DESIGN CONSIDERATIONS OF SONAR PROJECTOR ARRAYS WITH IMPROVED PERFORMANCE

A Thesis submitted by

P. M. JOSEPH

in partial fulfilment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

under the

FACULTY OF TECHNOLOGY

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

MAY 1992

CERTIFICATE

This is to certify that the thesis entitled "Design Considerations of Sonar Projector Arrays with Improved Performance" is a bona fide record of the research work carried out by Mr. P.M.Joseph under my supervision in the Department of Electronics, Cochin University of Science and 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)
Reader, Dept. of Electronics
Cochin University of Science
and Technology

Cochin 682 022

May 25, 1992

DECLARATION

I hereby declare that this thesis entitled "Design Considerations of Sonar Projector Arrays with Improved Performance" is a bona fide record of the research work done by me under the supervision of Dr. P.R.Saseendran Pillai, in the Department of Electronics, Cochin University of Science and Technology, and that no part thereof has been presented for the award of any other degree.

Cochin 682 022

May 25, 1992

P.M. JOSEPH

ACKNOWLEDGEMENTS

Words are inadequate to express my profound sense of gratitude to my research guide Dr. P.R.Saseendran Pillai, Reader, Department of Electronics, Cochin University of Science and Technology (CUSAT), for his valuable guidance, inspiration and support. This thesis would not have been in the present form without his constant encouragement and supervision.

I am deeply indebted to Dr. K.G.Nair, Professor and Head, Department of Electronics, CUSAT, for the genuine interest he has shown in the progress of my research work.

I wish to place on record my sincere gratitude to Dr. C.S.Sridhar, Professor, Department of Electronics for his valuable suggestions and the enlightening discussions.

My sincere thanks are due to all the faculty members of the Department of Electronics, CUSAT, for the kind help rendered over me during the tenure of my research work.

I am indebted to all the research scholars of the Department of Electronics, CUSAT, and a special expression of gratitude is reserved to my colleagues Mr. J.Jagannath Bhatt, Mr. P.P.Thomson and Ms. R.Sumangala for their encouragement, suggestions and goodwill.

The scientific community of NPOL, Cochin, deserves a special thanks for their timely help and co-operation.

I wish to acknowledge Cochin University of Science and Technology, STEC-Kerala, MHRD and CSIR for the financial assistance provided in the form of fellowships during the course of my research work.

It is a great pleasure to me to acknowledge the help rendered by Mr. C.B.Muraleedharan, Department of Electronics, CUSAT and a few of my gifted friends for the neat drawings of the figures. Again I am obliged to all the technical and non-teaching staff of the Department of Electronics for their sincere co-operation.

This thesis is brought in this form by the timely help rendered to me by Mr. K.P. Sibiraj and M/s. Maptho Printers, Kalamassery. I take the liberty of expressing my sincere thanks to them.

P.M. JOSEPH

CONTENTS

CHAPTER 1

INTRODUCTION

Chapter 1

INTRODUCTION

1.1 ACOUSTIC RADIATION: A TOOL FOR UNDERWATER EXPLORATION

The potential of ocean as a source of natural resources is very great compared to that of land. Harnessing of these immense resources requires exploration of the ocean. The exploration and use of the ocean, whether for scientific, commercial, military or for other purposes, faces sensory and communication problems unlike those met in any other environment.

Short range communication is feasible using cables but is practically impossible for long range. Ocean is essentially impenetrable to visible light, infrared, radio and microwaves. Electromagnetic waves get highly attenuated in the ocean. Sea water, a good conductor of electricity dissipates the electrical energy into heat energy limiting the penetration [1]. Clear water has an optical visibility range of 30-60 M, but most ocean waters are turbid. Hence, it is necessary to resort to some other form of energy to transmit information.

Acoustic signals are the most suitable and probably the only feasible tool for underwater observations. Attenuation of acoustic signals in water is much less compared to electromagnetic waves, hence, propagates long distances. Propagation velocity of sound in water is 1500 m/sec, much greater than its value in air.

1.2 HISTORICAL SURVEY OF DEVELOPMENTS

The history of underwater acoustics can be traced back to 1490 when Leonardo da Vinci introduced the idea of listening to distant ships using an air filled tube between the sea and the listener's ear [2]. One of the earliest attempts on quantitative measurements of acoustic parameters was made in 1635 by a French philosopher Pierri Gassendi, who obtained the speed of sound as 1569 ft/sec. About the same time another French scientist Marin Mersenne measured the speed of sound to 10% better accuracy. In 1687, Sir Issac Newton observed that the propagation of sound in fluids is related to measurable quantities like density and elasticity. Laplace applied a correction to include specific heat ratio [3].

It was in 1827, an accurate measurement of the speed of sound was made by Danniel Colladon, a Swiss phycisist, and Charles Francois Sturn, a French mathematician. They used a light flash coupled with the sounding of an underwater bell at Lake Geneva and obtained a speed of 4707 ft/sec. for sound [1-4].

The discovery of piezo-electricity by Jacques and Pierre Curie, in 1880, is a significant event which contributed much to the development of underwater communication technology. In 1912, Fessenden developed the first high power underwater source, the Fessenden Oscillator. Operating in the range 500 to 1000 Hz, it was capable of acting as an underwater receiver as well as transmitter. In 1914, stimulated by the sinking of the Titanic in 1912, Fessenden used his device to demonstrate echo ranging on an iceberg at a range of 2 miles. Because of its simplicity and reliability, the Fessenden oscillator remained in use as a source of underwater sinusoidal signals until relatively modern times.

The noted French physicist Paul Langevin, after several years of work, demonstrated the detection of a submarine with an active system in 1917. He used radio transmitting equipment, operating at 38 KHz, to drive a piezo-electric transducer. The transducer was large enough to create a narrow beam of energy in water so that both range and bearing of the target could be determined [3].

