DESIGN CONSIDERATIONS OF SONAR PROJECTOR ARRAYS WITH IMPROVED PERFORMANCE

A Thesis submitted by
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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.

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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.

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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.

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CHAPTER 1

INTRODUCTION

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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.

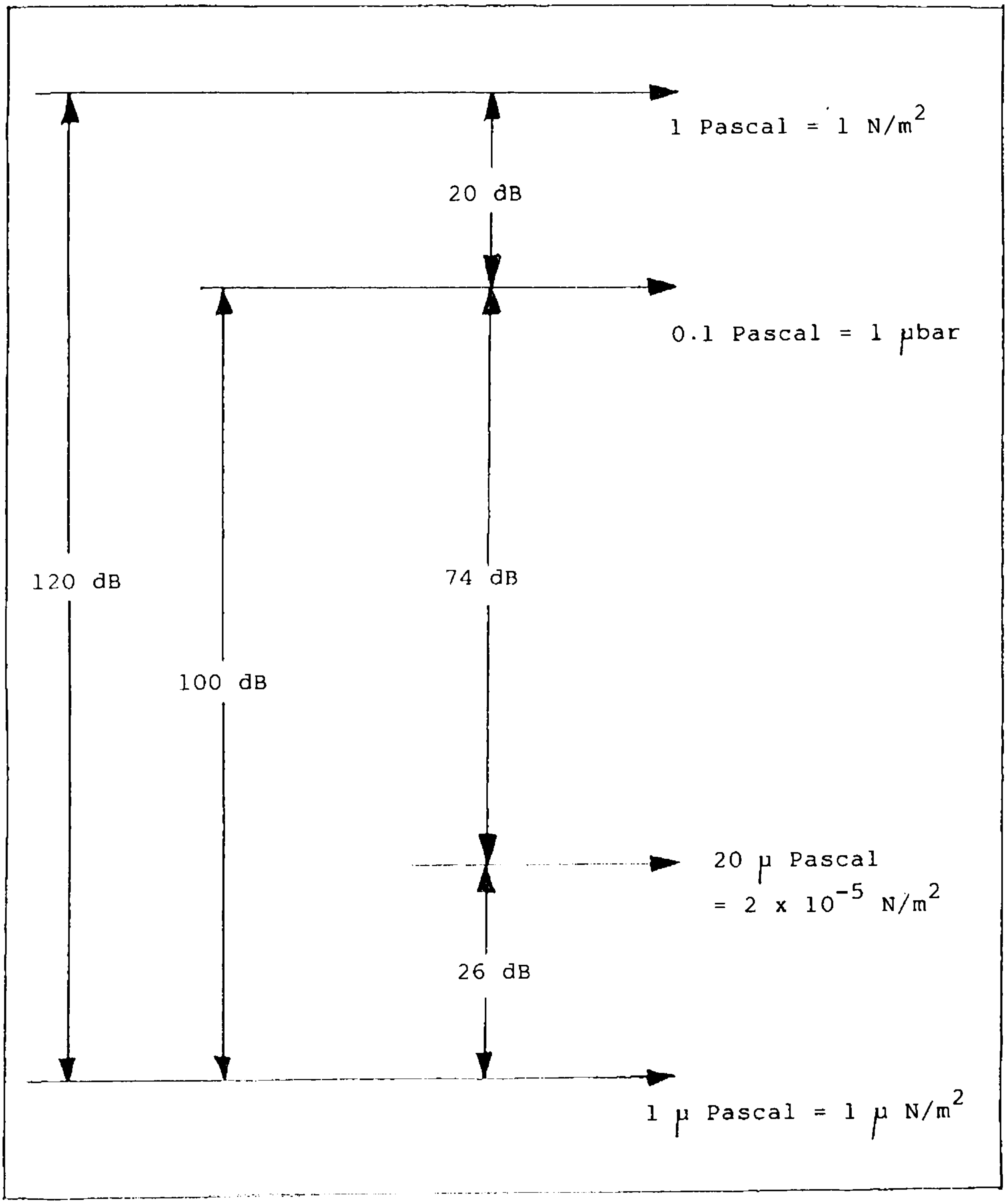


Fig.1.1: Reference pressure levels

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,

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

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,

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

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],

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

$$\frac{\sin N\pi\alpha\gamma}{N \sin \pi\alpha\gamma}$$

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 0.1λ. The interelement spacing for the proposed array format is determined from this variation. The optimum interelement 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

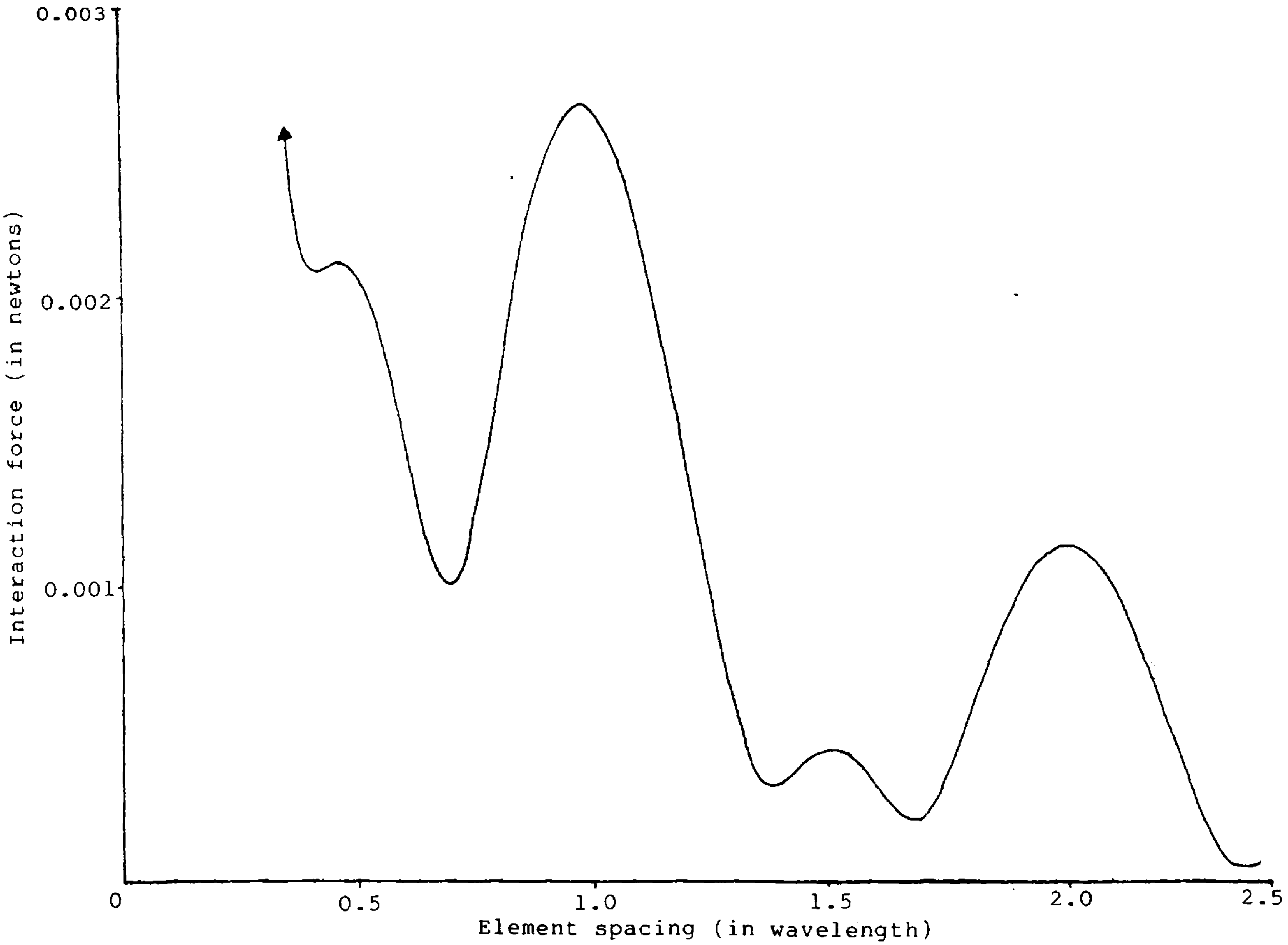


Fig.2.1: Spatial variation of interaction force for a 4-element uniform linear array

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 $\lambda/2$ 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 $\lambda/2$

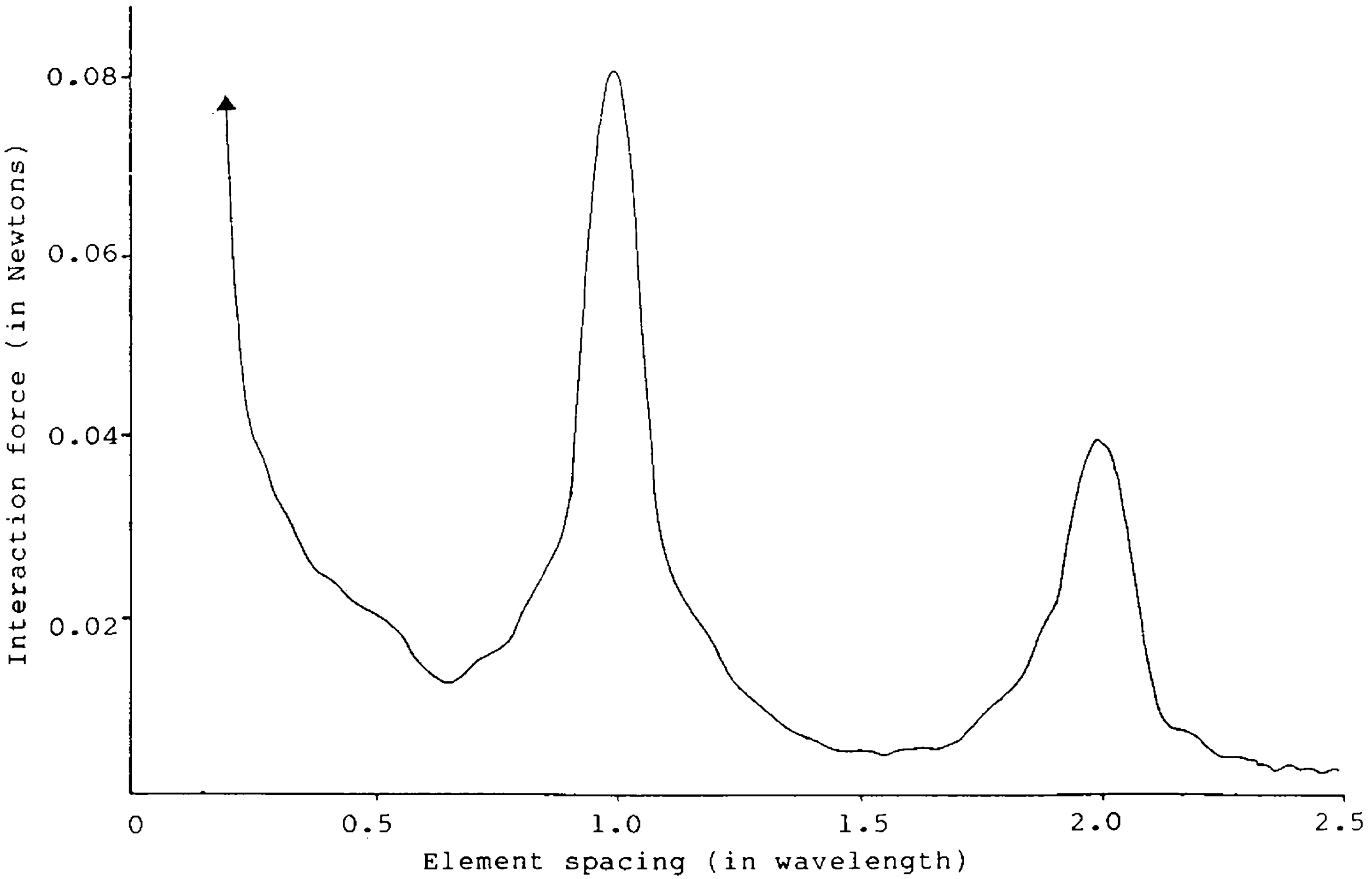


Fig.2.2: The spatial variation of interaction force acting on a 10 element uniform linear array

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.

