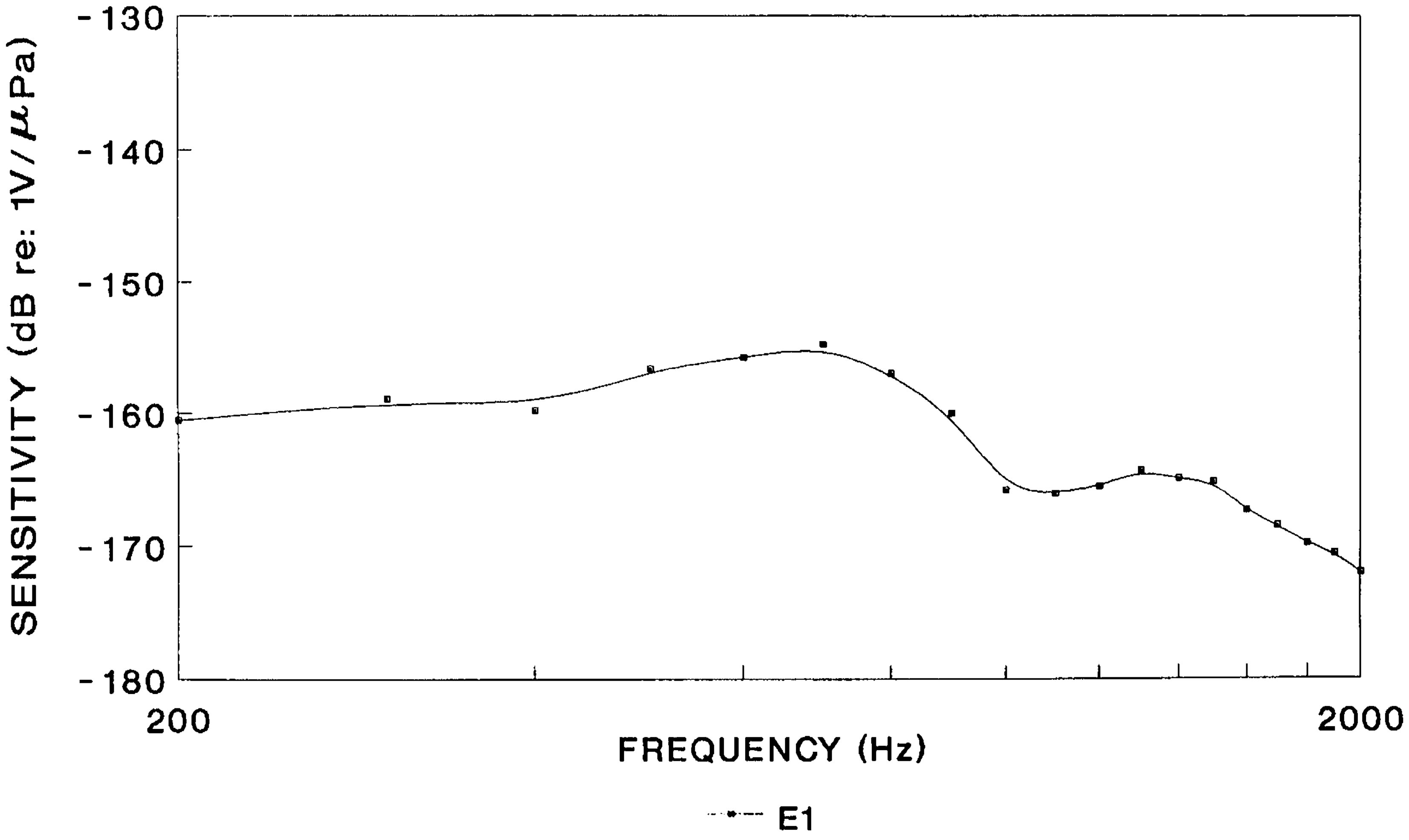


Fig. 5.15 : Frequency response of E series hydrophone in air

Chapter 6

Multifilm design

The main theme of this chapter is the design of multifilm hydrophone. Flexure mode devices with multifilm/multielement constructions are already reported in the open literature [92][102]. In a flexure bimorph configuration, two piezoelectric films are sandwiched together and are bonded to a non piezoelectric substrate. According to the external electrical connections, two configurations are possible for bimorph devices. In series bimorph the polymer films are connected electrically in series, where as in parallel bimorphs they are electrically parallel. In the construction of bimorphs, the thickness and mechanical properties of the bonding layer must be considered to determine the performance of the bimorph. In some cases, instead of two films, more number of piezoelectric layers are laminated resulting in a structure known as multimorph.

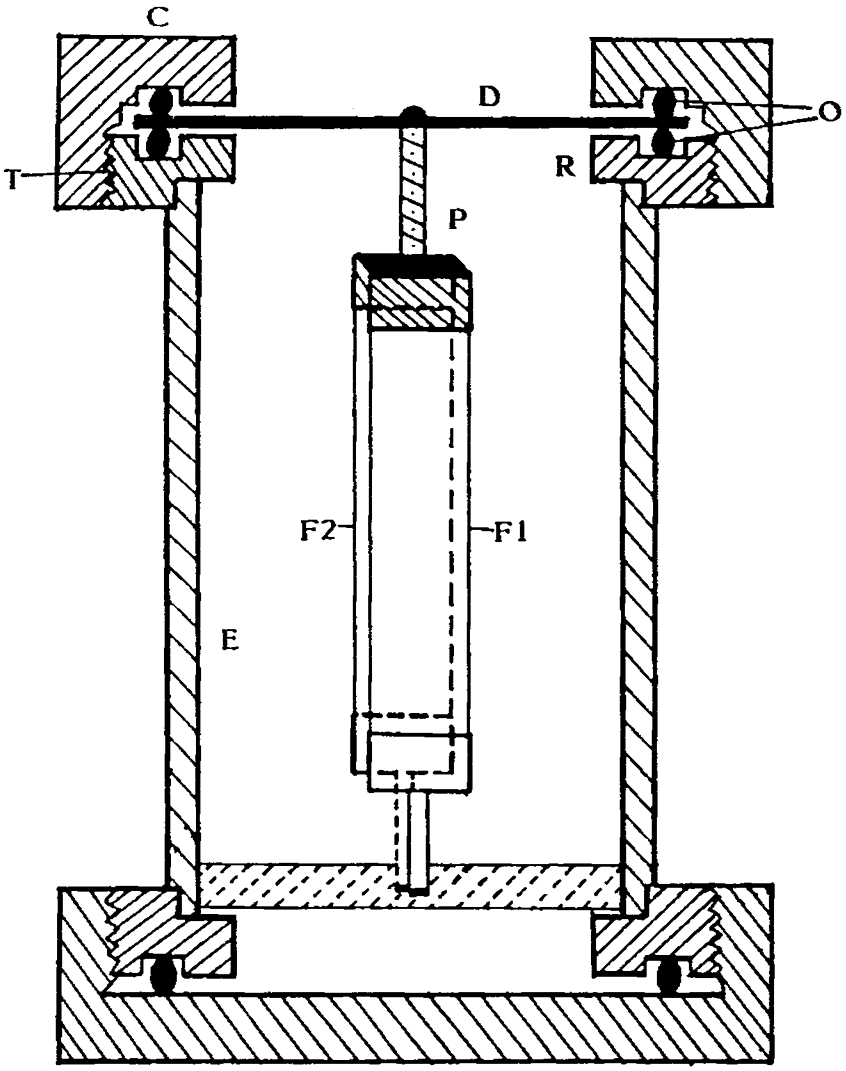
The multifilm designs described here are not bimorphs, but a variant of this extended to the (3,1) drive design. These are made up of two independently mounted PVDF films coupled to each other mechanically. The two multifilm designs described here are :

1. MF 01
2. MF 02

The major difference between these two designs lies in the distinct approaches for the mounting of the films.

6.1 MF 01

A cross-sectional view of the hydrophone design is shown in Fig. 6.1. A circular phosphor bronze sheet of diameter 5.5 cm and thickness 1 mm serves as the diaphragm for transferring the impinging acoustic energy to the active element. A perspex annular ring with sides threaded and a groove at the top for a rubber O-ring, is fixed over a cylindrical enclosure. A perspex cap with its innersides threaded and a groove at the bottom, for a second O-ring, forms the upper part of the head assembly. The diaphragm is placed over the perspex ring with O-rings on both sides, and is tightened properly with the cap, so that the diaphragm is pressed uniformly. An opening of approximately 5 cm is provided at the centre of the cap for exposing the diaphragm to the external pressure field. A brass driver pin of length 2 cm and diameter 1 mm is fixed at the centre of the diaphragm. At the other end of the pin a rectangular sheet of copper of 1 cm × 0.5 cm is soldered. To both sides of this strip two PVDF films of 5 cm × 1 cm × 52 μm are adhered. The films are stretched independently and the terminal electrodes are connected



C : PERSPEX CAP
D : PHOSPHOR BRONZE DIAPHRAGM
T : THREADINGS
R : PERSPEX ANNULAR RING
O : RUBBER 'O' RINGS
P : DRIVER PIN
F1,F2 : PVDF FILMS
E : WATER TIGHT ENCLOSURE

Fig. 6.1 : A cross-sectional view of MF 01.

separately. Hence this assembly can be considered as having two parallel fixed films attached to a phosphor bronze diaphragm through a driver pin.

The principle of working of this design is similar to the refined model except that the present design uses two films which are excited by the same incident acoustic pressure. With this arrangement the voltage outputs will be developed across the films simultaneously, which can be extracted through the terminal electrodes.

In order to facilitate different combination of the film outputs, the tail assembly of the enclosure is made similar to the top one, except that the opening at the top assembly is absent at the bottom cap. Underwater connector is used for taking the cumulative output. So the hydrophone's tail part can be opened and the outputs of the films can be suitably combined and tapped to the underwater connector. As in the earlier designs MOSFET preamplifier AMP 4002 is also connected at the output with an extended cable length of 25 metres.

The response of this hydrophone was evaluated in air and water for individual films and for their series combination. B&K 8104 was used as the reference transducer in air and the sensitivity of the unknown transducer was calculated using comparison method. Fig. 6.2 illustrates the response of the hydrophone in air for individual films and for their series combinations in the frequency region of 300 Hz to 2.5 kHz.

Evaluation of the hydrophone performance in water was carried out at the Lake Facility. UW 15 was used as the projector and ITC 1042 as the reference

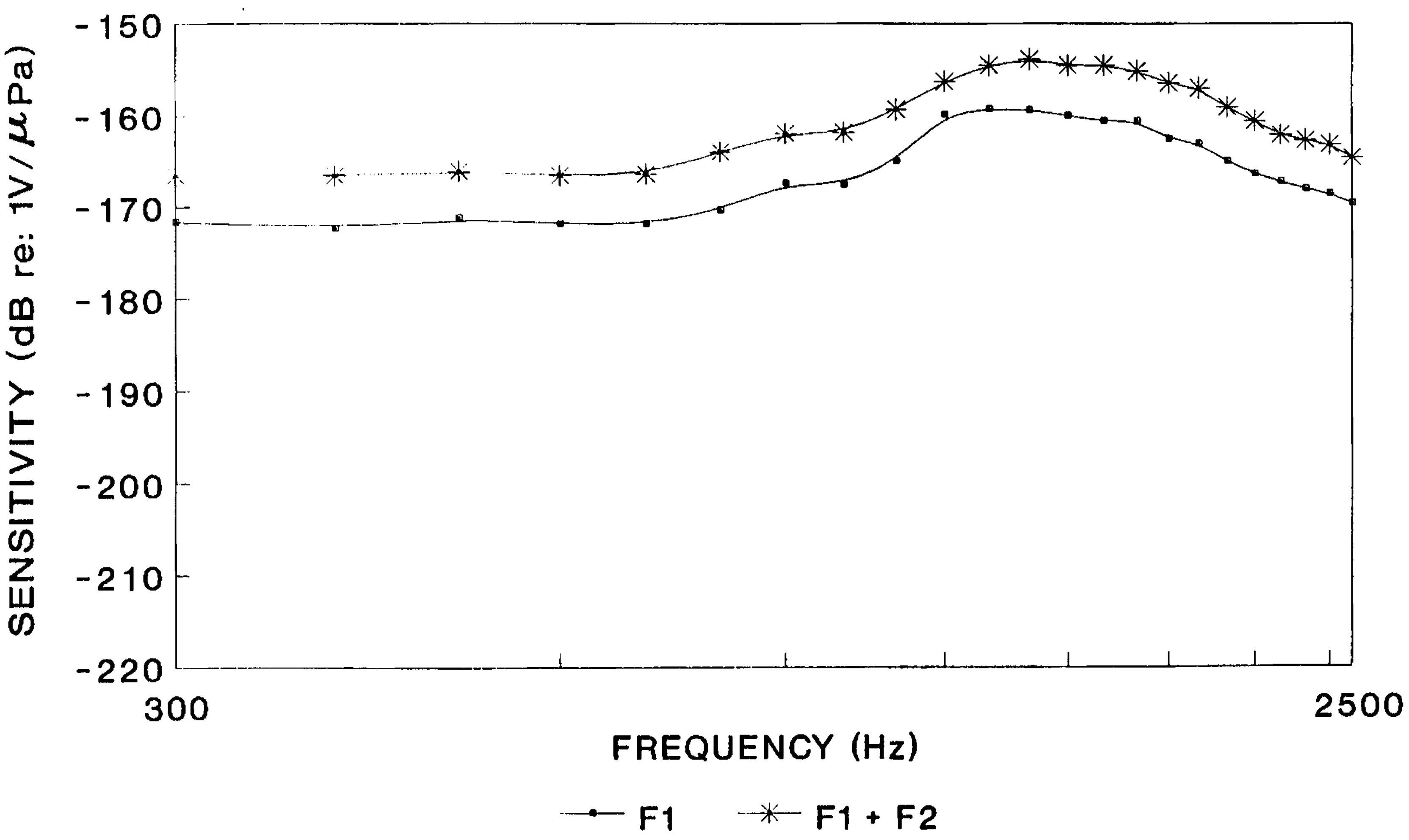


Fig. 6.2 : Frequency response of MF 01 in air a single film and for its series combination with a second one.

hydrophone. Fig. 6.3 depicts its response for individual films and their series combinations, in water.

The response of the hydrophone with the individual films (F1 or F2) was similar and hence only one of the responses is shown.

6.2 MF 02

MF 02 is similar to the MF 01 except that it uses two opposed films instead of two parallel films as in MF 01. Fig. 6.4 describes a sketch of this reformed multifilm version. Here also the head and tail assemblies are similar to MF 01 with a difference in the structure of the mounting of polymer films. In the head assembly, it also uses a phosphor bronze diaphragm of diameter 5 cm and thickness 1 mm, which is squeezed in between two rubber O-rings. One end of a driver pin is attached to the centre of the diaphragm and the other end to a '[' shaped structure as shown. This structure has length 7 cm, breadth 1 cm and thickness 1.5 mm, is made of perspex and is terminated with a rectangular perspex sheet of 1.5 cm × 1 cm × 1.5 mm. To this rectangular sheet two polarised PVDF films of 5 cm × 1 cm × 52 μm are glued as shown. The films are stretched independently and the outputs are taken across them individually. So the whole assembly can be considered to be having two opposed polymer films attached to a phosphor bronze diaphragm through a perspex structure.