During the time of the First World War, the echo ranging system was used for military purposes under the name ASDIC. From the Second World War onwards, ASDICs are being used for both military and non-military applications. Since ASDIC has certain degree of naval implications, it is now-a-days referred to as SONAR. Important military and non-military applications of underwater sound are listed in Appendix I [4-8].

Research in the field of underwater acoustics is reported to have achieved considerable progress during the last few decades.

1.3 BRIEF DESCRIPTION OF THE PRESENT WORK

Systems which employ underwater acoustic energy for observation or communication are called sonar systems. The active and passive sonars are the two types of systems used for the detection and localisation of targets in underwater. Active sonar involves the transmission of an acoustic signal which, when reflected from a target, provides the sonar receiver with a basis for the detection and estimation. Passive sonar bases its detection and estimation on sounds which emanate from the target itself--Machinery noise, flow noise, transmission from its own active sonar etc.

Electroacoustic transducers are used in sonar systems for the transmission and detection of acoustic energy. The transducer which is used for the transmission of acoustic energy is called projector and the one used for reception is called hydrophone. Since a single transducer is not sufficient enough for long range and directional transmission, a properly distributed array of transducers are to be used [9-11].

The need and requirement for spatial processing to generate the most favourable directivity patterns for transducer systems used in underwater applications have already been analysed by several investigators [12-21].

The desired directivity pattern can be either generated by the use of suitable focussing techniques or by an array of non-directional sensor elements, whose arrangements, spacing and the mode of excitation provide the required radiation pattern or by the combination of these.

While computing the directivity pattern, it is assumed that the source strength of the elements are unaffected by the acoustic pressure at each source. However, in closely packed arrays, the acoustic interaction effects experienced among the elements will modify the behaviour of individual elements and in turn will reduce the acoustic source level with respect to the maximum theoretical value as well as degrade the beam pattern. This effect should be reduced in systems that are intended to generate high acoustic power output and unperturbed beam patterns [2,22-31].

The work herein presented includes an approach for designing efficient and well behaved underwater transducer arrays, taking into account the acoustic interaction effect experienced among the closely packed multielement arrays.

Architectural modifications are proposed for reducing the interaction effect in arrays having different radiating apertures.

1.4 REVIEW OF THE PAST WORK

The acoustic interaction effect experienced among the closely packed projector elements of the array has been studied theoretically by several researchers over the last few decades. One among them, Carson [32] diagnosed the root cause of the interaction phenomena among the elements of multi-element arrays and suggested the following cure measures for minimising it by treating it in terms of mutual radiation impedance.

i) Increase the spacing between the elements. This will reduce the mutual radiation impedance.

ii) Make the elements of the array individually large enough so that their self radiation impedance exceeds the mutual radiation impedance.

iii) Use separate tuning inductor with each transducer.

iv) Use of feedback technique to force the piston velocity to match a prescribed reference velocity.

Rusby [33] has also studied this effect by investigating the behaviour of five projector elements arranged in a cruciform array. This study led to the conclusion that the erratic velocity distribution is due to the high mutual impedance values of projectors and this is varying from one element to the other, depending on its position in the array. As the value of mechanical impedance is approaching zero near resonance, excessive changes in total radiation impedance and mechanical displacement of projectors are occurring. Various remedies have been suggested to overcome this effect.

Sherman [34] studied the interaction problem in transducer arrays and suggested methods for analysing array behaviour based on a knowledge of the transducer characteristics and the mutual radiation impedance among the elements. Pritchard [35] developed series expressions for computing the mutual radiation impedance between circular pistons and arrived at some useful numerical results. Arase [36] addressed the problem of evaluating the mutual radiation impedance between rectangular and square pistons.

Stumpf and Lukman [37] experimentally measured the radiation resistance of a nickel magnetostrictive stack transducer in the presence of an identical in-phase transducer at an air-water surface. It is found that the magnitude of radiation resistance of the transducer is increasing with the driving force of the second transducer and this dependence is seen to be negligible beyond 2λ separations.

In another experimental work Mohammed Ezz-Er-Arab [38] proposed a simple method to estimate the mutual interaction of nearest neighbours in a compact planar array.

Stephanishen [39] developed a time domain approach for computing the time dependent head velocities of transducers within an array, resulting from a set of specified electrical inputs which may be non-sinusoidal. The approach is based on the use of Fourier transform techniques to solve the coupled-system time-dependent boundary value problem. This leads to a set of time domain equations that can be utilized for evaluating the transient response of an array of transducers with different characteristics. This time domain approach affords a clear physical understanding of the transient behaviour of the arrays, while also leading to a more basic understanding of array operation and limitations caused by its transient behaviour.

Additional references to other contributions in this area are indicated in the cited references [40-61].

1.5 SCHEME OF THE PRESENT WORK

There are several electrical and mechanical factors that limit the power output of transducers used for sonic and ultrasonic applications. Some of these limitations can be envisaged as due to effects that are primarily internal to the transducer and also external to it [62]. Typical internal limitations are caused by,

a) non-linearity in the electrical, piezo-electric and elastic properties of the components which arise due to large amplitudes

b) mechanical breakdown due to large stresses or fatigue

c) electrical breakdown due to excessive electrical fields

d) thermal heating effects which alter the characteristics of the material

Limitations external to the transducer are caused by,

a) impedance mismatching due to such effects as cavitation

b) non-linearities in the medium

c) radiation impedance anomalies, such as acoustic interaction effect.

Of these, the main factors that limit the high power output of transducer array are cavitation and acoustic interaction effects. The reduction in acoustic power output and the degradation in beam pattern due to the acoustic interaction effect are discussed in this work and a novel method for reducing this effect in sonar projector arrays has also been suggested.

Due to the low emission level and power output, single low frequency projectors are generally insufficient and this necessitates the use of closely packed multielement arrays. These closely packed multielement arrays seriously suffers from the so-called 'acoustic interaction effect'. This effect should be minimised in systems that are intended to achieve higher transmission range.