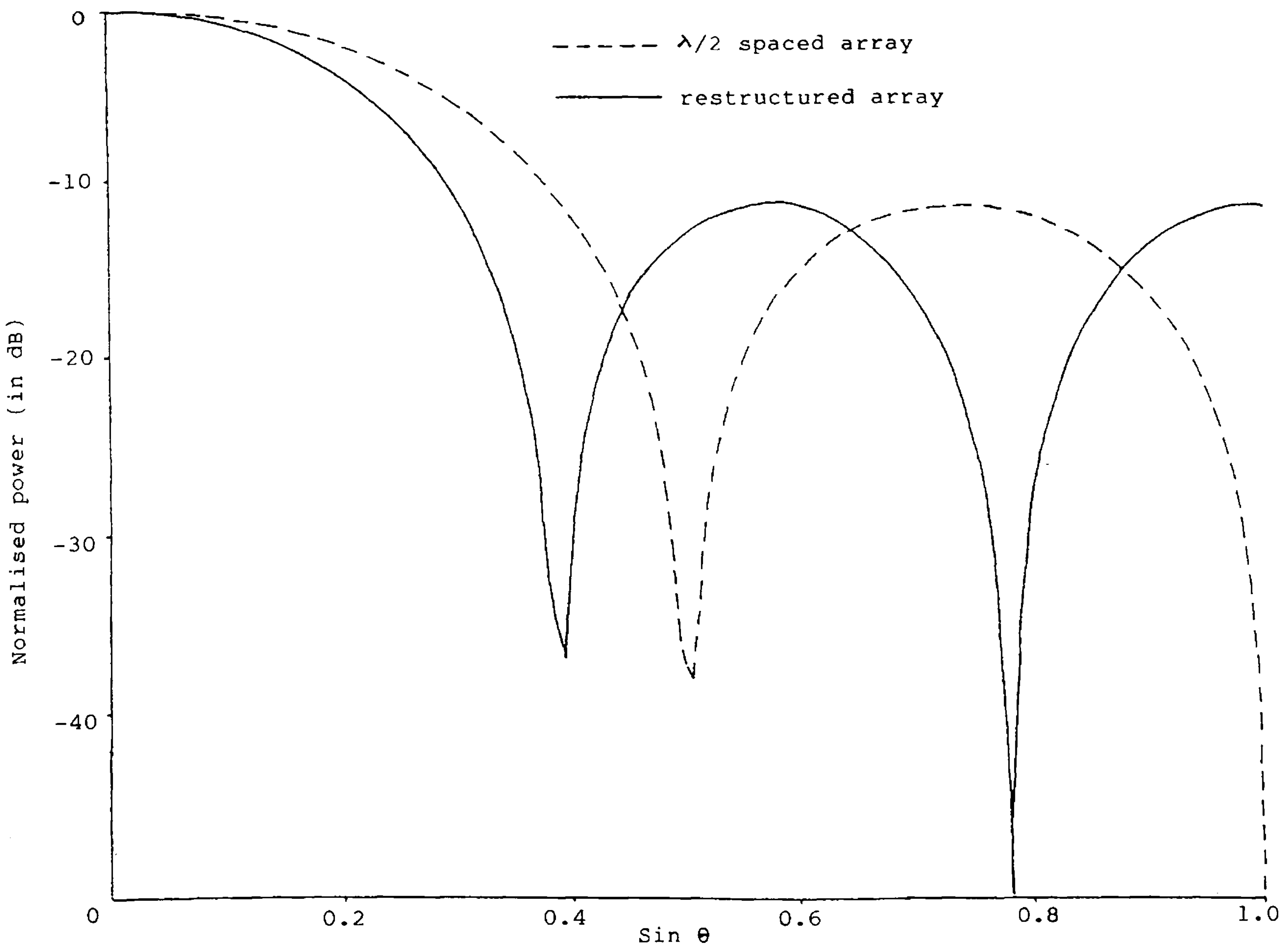


Fig.2.3: The broadside beam pattern of 4 element uniform linear array

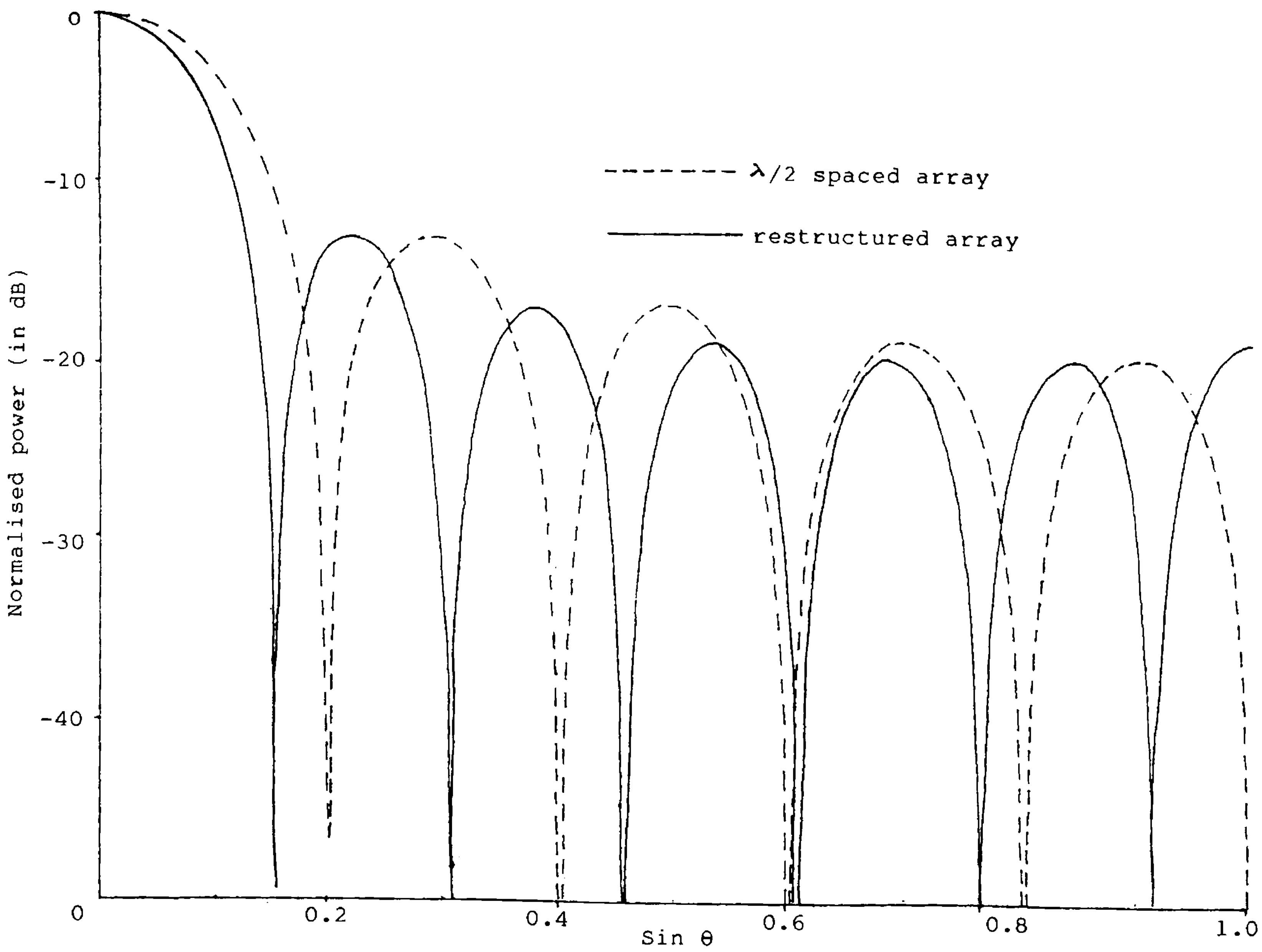


Fig.2.4: The broadside beam pattern of 10 element uniform linear array

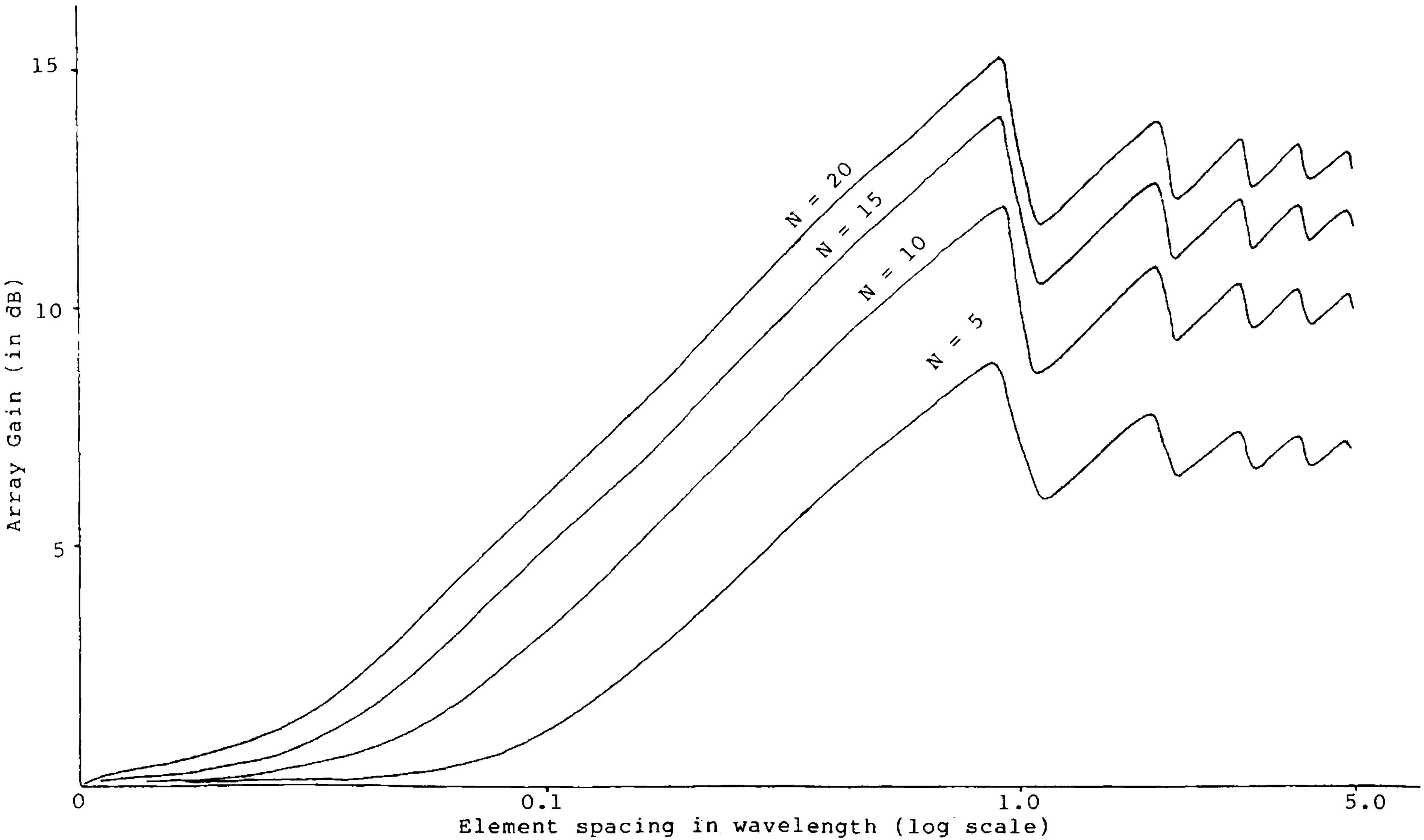


Fig.2.5: Spatial variation of array gain, for various uniform linear array formats

Table 2.1: The relevant parameters of various linear array formats at $\lambda/2$ and minimum force spacings

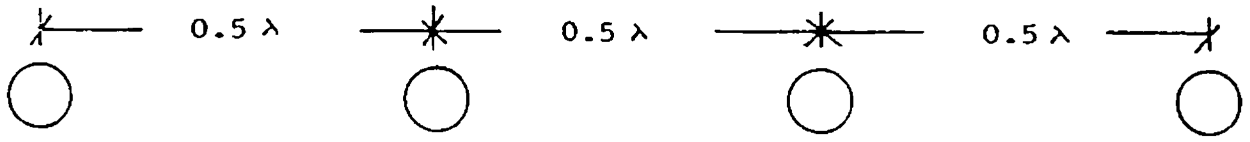
Number of elements in the linear array (N)	Spacing at which interaction force is minimum (d_{min}/λ)	% reduction in interaction force	Array Gain (in dB)	
			at $\lambda/2$ spacing	at d_{min}/λ spacing
4	0.643	60.26	6.02	6.925
5	0.707	21.18	6.99	8.275
6	0.595	43.48	7.78	8.450
10	0.656	40.88	10.00	11.100
15	0.637	26.52	11.76	12.770
20	0.627	33.95	13.01	13.970

Eventhough a remarkable reduction in interaction force is achieved by this approach, the interaction force acting on each element may not be minimum. This can be achieved by incorporating the non-uniform array concept [77-83].