When the diaphragm vibrates due to the external acoustic pressure, the perspex structure coupled to it will also vibrate in accordance. This will make one of the films to expand and the other to contract. Corresponding to these strains on

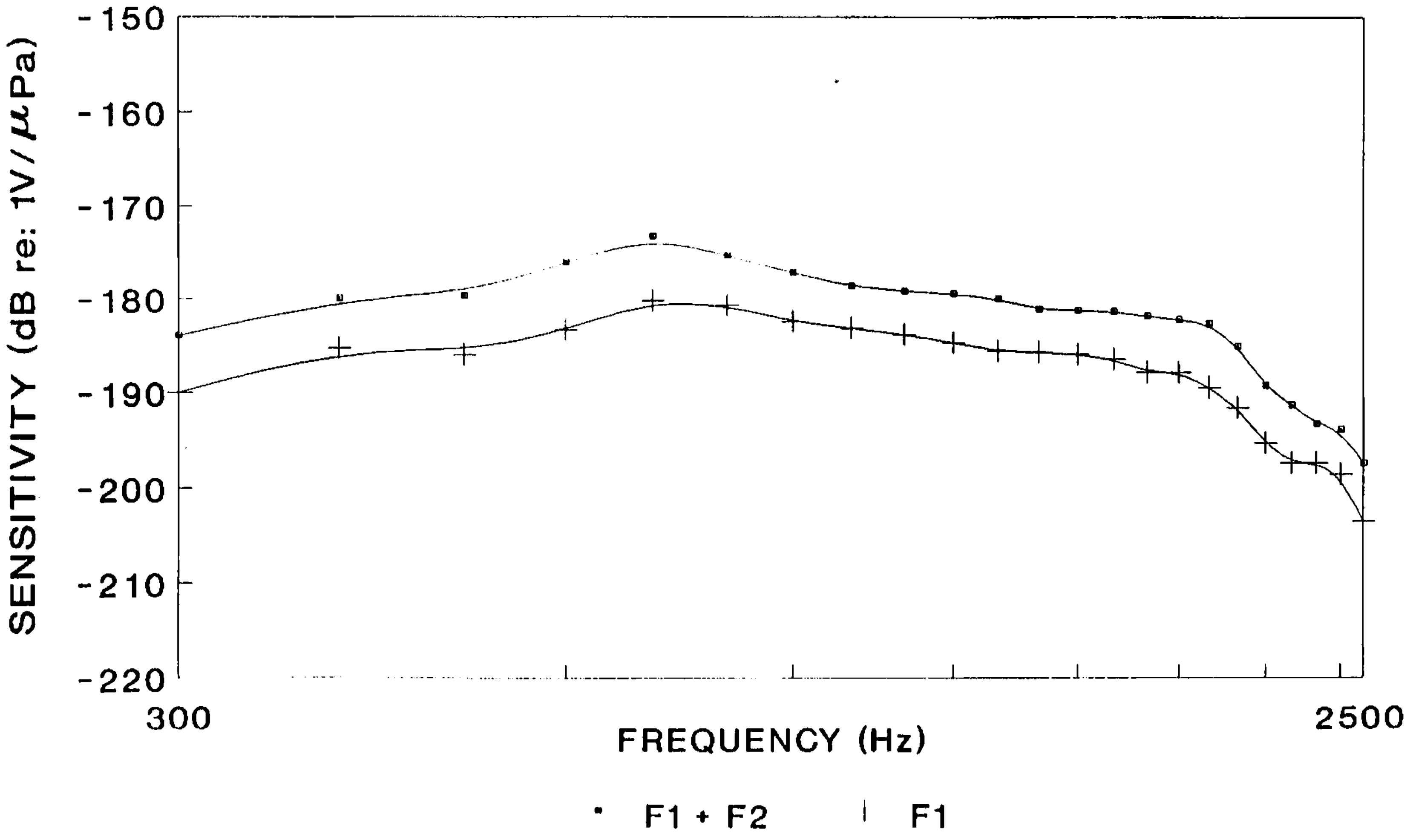
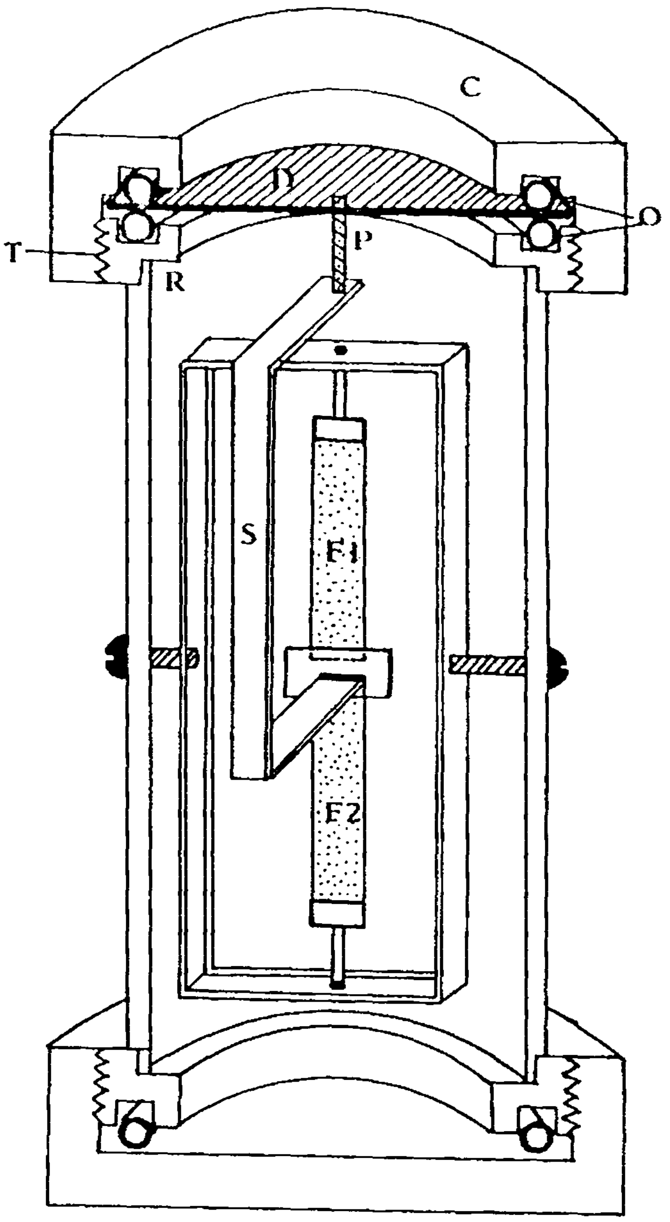


Fig. 6.3 : Frequency response of MF 01 in water with single film and its series combination with a second one.



C : PERSPEX CAP
D : PHOSPHOR BRONZE DIAPHRAGM
O : RUBBER 'O' RINGS
R : PERSPEX ANNULAR RING
T : THREADINGS
P : DRIVER PIN
S : '⊏' SHAPED STRUCTURE
F1,F2 : PVDF FILMS

Fig. 6.4 : A cross-sectional view of MF 02.

the films, voltages will be developed across them simultaneously. The outputs are extracted through the separate output electrodes and are suitably combined.

Response of the hydrophone was evaluated in air and water. Figs. 6.5 and 6.6 show its response in air and water respectively for the individual films and for their series combination.

The purpose of both the designs described above is to increase the sensitivity of the hydrophone by adding up the voltages developed across the films due to a given incident acoustic pressure. While comparing the different plots furnished, it is clear that the procedure adopted for adding up of the voltages developed in two different films of both the hydrophone designs achieved the desired results. Of the two multifilm designs, MF 02 behaved in a better way than MF 01, particularly where the band of operation is concerned. But the design of MF 01 is more compact and simpler than MF 02, as mounting of the film is not complex.

It may be possible to enhance the sensitivity further by increasing the number of films. But it is to be noted that, when the number of films increases, their effective electrical impedance will also increase, as they are connected electrically in series. This increased impedance will drastically dampen the resultant output, if necessary precautions like suitable means to convert the signal path from high impedance to low impedance *etc.* are not taken. The graph shown in Fig. 6.7 is the impedance plot of MF 02, which throws light on the impedances of individual films and for their series combination in the frequency range of 300 Hz to 4 kHz. It can be inferred from the plot that the trend of increasing impedance is higher at lower frequencies.

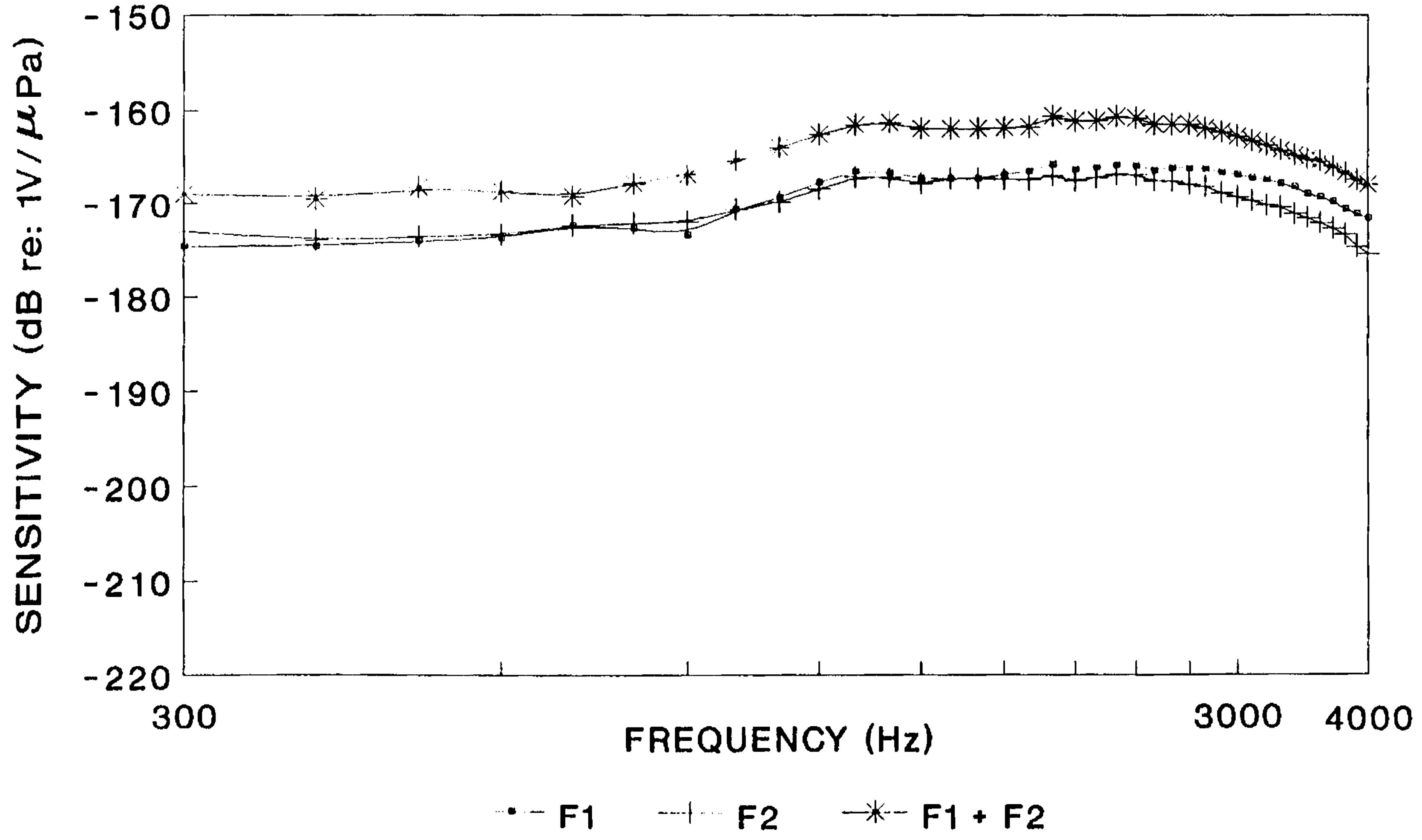


Fig. 6.5 : Frequency response of MF 02 in air for individual films and for their series combinations.

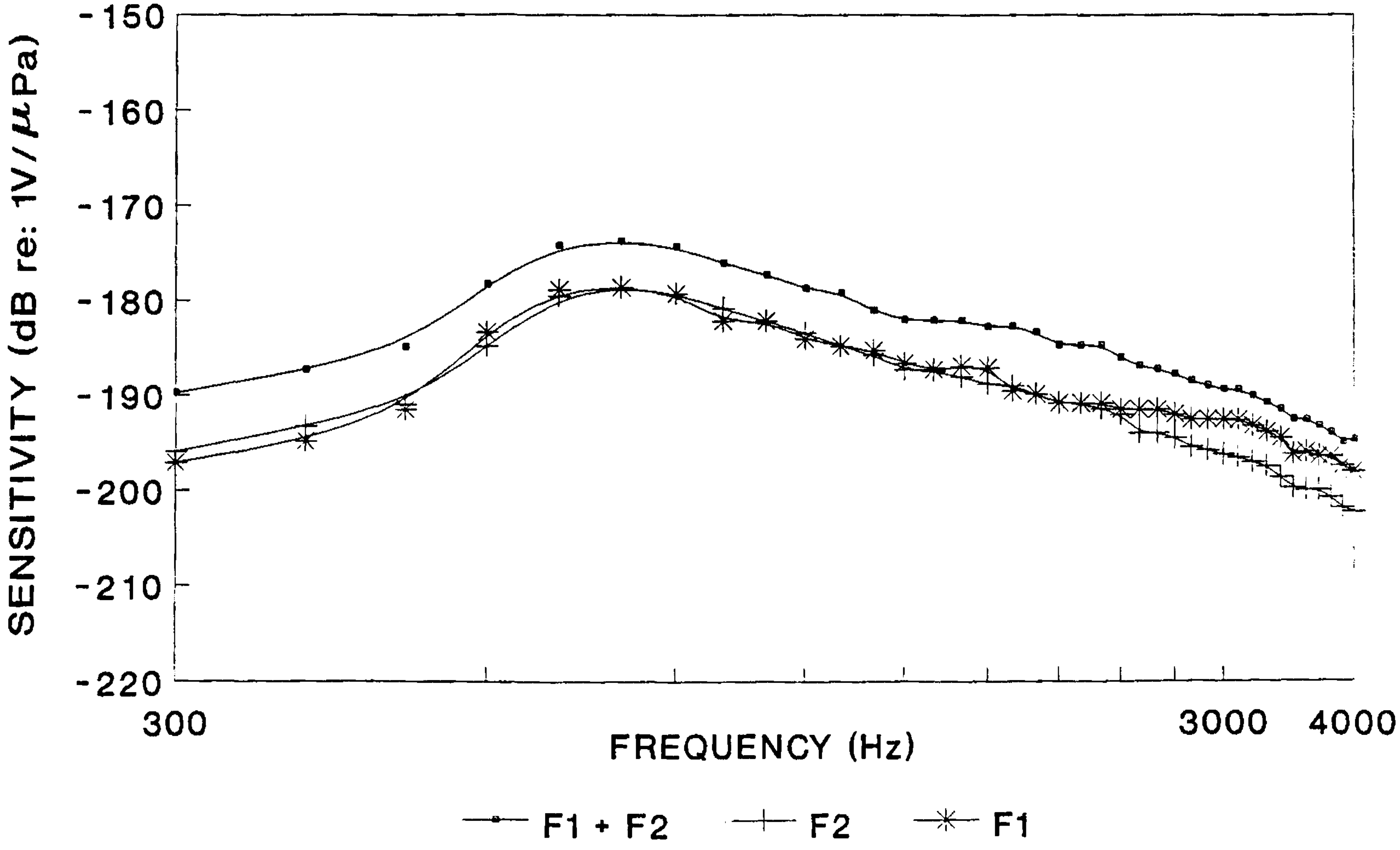


Fig. 6.6 : Frequency response of MF 02 in water for individual films and for their series combinations.