Chapter 2 addresses some of the procedures to be adopted for reducing the acoustic interaction effect in linear arrays. This procedure suggests an architectural modification of the arrays with new inter-element spacings, which minimises the interaction force. A simple method for arriving at the optimum spacing for restructuring the array is presented in this chapter. Linear arrays are evolved with these spacings and the performance of these arrays are evaluated. In practical sonars, as the same transducer system is used for both projector and hydrophone applications, the impact of the proposed structural modifications on the array gain, which is the most notable and significant parameter of a hydrophone array, has to be taken into account. The results and outcomes of the attempt made in reducing the mutual interaction force further by incorporating the non-uniform array concept is also discussed in this chapter. Total enumeration method is used for determining the optimum set of spacings for the non-uniform array and the performance of this array is compared with that of conventional $\lambda/2$ spaced and restructured arrays. The total enumeration method being computationally a tough process, for alleviating the computational burden, the gaussian distributed element spacing is used for determining the optimum set of spacings for the non-uniform array.

The forementioned procedure for reducing the interaction effect has been extended to the case of planar arrays. The optimum element configuration for various planar arrays with square and circular radiating apertures are presented in chapter 3. The performance of the non-uniform planar arrays formulated using total enumeration technique and gaussian distributed spacings are compared with that of conventional $\lambda/2$ spaced and restructured arrays for both transmitting and receiving applications.

A programmable switching system can be used for generating various arrays from an optimally formulated planar array and the design and development of this system is presented in chapter 4. This system is designed around the 8085 microprocessor. The software for generating different subarray formats from a parent array has also been developed.

Computer simulation study has been made for predicting the optimum element configuration of the array, based on the requirements of the user, taking into account of the acoustic interaction. A software package has been developed for designing the optimum array and is described in chapter 5.

Finally, the highlights and a brief survey of the results presented in this work towards the scope for future developments are discussed in chapter 6.

1.6 DECIBELS

The most widely used reference unit in underwater acoustic measurements is the decibel system. There are several reasons for choosing the decibel for acoustic measurements. One of the reasons is that it helps in handling conveniently extremely wide range of values without the use of exponents. Secondly, in underwater acoustic measurements and many other areas in communication engineering, one is interested in signal ratios, rather than the absolute values. Decibel system gives a convenient measure of ratios [63].

Decibel is defined as,

$$\text{Sound level in dB} = 10 \log_{10} I_r$$

$$= 20 \log_{10} P_r$$

where, $I_r = \frac{I}{I_o}$, I being the acoustic intensity and I_o the reference acoustic intensity and

$P_r = \frac{P}{P_o}$, P being the acoustic pressure and P_o the reference acoustic pressure.

The conversion chart shown in Figure 1.1 shows how exponential pressure levels are conveniently handled with the decibel system of units.