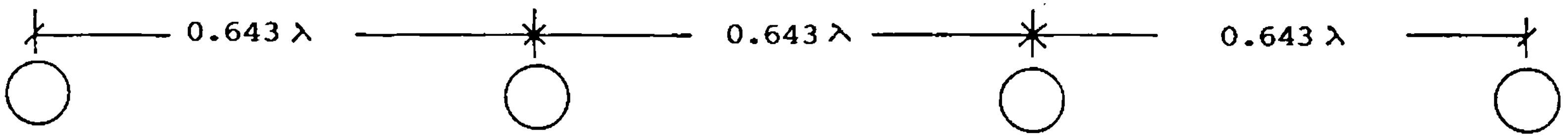
2.7 DESIGN CONSIDERATIONS OF NON-UNIFORM ARRAYS

One of the popular methods for designing an array with non-uniform spacings is the total enumeration method. In this approach, all possible combinations of spacings are examined, the criteria for the desired array is computed for each combination and the one which yields the best suited result is selected [84]. As the beam pattern mainly depends on its array element configuration, the formulation of non-uniform array for reducing the interaction force will affect the beam characteristics. Thus the suitable set of spacings that reduce the interaction force to a lowest possible value, without considerably affecting the beam characteristics is to be selected.

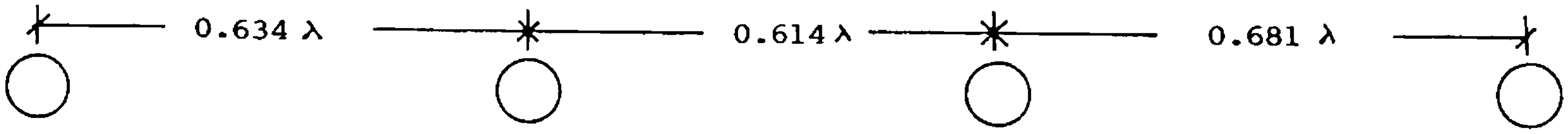
Using the formentioned method, the appropriate set of spacings that yield reduced interaction force and a beam pattern, within the limit of acceptability, is determined for various linear array formats by keeping the array dimension same as that of the restructured array. The element configuration of the non-uniformly spaced 4 element linear array along with that of the conventional $\lambda/2$ spaced and restructured arrays are shown in Figure 2.6. The broadside beampattern of the non-uniformly formulated 4 and 10 element linear arrays are given in Figures 2.7 and 2.8, respectively, along with that of the $\lambda/2$ spaced and restructured arrays. It may be noted that, as the array apertures of both the non-uniform and restructured arrays are retained the same, beamwidths remain unaltered. The only notable peculiarity in the beam patterns of the non-uniformly formulated array is the slight increase in the sidelobe level at far outside the main beam and this can be neglected as it will not present much ambiguity in detecting the bearing of the targets. The appropriate set of spacings for designing the various linear arrays are determined using the same method and the results are summarised in Table 2.2 along with other parameters that describe the performance of these arrays.



(a) λ/2 spaced array



(b) restructured array



(c) non-uniform spaced array

Fig.2.6: The element configuration of the non-uniformly formulated 4 element linear array along with λ/2 spaced and restructured arrays

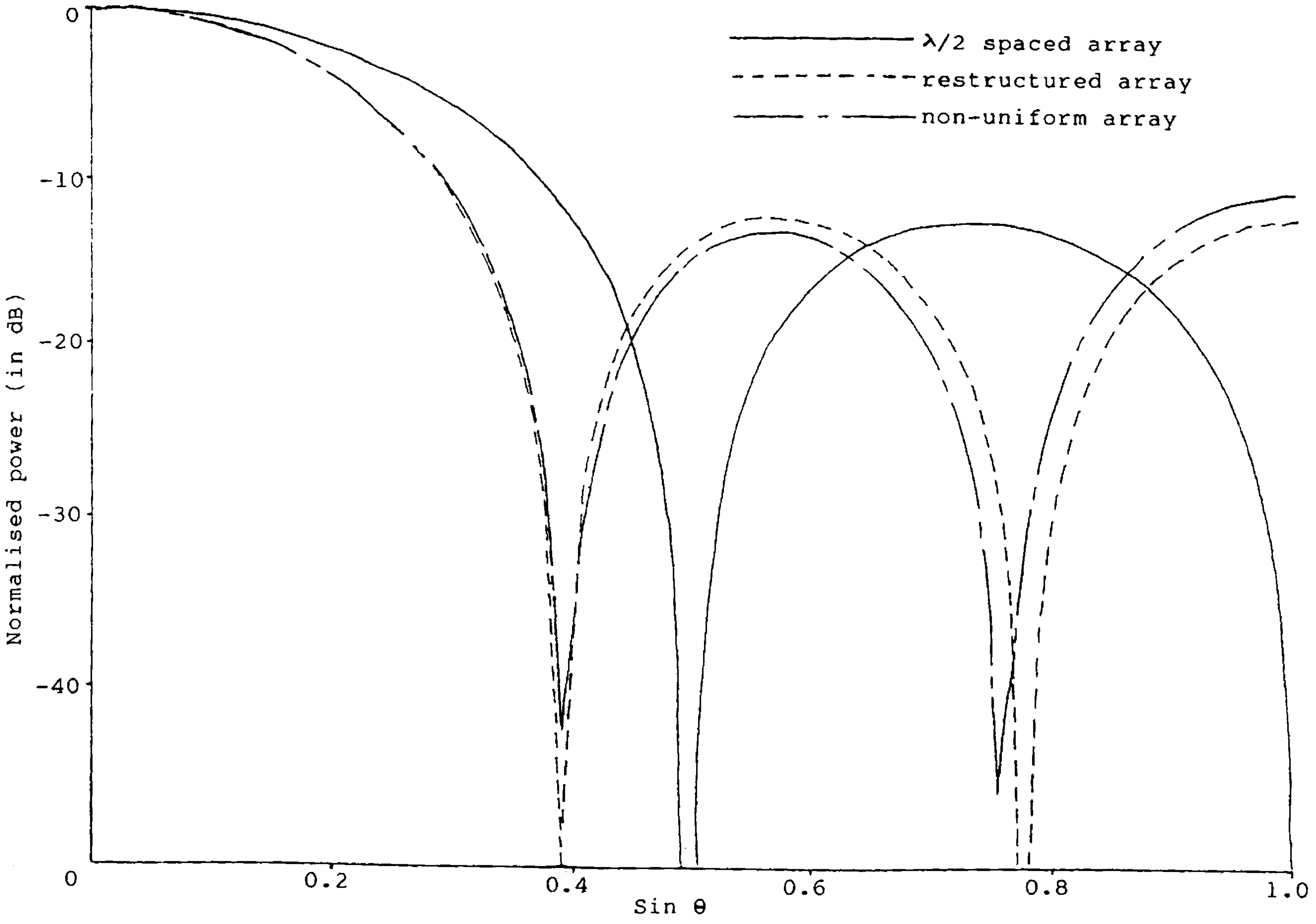


Fig.2.7: The broadside beam pattern of 4 element linear array

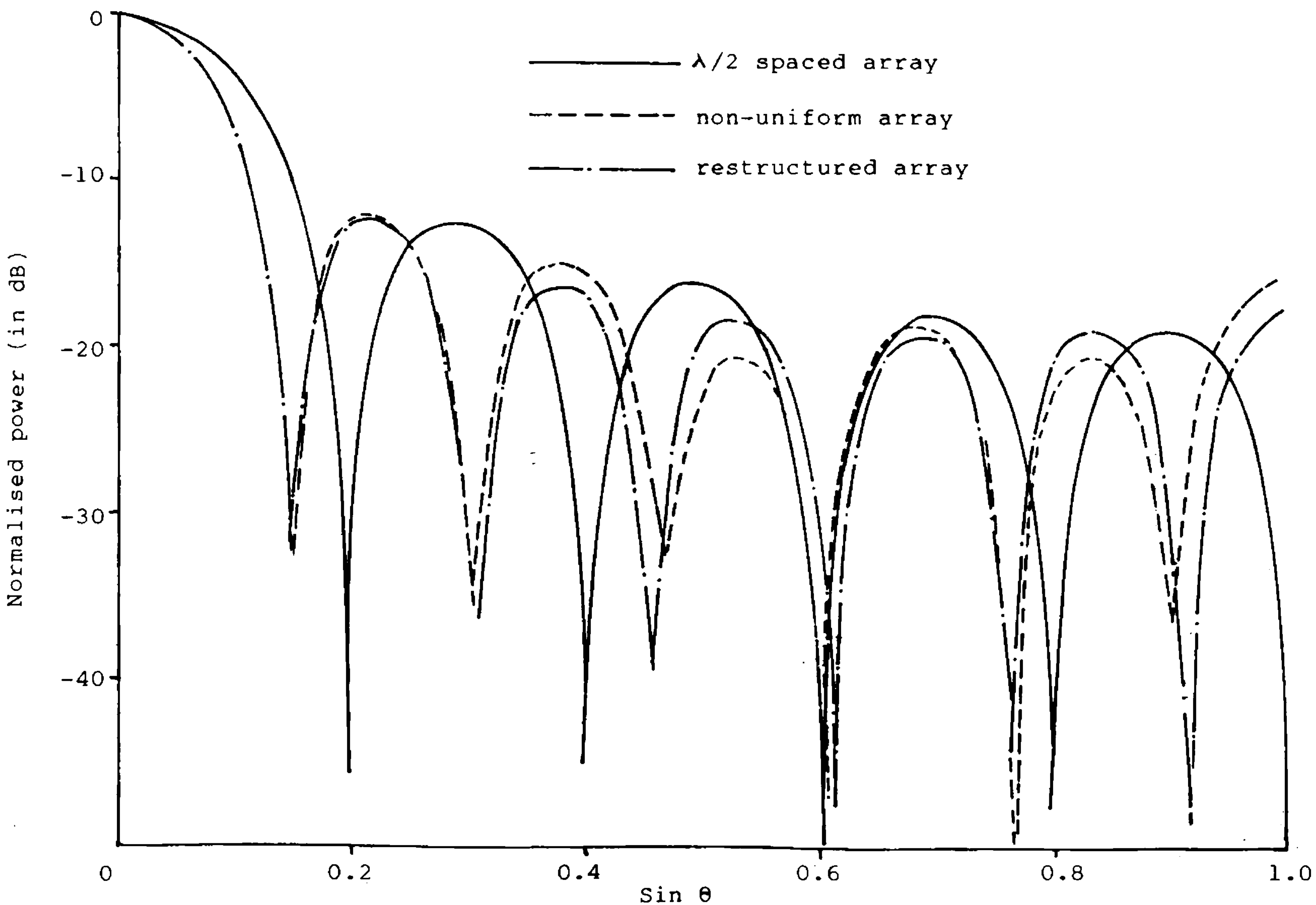


Fig.2.8: The broadside beam pattern of a 10 element linear array

Table 2.2: The transmitting/receiving parameters of various non-uniformly spaced linear arrays are compared with $\lambda/2$ spaced and restructured arrays

Number of elements in the linear array (N)	Recommended interelement spacings of the non-uniform array $d_1, d_2, \ldots\ldots\ldots d_{N-1}$ (in λ)	% reduction in interaction force of non-uniform array with		Peak sidelobe level (in dB)			Array Gain (in dB)		
		$\lambda/2$ spaced array	Restructured array	$\lambda/2$ spaced array	Restructured array	Non-uniform array	$\lambda/2$ spaced array	Restructured array	Non-uniform array
4	0.634, 0.614, 0.681	68.90	21.74	-11.31	-11.32	10.00	6.02	6.925	6.82
5	0.699, 0.731, 0.659, 0.739	32.50	14.36	-12.04	-12.04	-11.04	6.99	8.275	8.22
6	0.589, 0.557, 0.637, 0.557, 0.638	64.70	37.50	-12.40	-12.39	-12.04	7.78	8.45	8.40
10	0.605, 0.605, 0.70, 0.70, 0.605, 0.70, 0.676, 0.629, 0.684	61.00	34.00	-12.98	-12.98	-12.68	10.00	11.10	11.04
15	0.597, 0.58, 0.656, 0.627, 0.589, 0.665, 0.589, 0.66, 0.662, 0.589, 0.66, 0.662, 0.625, 0.67	46.00	26.51	-13.14	-13.14	-13.10	11.76	12.77	12.70
20	0.62, 0.599, 0.591, 0.59, 0.67, 0.64, 0.59, 0.662, 0.58, 0.671, 0.64, 0.66, 0.589, 0.671, 0.58, 0.65, 0.67, 0.588, 0.68	49.70	23.85	-13.20	-13.20	-13.30	13.01	13.97	13.93

Although it is possible, in principle, to carry out such a trial and error method, it is generally not practical to do so except in simple cases. In an N element linear array, if each of the N elements can occupy any one of the 'M' possible positions within the aperture, there are a total of M^N combinations that must be checked. For even a small number of elements and for a limited number of positions for each elements, the number of trials required to examine all possible combinations quickly gets out of hand because of the exponential relationship [84]. Thus, this method cannot be recommended for arrays comprising of large number of elements, as it involves cumbersome computations.