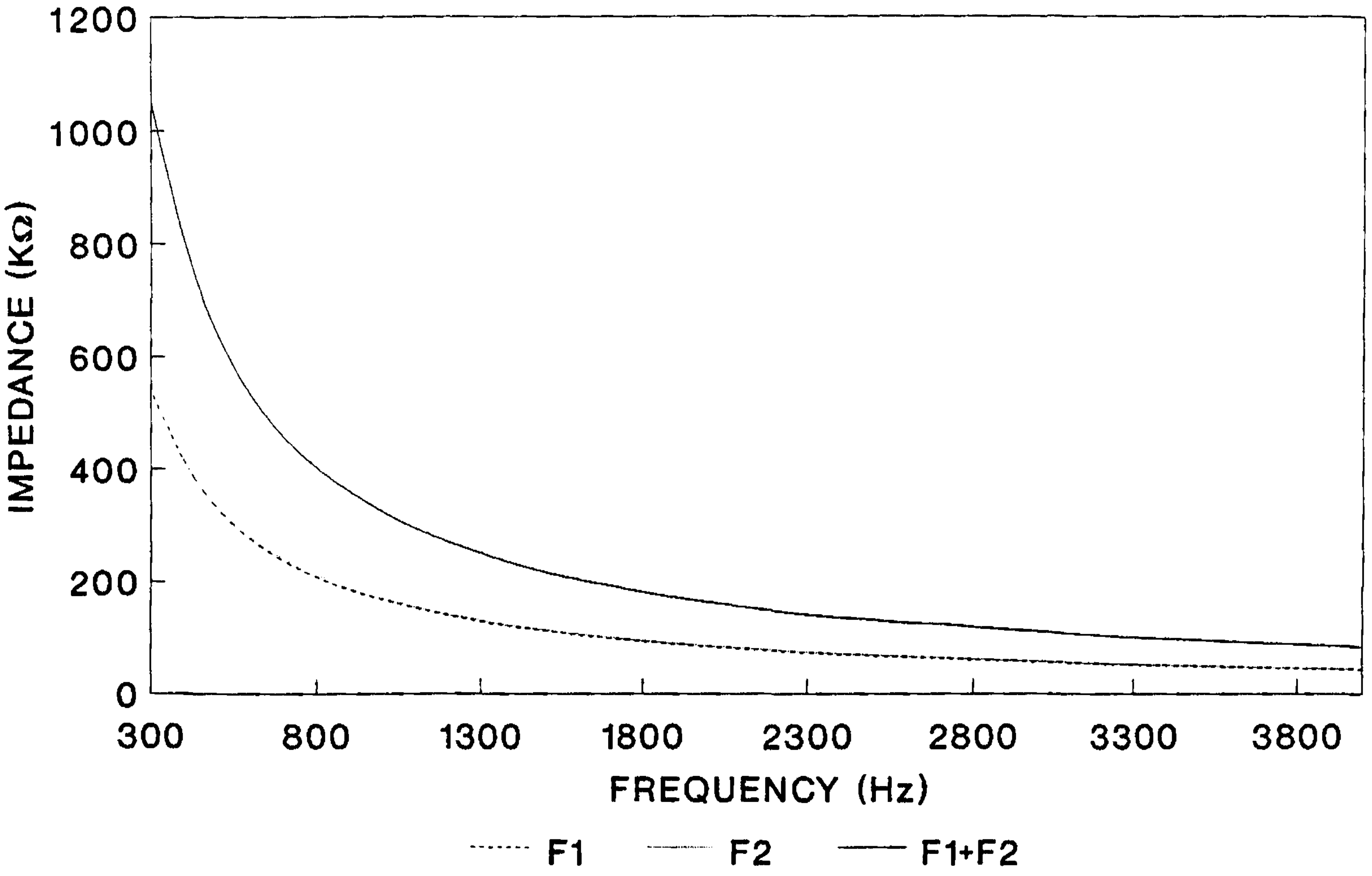


Fig. 6.7 : Frequency versus Impedance plot of MF 02.

Chapter 7

Conclusions

This chapter presents the overall conclusions drawn and inferences gathered from the various (3,1) drive hydrophone designs attempted and the experimental and theoretical results obtained. The chapter concludes with a brief description on the scope for further studies in this field.

The main objective of the investigation was to design and develop low frequency piezopolymer hydrophones with improved performance. As the piezofilm is highly anisotropic the advantages and disadvantages of different drives of vibration of the film were first surveyed. From Table 3.2, it was established that, the (3,1) drive or stretch drive of vibration will bring forth a higher voltage output compared with the other drives. Hence this drive of vibration was adopted in the hydrophone design. The process of designing a suitable mechanical structure for vibrating the polymer film in the stretch drive was difficult due to structural constraints. So a number of attempts were made with a view to arriving at a satisfactory (3,1) drive hydrophone design which fulfils the required criteria such as high sensitivity, low resonance frequency *etc.*

7.1 HIGHLIGHTS

Hydrophones T0 and T1 were the preliminary designs attempted to establish the feasibility of (3,1) drive of operation. T2, the prototype hydrophone and was found to have a sensitivity of -170 dB re: 1V/μPa in water, which is approximately 30 dB higher than that of the conventional designs. The design in short, consists of a diaphragm which was rigidly fixed over a cylindrical enclosure. One end of a small driver pin was fixed at the centre of the diaphragm and a polymer film at the other end.

A pressure balanced type design was attempted but it did not give the desired results. Even though this design balanced the diaphragm to the ambient hydrostatic pressure, the rubber bellow used was found to dampen its vibrations, as the bellow was fixed at the centre of the diaphragm. Moreover, at greater depths, the bellow itself was found to shrink. restricting the movement of the driver pin. Hence a reduction in sensitivity was observed with this approach.

The influence of the film and diaphragm dimensions on the overall performance of the hydrophone was studied. The sensitivity was found to increase with the length and thickness of the film, where as it decreased with increase in breadth. Also the film dimensions have a less significant role in determining the resonance frequency of the hydrophone, and it was totally determined by the diaphragm constituents. The resonance frequency increases with increase in thickness of the diaphragm and decreases with its diameter. But in both the cases the sensitivity was also found to decrease, because the effective area of the diaphragm decreases if the diameter was decreased and it would become more rigid if the thickness was increased. The stretching of the film and dimensions of the driver pin have only nominal influence on the performance of the hydrophone. When the air column was eliminated by filling the air cavity with polyurethane in FIL 14, the sensitivity was found to be reduced due to the severe restriction imposed on the film movement by the surrounding material.

In the refined model, the diaphragm was provided with a uniform mounting, which ensured consistent transfer of energy from the diaphragm to the film. With this approach, the reproducibility was found to be enhanced and the hydrophone enclosure was made reliably waterproof.

The directional response of the hydrophones constructed with the refined design was evaluated in water for 2 kHz. As expected all the hydrophones tested were found to be showing omnidirectional response.

In the theoretical approach developed, it was assumed that the compliance of the diaphragm is very small compared to the other components of the hydrophone so that its resonance frequency is solely determined by the vibrational modes of the diaphragm. The diaphragm is considered to be a circular plate with edges clamped and a point mass at the centre, constituted by the driver pin and the film. From Table 5.4, it is clear that the theoretical resonance frequency values agree with the experimental ones. In order to make sure the trustworthiness of the theory, it was extended to hydrophones with different diaphragm materials and also for a hydrophone with a diaphragm of 10 cm diameter.

The multifilm designs have the advantage of adding up the voltages produced in different films for a given input acoustic pressure. The two multifilm designs described were with two polymer films each and in both of these, the films were stretched independently and the outputs were taken separately. The response of both the hydrophones were evaluated in water and air, with individual films and with their series combinations, and when the signals were combined in series, the hydrophone sensitivity was found to be higher than that with a single film. The design of MF 02 was slightly complicated than MF 01, as it uses an additional structure. But the operational band of MF 02 was higher than MF 01. The response of MF 01 was more flat than MF 02. From the electrical impedance curve of MF 02 given at the end of the chapter 6, it can be inferred that as the number of films increases, the effective electrical impedance also increases, which may hamper the resultant output if proper precautions are not taken.

All the hydrophones described worked on the basic principle that, when the diaphragm vibrates due to the incident acoustic pressure, the film will also vibrate in accordance and the strains developed in the film due to these vibrations will result in the generation of a potential difference across it.

Fig. 7.1 is a photograph showing some of the (3,1) drive PVDF hydrophones.

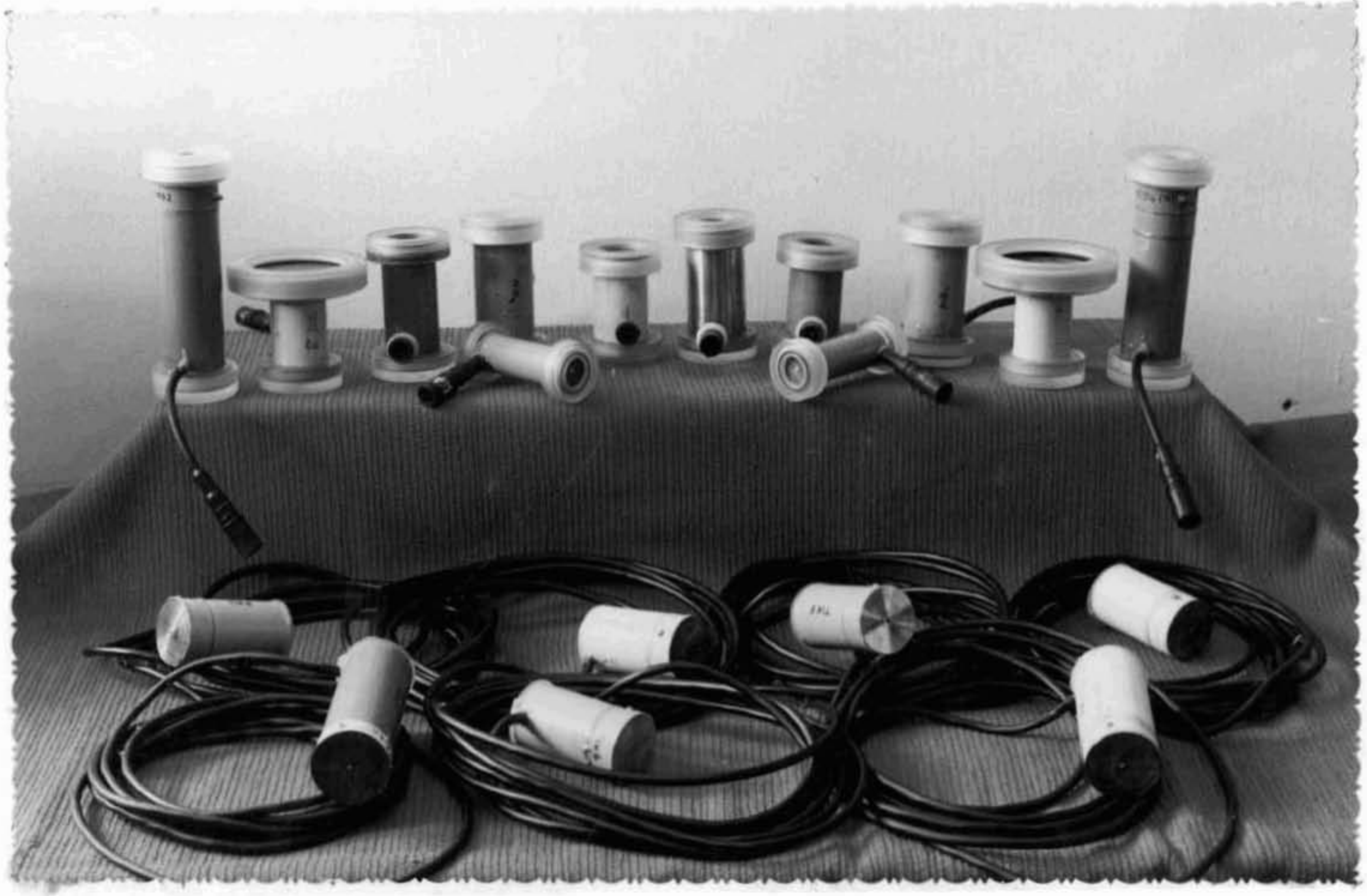


Fig. 7.1 : A photograph showing some of the (3,1) drive PVDF hydrophones.

By using AMP 4001 and AMP 4002, the damping of the output signal due to the capacitance of the signal cable, was reduced to a certain extent. Particularly AMP 4002, a differential amplifier was found to be more effective in enhancing the signal-to-noise ratio. Yet another aspect worth mentioning is the technique used for extracting the output from the film surface using electrodes. Having a very simple design, these electrodes were used in all the hydrophones, including the multifilm designs. The added advantage of these electrodes were that, they simultaneously played the role of tapping the output from the film surface and providing a firm grip for holding the stretched film.

Thus the hydrophones described can be effectively used for low frequency high sensitivity applications like those in passive receivers and in sonobuoys. Even though the various designs described were experimental versions, they can be converted to the equivalent engineering designs by incorporating some minor alterations, like moulding the whole enclosure to ensure water sealing and using good quality and low capacitance underwater signal cables.

7.2 SCOPE FOR FURTHER WORK IN THE FIELD

There is an immense scope for doing further work in this field and improving the performance of the hydrophones further, leading to a more versatile engineering model which can be adapted straight away for field use. The overall work envisaged can be divided as follows

1. To enhance the useful band of operation of the hydrophone further

keeping the sensitivity high, by suitably changing the design.

2. To make the hydrophone more compact and handy.
3. To formulate suitable design changes like incorporation of more number of films, so that the sensitivity can be improved further.
4. Formulation of an engineering model which can be easily adapted for field applications.

In the different hydrophone designs described, it is observed that all of them resonate around 1 kHz, thus limiting the frequency of operation below it. But as described earlier, by increasing the thickness of the diaphragm or decreasing its diameter, the resonance frequency can be extended. But this will adversely affect the sensitivity. So suitable changes are to be incorporated with the design, such as choosing a diaphragm material with high elastic constants, low density *etc.*, so that the band of operation can be extended further.

In the design described, the film occupies only a limited space. So it is possible to decrease the overall size of the hydrophone, particularly that of the enclosure, there by making the hydrophone more handy and compact.

It is viable to accommodate more number of films in a single hydrophone, so that by suitably adjusting their outputs the sensitivity can be improved. The different films have to be properly coupled to the diaphragm, in order to make them vibrate simultaneously. A mechanism for converting the signal path from high impedance to low impedance has also to be incorporated.

The hydrophone design can be properly modelled, so that different modes of vibrations of the diaphragm along with the influence of the mechanical coupling of the driver pin and film can be evaluated. This will help in computing the response and sensitivity of the hydrophone theoretically, which in turn will facilitate in designing hydrophones with the desired characteristics.

REFERENCES

[1] A.A. Winder, "Sonar system technology", IEEE Trans. Sonics Ultrason. SU-22, No.5, 291-332 (1975).

[2] D.G. Tucker and B.K. Gazey, "Applied underwater acoustics", Pergamon Press, London (1966).

[3] V.K. Aatre, "Sonars and ASW sensors", IETE Technical Review, Vol.10, No.2, 81-91 (1993).

[4] M. Laskey, "Review of underwater acoustics to 1950", J.Acoust.Soc.Am., 61, 283-297 (1977).

[5] R.J. Urick, "Principles of underwater sound", Mc.Graw-Hill Company, New York, (1975).

[6] M. Mersenne, "On the velocity of sound in air", Benchmark Papers in Acoustics, Dowden, Hutchinson & Ross, Inc., Pennsylvania, USA, 64-66 (1943).

[7] D. Colladon, "Experiments on the velocity of sound in water", Benchmark Papers in Acoustics, Dowden, Hutchinson & Ross, Inc., Pennsylvania, USA, 194-201 (1943).

[8] J. Joule, "On the effects of magnetism up on the dimensions of iron and steel bars", Benchmark Papers in Acoustics, Dowden, Hutchinson & Ross, Inc., Pennsylvania, USA, 248-260 (1943).