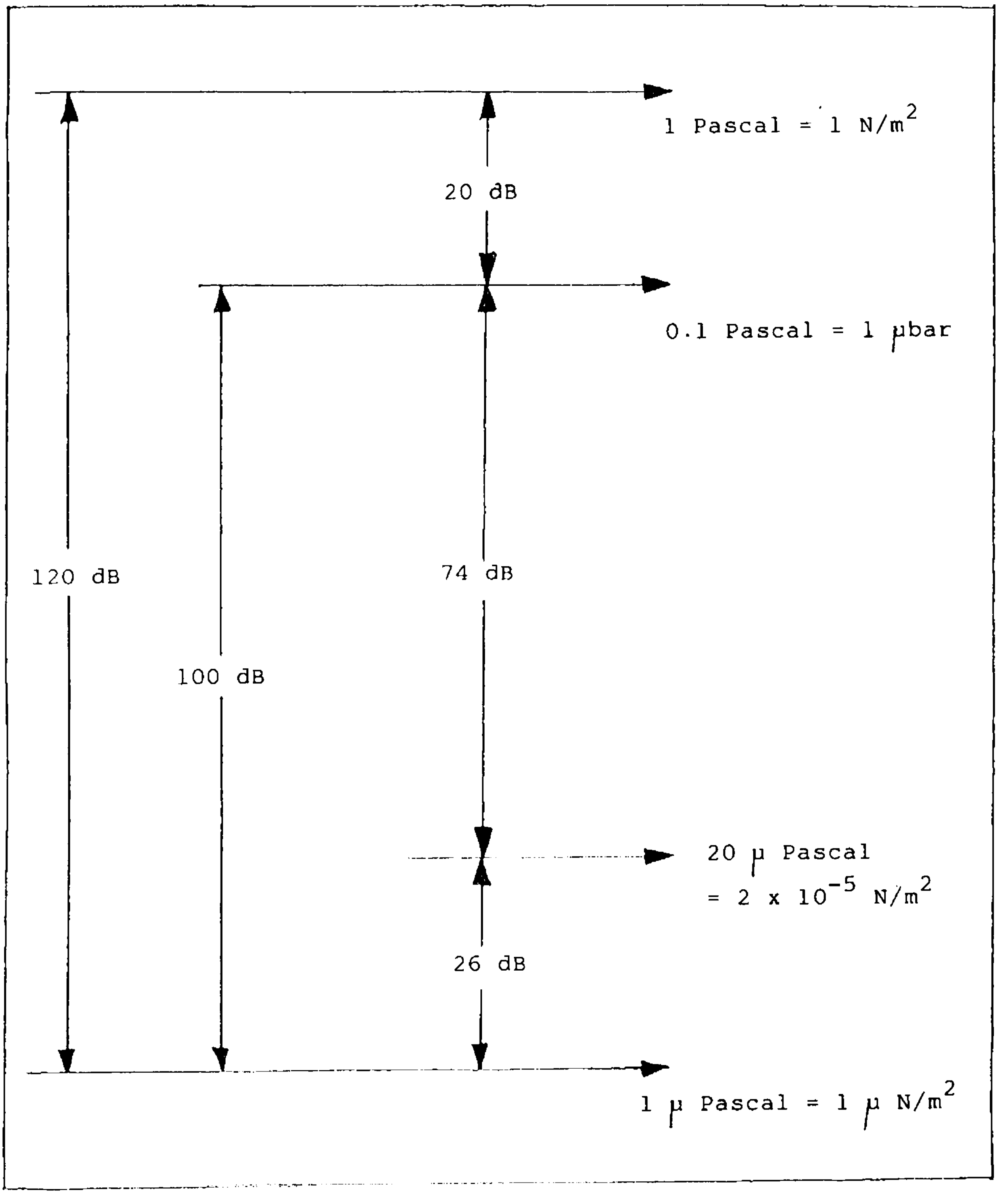

Fig.1.1: Reference pressure levels

CHAPTER 2

OPTIMUM ELEMENT CONFIGURATION FOR HIGH EFFICIENT LINEAR PROJECTOR ARRAYS

Chapter 2

OPTIMUM ELEMENT CONFIGURATION FOR HIGH EFFICIENT LINEAR PROJECTOR ARRAYS

2.1 INTRODUCTION

An electroacoustic transducer is a device ordinarily used for transmitting and receiving acoustic energy. It has a certain form of energy distribution with respect to its orientation. A completely non-directional or omnidirectional radiator radiates uniformly in all directions and is termed as an isotropic radiator. One of the major requirements of an efficient transmitting system is its directionality for the accurate determination of bearing of the targets.

With a single transducer element, it is not possible to obtain highly directional pencil beams. One convenient method of overcoming this difficulty is to form transducer arrays composed of several similar individual elements. The directivity of such an array depends on the spatial distribution, strength and relative phases of the sources. By a suitable choice of excitation in amplitude and phase of individual radiators and of their spatial distribution, the properties of the entire system, which are essentially better than those of the separate elements will be obtained. This fact depends upon the displacement in time and space of the fields originating from the single elements. Normally most of the transducer arrays are fabricated by keeping a uniform spacing between the elements with all the elements in phase.

Although maximum gain is obtained with uniform distribution, the resulting beam pattern exhibits higher sidelobe levels. High sidelobe levels introduce ambiguity in the bearing of the target to be detected. In a directional transducer system with narrow beamwidth, if a strong sidelobe is present, it can detect objects located in directions other than the main beam as well. In addition to this, a strong sidelobe can pick up reverberation from directions other than the direction of the main beam, thereby causing unnecessary interference. Hence, narrow beamwidth and low sidelobe levels are two of the important requirements of a directional transducer system. Reduction of the sidelobe level is invariably accompanied by an increase in the width of the main beam. Conversely, increase in the minor lobe level results from a decrease in the width of the main lobe. Hence, to achieve a narrow beam and at the same time to suppress the sidelobes below a desired level are conflicting requirements, if the size of the transducer array is already fixed. If a transducer array of limited size with narrow beam and suppressed sidelobes together with reasonably good sensitivity is to be designed, a compromise between the beamwidth and the level of the sidelobe seems inevitable [21-64].

The shape of the directional pattern of an array can be controlled, to some extent, making use of a method referred to as shading. Amplitude and phase shadings are the two common forms of shading. Usually, in amplitude shading the centre of the array has maximum response and ends have minimum response, thereby varying the sensitivity from a high value at the centre to a lower value at the edges. Binomial shading produces a wide beam with reduced sidelobe level, while edge distribution produces a narrow beam with sidelobes of amplitudes closer to that of the main beam. Eventhough binomial shading produces reduced sidelobe levels and edge distribution produces narrow beamwidth, a combination of these two has been found to yield unfavourable array performance. Hence, Dolph suggested an amplitude distribution based on the properties of Chebyshev polynomials known as Dolph-Chebyshev distribution. This shading results in a narrow mainlobe with sidelobes at a specified level. Heavy shading should not be used under conditions of low signal to noise ratios, where the array gain is an important consideration.

2.2 LIMITATIONS ON SONAR POWER

In order to achieve maximum range, it is desirable to generate large amount of acoustic power. This is necessary atleast until the just detectable echo occurs in a background of reverberation rather than noise. But when the acoustic power is increased, certain high power limitations are encountered like cavitation effect and interaction effect [2]. This chapter presents an account of the method to reduce the interaction effect in linear projector arrays.

2.3 INTERACTION EFFECT

Usually, when a sonar projector array is designed, a specific velocity distribution for the radiating faces of the elements is assumed. For example, in a uniform velocity distribution environment, all elements of the array have velocities identical both in phase and magnitude. However, in practical arrays, the velocity of the elements are found to be randomly varying, both in magnitude and phase due to the acoustic interaction effects experienced among its elements.

This effect is much pronounced in arrays working in a frequency region near mechanical resonance. As the mechanical impedance is approaching zero near resonance, the mutual radiation impedance becomes the dominant factor in controlling the velocity of the elements in the array. This will produce excessive changes in the total radiation impedance and mechanical displacement of the projector elements in the array, as the mutual radiation impedance of each and every element is not same, but vary randomly depending on its position in the array. Thus, the assumption of uniform velocity distribution among the elements of the array become quite irrelavent and in turn will lead to large differences between the design predictions and the actual performance of the arrays.

The importance of this interaction can be appreciated in a case, where the radiation resistance presented to a particular element becomes negative. In this case, the resultant acoustic pressure at the face of the element due to the sound radiated by all elements of the array is larger than and of opposite phase from the sound pressure that the element itself would radiate. Such elements will be absorbing power rather than radiating it, resulting in the reduction of total acoustic power output of the array and may cause mechanical failure of the element itself. Thus, the practical realisation of conventional design goals become increasingly difficult, even at low drive levels, due to this interaction effect. This effect should be reduced in systems that need longer transmission range and unperturbed beam patterns.

This problem has already been analysed by several authors by treating it in terms of mutual radiation impedance and have suggested cure measures for minimising it [32-61]. From the economical and practical point of view, these are not fully viable. In the approach presented in this chapter, the problem is analysed in a slightly different manner, though very close to the analysis already attempted, and it yields results that are entirely different.