2.8 OPTIMALLY FORMULATED ARRAYS

For alleviating the computational burden, different sets of spacings were generated using various distribution formulae and its suitability in reducing the interaction force is checked [85-87]. The spacings that are generated using the gaussian distribution formula show good agreement in reducing the interaction force to a lower value.

The gaussian distributed random numbers are given by

$$G = \sigma \left(\sum_{i=1}^{N} x_i - \frac{N}{2} \right) \sqrt{\frac{12}{N}} + \mu \qquad (2.7)$$

where σ is the standard deviation

x_i is the uniformly distributed random numbers

N is the number of uniformly distributed random numbers used to generate the required one d and

μ is the mean.

These spacings are generated by assigning the optimum spacing (d_{min}) as the mean and by keeping the aperture dimension same as that of the restructured array.

The optimum element configuration of various linear arrays are determined using the forementioned method with a given standard deviation and the interaction force acting on these arrays have been computed. Eventhough a large value of deviation will result in greater reduction in interaction force, it cannot be adopted as this is inevitably associated with an increase in sidelobe level at the extremes of the visible region. Hence, reducing the interaction force to a much lower level and at the same time suppressing the sidelobes to a desired value are conflicting requirements, if the size of the array is fixed. Thus, a suitable deviation value that gives reduced interaction force with reasonable beam pattern has been selected.

The impact of this modification on the beam characteristics can be seen from the Figures 2.9 and 2.10 which are plotted with the broadside beam patterns of the optimally formulated 4 and 10 element linear arrays, along with that of the $\lambda/2$ spaced and restructured arrays. The only notable peculiarity in the beam pattern is the slight increase in sidelobe level at far out side main beam which can be neglected considering the overall improvement in the performance of the array. The superiority of the proposed optimum array over both conventional $\lambda/2$ spaced and restructured arrays is well evident from the Table 2.3, which summarises the parameters that describe the performance of arrays in both transmitting and receiving applications.

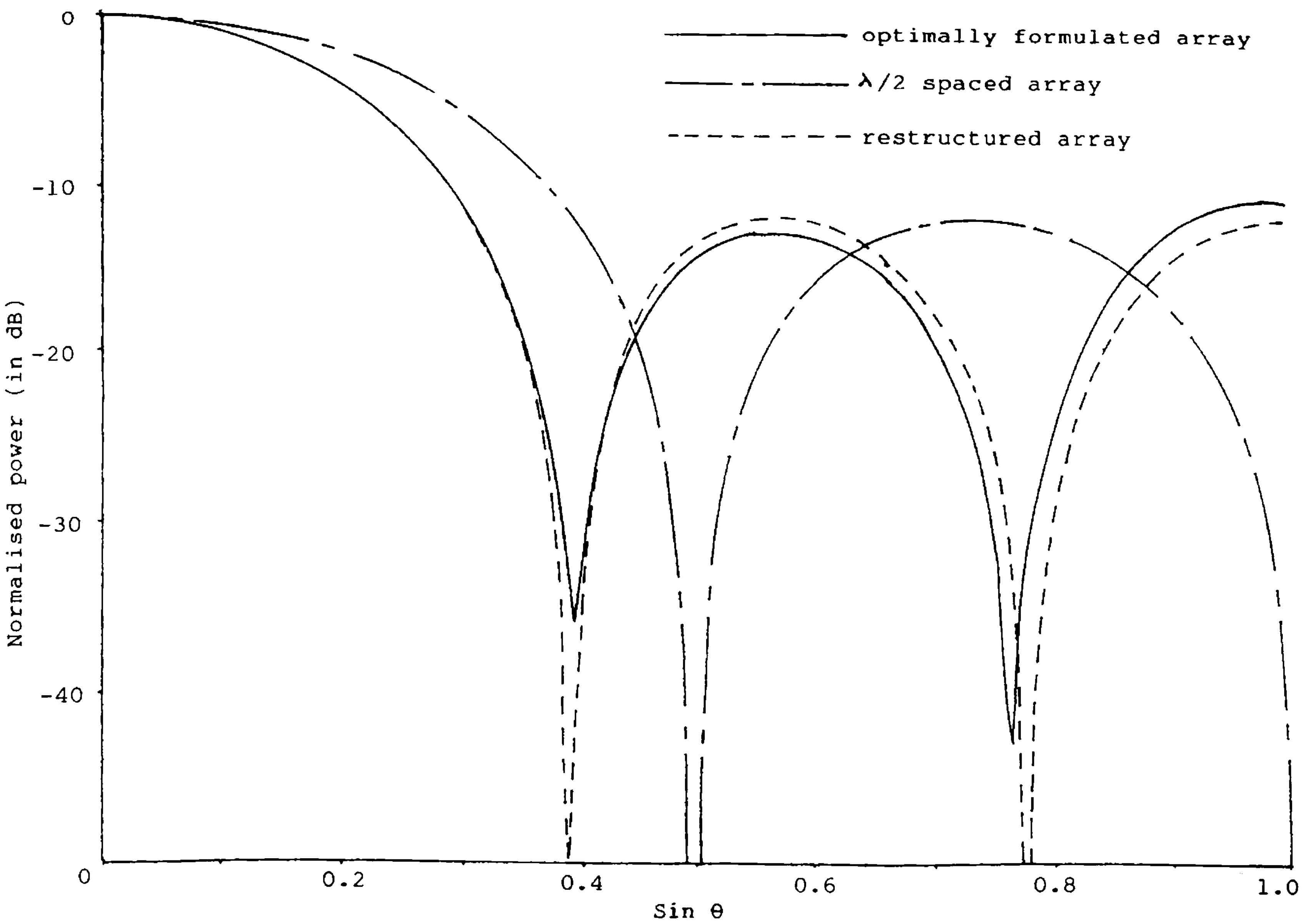


Fig.2.9: The broadside beam pattern of 4 element linear array

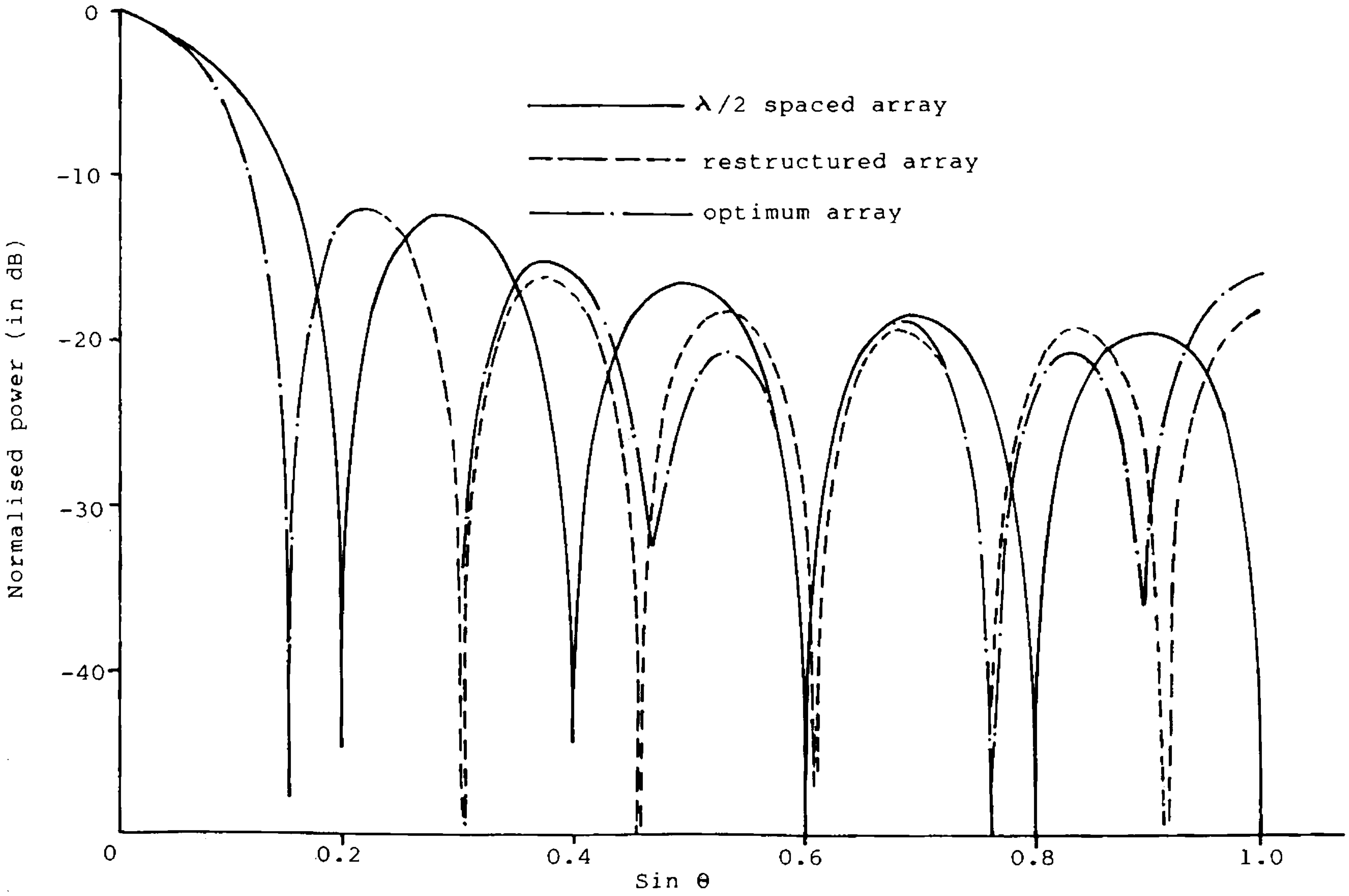


Fig.2.10: The broadside beam pattern of a 10 element linear array

Table 2.3: A comparative study of significant features of the optimally formulated linear arrays with that of $\lambda/2$ spaced and restructured arrays

Number of elements in the linear array (N)	Recommended interelement spacings of the optimally formulated array $d_1, d_2, \ldots, d_{N-1}$ (in λ)	% reduction in interaction force of the optimally formulated array		Peak sidelobe level (in dB)			Array gain (in dB)		
		$\lambda/2$ spaced array	Restructured array	$\lambda/2$ spaced array	Restructured array	Optimum array	$\lambda/2$ spaced array	Restructured array	Optimum array
4	0.650, 0.613, 0.67	69.40	22.99	-11.31	-11.32	-10.00	6.02	6.925	6.89
5	0.705, 0.67, 0.716, 0.732	32.64	14.54	-12.04	-12.04	-10.82	6.99	8.275	8.24
6	0.60, 0.57, 0.62, 0.63, 0.554	49.80	11.18	-12.40	-12.39	-11.91	7.78	8.45	8.44
10	0.690, 0.625, 0.72, 0.737, 0.60, 0.602, 0.61, 0.633, 0.670	57.70	28.45	-12.98	-12.98	-13.02	10.00	11.10	11.04
15	0.670, 0.62, 0.695, 0.707, 0.606, 0.61, 0.605, 0.635, 0.653, 0.603, 0.60, 0.646, 0.639, 0.62	47.12	28.03	-13.14	-13.14	-13.12	11.76	12.77	12.62
20	0.663, 0.615, 0.688, 0.70, 0.60, 0.60, 0.597, 0.627, 0.646, 0.595, 0.59, 0.638, 0.631, 0.614, 0.57, 0.645, 0.626, 0.627, 0.629	48.60	22.18	-13.20	-13.20	-13.26	13.01	13.97	13.90

2.9 CONCLUSIONS

The beam patterns obtained from theoretical analysis differ from those measured experimentally, mainly due to the acoustic interaction effect experienced among its elements. As this effect is much alleviated in the proposed array format, it seems reasonable to expect a close similarity in experimental and theoretical beam patterns.

Eventhough the interelement spacings in the restructured array (d_{min}) for various arrays are different, an unperturbed beam pattern and improved array gain are obtained, as these spacings are well within $\lambda/2$ and λ. The proposed projector arrays can well be used as a hydrophone system as it improves the array gain, quite favourably, for certain signal and noise environments. The radiation efficiency of linear array formats can be seen to be much improved at the expense of slight degradations in the sidelobe level at far outside the main beam.