[9] W.S. Burdic, "Underwater acoustic system analysis", Prentice-Hall Inc., New Jersey, (1984).

[10] W.C. Knight, R.G. Pridham and S.M. Kay, "Digital signal processing for sonar", IEEE Trans. Sonics Ultrason. SU-69, No,11, 1451-1506 (1981).

[11] J.K. Hilliard, "Electroacoustics to 1940", J.Acoust.Soc.Am., 61, 267-273 (1977).

[12] F.V. Hunt, "The past twenty years in underwater acoustics : Introductory retrospection", J.Acoust.Soc.Am., 51, 992-993 (1972).

[13] T.F. Hueter, "Twenty years in underwater acoustics : Generation and reception", J.Acoust.Soc.Am., 51, 1025-1040 (1972).

[14] E. Klein, "Underwater sound and naval acoustical research and applications before 1939", J.Acoust.Soc.Am., 43, 931-947 (1968).

[15] O.B. Wilson, "Introduction to theory and design of sonar transducers", Penninsula Publishing, California, USA (1988).

[16] C.H. Sherman, "Underwater sound - A review, 1. Underwater sound transducers", IEEE Trans. Sonics Ultrason. SU-22, No.5, 281-290 (1975).

[17] "Kynar piezofilm manual", Pennwalt Corporation, USA, 1983.

[18] L.E. Kinsler and A.R. Frey, "Fundamentals of acoustics", Wiley Eastern Ltd., New Delhi, (1978).

[19] L.L. Beranek, "Acoustics", Acoustic Society of America, USA, (1986).

[20] L. Camp, "Underwater acoustics", John Wiley & Sons Inc., New York. 1970.

[21] E.G. Thurston, "The theoretical sensitivity of three types of rectangular bimorph transducers", J.Acoust.Soc.Am., 25(5), 870 (1953).

[22] R.A. Langevin, "The electroacoustic sensitivity of cylindrical ceramic tubes", J.Acoust.Soc.Am. 26(3), 421-427 (1954).

[23] C.P. Germano, "Supplement to : The electroacoustic sensitivity of cylindrical ceramic tubes by R.A. Langevin", J.Acoust.Soc.Am. 34(8), 1139-1140 (1962).

[24] C.V. Stephenson, "Vibrations of long rods of barium titanate with electric field parallel to the length", J.Acoust.Soc.Am. 28(6), 1192-1194 (1956).

[25] E.A.G. Shaw, "On the resonant vibrations of thick barium titanate disks", J.Acoust.Soc.Am. 28(1), 38-50 (1956).

[26] C.C. Sims, "Bubble transducer for radiating high power low frequency sound in water", J.Acoust.Soc.Am. 32(10), 1305-1308 (1960).

[27] M. Redwood, "Transient performance of a piezoelectric transducer", J.Acoust.Soc.Am. 33(4), 527-535 (1961).

[28] P.M. Kendig, "Factors that determine the equivalent noise pressure, free-Field voltage response and efficiency of a transducer at low frequencies", J.Acoust.Soc.Am. 33(5), 674-676 (1961).

[29] T.F. Hueter and P.H. Moose, "Optimum hydrophone design for low frequencies", J.Acoust.Soc.Am. 33(11), 1628-1629 (1961).

[30] R.S. Wooleett, "Hydrophone design for a receiving system in which amplifier noise is dominant", J.Acoust.Soc.Am. 34(4), 522-523 (1962).

[31] H.F. Tiersten, "Thickness vibrations of piezoelectric plates", J.Acoust.Soc.Am. 35(1), 53-57 (1963).

[32] G.E. Martin, "Vibrations of longitudinally polarised ferroelectric cylindrical tubes", J.Acoust.Soc.Am. 35(4), 510-520 (1963).

[33] G. Kossoff, "The effects of backing and matching on the performance of piezoelectric ceramic transducers", IEEE Trans. Sonics Ultrason., SU-13, No.1, 20-30 (1966).

[34] L.H. Royster, "Flextensional underwater acoustics transducer", J.Acoust.Soc.Am. 45(3), 671-682 (1968).

[35] R.A. Nelson Jr. and L.H. Royster, "Development of a mathematical model for the Class V flextensional underwater acoustic transducer", J.Acoust.Soc.Am. 49(5), 1609-1620 (1970).

[36] R. Dominguez and C. Ranz, "Sandwich transducer, simplified mathematical model(I)", Acoustica 29, 156-166 (1973).

[37] A.P. Hulst, "On a family of high power transducers", Proc. of Ultrasonic International Conference, 285-295 (1973).

[38] A.F. Brown and J.P. Weight, "Generation and reception of wideband ultrasound", Ultrasonics, 161-167 (1974).

[39] C.S. Desilets, J.D. Fraser and G.S. Kino, "The design of efficient broadband piezoelectric transducers", IEEE Trans. Sonics Ultrason. SU-25, No.3, 115-125 (1978).

[40] K.L. Narayana, K.M. Swamy and R.S. Rohella, "Sandwich transducer design and its testing", J.Instn.Elec. and Telecom. Engns. 24(6), 260-262 (1978).

[41] F.S. Foster and J.W. Hunt, "The design and characterization of short pulse ultrasonic transducers", Ultrasonics, 116-122 (1978).

[42] J.H. Goll, "The design of broad band fluid loaded ultrasonic transducers", IEEE Trans. Sonics Ultrason. SU-26, No.6 (1979).

[43] D.F. Mc Cammon, W. Thompson Jr., "The design of Tonpilz piezoelectric transducers using non-linear goal programming", J.Acoust.Soc.Am. 68(3), 754-757 (1980).

[44] T.A. Henriquez and A.M. Young, "The Helmholtz resonator as a high-power deep-submergence source for frequencies below 500 Hz", J.Acoust.Soc.Am. 67(5), 1555-1558 (1980).

[45] W. Werging, "Low Q PZT ceramics", Ferroelectrics, Vol.26, No.14, 783-786 (1980).

[46] S.M. Cohick and J.L. Butler, "Rare-earth iron "square ring" dipole transducer", J.Acoust.Soc.Am. 72(2), 313-315 (1982).

[47] T.M. Proctor Jr., "An improved piezoelectric acoustic emission transducer", J.Acoust.Soc.Am. 71(5), 1163-1169 (1982).

[48] J.J. Bernstein and R.M. White, "Thin film electret and condenser ultrasonic transducers, Proc. IEEE Ultrasonics Symposium, 525-528 (1982).

[49] T.R. Gururaja, W.A. Schulze, L.E. Cross, R.E. Newnham, B.A. Auld and Y.J. Wang, "Piezoelectric composite materials for ultrasonic transducer applications; Part I - Resonant modes of vibrations on PZT-Rod polymer composites", IEEE Trans. Sonics Ultrason. SU-80, No.4, 481-497 (1985).

[50] G. Hayward and M.N. Jackson, "A lattice model of the thickness mode piezoelectric transducer", IEEE Trans. Ultrason. Ferroelec. Freq. Control. UFFC-33, No.1, 41-50 (1986).

[51] S.C. Shorter and B. Bridge, "Design, manufacture and performance of a narrow band ultrasonic immersion probes for multiple frequency operation in the range 3-170 MHz", Ultrasonics, Vol.24, No.3, 117-132 (1986).

[52] M.W. Godfrey, L.A. Mahmood and D.C. Emmony, "An improved design of point contact transducer", NDT International Vol.19, No.2, ,(1986).

[53] M.B. Moffett, J.M. Powers and W.L. Clay Jr., "Ultrasonic microprobe hydrophones", J.Acoust.Soc.Am. 84(4), 1186-1194 (1988).

[54] A.E. Karpel'Son, "Ultrasonic piezoelectric transducer that forms a specified directivity pattern", Translated from Defektoskopiya, No.7, 69-79 (1988).

[55] Francois Chapeau - Blondeau, J.F. Greenleaf, W.B. Harrison and M.R.B. Hanson, "An experimental study of acoustoelectric transducers with non uniform

distribution of the piezoelectric coefficient", J.Acoust.Soc.Am. 86(4), 1223-1229 (1989).

[56] J.A. Gallego - Juarez, "Piezoelectric ceramics and ultrasonic transducers", J.Phys.E: Sci Instrum., 22, 804-816 (1989).

[57] N.M. Shorrocks, R.W. Whatmore, M.T. Goosey, P. Seth and F.W. Ainger, "0-3 piezoelectric composites for large area hydrophones", Ferroelectrics, Vol.93, 169-176 (1989).

[58] R. Salaman, "Design methods for wide band piezoelectric transducers using matching layers", Acustica, Vol.69, No.4, 163-174 (1989).

[59] W.A. Smith, A.A. Shaular and B.A. Auld, "Design of piezo composites for ultrasonic transducers", Ferroelectrics, Vol.91, 155-162 (1989).

[60] R.Y. Ting, "The hydroacoustic behaviour of piezoelectric composite materials", Ferroelectrics, Vol.102, 215-224 (1990).

[61] J.L. Butler, S.C. Butler and A.E. Clark, "Unidirectional magnetostrictive/piezoelectric hybrid transducer", J.Acoust.Soc.Am. 88(1), 7-11 (1990).

[62] K.D. Rolt, "History of the flextensional electroacoustic transducer", J.Acoust.Soc.Am. 87(3), 1340-1349 (1990).

[63] J.E. Blue, A.L. Van Buren and P.A. Samper, "A low frequency tow powered sound source", Proc. International Workshop on Power Transducers for Sonics and Ultrasonics, France, 178-185 (1990).

[64] R.W. Timme, A.M. Young and J.E. Blue, "Transducer needs for low frequency sonar", Proc. International Workshop on Power Transducers for Sonics and Ultrasonics, France, 3-13 (1990).

[65] P.J. Kielczynski, W. Pajewski and M. Szaleswski, "Ring piezoelectric transducer radiating ultrasonic energy into air", IEEE Trans. Ultrason. Ferroelec. Freq.

Control. UFFC-37, No.1, 38-43 (1990).

[66] H.A. Kunkel, S.Locke and B. Pikeroen, "Finite element analysis of vibrational modes in piezoceramic disks", IEEE Trans. Sonics Ultrason. SU-37, No.4, 316-328 (1990).

[67] M. Bandys, M. Veselsky and J. Hejhalek,"Characterization of ceramics for power electronics", Ferroelectrics, Vol.109, 259-264 (1990).

[68] J.N. Dacarpigny, B. Hamoik and O.B. Wilson Jr., "The design of low frequency underwater acoustic projectors", IEEE J.Ocean.Eng. 16(1), 107-122 (1991).

[69] H. Kawai, "The piezoelectricity of polyvinylidene fluoride", Jpn.J.Appl.Phy. 8, 975-976 (1969).

[70] S. Edelman, L.R. Grisham, S.C. Roth and J.Cohen, "Improved piezoelectric effect in polymers", J.Acoust.Soc.Am. 48(5), 1041-1043 (1970).

[71] J.H. Mc Fee, J.G. Bergman Jr and G.R. Crane, "Pyroelectric and non-linear optical properties of poled polyvinylidene fluoride films", IEEE Trans. Sonics Ultrason. SU-19, 305-313 (1972).

[72] M. Tamura, T. Yamaguchi, T. Oyaba and T. Yoshimi, "Electroacoustic transducers with piezoelectric high polymer films", J.Audio.Eng.Soc. 23(1), 21-25 (1975).

[73] N. Murayama, K. Nakamura, H. Obara and M. Segawa, "The strong piezoelectricity in polyvinylidene fluoride (PVDF)", Ultrasonics, 15-23 (1976).

[74] L. Bui, H.J. Shaw and L.T. Zitelli, "Experimental broadband ultrasonic transducers using PVF_2 piezoelectric film", Electronics Letters, Vol.12, No.16, 393-394 (1976).

[75] B. Woodward, "The suitability of polyvinylidene fluoride as an underwater transducer material", Acoustica, 38, 264-268 (1977).

[76] L. Bui, H.J. Shaw and L.T. Zitelli, "Study of acoustic wave resonance in

piezoelectric PVF_2 film", IEEE Trans. Sonics Ultrason. SU-24, No.5, 331-336 (1977).

[77] S.D. Bennett and J. Chambers, "Novel variable focus ultrasonic transducer", Electronics Letters, Vol.13, No.4, 110-111 (1977).

[78] N. Chubachi and T. Sannomiya, "Composite resonator using PVF_2 film and its application to concave transducer for focusing radiation of VHF ultrasonic waves", Proc. of IEEE Ultrasonics Symposium, (1977).

[79] T.D. Sullivan and J.M. Powers, "Piezoelectric polymer flexural disk hydrophone", J.Acoust.Soc.Am. 63(5), 1396-1401 (1978).

[80] G.R. Crane, "Poly(vinylidene) fluoride used for piezoelectric coin sensors", IEEE Trans. Sonics Ultrason. SU-25, No.6, 393-395 (1978).

[81] F. Micheron and C. Lemonon, "Moulded piezoelectric transducers using polar polymers", J.Acoust.Soc.Am. 64(6), 1720-1721 (1978).

[82] N.C. Sasady and A. Hartig, "Development of some transducers based on polyvinylidene fluoride", Ultrasonics, 468-475 (1979).

[83] R. Lerch, "Electroacoustic transducers using piezoelectric polyvinylidene fluoride films", J.Acoust.Soc.Am. 66(4), 952-954 (1979).

[84] E. Carana, K. Fesler, H.J. Shaw, D. Weinstein and L.T. Zitelli, "PVF_2 surface wave transducers", 1979 Ultrasonics Symposium Proc., USA, 26-28 (1979).

[85] D.T. Wilson, R.H. Tancrell and J. Callerame, "PVF_2 polymer microprobe", 1979 Ultrasonics Symposium Proc., USA, 26-28 (1979).

[86] J. Sussner, "The piezoelectric polymer PVF_2 and its applications", 1979 Ultrasonics Symposium Proc., USA, 32-34 (1979).

[87] W.R. Scott and P.E. Bloomfield, "Durable lead attachment techniques for PVDF polymer transducers with applications to ultrasonics", Ferroelectrics, Vol.28, No.14, 315 (1980).

[88] R. Lerch and G.M. Sessler, "Microphones with rigidly supported piezopolymer membranes", J.Acoust.Soc.Am. 67(4), 1379-1381 (1980).

[89] R.G. Swartz and J.D. Plummer, "On the generation of high frequency acoustic energy with polyvinylidene fluoride", IEEE Trans. Sonics Ultrason. SU-27, No.6, 295-302 (1980).

[90] K.C. Shotton, D.R. Bacon and R.M. Quilliam, "A PVDF membrane hydrophone for operation in the range 0.5 MHz to 15 MHz", Ultrasonics, 123-126 (1980).

[91] S. Kovnovich and E. Harnik, "Generation and detection of short duration unipolar stress pulses using poled PVF_2 films", Electronics Letters, Vol.16, No.20, 776-777 (1980).

[92] M. Toda, S. Osaka and S. Tosima, "Large area display element using PVF_2 bimorph with double support structure", Ferroelectrics, Vol.23, No. 1-2, 115-120 (1980).

[93] R. Lerch, "Piezopolymer transducers with point supported membranes", J.Acoust.Soc.Am. 70(5), 1229-1234 (1981).

[94] N.F. Foster, "Piezoelectricity in thin film materials", J.Acoust.Soc.Am. 70(6), 1609-1614 (1981).

[95] M.A. Marcus, "Ferroelectric polymers and their applications", Proc. of Fifth International Symposium on Ferroelectricity, Pennsylvania State University, (1981).

[96] A.S. De Reggi, S.C. Roth, J.M. Kenney, S. Edelman and G.R. Harris, "Piezoelectric polymer probe for ultrasonic applications", J.Acoust.Soc.Am. 69(3), 853-859 (1981).