Since the interaction mainly depends on the array geometry, the effective interaction force acting on a uniform linear array is computed as a function of element separation. The optimum spacing at which this force becomes minimum is determined from this computation. Arrays with improved performance can be evolved by restructuring the arrays with this optimum spacing as the interelement spacing.

2.3.1 Interaction Force

As mentioned already, the acoustic interaction effects among the radiators in an array occurs, when the acoustic pressure fields produced by one transducer exerts a force on the other elements [34]. This will produce excessive changes in the total radiation impedance and mechanical displacement of projector elements in the array. This interaction exists among all the elements of the array and the assumption of independently behaving elements become less accurate in the array treatment. This interaction can be analysed in terms of mutual radiation impedance and velocity.

For an array of N radiators the force on one radiator, say m^{th}, due to the radiation from each of the radiators can be expressed as [35],

$$F_m = \sum_{n=1}^{N} Z_{mn} V_n \qquad (2.1)$$

where Z_{mn} is the mutual radiation impedance between m^{th} and n^{th} radiator and

V_n is the velocity of the n^{th} radiator.

Taking into account the non-uniform velocity distribution among the elements of the array, the equation takes the form,

$$F_m = \sum_{n=1}^{N} Z_{mn} V_n e^{j\delta mn} \qquad (2.2)$$

where δ_{mn} is the phase difference between the velocity distribution of m^{th} and n^{th} elements. The magnitude of the interaction force can be expressed in terms of simple trignometric functions using the series solution developed for the mutual radiation impedance between two identical circular disks [35] and is given by,

$$F_m = \left\{ \left[\sum_{n=1}^{N} \rho c \frac{\pi a^2}{2} (ka)^2 \frac{\sin(k\, d_{mn})}{k\, d_{mn}} V_n\, e^{j\delta mn} \right]^2 + \left[\sum_{n=1}^{N} \rho c \frac{\pi a^2}{2} (ka)^2 \frac{\cos(k\, d_{mn})}{k\, d_{mn}} V_n\, e^{j\delta mn} \right]^2 \right\}^{\frac{1}{2}} \quad (2.3)$$

where d_{mn} = the interelement spacing between m^{th} and n^{th} element,

ρ = density of the medium,

c = velocity of sound in the medium,

a = radius of the element and

k = $2\pi/\lambda$, the wave vector.

Hence, the force experienced on the array system which is the sum of the forces acting on each and every element can be shown to be,

$$F = \left\{ \left[\sum_{m=1}^{N} \sum_{n=1}^{N} \rho c \pi \frac{a^2 (ka)^2}{2} \frac{\sin(k\, d_{mn})}{k\, d_{mn}} V_n\, e^{j \delta mn} \right]^2 + \left[\sum_{m=1}^{N} \sum_{n=1}^{N} \rho c \pi \frac{a^2 (ka)^2}{2} \frac{\cos(k\, d_{mn})}{k\, d_{mn}} V_n\, e^{j \delta mn} \right]^2 \right\}^{\frac{1}{2}} \tag{2.4}$$

2.4 BEAM PATTERN

The main function of an array is to confine acoustic energy into desired directions and what is more important is to suppress the radiations in the unwanted directions. The beam pattern of an array is the graphical representation of spatial distribution of acoustic energy around the radiator [70-75].

The broadside beam pattern of an N-element uniform linear array of point sources can be computed using equation [2],

$$B(\Theta) = \left[\frac{\sin(N \pi d \sin \Theta / \lambda)}{N \sin(\pi d \sin \Theta / \lambda)} \right]^2 \tag{2.5}$$

where Θ is the angle which the direction of the arrival of the signal makes with the array axis and

d is the spacing between the elements.

If a transducer array is reciprocal, its transmitting and receiving patterns are same, eventhough they have different physical meanings. The transmitting pattern is essentially a diagram of how much energy emanates from an array simultaneously in different directions. The receiving pattern is a measure of the average pressure acting on a transducer diaphragm as a function of the direction of an impinging plane wave.

2.5 ARRAY GAIN

Now-a-days, most of the modern sonar systems are using the same array for both transmission and reception purposes. Hence, whenever an architectural modification that optimises the transmitting characteristics of an array is made, the designer should see that the proposed modifications do not adversely affect the receiving performance of the system.

Interaction effects are most pronounced in a frequency of operation, which is close to the mechanical resonance of the transducers, where the total radiation impedance is comparable to the internal mechanical impedance. This problem is often observed in transmitting arrays, as they are usually operated near resonance [34]. When these modifications, that minimise the acoustic interaction effect are incorporated, the impact of such modifications on array gain, which is one of the most notable and significant parameters of a hydrophone array should be taken into account. Array gain is a measure of the signal to noise ratio and it is the ability of an array to distinguish various sources located in different spatial locations.

For a unidirectional signal in an isotropic noise field, the array gain is given by [2],

$$\text{Array gain} = \frac{\sum_m \sum_n (\rho_s)_{mn}}{\sum_m \sum_n (\rho_n)_{mn}} \qquad (2.6)$$

where ρ_s and ρ_n are the cross correlation coefficients of signal and noise respectively, which for a single frequency and zero time delay are given by,

$$\rho_s = \cos\left(\frac{2\pi d}{\lambda}\cos\beta\right)$$

$$\rho_n = \frac{\sin(2\pi d/\lambda)}{(2\pi d/\lambda)}$$

where d is the separation of the array elements and

β is the angle between the incident radiation and line joining the two elements.