CHAPTER 3

AN OPTIMISED DESIGN APPROACH FOR MINIMISING THE INTERACTION EFFECT IN PLANAR ARRAYS

Chapter 3

AN OPTIMISED DESIGN APPROACH FOR MINIMISING THE INTERACTION EFFECT IN PLANAR ARRAYS

3.1 INTRODUCTION

In practical applications of arrays, it is essential to control and modify its radiation pattern as desired. Planar arrays which are more versatile than the linear arrays, provide additional variables for this purpose. Moreover, they have a more symmetrical pattern with lower sidelobes and the main beam can be scanned towards any point in space [71].

The performance of these arrays are much degraded due to the acoustic interaction effect experienced among its elements. For reducing the acoustic interaction effect in planar arrays, the procedure adopted for linear arrays can be extended to the planar case as well. This chapter discusses the restructuring of planar arrays of various radiating apertures for reducing the interaction effect.

3.2 FORMULATION OF UNIFORMLY SPACED ARRAYS

3.2.1 Planar Arrays with Square Radiating Aperture

In addition to placing the elements along a line, individual radiators can be positioned along a plane to form a planar array. Fig.3.1 shows the geometry of an M x N element planar array.

The effective interaction force which is the sum of the forces acting on each and every element has been computed for various planar arrays with square radiating apertures using a modified version of equation (2.4).

The interaction force for a planar array of M x N element configuration is,

$$F = \left\{ \left[\sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=1}^{N} \sum_{l=1}^{M} \rho c \frac{\pi}{2} a^2 (ka)^2 \frac{\sin kd\sqrt{(l-j)^2 + (k-i)^2}}{kd\sqrt{(l-j)^2 + (k-i)^2}} V_n e^{j\delta mn} \right]^2 + \left[\sum_{i=1}^{N} \sum_{j=1}^{M} \sum_{k=1}^{N} \sum_{l=1}^{M} \rho c \frac{\pi}{2} a^2 (ka)^2 \frac{\cos kd\sqrt{(l-j)^2 + (k-i)^2}}{kd\sqrt{(l-j)^2 + (k-i)^2}} V_n e^{j\delta mn} \right]^2 \right\}^{\frac{1}{2}} \tag{3.1}$$

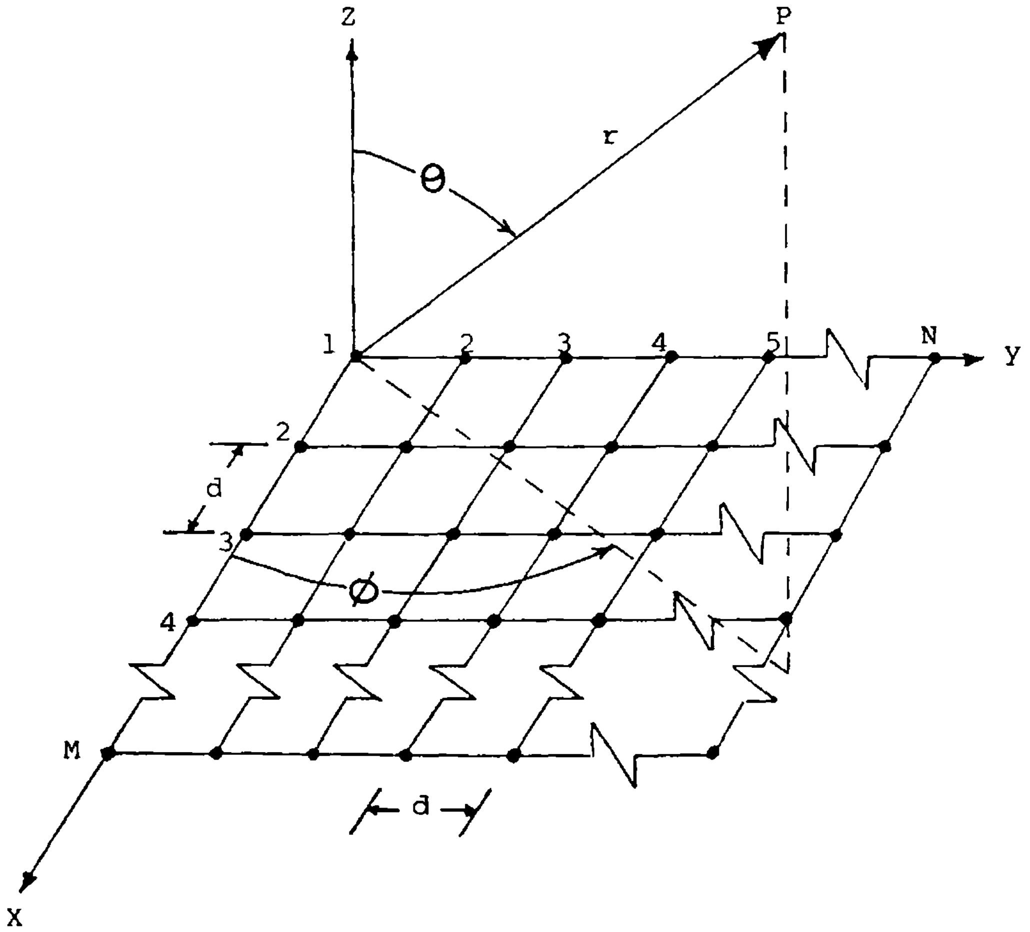


Fig.3.1: M x N element planar array geometry

The beam pattern of an M x N element (uniformly spaced) planar array of point sources can be shown to be given by [71].

$$B(\theta,\phi) = \left[\frac{1}{M}\,\frac{\sin(\frac{M}{2}\Psi_x)}{\sin(\frac{\Psi_x}{2})}\right]^2 \left[\frac{1}{N}\,\frac{\sin(\frac{N}{2}\Psi_y)}{\sin(\frac{\Psi_y}{2})}\right]^2 \qquad (3.2)$$

where Ψ_x = kd sin θ cos ϕ

Ψ_y = kd sin θ sin ϕ

where ϕ is the angular position of the reference point on the X-Y plane (see Figure 3.1).

The spatial variation of interaction force acting on a 6 x 6 element uniform planar array has been computed using equation (3.1) and is shown in Fig.3.2. The spacing at which this force becomes minimum (d_{min}) is determined from this variation and is found to be 0.59 λ. The 6 x 6 element restructured array has been evolved with d_{min} as the interelement spacing and the percentage reduction in interaction force has been found to be 24.7.

In almost all array design, an interelement spacing of half-a-wavelength is preferred due to its

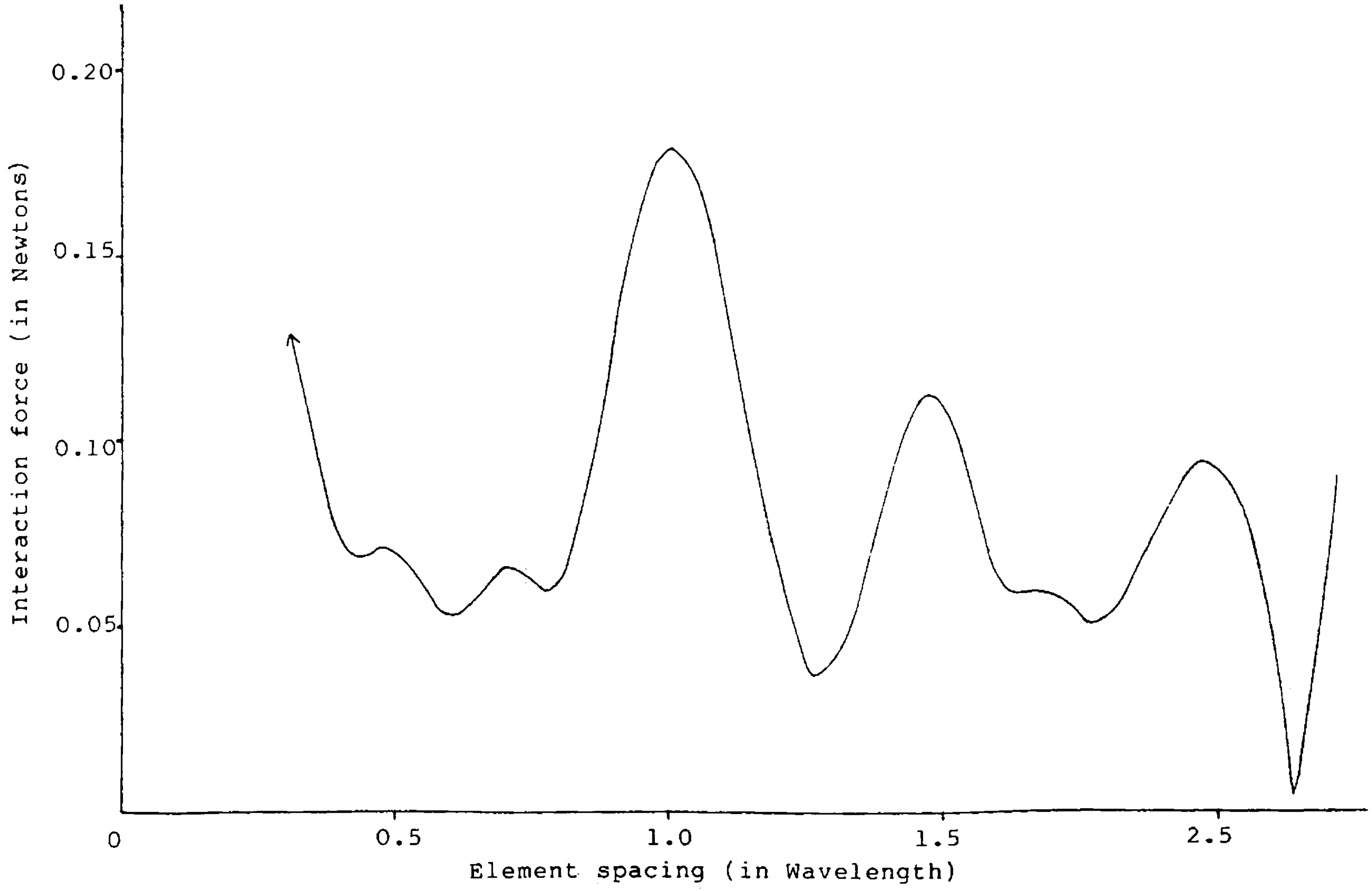


Fig.3.2: The spatial variation of interaction force acting on a 6 x 6 element planar array

commendable beam characteristics. As the interelement spacing is altered in the restructured array, a variation in the beam characteristics is imminent and this can be seen from Fig.3.3 which shows the beam pattern of both $\lambda/2$ spaced and restructured arrays. A reduction in mainlobe width and reorientation of sidelobes are the notable peculiarities and these are to be expected in the restructured array due to the increase in the array aperture.

Using the same procedure, a 10 x 10 element planar array has also been formulated whose spatial variation of interaction force is shown in Fig.3.4. The minimum force spacing (d_{min}) for this array is chosen as 0.653 λ and the reduction in interaction force is seen to be 19%. The beam pattern of this array is shown in Fig.3.5 along with that of the $\lambda/2$ spaced array.

Various uniform planar arrays have been formulated using this approach and the recommended spacings (d_{min}) of these arrays are tabulated in Table 3.1 along with other relevant parameters.