[97] R.M. White, C.T. Chuang and Ardian C. C. Lee, "Bulk ultrasonic transducer employing piezoelectric film on thin metal sheet", IEEE Trans. Sonics Ultrason. SU-28, No.1, 8-13 (1981).

[98] G.R. Harris, "Sensitivity consideration for PVDF hydrophones using spot poled membrane design", IEEE Trans. Sonics Ultrason. SU-29, No.6, 370-377 (1982).

[99] D.R. Bacon, "Characteristics of a PVDF membrane hydrophone for use in the range 1-100 MHz", IEEE Trans. Sonics Ultrason. SU-29, No.1, 18-25 (1982).

[100] T.A. Henriquez, "Applications of tubular PVDF to shock resistant hydrophones", Ferroelectrics, Vol.50, 39-44 (1983).

[101] G.R. Harris, Edward S. Carome and Henry D. Dardy, "An analysis of pulsed ultrasonic fields as measured by PVDF spot poled membrane hydrophones", IEEE Trans. Sonics Ultrason. SU-30, No.5, 295-303 (1983).

[102] M.A. Marcus, "Performance characteristics of piezoelectric polymer flexure mode devices", Ferroelectrics, 57, 203-220 (1984).

[103] P.A. Lewin, "Miniature piezoelectric polymer hydrophones in biomedical ultrasonics", Ferroelectrics, Vol.60, 127-139 (1984).

[104] A.A. Schoenberg, D.M. Sullivan, C.D. Baker, H.E. Booth and C. Galway, "Ultrasonic PVF_2 transducers for sensing tactile force", Ferroelectrics, Vol.60, 239-250 (1984).

[105] A.N. Hedjicostis and C.F. Hottinger, J.J Rosen and P.N.T. Wells, "Ultrasonic transducer materials for medical applications", Ferroelectrics, Vol.60, 107-126 (1984).

[106] P. Dario, D. De Rossi, R. Bedini, R. Francesconi and M.G. Trivella, "PVF_2 catheter tip transducers for pressure, sound and flow measurements", Ferroelectrics, Vol.60, 149-162 (1984).

[107] P.TH.A. Klaase, "Low frequency and ultrasonic applications of piezoelectric PVDF films", Ferroelectrics, Vol.60, 215-225 (1984).

[108] P.H. Brown, "Ultrasonic imaging with an electron beam scanned PVDF sensor", Ferroelectrics, Vol.60, 251-261 (1984).

[109] M.B. Moffett, James M. Powers and John C. McGrath, "A ρc hydrophone", J.Acoust.Soc.Am. 80(2), 375-381 (1986).

[110] H.R. Galeantree, "PVDF membrane hydrophones - An ultrasonic characteristic tool", Marconi Research centre, U.K., (1987).

[111] D.A. Hutchins, H.D. Mair and R.G. Taylor, "Transient pressure fields of PVDF transducers", J.Acoust.Soc.Am. 82(1), 183-192 (1987).

[112] D.R. Fox, "A low density extended acoustic sensor for low frequency arrays", IEEE J.Oceanic Eng., Vol.13, No.4, 291-295 (1988).

[113] S.P. Robinson, "A comparison of the frequency response of membrane and needle probe PVDF hydrophones", National Physical Laboratory, U.K.

[114] C.C. Habeger, W.A. Wink and M.L. Van Zummeren, "Using Neoprene faced PVDF transducers to couple ultrasound into solids", J.Acoust.Soc.Am. 84(4), 1388-1396 (1988).

[115] B.G. Kim, J.O. Lee and S.Lee, "Development of surface point focusing ultrasonic transducer using PVDF", Proc. IEEE Ultrasonic Symposium, Vol.1, 609-612 (1989).

[116] H.L.W. Chan, A.H. Ramelan, I.L. Guy and D.C. Price, "VF_2/VF_3 co-polymer hydrophone for ultrasonic power measurements", Proc. IEEE Ultrasonic Symposium, Vol.1, 617-620 (1989).

[117] L.F. Brown and D.L. Carlson, "Ultrasound transducer models for piezoelectric polymer films", IEEE Trans. Ultrason. Ferroelec. Freq. Control. UFFC-36, No.3, 313-317 (1989).

[118] C.C. Habegar and W.A. Wink, "Development of a double element pulse echo PVDF transducers", Ultrasonics, Vol.28, No.1, 52-54 (1990).

[119] M. Platte, "PVDF ultrasonic transducers for NDT", Ferroelectrics, Vol.115, No.4, 229-246 (1991).

[120] S. Hurmila, H. Stubb, J. Pitkanen, K. Lahdenpera, A. Penttinen, V. Suorsa and A. Taurianiers, "Ultrasonic transducers using PVDF", Ferroelectrics, Vol.115, No.4, 267-278 (1991).

[121] V.N. Bindal, T.K. Saksena, J.N. Sam and S. Chandra, "Absolute determination of sensitivity of miniature piezoelectric ceramic hydrophone using reciprocity technique", Indian J. Pure & Appl. Phy., Vol.28, No.12, 697-701 (1990).

[122] W.J. Trott, "A Portable hydrophone calibrator", J.Acoust.Soc.Am., 49, 850-855 (1971).

[123] G.A. Sabin, "Transducer calibration by impedance measurements", J.Acoust.Soc.Am., 28, 697-701 (1990).

[124] A.R. Laufer and G.L. Thomas, "New method for the calibration of a plane hydrophone", J.Acoust.Soc.Am., 28, 951 (1956).

[125] R.J. Bobber, "Electronic hydrophone for calibration at very low frequencies", J.Acoust.Soc.Am., 26, 1080-1081 (1954).

[126] R.J. Bobber, "Underwater electroacoustic measurements", Penninsula Publishing, California, USA, (1988).

[127] Bruel & Kjaer, "Application notes on hydrophones - Their characteristics and applications".

[128] L.A. Warnes, "Cable correction for hydrophones", Ultrasonics, Vol.29, No.2, 138-140 (1991).

[129] J. Millman and C.C. Halkias, "Integrated electronics", Tata Mc Graw-Hill Ltd, New Delhi, (1991).

[130] George Clayton and Bruce Newby, "Operational Amplifiers", IIIrd edition, Butterworth-Heinemann Ltd., Oxford, UK, (1992).

[131] G.R. Kirchhoff, J.Math.(Crelle) 40, 1850.

[132] L. Rayleigh, "Theory of sound", Dover Publications, New York, Vol.I, (1945).

[133] M.Timoshenko, D.H. Young and W. Weaver, Jr., "Vibrations problems in engineering", John Wiley & Sons, New York, (1974).

[134] T. Wah, "Vibration of circular plates", J.Acoust.Soc.Am., 34, 275-281 (1962).

[135] R.D. Blevins, "Formulas for natural frequency and mode shape", Von Nostrand Reinhold Company, New York, (1979).

[136] R.E. Roberson, "Vibration of a clamped circular plate carrying a concentrated mass", J. Appl. Mech., 18, 349-352 (1951).

[137] H. Lamb, "On the vibration of an elastic plate in contact with water", Proc. R. Soc. London, 98, 205 (1921).

Index

List of Publications

Journal Papers

1. "Design and Development of a Highly Sensitive Piezofilm Sensor", Journal of Acoustical Society of India, Vol. XVIII (3&4), 188-191, 1990.

2. "Development of a (3,1) Drive Low Frequency Piezofilm Hydrophones with Improved Sensitivity", Journal of Acoustical Society of America, USA, 94(6), 3053-3056, 1993.

3. "Development of a (3,1) Drive Multifilm Piezopolymer Hydrophone", IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, USA, UFFC-42, No.1, 1995. (in press)

4. "Design and Development of Refined (3,1) Drive Low Frequency Piezofilm Hydrophones", Journal of Acoustical Society of America, USA, 97(2), 1995. (in press)

Symposium Papers

1. "Design Considerations of a Modified Flexural Mode Piezofilm Sensor", Presented at the National Symposium on Ultrasonics, New Delhi, (1992).

2. "A Modified Flexural Mode Piezofilm Hydrophone", Proc. of National Symposium on Ocean Electronics (SYMPOL), Cochin, 30-34, (1993).

REPRINTS OF THE JOURNAL PAPERS PUBLISHED

BY THE AUTHOR

J. Acoust. Soc. Ind.
Vol. XVIII (3 & 4), November 1990

DESIGN AND DEVELOPMENT OF A HIGHLY SENSITIVE PIEZOFILM SENSOR

J. Jagannath Bhat, P.P. Thomson and P.R. Saseendran Pillai

Department of Electronics, Cochin University of Science & Technology,
Cochin 682 022.

ABSTRACT. The piezofilm made of polyvinylidene fluoride is being used as an efficient transduction material for the construction of microphones and hydrophones nowadays. An innovative new transducer design for generating comparatively higher voltage output by concentrating the acoustic force to a small cross sectional area is proposed in this paper. In this design, the film is made to vibrate in the (3,1) mode by a modified structural assembly, utilising a perspex diaphragm and a driver pin. Calculations show that, the voltage generated in the (3,1) mode transducer will be approximately 500 times that in the (3,3) mode of construction for the same level of applied force input. Experimentally the receiving sensitivity of the (3,1) mode piezofilm sensor in air is found to be approximately -153 dB re 1V/μ Pa, at around 1.5kHz.

INTRODUCTION

Piezoelectric polymer films have become commercially available and it is widely used in air and underwater applications (1), (2), as an active material for the construction of transducers. The advantageous and meritorious features of piezofilm like, toughness, light weight, flexibility to adhere to irregular and complex structures etc. facilitate the widespread use of this material for the design of transducer systems. Besides, it has got impedance closer to that of water and this along with other attractive features like wide frequency coverage and broad dynamic response offer several potential applications for the piezofilm transducers.

Almost all the transducer designs reported in open literature using piezofilms are operating in the (3,3) mode of vibration. In this mode, the area of the film exposed to the incoming acoustic pressure is relatively large, hence the stress experienced by the film will be less and therefore the voltage generated will also be less. This will reduce the sensitivity of the transducer. On the other hand, if the area of the film that is exposed to the incoming pressure can be reduced, the voltage generated will be large. This is the basic principle that is made use of in the design of transducers operating in the (3,1) mode. The main difference between the (3,3) and (3,1) modes is that, in the former the film is made to vibrate in thickness mode whereas in the latter the film vibrates in length mode.

The piezo stress constant g(3,1) is relatively high and piezo strain constant d(3,1) is relatively low compared to ceramics and other piezoelectric materials. Hence piezofilm hydrophones exhibit high voltage sensitivity and low charge sensitivity.

To illustrate the superiority of the (3,1) mode transducer design over the conventional (3,3) mode of construction, consider a piezofilm of thickness t, subjected to an applied compressive stress of X newtons per square metre distributed over its metallised surface. The voltage generated can be shown to be (3)

$$V(3,3) = g(3,3)\ X(3)\ t$$

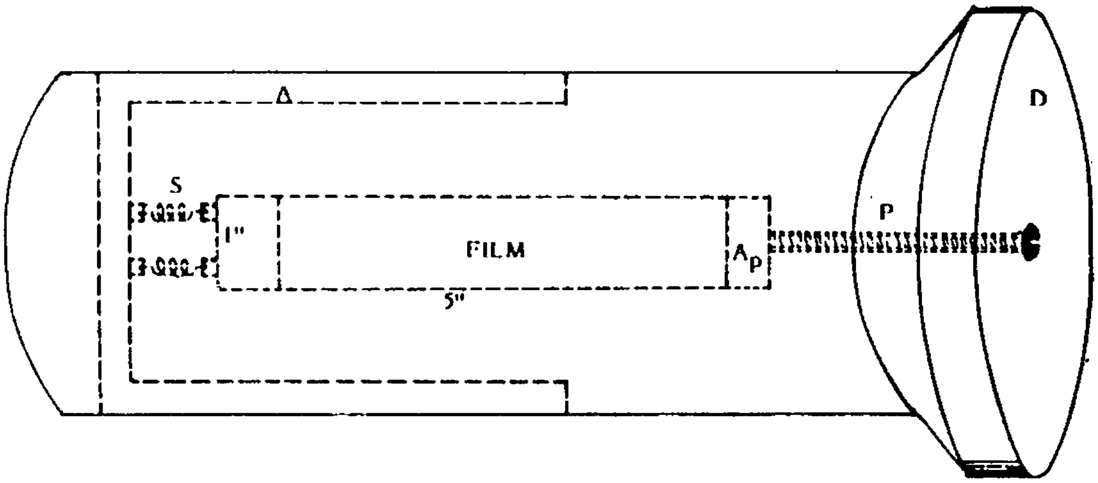
If the film is pulled to and fro in the length (stretching) direction with the same force by a modified structural assembly, the voltage generated becomes:

$$V(3,1) = g(3,1)\ X(1)\ t$$

Calculations show that the voltage generated in the (3,1) mode of construction will be about 500 times greater than that in the (3,3) mode. This sharp increase in the voltage for the same level of force input is the result of the concentration of the applied force to a smaller cross sectional area.

DESIGN

The constructional details and structural assembly of the piezofilm transducer operating in the (3,1) mode of vibration is shown in Figure 1. The film was made to vibrate in the (3,1) mode by a special structural assembly, consisting of the diaphragm D and the driver pin P. The vibrations which impinge on a perspex diaphragm of diameter 5 cms and thickness 1mm, which was adhered to the main enclosure were transferred to the film through the driver pin. A film of length 5 cms , breadth 1.5 cms and thickness 28 micron was suitably pre-stretched by properly adjusting the two spring loaded screws S, which were provided at the other end of the film. The whole system was enclosed in a



A : Aluminium frame
A_p : Aluminium plate

P : Driver pin
D : Diaphragm
S : Loaded spring

Fig. 1 : Constructional details of the (3,1) mode transducer with phosphor bronze diaphragm.

cylindrical chamber.

EXPERIMENTAL SET-UP AND MEASUREMENTS

The experimental set-up for measuring the sensitivity of the transducer is as shown in Figure 2. The gated sinusoidal waves from the gating system are amplified by a power amplifier and these signals were used to generate acoustic waves of desired amplitude and frequency using a Philips high Q speaker.

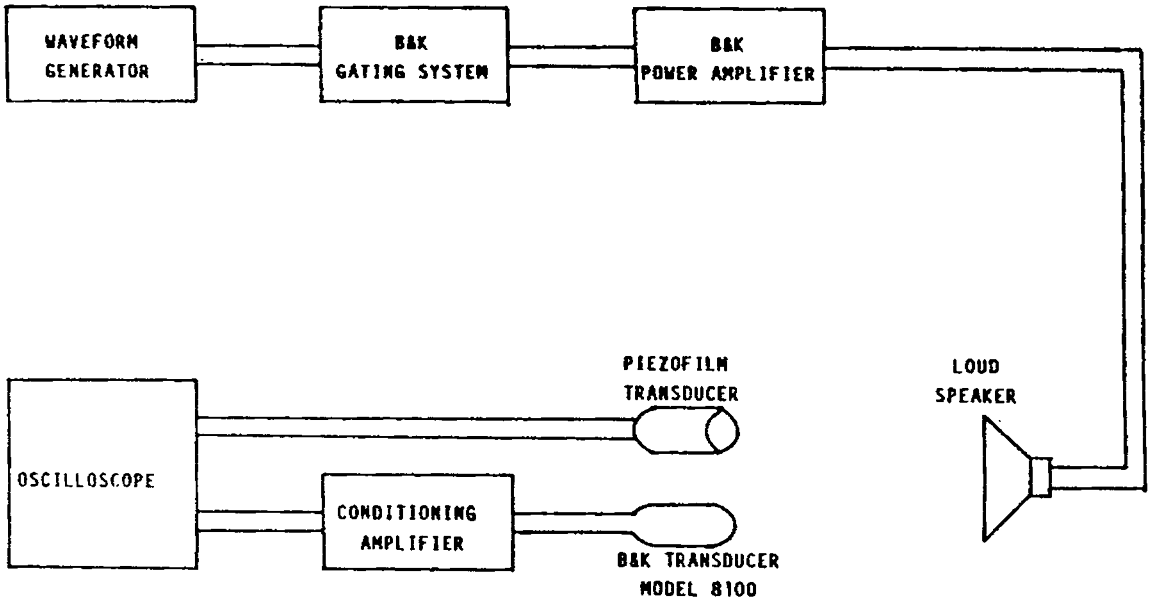


Fig.2: Experimental set-up for evaluating the performance of the (3,1) mode piezofilm transducer in air.