2.6 DESIGN CONSIDERATIONS OF RESTRUCTURED ARRAYS

The effective interaction force acting on various uniform linear array formats have been computed, using equation (2.4), as a function of interelement spacing. The spatial variation of interaction force acting on a 4-element uniform linear array is shown in Figure 2.1. The array elements are assumed to be point sources of diameter 0.1 λ. The interelement spacing for the proposed array format is determined from this variation. The optimum inter-element spacing (d_{min}) is chosen to be the spacing, where the interaction force is minimum. Normally, if the element spacing exceeds λ, the beam pattern will be aggrevated by additional grating lobes moving into the

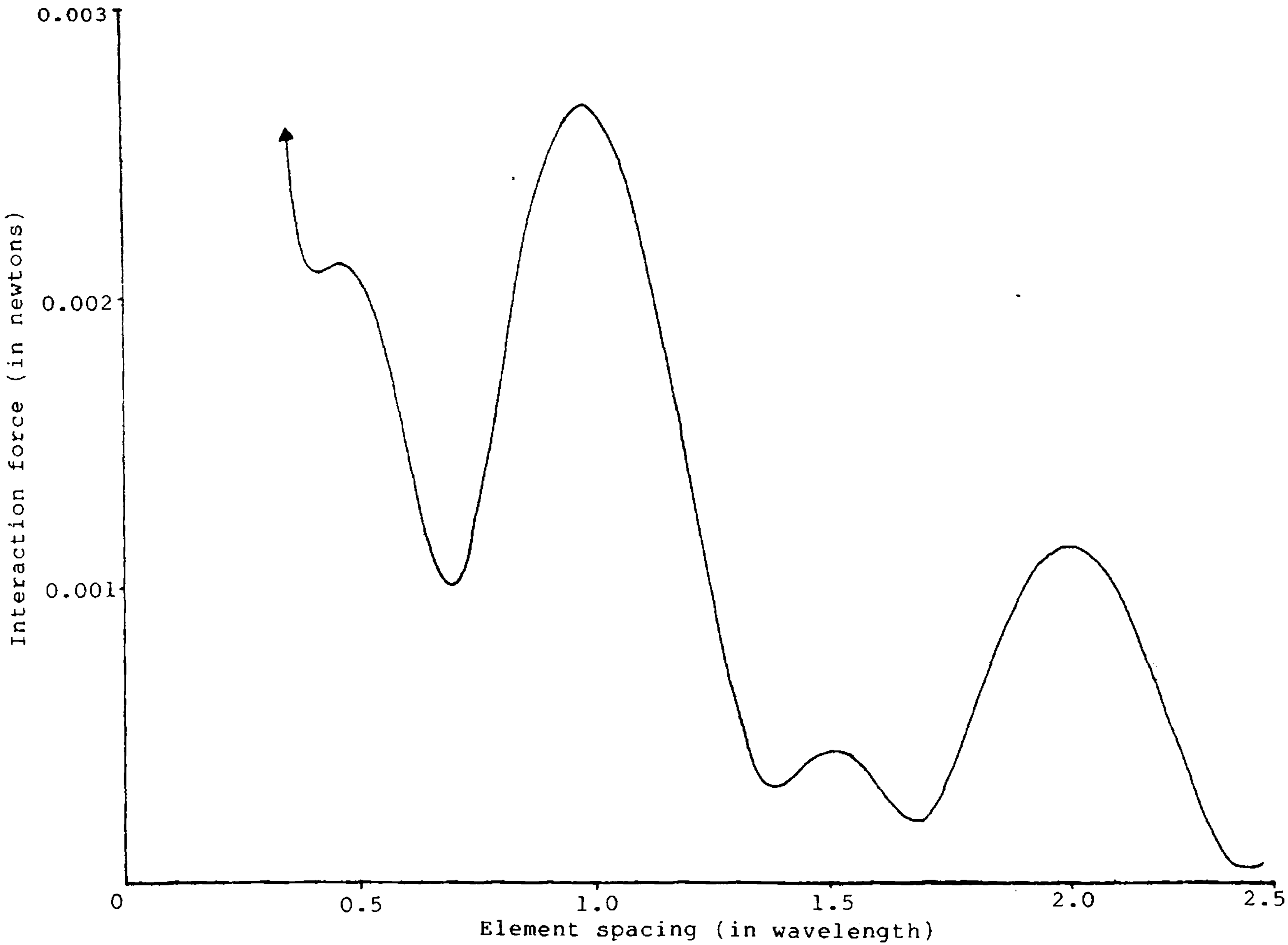

Fig.2.1: Spatial variation of interaction force for a 4-element uniform linear array

real pattern region. Thus, the spacing within λ, where the interaction force becomes minimum is taken as the optimum spacing for restructuring the array. It may be noted from Figure 2.1 that the recommended spacing (d_{min}) for the 4 element linear array is 0.643 λ and the interaction force is reduced by 60.26%, compared to that of conventional λ/2 spaced array.

One of the factors affecting the efficiency of an array is the change in the radiation resistance of the individual transducers caused by the interaction effect [37]. Since the power radiated by a transducer is proportional to the radiation resistance, this reduction in interaction force can be taken as a measure of the improvement in radiation efficiency.

A 10 element uniform linear array has also been formulated using this approach, whose spatial variation of interaction force is shown in Figure 2.2. The optimum spacing (d_{min}) for this array is 0.656 λ and the reduction in interaction force in this array is seen to be 40.88%.

The effect of the proposed structural modification on the beam characteristics for the λ /2