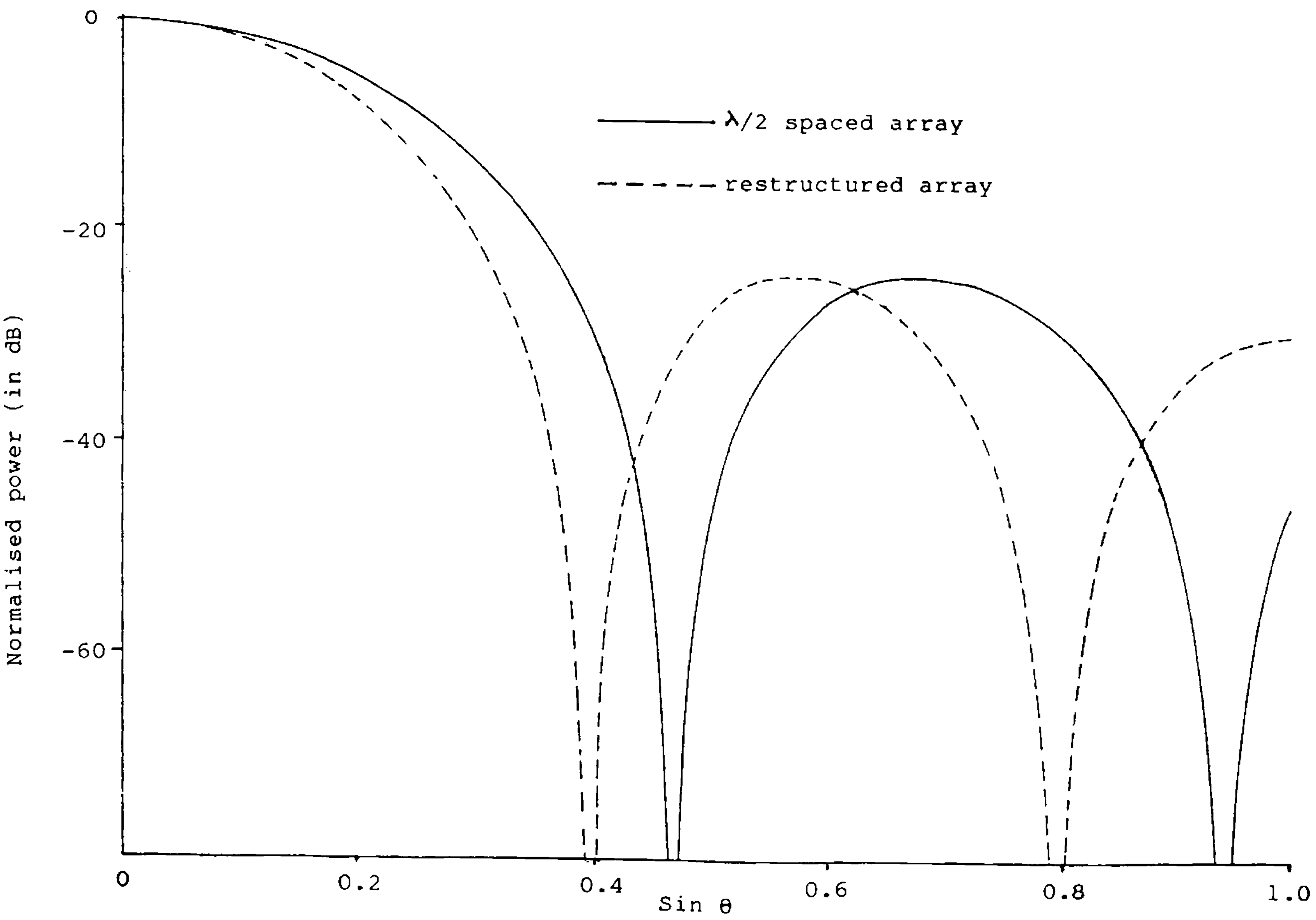


Fig.3.3: The beam pattern of 6 x 6 element uniform planar array (at Ø = 45°)

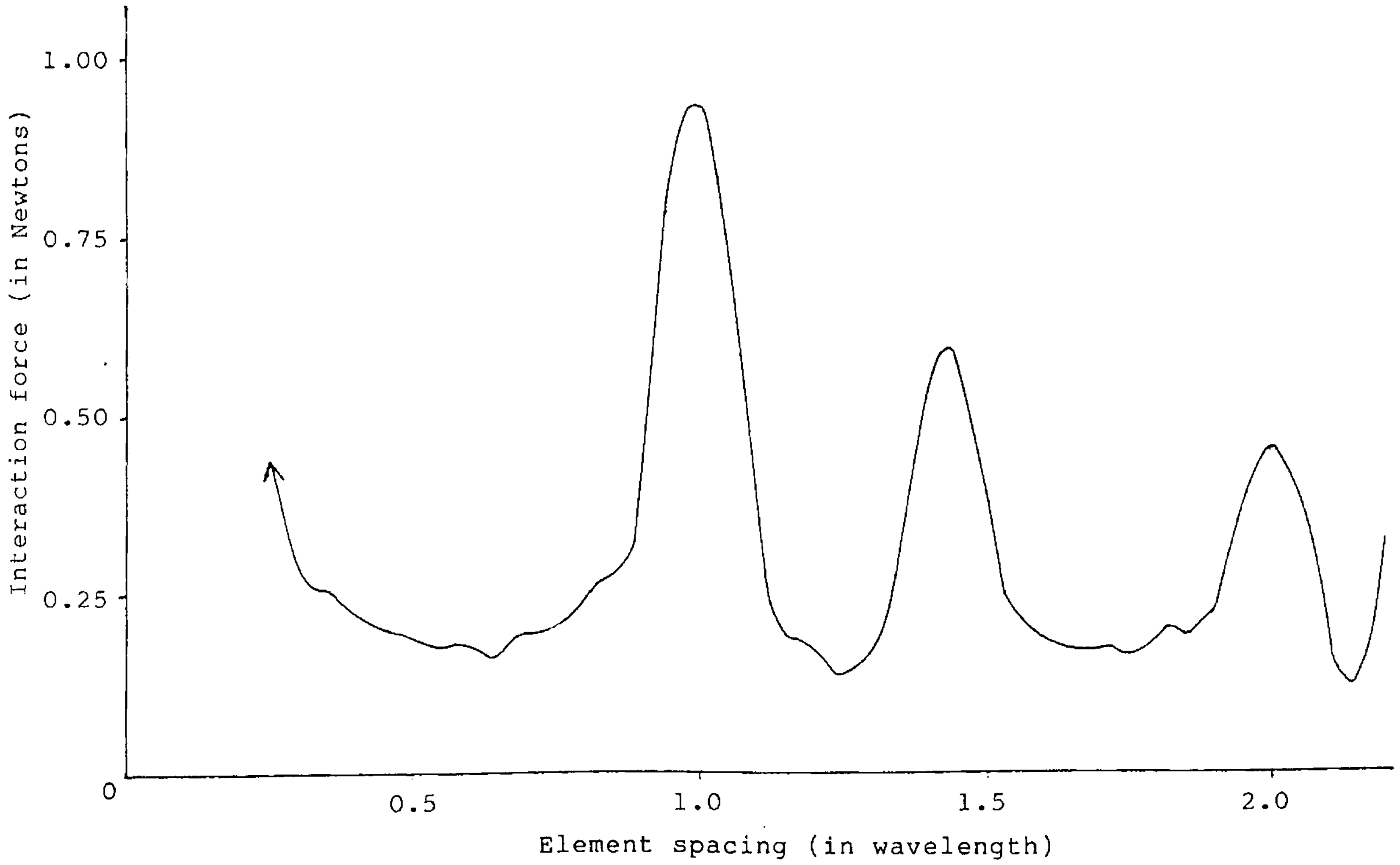


Fig.3.4: The spatial variation of interaction force acting on a 10 x 10 element planar array

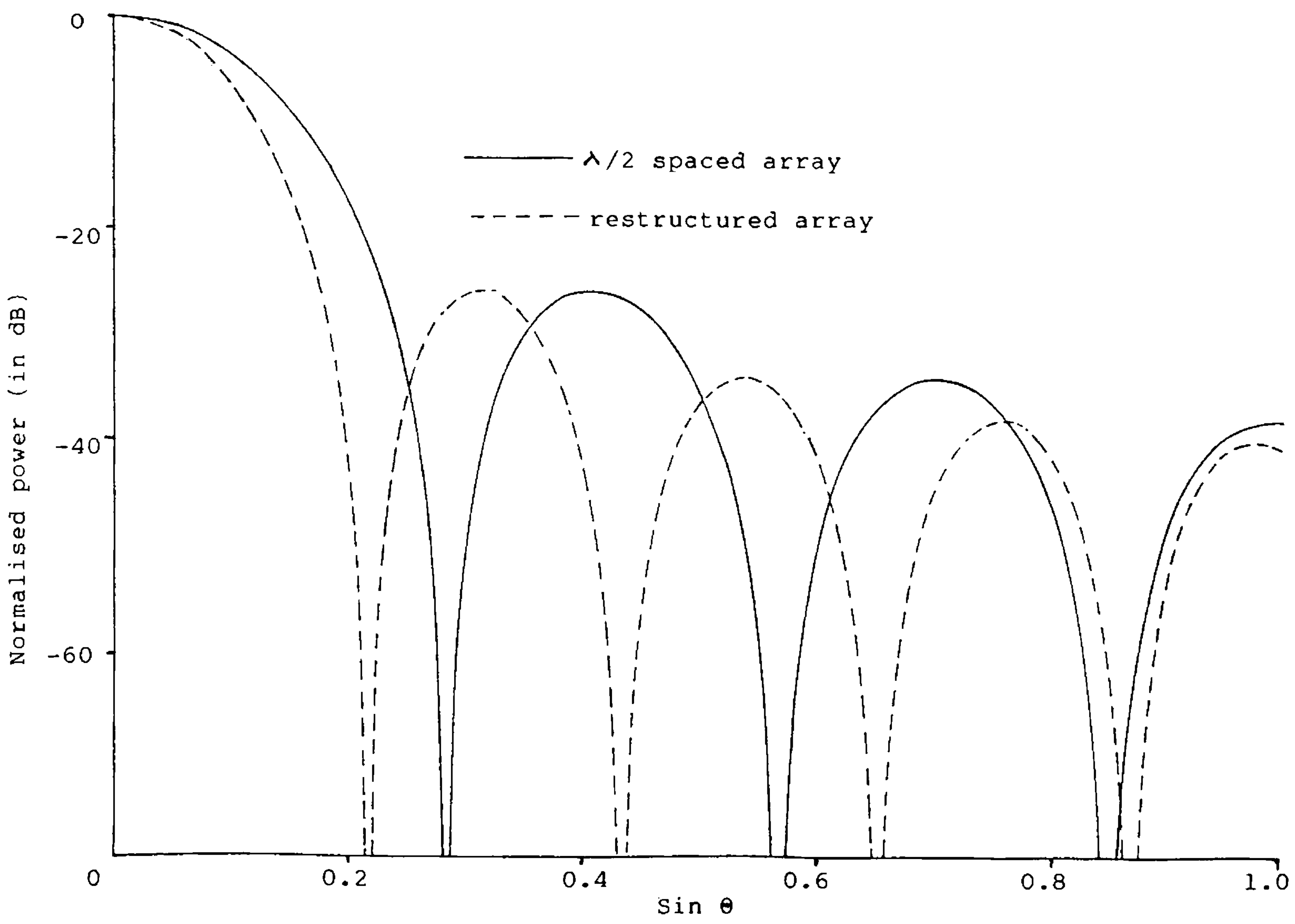


Fig.3.5: The beam pattern of 10 x 10 element uniform planar array (at $\phi = 45°$)

Table 3.1: The recommended spacings for various restructured planar arrays along with its percentage reduction in interaction force and array gain.

Number of elements in the planar array	Spacing at which interaction force is minimum (d_{min}/λ)	% reduction in interaction force	Array Gain (in dB)	
			at $\lambda/2$ spacing	at d_{min}/λ spacing
4 x 4	0.638	32.5	13.51	14.78
5 x 5	0.713	6.5	15.28	17.51
6 x 6	0.590	24.7	17.16	18.23
10 x 10	0.653	19.0	21.73	23.70
15 x 15	0.637	8.0	25.26	27.21
20 x 20	0.629	16.0	27.86	29.90

3.2.2 Planar Arrays with Circular Radiating Aperture

The element configuration of a 19 element planar array with circular radiating aperture is shown in Fig.3.6. The elements are arranged on 3 concentric circles each of radii 0.5 λ, 0.866 λ and 1.0 λ, respectively, measured from centre element such that the interelement spacing between the nearest neighbours will be 0.5 λ. The interaction force acting on an N-element circular array can be computed using equation (2.4), which is given by,

$$F = \left\{ \left[\sum_{m=1}^{N} \sum_{n=1}^{N} \rho c \pi \frac{a^2}{2} (ka)^2 \frac{\sin(kd_{mn})}{kd_{mn}} V_n e^{j\delta mn} \right]^2 + \left[\sum_{m=1}^{N} \sum_{n=1}^{N} \rho c \pi \frac{a^2}{2} (ka)^2 \frac{\cos(kd_{mn})}{kd_{mn}} V_n e^{j\delta mn} \right]^2 \right\}^{\frac{1}{2}} \qquad (3.3)$$

where d_{mn} is the spacing between the m^{th} and n^{th} elements This spacing can be shown to be given by,

$$d_{mn} = [R_i^2 + R_j^2 - 2 R_i R_j \cos \phi_{ij}]^{\frac{1}{2}}$$

Where R_i and R_j are the radii of the i^{th} and j^{th} circles on which the m^{th} and n^{th} elements are situated and ϕ_{ij} is the angle between the line joining each elements with the centre of the array.