For computing the sensitivity of the piezofilm transducer in air, it was placed along with a standard B&K 8100 transducer. The standard transducer has a sensitivity that is almost constant from low frequency to about 2 kHz in air and then decreases linearly with frequency. The experimental as well as the standard transducers were placed at equal distances from the speaker. The frequency was swept from 500 Hz to 5 kHz and the voltage generated in both the receiving transducers were measured. For calculating the sensitivity, comparison method was adopted, which is convenient and accurate within the limits of the experimental error. In this method, the output voltages obtained for both the experimental and standard transducers are compared and the sensitivity is calculated using (4).

$$S_2 = S_1 - 20 \log(V_1/V_2) \text{ dB re } 1\text{V}/\mu\text{Pa}$$

where S_1 is the sensitivity of the standard transducer
S_2 is the sensitivity of the experimental transducer
V_1 is the output voltage of the standard transducer &
V_2 is the output voltage of the experimental transducer.

The frequency response of the experimental transducer is shown in Figure 3. From the graph, it is seen that the maximum receiving sensitivity of the piezofilm transducer in air is approximately -153 dB re 1V/μ Pa, at around 1.5 kHz and is almost flat on either side of the resonance peak.

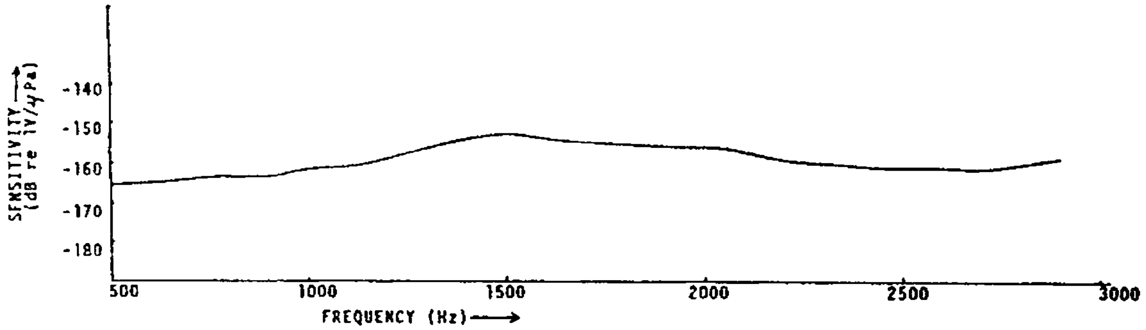


Fig.3: Frequency response of the (3,1) mode transducer in air

CONCLUSIONS

The frequency response of piezofilm sensor clearly reveals that there is a considerable improvement in its sensitivity over conventional microphones. This enhancement in the receiving sensitivity can be seen to be the direct result of concentration of the force to a much smaller cross sectional area. The smaller cross sectional areas result in correspondingly larger stresses and hence larger voltages.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support from the Department of Electronics, Government of India.

REFERENCES

1. T.D. Sullivan and J.M. Powers, 'Piezoelectric Polymer Flexural Disc Hydrophone', J. Acoust. Amer., 63(5), 1396 (1978)
2. R. Lerch, 'Electroacoustic Properties of Piezopolymer Microphones', ibid, 69(6), 1809 (1981)
3. Kynar Piezofilm Technical Manual, Pennwalt Corporation, USA, 36 (1983)
4. Bruel & Kjaer Application Notes on Hydrophones-their characteristics and applications

Development of (3,1) drive low-frequency piezofilm hydrophones with improved sensitivity

J. Jagannath Bhat, P. Philip Thomson, and P. R. Saseendran Pillai
Department of Electronics, Cochin University of Science & Technology, Cochin 682 022, India

(Received 22 January 1993; accepted for publication 7 August 1993)

Piezopolymers are becoming popular as the active material for the design of probes for sensing ultrasonic fields and quantitative determination of acoustic field parameters in water and biological media. A new innovative transducer design proposed here utilizes a poled piezofilm which is made to vibrate in (3,1) drive by a modified structural assembly. The voltage generated in this design is found to be greater compared to that in the conventional design, due to the concentration of acoustic pressure to a very small cross-sectional area. The prototype design consists of a prestretched piezofilm fixed to a phosphor bronze diaphragm through a driver pin. The proposed design yielded sensitivities to the extent of -170 dB *re*: 1 V/μPa in water at around 1.5 kHz.

PACS numbers: 43.88.Ar, 43.88.Fx, 43.30.Yj

INTRODUCTION

Since the discovery of piezopolymer films, they are widely used for transducer applications, particularly for underwater detection purposes. In 1969 Kawai[1] discovered that certain polymers can be poled to a level of activity not previously achieved with any other polymeric material.

Piezopolymers offer several potential advantages[2] such as high chemical resistance, high breakdown field strength, low density, low acoustic impedance, high sensitivity for vibration detection, low wear, high flexibility, easily obtainable film shape, and low cost over the conventional ceramic materials, which are difficult to produce in large size and impractical to machine in complex shapes. Since ceramics are brittle and stiff, they require bases with flat surfaces for mounting. One of the outstanding features of the piezofilm is its low acoustic impedance relative to ceramics, which aids in sorting out the impedance matching problems to water when used in an underwater transducer assembly. The high piezoelectric stress constant and low piezoelectric strain constant make the piezofilm highly voltage sensitive. The product of stress and strain constants is a measure of the figure of merit of hydrophones, which for piezofilms is approximately 2.5 times greater than ceramics.

I. DESIGN PHILOSOPHY

Most of the conventional transducers reported in the open literature[3–5] utilize the (3,3) drive of vibrations, which makes use of the flexure and thickness modes of vibration. Of all the varieties of flexure mode designs, the simplest is the unimorph, which consists of a single piezoelectric layer bonded to a nonpiezoelectric substrate. The working principle of the flexure mode devices relies on the fact that the external applied force causes it to flex and which, in turn, produces inward and outward excursions in the planes of the active material, and these fluctuating strains will induce a corresponding potential difference proportional to the stress, across the surface of the active material. A multimorph has many layers of active material bonded between backing and radiating faces. In sandwich-type constructions a single disc or paired discs of piezoelectric materials will be packed between metal plates and placed under compression by means of stress bolts.

Due to the anisotropic nature of the piezofilms, the voltage generated for a particular acoustic pressure depends greatly on the mode in which it vibrates. It has been found that the voltage generated across the piezofilm can be increased by concentrating the acoustic pressure field to a much smaller cross-sectional area with the help of a modified structural assembly, resulting in the so-called (3,1) drive transducer.

The superiority of the (3,1) drive design over the conventional (3,3) drive can be further illustrated[6] by considering the mode of vibration as a parameter of the piezofilm for a given acoustic pressure input.

The voltage generated in a piezofilm of length *l*, width *w*, and thickness *t*, subjected to a compressive stress of *T* Newton per square meter distributed over its metallized surface is

$$V_3 = g_{33} T t.$$

In the (3,1) drive of vibration the voltage output produced by the same input acoustic pressure can be computed as[6]

$$V_1 = g_{31} F / w,$$

TABLE I. Voltages computed in (3,1) and (3,3) drives for a uniform stress of 100 N/m^2.

Film dimensions $l \times w \times t$	Voltage computed in (3,1) drive	Voltage computed in (3,3) drive	The ratio of computed stress developed in the (3,1) drive to that in the (3,3) drive
5 cm$\times$1 cm$\times$28 μm	1.08 V	0.95 mV	1785
4 cm$\times$2 cm$\times$28 μm	0.86 V	0.95 mV	1428
3 cm$\times$3 cm$\times$28 μm	0.65 V	0.95 mV	1071

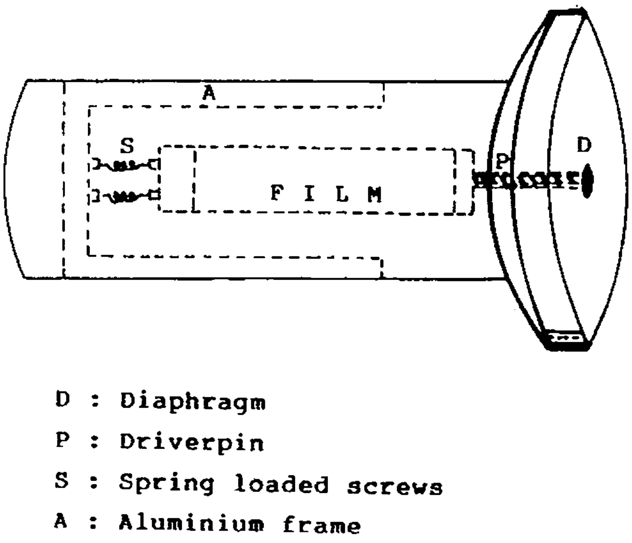


FIG. 1. Cross-sectional view of the (3,1) drive transducer, showing its structural components.

where F is the force acting over the given metallized area, and g_{31} and g_{33} are the piezoelectric voltage constants for the piezofilm. Calculations reveal that the voltage generated in the (3,1) drive will be very much greater than that generated in the (3,3) drive for a given force input. This sharp increase can be explained as due to the concentration of the applied force to a smaller cross-sectional area. Typical voltages computed for (3,3) and (3,1) drives for a given stress input of 100 N/m^2 are shown in Table I, along with the ratio of stress developed.[6]

II. FORMULATION OF A TEST MODEL

By extracting some of the meritorious features offered by the (3,1) drive of operation, a transducer was designed and fabricated with the help of a modified structural assembly which pulls the piezofilm in the direction of stretching. The cross-sectional view of the (3,1) drive transducer showing the structural components of the system is shown in Fig. 1. The first practical sensor evolved for validating the performance of the (3,1) drive system basically consisted of a perspex diaphragm of diameter 5 cm and of thickness 1 mm, which is firmly adhered to the main enclosure. The diaphragm vibrates in accordance with the incoming acoustic pressure field, and these vibrations are transferred to a prestretched film of length 5 cm, breadth 1.5 cm, and thickness 28 μm through a driver pin, which is rigidly fixed to the center of the diaphragm. The whole assembly is enclosed in a cylindrical chamber. The film is stretched by adhering one of its ends to the driver pin and the other to two spring-loaded screws. The film can be properly stretched by suitably adjusting these screws.

Perspex is a very light material and has a low spring constant; hence, it is not suitable for underwater applications such as a diaphragm material. Therefore, phosphor bronze, a material with a high spring constant, has been used as a diaphragm material for evolving the (3,1) drive piezofilm underwater transducer.

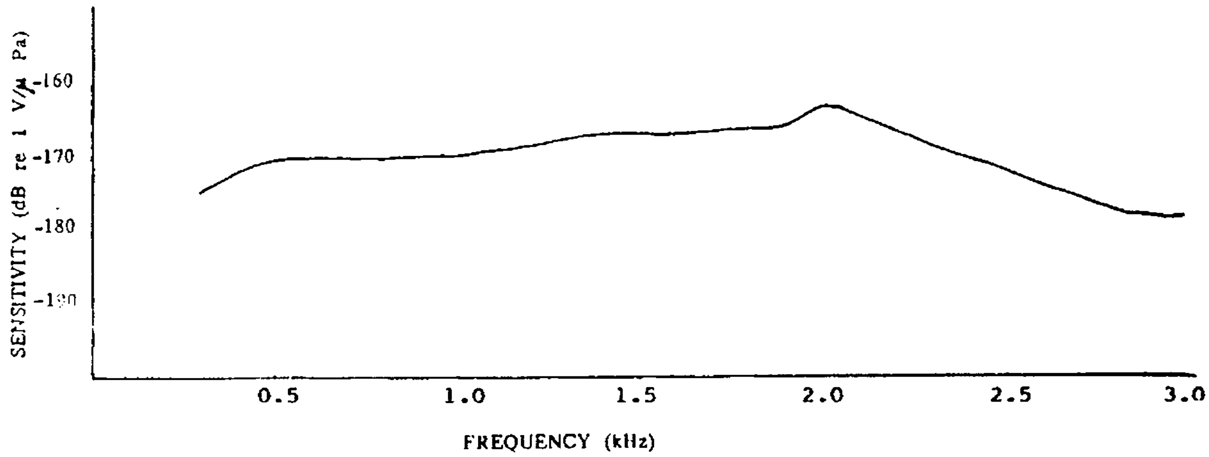


FIG. 2. Frequency response of the (3,1) drive transducer in air.

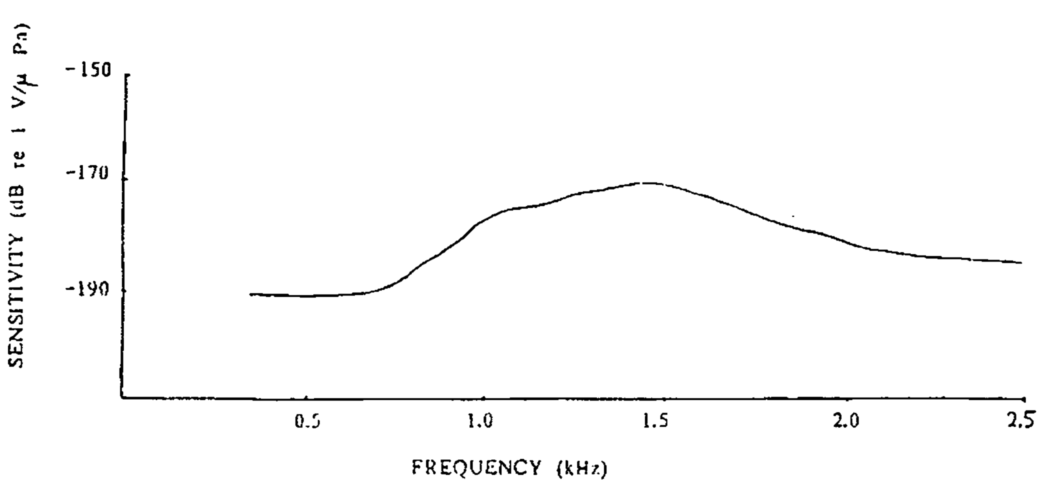


FIG. 3. Frequency response of the (3,1) drive transducer in water.

A prototype version of the (3,1) drive transducer with the phosphor bronze diaphragm of diameter 5 cm and thickness of 1.8 mm has been constructed. Any acoustic pressure variations on the diaphragm is directly transferred to the film through a driver pin of length 1.5 cm. The piezofilm is prestretched by the spring-loaded screws, and the whole assembly is enclosed in a water-tight enclosure.

To facilitate the performance evaluation of the transducer at greater depths in water and also to reduce the attenuation of the signal due to high capacitance of the signal cable, a unity gain MOSFET buffer has been used with a cable length of 30 m.

III. EXPERIMENTAL SETUP AND MEASUREMENTS

To validate the performance in air, the sinusoidal signals from the signal generator are gated and are amplified by a power amplifier and fed to a loudspeaker, which acts as the transmitter. A standard B&K 8100 transducer is placed along with the experimental transducer at about 5 m away from the transmitter. The frequency was swept from 300 Hz to 3 kHz and the voltages generated in both the transducers were measured.