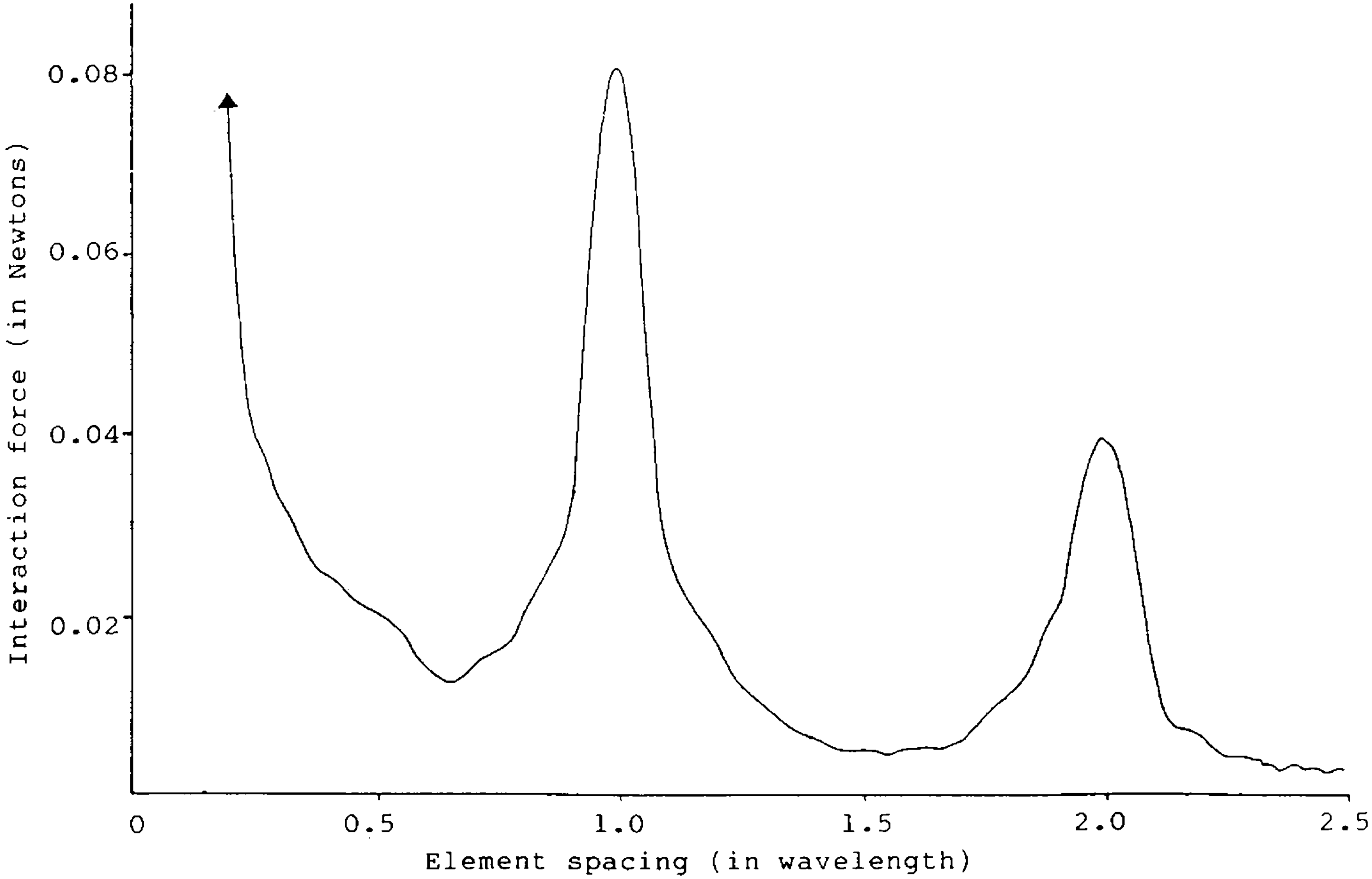

Fig.2.2: The spatial variation of interaction force acting on a 10 element uniform linear array

and restructured 4 and 10 element uniform linear arrays can be seen from Figures 2.3 and 2.4. The beam pattern of the restructured array is found to be largely unaffected, except for the occurrence of additional sidelobes in the visible region and narrowing of the main beam. An appreciable reduction in beamwidth and the occurrence of additional sidelobes are to be expected in the proposed array, as the array aperture is extended due to the slight increase in the interelement spacing [70-75].

The array gain of the restructured array is found to be improved, as clear from the spatial variation of array gain for a unidirectional signal in an isotropic noise shown in Figure 2.5 for different uniform linear array formats.

The features of the $\lambda/2$ spaced arrays are compared with those of the restructured arrays and the results are summarised in Table 2.1. It is to be noted from this table that, for certain array formats, the percentage reduction in interaction force is very high.