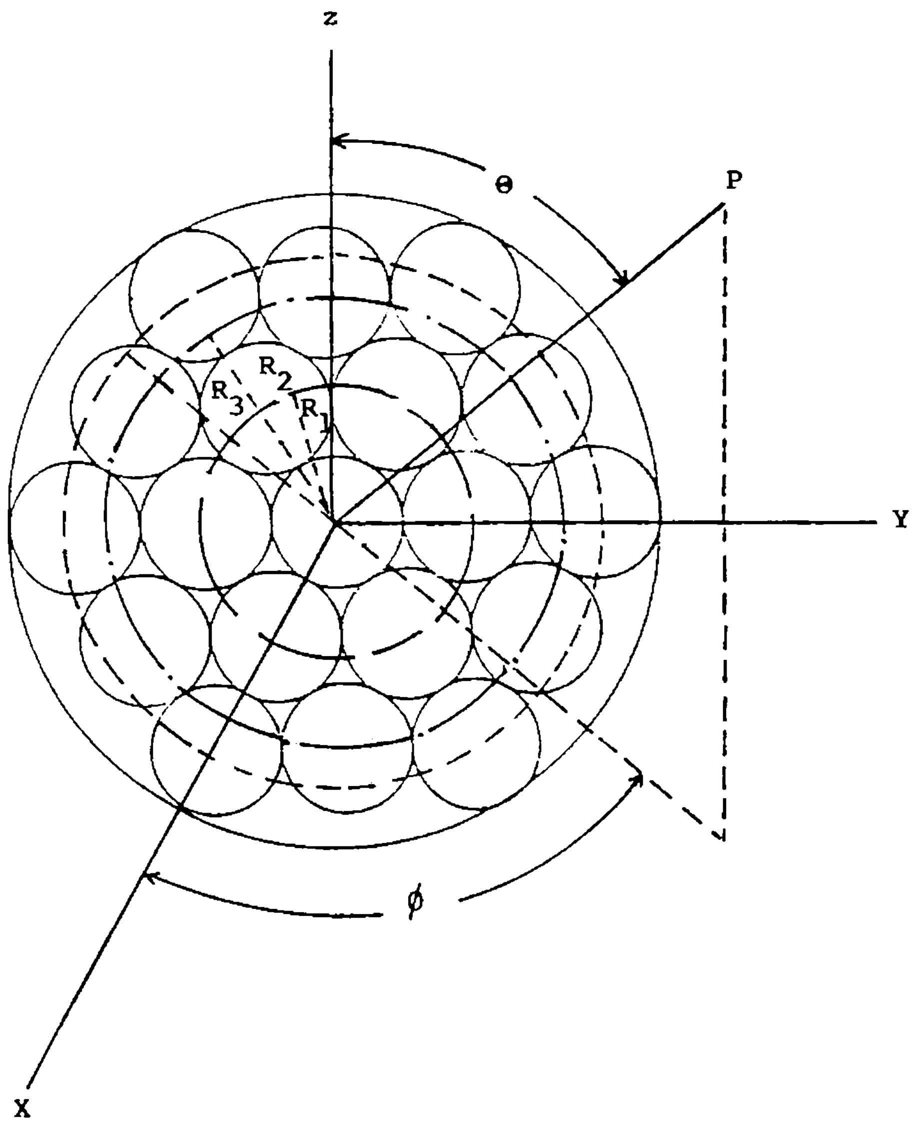


Fig.3.6: Element configuration of a 19-element circular array

The beam pattern of a circular array, whose elements are arranged on concentric circles, can be shown to be given by [71,88],

$$B(\theta, \phi) = [1 + \sum_{i=1}^{m} \sum_{j=1}^{n} \cos(\frac{2\pi}{\lambda} R_i \sin\theta \cos(\phi - \phi_{ij}))]^2 \qquad (3.4)$$

where m is the number of circles

n is the number of elements on each circle

R_i is the radius of the i^{th} circle

ϕ_{ij} is the angular position of j^{th} element of the i^{th} circle on the X-Y plane.

The interaction force acting on 19 and 37 element planar circular arrays has been computed as a function of spacing and are shown in Figs.3.7 and 3.8. The minimum force spacings (d_{min}) for these arrays are chosen as 0.593 λ and 0.587 λ respectively. Uniform planar arrays with improved performance have been evolved by restructuring it with these (d_{min}) spacings.

The beam patterns of the 19 and 37 element circular arrays are shown in Figs.3.9 and 3.10, for both λ/2 spaced and restructured arrays. Table 3.2

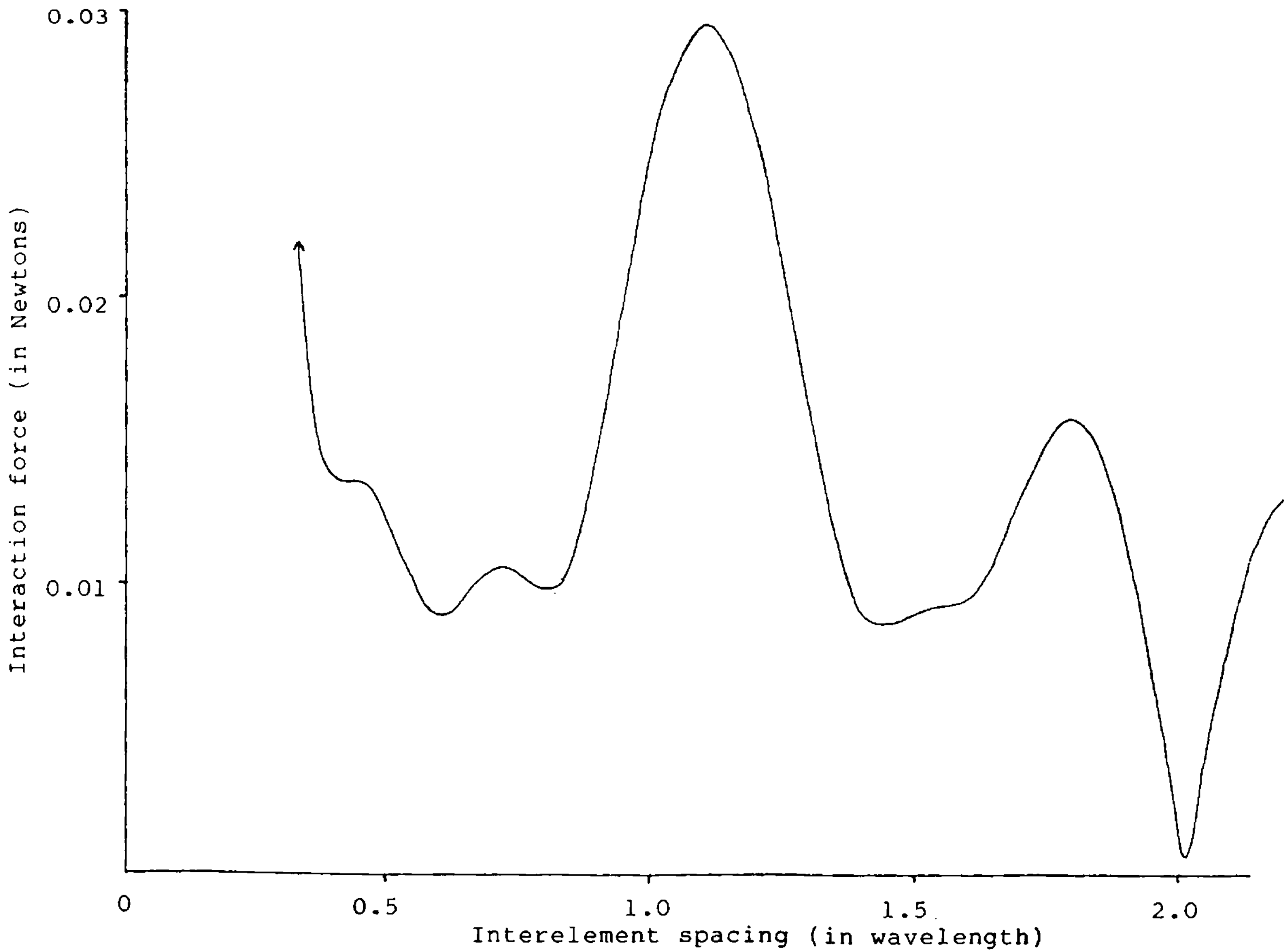


Fig.3.7: The spatial variation of interaction force acting on a 19 element circular array

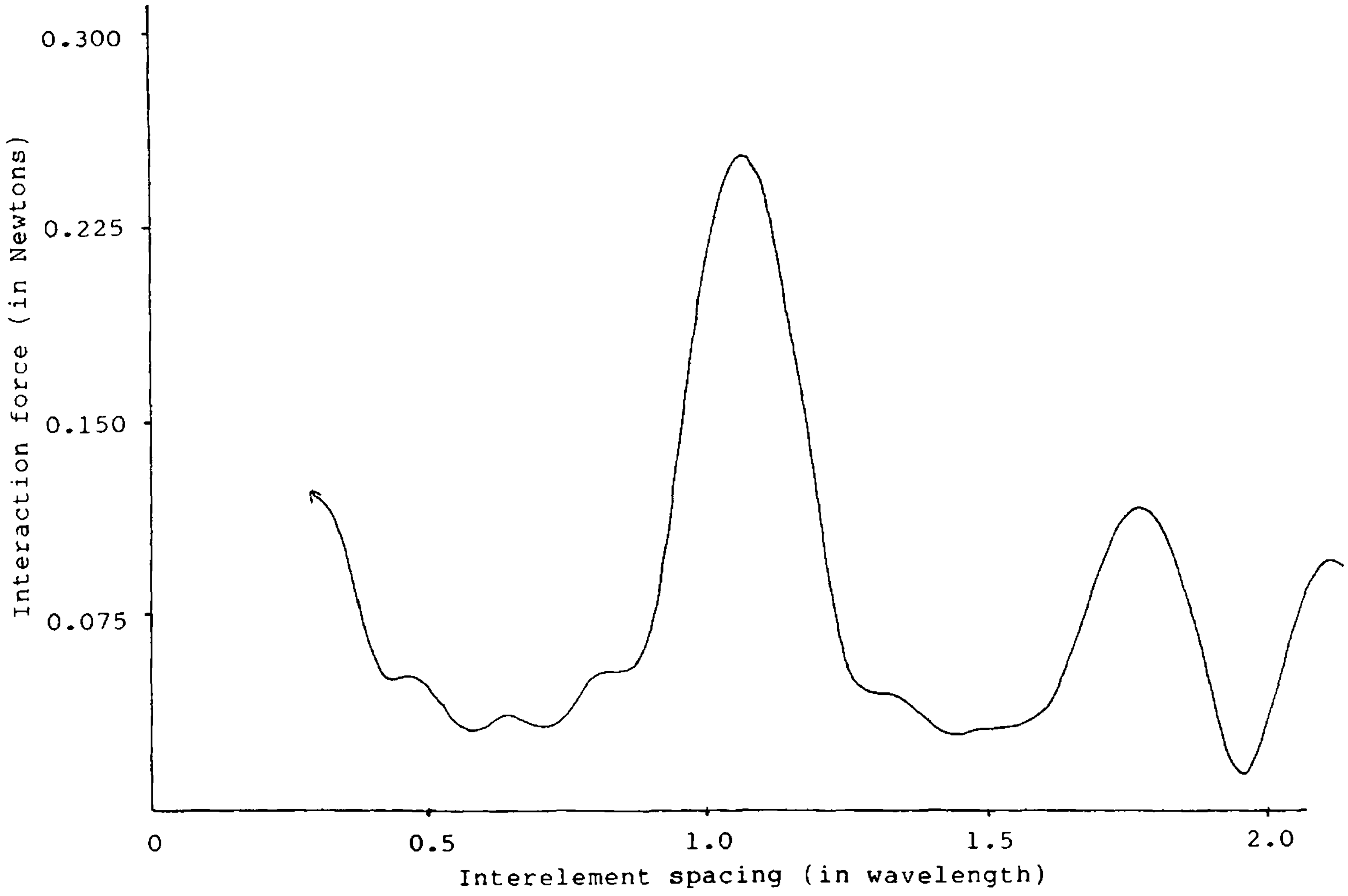


Fig.3.8: The spatial variation of interaction force acting on a 37 element circular array