A comparison method has been used for computing the sensitivity of the experimental transducer. It utilizes the method[7] of comparing the voltage generated in both the standard and the experimental transducers for a particular acoustic pressure, and the sensitivity has been calculated using

$$S_e = S_s - 20\log(V_s/V_e)\ \text{dB}\ re\text{: } 1\text{V}/\mu\text{Pa},$$

where S_e is the sensitivity of the experimental transducer, S_s is the sensitivity of the standard transducer, V_s is the voltage output of the standard transducer, and V_e is the voltage output of the experimental transducer. Figure 2 shows the frequency response of the (3,1) drive transducer with the phosphor bronze diaphragm in air.

The water measurements were carried out at a dam site, with a floating platform, which can be anchored anywhere in the dam. The experimental transducer was dipped along with the standard B&K 8100 transducer at about 3-m depth. The underwater speaker UW-60 was used as the low-frequency projector, and it was placed at about 10 m away from the receivers at the same depth. The experimental setup was the same as that used for air measurements. The frequency was swept from 400 Hz to 2.5 kHz, and the sensitivity of the experimental transducer was computed by the comparison method. Figure 3 shows the frequency response of the transducer in water.

IV. RESULTS AND DISCUSSIONS

The frequency responses of the (3,1) drive piezofilm transducer shown in Figs. 2 and 3 clearly reveal that there is a considerable improvement in the receiving sensitivity at certain range of frequencies compared to the conventional ones. This improvement in sensitivity can be explained as due to the concentration of the force to a much smaller cross-sectional area.

The leak testing of the transducer has been performed by constantly immersing the transducer at 5-m depth in the dam for 3 days and revalidating its frequency response to a better level of accuracy within the tolerable limit of repeatability.

V. CONCLUSIONS

Low-frequency piezofilm transducers with improved performance have been evolved by utilizing the concept of concentrating the given force input to a much smaller cross-sectional area with the help of a modified structural assembly. Such types of (3,1) drive transducers can be effectively utilized for sonobuoy or other similar applications.

Attempts are being made to miniaturize the design so that the product will be more handy and compact.

ACKNOWLEDGMENTS

The authors gratefully thank the Department of Electronics, Government of India, for the financial support and are indebted to the Department of Electronics, Cochin University of Science & Technology for providing the necessary infrastructural facilities to carry out this work.

[1] H. Kawai, Jpn. J. Appl. Phys. 8, 975 (1969).

[2] R. Lerch, "Electroacoustic Properties of Piezopolymer Microphones," J. Acoust. Soc. Am. 69, 1809 (1981).

[3] R. Lerch, "Electroacoustic Transducers using Piezoelectric Polyvinyledene Flouride Films," J. Acoust. Soc. Am. 66, 952 (1979).

[4] M. A. Marcus, "Performance Characteristics of Piezoelectric Polymer Flexure Mode Devices," Ferroelectrics 57, 203 (1984).

[5] T. D. Sullivan and J. M. Powers, "Piezoelectric Polymer Flexure Disc Hydrophones," J. Acoust. Soc. Am. 63, 1396 (1978).

[6] "Kynar Piezofilm Manual," Pennwalt Corporation, USA, 36(1983).

[7] Bruel & Kjaer, "Application Notes on Hydrophones—Their Characteristics and Applications."

Correspondence

Development of a (3,1) Drive Multifilm Piezopolymer Hydrophone

J. Jagannath Bhat and P. R. Saseendran Pillai

***Abstract*— A modified (3, 1) drive hydrophone design described here utilizes polarized piezopolymer films taut in the stretch direction by a reformed structural construction. It mainly consists of two opposed polymer films attached to a phosphor bronze diaphragm through a perspex structure. Enhancement in sensitivity is achieved, by connecting the films electrically in series thereby adding up the voltages developed across them due to a given acoustic pressure. The response of the hydrophone for individual films and for their series combination, are measured from 300 Hz to 4 kHz.**

I. INTRODUCTION

Low frequency hydrophones are finding several potential applications, particularly for long range detection measurements and in sonobuoys. It was shown by many authors [1], [2] that polarized piezopolymers can be effectively employed as the transduction materials for the construction of transducers. The superiority of the polymers can be inferred from their high chemical resistance, high breakdown field strength, low density, low acoustic impedance, high sensitivity for vibration detection, low wear, high flexibility, easily obtainable film shape and low cost over its counterparts like ceramics. The piezoelectric stress constant is very high for piezopolymers compared to ceramics, which make the polymers suitable for hydrophone applications. The anisotropic nature of the piezofilm restrains the possible modes in which the piezofilm can be put to vibrate for better outputs. Of the different modes in which the piezofilm can be made to vibrate, most prominent one is the (3, 3) drive, which makes use of thickness or flexure mode of vibration. In the thickness mode the film is made to vibrate normal to its surface, where as in flexure mode it is made to flex in accordance with the applied force, in both the cases the output is taken across the film surface. From the calculations it has been shown [3], [4] that the stretch mode vibration called (3, 1) drive will bring forth a higher output voltage than any other mode for a given acoustic input. A relatively higher output obtained in the stretch mode of vibration is the result of the increased stress the film experiences due to the concentration of the given force input to a much smaller cross-sectional area. Utilizing these properties, the hydrophone [4] designed to operate in the low frequency range was found to exhibit better sensitivity compared to the conventional ones.

II. DESCRIPTION OF THE IMPROVED DESIGN

A cross-sectional view of the improved design is shown in Fig. 1. A circular phosphor bronze sheet of diameter 5.5 cm and thickness 1 mm serves as the diaphragm for transferring the impinging acoustic energy to the active element. A perspex annular ring with sides threaded and a groove at the top for an *'O'ring*, is fixed over a cylindrical enclosure. A perspex cap is made with its innerside threaded and a groove at the bottom for a second *'O'ring* . The diaphragm is placed over the perspex ring with *'O'rings* on both sides, and is tightened properly with the cap, so that the diaphragm is pressed uniformly. An opening of approximately 5 cm is provided at the centre of the cap for exposing the diaphragm to the external pressure field. A brass driver pin of length 2 cm and thickness 1 mm is fixed at the centre of the diaphragm. At the other end of the pin a '[' shaped structure as shown in the figure is attached. This structure is made of perspex sheet of breadth 1 cm and thickness 1.5 mm, and is terminated with a rectangular perspex sheet of 1.5 cm × 1 cm, to which two polarized piezopolymer films of 5 cm × 1 cm × 52 μm are glued as shown. The films are stretched independently and the output is taken across them separately.

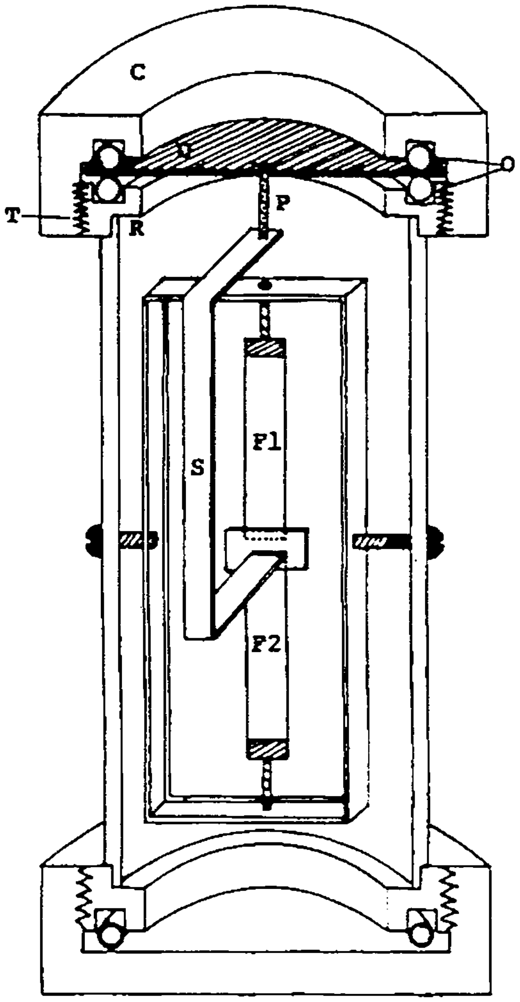


Fig. 1. Cross-sectional view of the modified Hydrophone design.

When the diaphragm vibrates due to the incident acoustic pressure, the perspex structure will also vibrate. This will make one of the films to expand and the other to contract. Corresponding to these strains in the films, voltages will be developed across them simultaneously. The outputs can be suitably extracted with the terminal electrodes.

Manuscript received May 31, 1994; revised July 29, 1994. This work was supported by the Council of Scientific and Industrial Research (New Delhi) and Department of Electronics (Government of India). This paper was recommended by Editor William D. O'Brien Jr.

The authors are with the Department of Electronics, Cochin University of Science & Technology, Cochin 682 022, India.

IEEE Log Number 9406692.

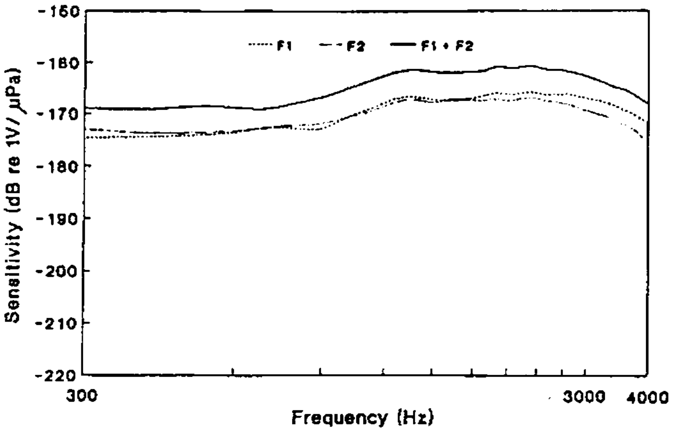


Fig. 2. Frequency response of the Hydrophone in air.

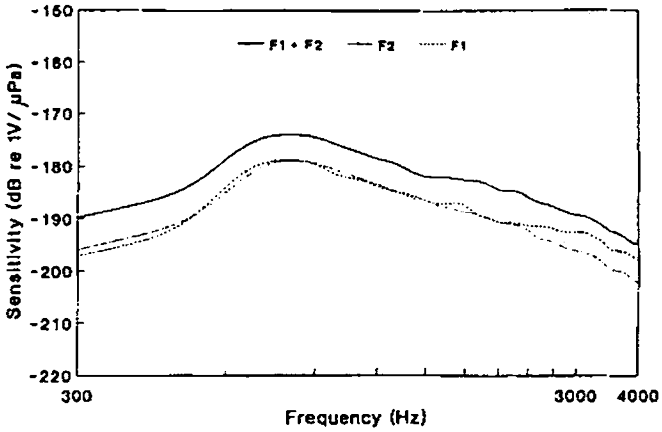


Fig. 3. Frequency response of the Hydrophone in water.

A differential amplifier is also connected with the test transducer for reducing the attenuation of the signal due to high capacitance of the signal cable.

III. Measurements and Results

The response of the hydrophone was measured in air and water for the individual films and for their series combination. To validate its performance in air, the sinusoidal signals from the signal generator were gated, amplified and then fed to a loud speaker. These signals were picked up by the test transducer along with a standard B&K 8100 transducer, which were kept about 5 m away from the transmitter. Comparison method [5] was adopted for computing the sensitivity of the test model. Fig. 2 illustrates the response of the hydrophone for individual films and for their series combination in the frequency range 300 Hz to 4 kHz.

Evaluation of performance of the hydrophone in water was carried out in a hydroelectric reservoir. ITC 1042 was used as the standard receiver and UW 15 as the transmitter. The frequency was swept from 300 Hz to 4 kHz, and the corresponding outputs of both the experimental and standard transducer were compared and the sensitivity was calculated. Fig. 3 depicts the response of the hydrophone for individual films and for their series combination.

IV. Conclusions

An improvement in sensitivity is observed when the films are electrically connected in series. This owed to the adding up of the voltages developed in the films due to the same acoustic input. It may be possible to increase the sensitivity further by connecting more films together. But it is to be quite noted that, when the number of films increases, the effective electrical impedance will also increase, which will eventually dampen the resultant output, if necessary precautions are not taken. This effect will be prominent particularly in the low frequency region.

References

[1] T. D. Sullivan and J. M. Powers, "Piezoelectric polymer flexure disk hydrophones," *J. Acoust. Soc. Am.*, vol. 63, no. 5, p. 1396, 1978.

[2] R. Lerch, "Electroacoustic transducers using piezoelectric polyvinylidene fluoride films," *J. Acoust. Soc. Am.*, vol. 66, no. 4, p. 952, 1979.

[3] "Kynar Piezofilm Manual," Pennwalt Corporation, USA, p. 36, 1983.

[4] J. J. Bhat, P. P. Thomson, and P. R. S. Pillai, "Development of (3, 1) drive low-frequency piezofilm hydrophones with improved sensitivity," *J. Acoust. Soc. Am.*, vol. 94, no. 6, pp. 3053-3056, 1993.

[5] Bruel and Kjaer, "Application notes on hydrophones—Their characteristics and applications."

AU: PLEASE PROVIDE PUBLICATION INFORMATION FOR REF. [5].

Design and development of refined (3,1) drive low-frequency piezofilm hydrophones

J. Jagannath Bhat, P. R. Saseendran Pillai, and Chetlur S. Sridhar
Department of Electronics, Cochin University of Science and Technology, Cochin 682 022, India

(Received 26 January 1994; accepted for publication 5 October 1994)

A hydrophone design using polarized polyvinylidene fluoride film held taut and made to vibrate in the stretch direction by a modified structural assembly is described in this paper. In this refined design, the diaphragm which is the active face of the hydrophone is uniformly mounted on the enclosure using two rubber O-rings, thereby ensuring smooth transfer of energy from the diaphragm to the polymer film. An acceptable level of reproducibility is also achieved with this approach. A mathematical model for determining the resonance frequency of the (3,1) drive design is also proposed by considering it as an assembly of a circular plate loaded with a point mass at the center and having uniformly clamped contour. Experimental and theoretical results are in good agreement.

PACS numbers: 43.38.Ar, 43.38.Fx

INTRODUCTION

Polarized piezopolymers are getting wide acceptance as transduction materials in audio and ultrasonic applications. The appealing factors that led to the popularity of polymers include their high chemical resistance, high breakdown field strength, low density, low specific acoustic impedance, high sensitivity for vibration detection, low wear, high flexibility, easily obtainable film shape, and low cost over their counterparts such as piezoceramics and quartz materials. For piezopolymers the piezoelectric stress constant is high and piezoelectric strain constant is low which account for a higher voltage sensitivity. The product of piezoelectric stress and strain constants known as the figure merit of hydrophones is 2.5× greater for piezopolymers than for ceramics. But the piezoelectric coupling factor is comparatively low for piezofilm and hence not usually recommended for projector applications.

The piezofilm is highly anisotropic and hence its electromechanical properties depend largely on the driving function and the mode of vibration. Most of the transducers using piezopolymers reported so far[1-3] in literature are driven to utilize either a thickness or flexure mode of vibration. In the thickness drive the piezofilm is made to vibrate perpendicular to its surface in accordance with the acoustic pressure variations, where as in flexure drive the film flexes with the impinging pressure. The simplicity of these designs make them most prevalent ones. But it has been found that[4] the voltage generated across the piezofilm for a given pressure input can be increased by concentrating it to a much smaller cross-sectional area of the film, with the help of a modified structural design called (3,1) drive of vibration.