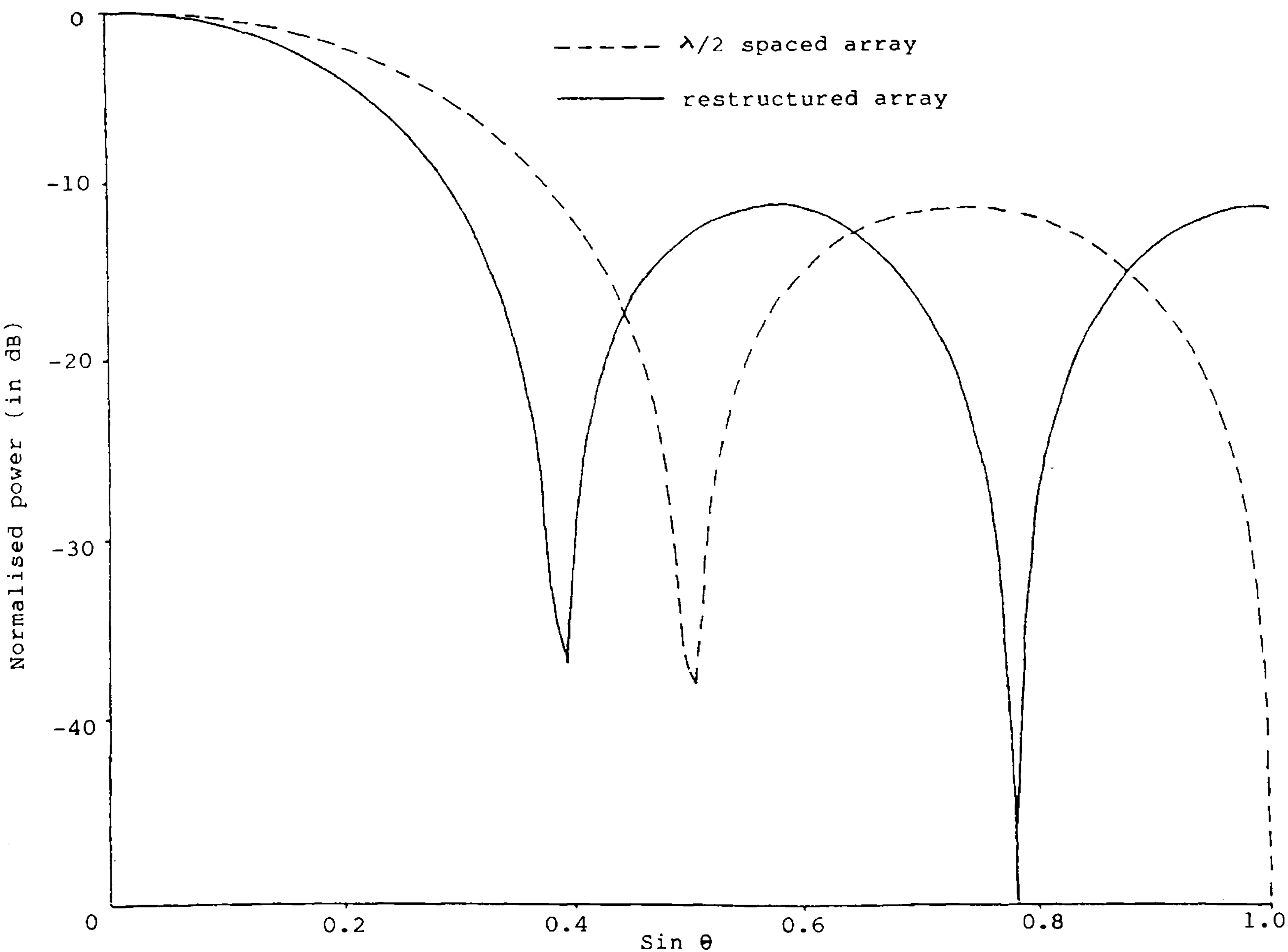

Fig.2.3: The broadside beam pattern of 4 element uniform linear array

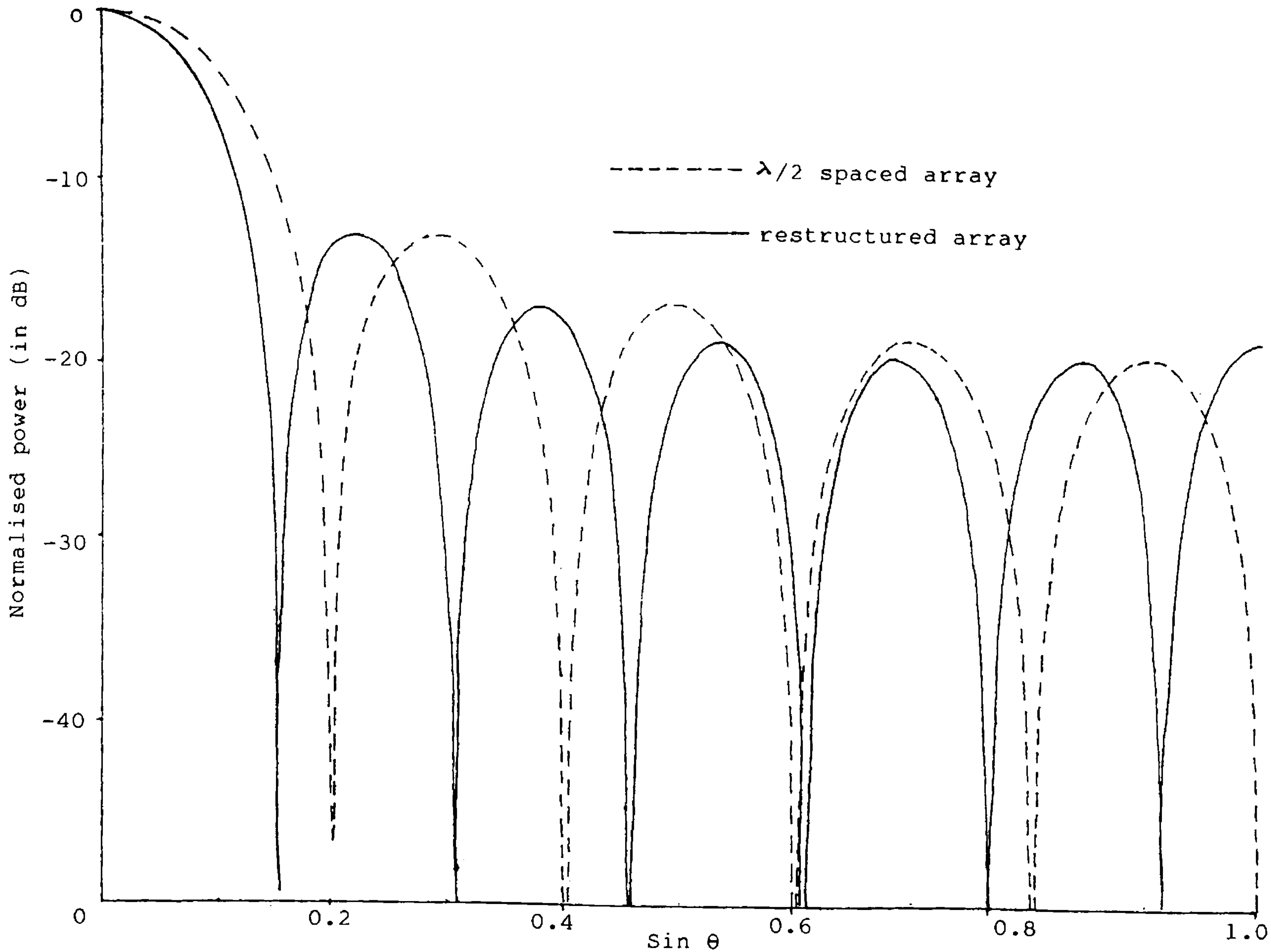

Fig.2.4: The broadside beam pattern of 10 element uniform linear array