This paper is an extension of an earlier work[5] in which the authors developed a (3,1) drive piezofilm hydrophone with improved sensitivity, making use of some of the advantageous features offered by the piezofilm when it vibrates in the (3,1) drive. This design basically consisted of a phosphor bronze diaphragm which was glued at the top of a cylindrical enclosure. One end of a small driver pin was rigidly fixed at the center of the diaphragm and a PVDF film of dimensions 5 cm×1 cm×28 μm was adhered to the other end. The film was fixed to the assembly with two spring-loaded screws and prestretched by properly adjusting these screws.

In this paper an attempt has been made to improve the reproducibility of the hydrophone by modifying the design, particularly the mounting of the active face of the hydrophone. As can be seen explicitly from the (3,1) drive design, one of the probable components which is likely to influence the overall performance of this transducer is the diaphragm, which is the only element exposed to acoustic pressure. A study is also undertaken for experimentally verifying the effect of diaphragm and film dimensions on the resonance frequency of the hydrophone. Mathematical support is also attempted in this paper by considering the hydrophone as having a diaphragm with clamped edges and a point mass at the center.

I. DESIGN

The principle of working of the hydrophone model described above is that acoustic pressure variations on the diaphragm are transferred to the taut film, resulting in the production of corresponding strains which develop charges on the surface of the film, and due to the metallic coating on its surface, the charges can be tapped through the terminal electrodes. Hence the active face contributes much to the transfer of vibrations from the medium to the active element. Therefore response of the hydrophone largely depends on the way in which the diaphragm vibrates, and for the consistent transfer of energy to the film, the diaphragm should have a uniform mounting. As the diaphragm was fixed with adhesives, it was very difficult to ensure a uniform mounting as well as a perfect sealing. Nonuniform diaphragm mountings lead to drastic variations in the hydrophone characteristics from piece to piece. Moreover, this type of mounting is not reliable because its stiffness and rigidity will dwindle due to aging and will result in the formation of cracks and flaws at the mounting surface. A uniform mounting along with a good water sealing is achieved by pressing the diaphragm between two rubber O-rings.

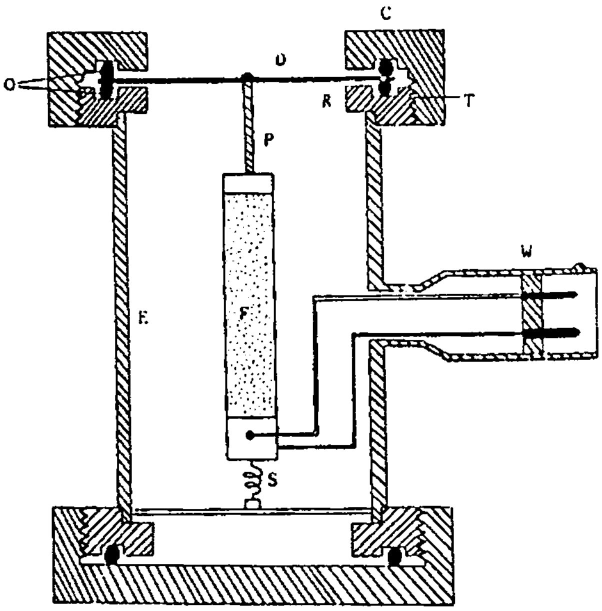


FIG. 1. Cross-sectional view of the modified (3,1) drive hydrophone. C: Perspex cap, D: phosphor bronze diaphragm, O: rubber O-rings, R: Perspex annular ring, T: threadings, P: driver pin, W: watertight connector, E: watertight enclosure, S: spring-loaded screw, F: piezopolymer film.

Figure 1 shows the cross-sectional view of the modified design. It basically consists of an enclosure over which a threaded Perspex annular ring is attached. The width of the Perspex ring is chosen to be approximately 1 cm, and a groove is provided at the top of this for the proper seating of an O-ring. A cap of Perspex with its inner side threaded and having an opening of approximately 5 cm at its center to expose the diaphragm to the external pressure is used to make the head assembly watertight. A groove is also provided at the bottom of this cap for the seating of second O-ring. The diaphragm is placed over the O-ring loaded Perspex ring and is tightened with the second O-ring on the threaded cap. One end of the driver pin is fixed to the center of the diaphragm and to the other end the polarized polyvinylidene fluoride (PVDF) film, as described in Ref. 5. The film is properly stretched, and the output is taken across the film through the terminal electrodes.

To ascertain the level of reproducibility that can be achieved with the refined design, and to investigate the effect of the diaphragm dimensions on the resonance frequency, three different sets of hydrophones with three similar pieces in each set were constructed. Table I shows their film, diaphragm, and O-ring dimensions in detail. Of the A, B, and C series hydrophones, in A and B the diaphragm dimensions are kept the same while the length of the film is varied, whereas in A and C the film lengths are same while the diaphragm dimensions are varied. To minimize the cable loss, a high input impedance MOSFET buffer amplifier is also connected very near to the hydrophone.

II. MEASUREMENTS AND RESULTS

The performance of these hydrophones was evaluated in water. The experimental hydrophone and a standard hydrophone were immersed to a depth of about 10 m in water and a low-frequency transmitter was kept about 10 m away from them at the same depth. The frequency response of the experimental transducer was studied using a comparison method,[6] by varying the frequency and comparing the outputs of both the standard and experimental hydrophones. Figure 2(a)–(c) depicts the frequency response for the A, B, and C series hydrophones.

All the three of A series behaved similarly in the region below resonance and had slight variations in their sensitivities thereafter, whereas in B series all but one responded similarly. The difference in its response can be explained as due to some structural inhomogeneities. It may be noted that for the C series there is no clear resonance, and also all the three behaved almost similarly. The reduction in sensitivity of the C series may be due to reduced exposed area of the diaphragm. However, the operating frequency range of the C series has been found to be enhanced.

III. ANALYSIS

For computing the resonance frequency of the design described, it is assumed that the compliance of the diaphragm is small compared to that of the other vibrating components in the model, so that the resonance frequency of the hydrophone is solely determined by the vibrational modes of the diaphragm. As the diaphragm is fixed over the enclosure with the edges clamped, and the driver pin attached at the center of the diaphragm, the whole assembly can be considered to be a circular plate with clamped edges and a point mass loaded at the center.

The frequency of vibration for different modes of a circular plate with free boundary was solved by G. R. Kirchhoff using Poisson–Kirchhoff theory and for the clamped edges by Rayleigh[7] and Timoshenko[8] using an energy method. The exact solution for the problem of vibration of a circular plate involves the use of Bessel functions. The Ritz method can be

TABLE I. Film, diaphragm and O-ring dimensions of the hydrophones.

Transducer type	Dimensions Film length×width×thickness	 Diaphragm diameter×thickness	 O-rings diameter×thickness
A series	4.5 cm×1 cm×28 μm	6.0 cm×1.2 mm	6.0 cm×4 mm
B series	6.0 cm×1 cm×28 μm	6.0 cm×1.2 mm	6.0 cm×4 mm
C series	4.5 cm×1 cm×28 μm	3.0 cm×1.2 mm	3.0 cm×3 mm

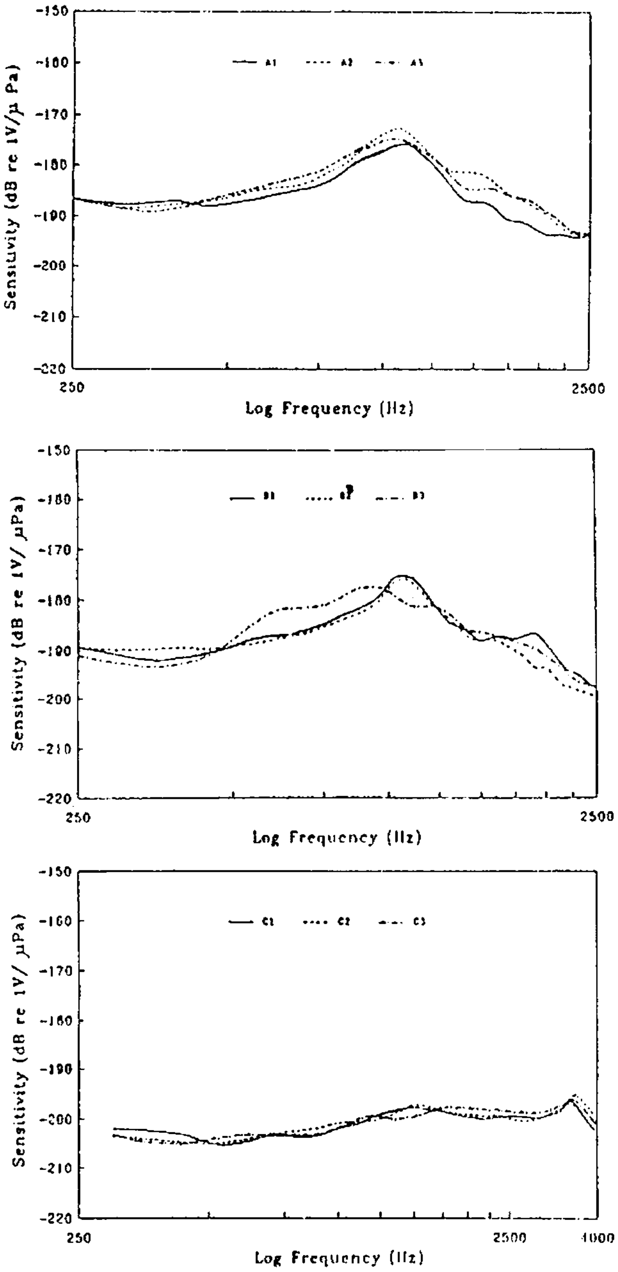


FIG. 2. (a) Frequency response of the (a) A series, (b) B series, and (c) C series hydrophones in water.

adopted for computing the fundamental mode of vibrations of plates having clamped or free edges, with sufficient accuracy.

In the case of the circular plate with edges clamped, the deflections are assumed to be symmetric about the center of the plate, and it deforms only through the flexural deformations, which are small in comparison with the thickness of the plate. The deflections parallel to the surface of the plate are neglected.

The angular frequency of vibration p, of the plate of radius a, and thickness h can be shown to be[9]

$$p=\frac{\lambda_{ij}^2}{a^2}\sqrt{\frac{D}{\rho h}}, \tag{1}$$

TABLE II. Mass of the plate, the center mass, and corresponding values for λ^2 for a circular plate vibrating in the fundamental mode, with edges clamped and point mass at the center.

Transducer type	Plate mass	Center mass	λ^2
A series	30 g	3.0 g	8.1
B series	30 g	3.0 g	8.1
C series	7.5 g	2.6 g	5.4

where λ_{ij} is a dimensionless parameter, which is a function of the mode indices (i,j), $D=Eh^3/12(1-\nu^2)$ is the flexural rigidity of the plate, E its Youngs modulus, ρ the density, and ν the Poissons ratio.

For the fundamental mode of vibration, $i=0$ and $j=0$. Hence the natural frequency of the circular plate with clamped edges is

$$f=\frac{\lambda^2}{2\pi a^2}\sqrt{\frac{D}{\rho h}}. \tag{2}$$

IV. COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL RESULTS

The proposed (3,1) drive transducer assembly can be assumed to be a vibrational system having a centrally loaded circular plate with clamped edges. In the case of a plate loaded at the center, the center mass will also contribute to the fundamental frequency, and the extent of influence can be taken into account by considering corresponding values of λ^2,[10] knowing the ratio of the sum of the masses of the driver pin and the film to the mass of the diaphragm. Table II describes the mass of the diaphragm, the center, mass and the corresponding values of λ^2 for all the three series of the experimental transducers.

When the hydrophone is immersed in water, the water surrounding it will act as a load and hence there will be considerable variation in the fundamental resonance frequency of the hydrophone compared to that in air. By knowing the frequency in air (f_{air}), that in water (f_{water}) can be computed using[9]

$$\frac{f_{\text{water}}}{f_{\text{air}}}=\frac{1}{(1+A_p/m_p)^{1/2}}, \tag{3}$$

where m_p is the mass of the plate and A_p the plate added mass, which is a function of the plate geometry, boundary conditions, and mode number. The above equation can be simplified as[11]

$$f_{\text{water}}=\frac{f_{\text{air}}}{[1+0.6689(\rho_w a/\rho h)]^{1/2}}, \tag{4}$$

where ρ_w is the density of water.

Using the following values for the physical constants of phosphor bronze in Eq. (4), the resonance frequency in water for all the three series of hydrophones are determined by taking the mass of the plate along with that of the driver pin and film assembly, which is acting as the center mass:

$E=11\times10^{10}$ N/m^2,

TABLE III. Comparative study of the experimental and theoretical resonance frequencies.

Transducer type	Resonance frequency (kHz)	
	Experimental	Theoretical
A series	1.00	1.11
B series	1.00	1.11
C series	3.50	3.614

$$\rho = 8.85 \times 10^3 \ \text{kg/m}^3,$$

$$\nu = 0.38.$$

Table III is a collation of the experimental and theoretical results.

V. CONCLUSIONS

The hydrophones described above exhibit better levels of reproducibility and sensitivity, which enhances the adaptability of this design. Ease and simplicity are some of the prime features offered by this model, particularly for the low-frequency transducer applications. The dimensions of the film have little impact on the resonance frequency as can be inferred by comparing the responses of the A and B series. As can be seen from the response of the C series, the sensitivity of the (3,1) drive design depends on the effective exposed area of the diaphragm.

The resonance frequency of hydrophone is determined theoretically and compared with the experimental results. In order to check its validity, this was extended to diaphragms of 10-cm diameter and also for hydrophones having diaphragms of a different materials like stainless steel, aluminum, etc. It is also evident from this design that along with the mass of the diaphragm and central point mass, which is constituted by the driver pin and film, another probable component that may influence the resonance frequency is the stretching of the film, which may restrict the flexing of the diaphragm. In order to study its influence, the film was fully released and stretched in steps of smaller intervals. For each interval of stretching the resonance frequency is noted, and no marked difference is observed. Hence it can also be inferred that the compliance of the diaphragm is small compared to those of PVDF film and the tensioning spring.

ACKNOWLEDGMENTS

The authors acknowledge the financial assistance from the Council of Scientific and Industrial Research, New Delhi and the Department of Electronics (Govt. of India).

[1] T. D. Sullivan and J. M. Powers, "Piezoelectric polymer flexure disk hydrophones," J. Acoust. Soc. Am. 63, 1396 (1978).
[2] M. A. Marcus, "Performance characteristics of piezoelectric polymer flexure mode devices," Ferroelectrics 57, 203 (1984).
[3] R. Lerch, "Electroacoustic transducers using piezoelectric polyvinylidene fluoride films," J. Acoust. Soc. Am. 66, 952 (1979).
[4] Kynar Piezofilm Manual, Pennwalt Corporation, ●●●, ●● (1983), p. 36.
[5] J. J. Bhat, P. P. Thomson, and P. R. S. Pillai, "Development of (3,1) drive low frequency piezofilm hydrophones with improved sensitivity," J. Acoust. Soc. Am. 94, 3053–3056 (1993).
[6] Bruel & Kajer, "Application notes on hydrophones—Their characteristics and applications."
[7] L. Rayleigh, *Theory of Sound* (Dover, New York, 1945), Vol. I, p. 359.
[8] S. Timoshenko, D. H. Young, and W. Weaver, Jr., *Vibration Problems in Engineering*, 4th ed. (Wiley, 1974), p. 500.
[9] R. D. Blevins, *Formulas for Natural Frequency and Mode Shape* (Van Nostrand Reinhold, New York, 1979), p. 402.
[10] R. E. Roberson, "Vibrations of a clamped circular plate carrying a concentrated mass," J. Appl. Mech. 18, 349 (1951).
[11] H. Lamb, "On the vibrations of an elastic plate in contact with water," Proc. R. Soc. London 98, 205 (1921).