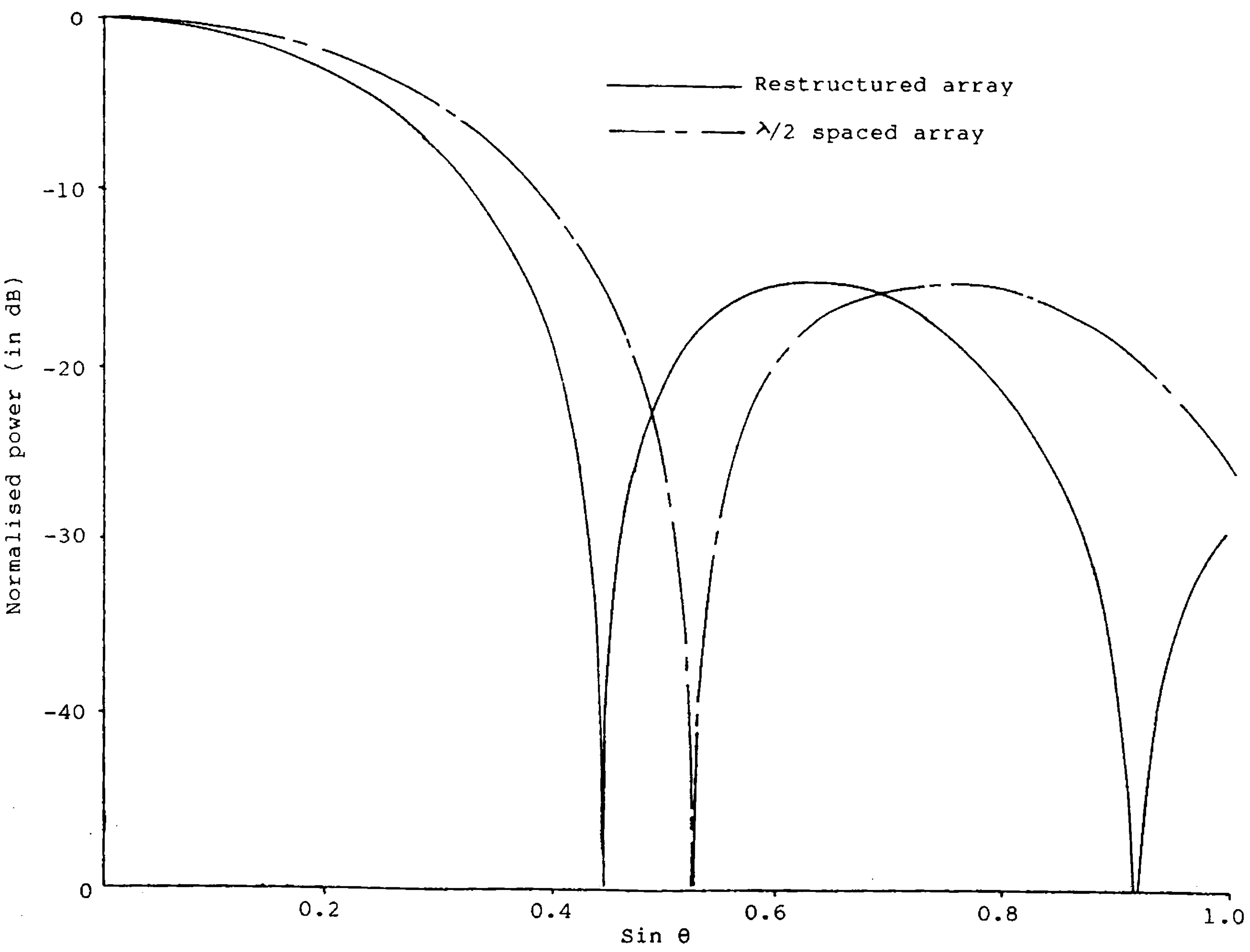


Fig.3.9: The beam pattern of 19 element uniform circular array (at Ø = 0°)

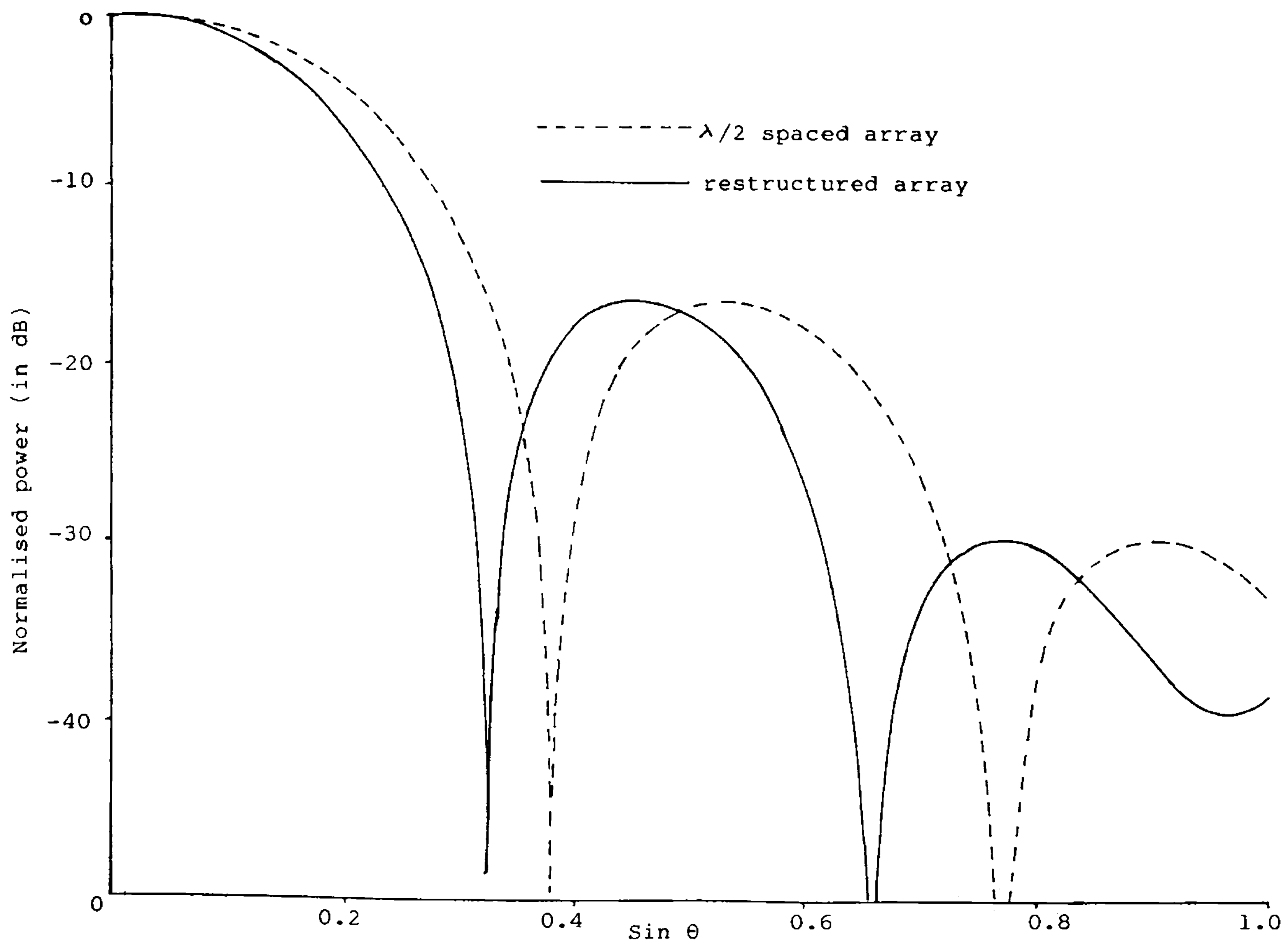


Fig.3.10: The beam pattern of 37 element uniform circular array (at Ø = 0°)

Table 3.2: Proposed minimum force spacings of various restructured circular arrays along with its percentage reduction in interaction force and array gain.

Number of elements in the circular array (N)	Spacing at which the interaction force is minimum (d_{min}/λ)	% reduction in interaction force	Array Gain (in dB)	
			at $\lambda/2$ spacing	at d_{min}/λ spacing
19	0.593	22.44	10.49	10.92
37	0.587	23.32	11.31	13.76
61	0.709	21.53	15.41	16.41
91	0.686	18.07	17.13	18.08

summarises the relevant array parameters that describes the performance in both transmitting and receiving applications.

3.3 NON-UNIFORMLY SPACED PLANAR ARRAYS

As mentioned in the previous chapter, further reduction in interaction force can be achieved by incorporating the non-uniform array concept. As a simple method, total enumeration is adopted for determining the optimum element configuration that reduce the interaction to an acceptably lower value, without much affecting the beam characteristics.

The appropriate set of spacings for various arrays are determined using total enumeration method and the beam pattern of 6 x 6 and 10 x 10 element planar arrays formulated with these spacings are shown in Figs.3.11 and 3.12, respectively. There is an inevitable increase in sidelobe level at far outside the main beam due to the randomness in element positions. This slight increase in sidelobe level can be neglected, only as a small price to be paid in return for the benefits that it provides to the overall improvement in the performance of the array.

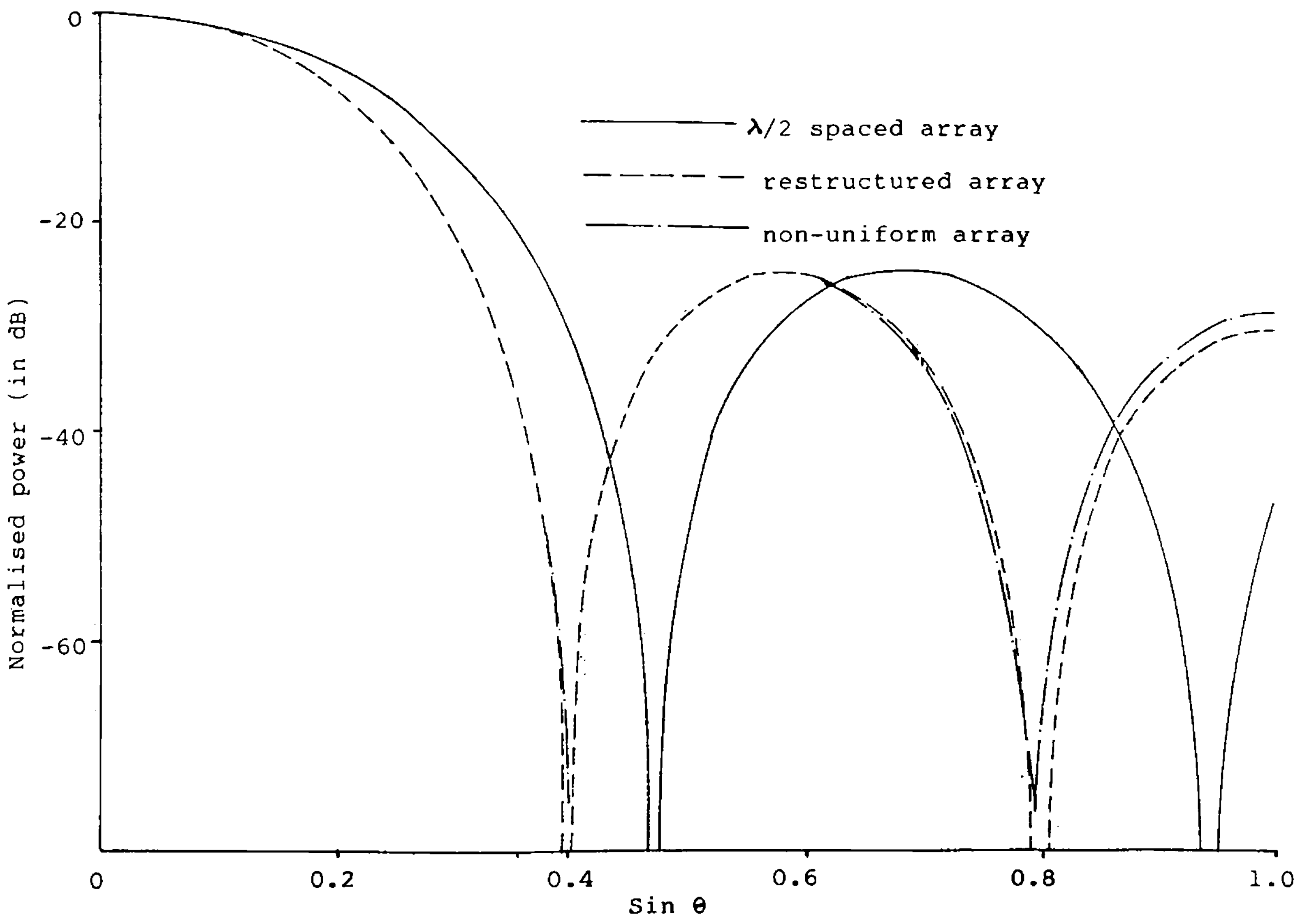


Fig.3.11: The beam pattern of 6 x 6 element planar array (at Ø = 45°)

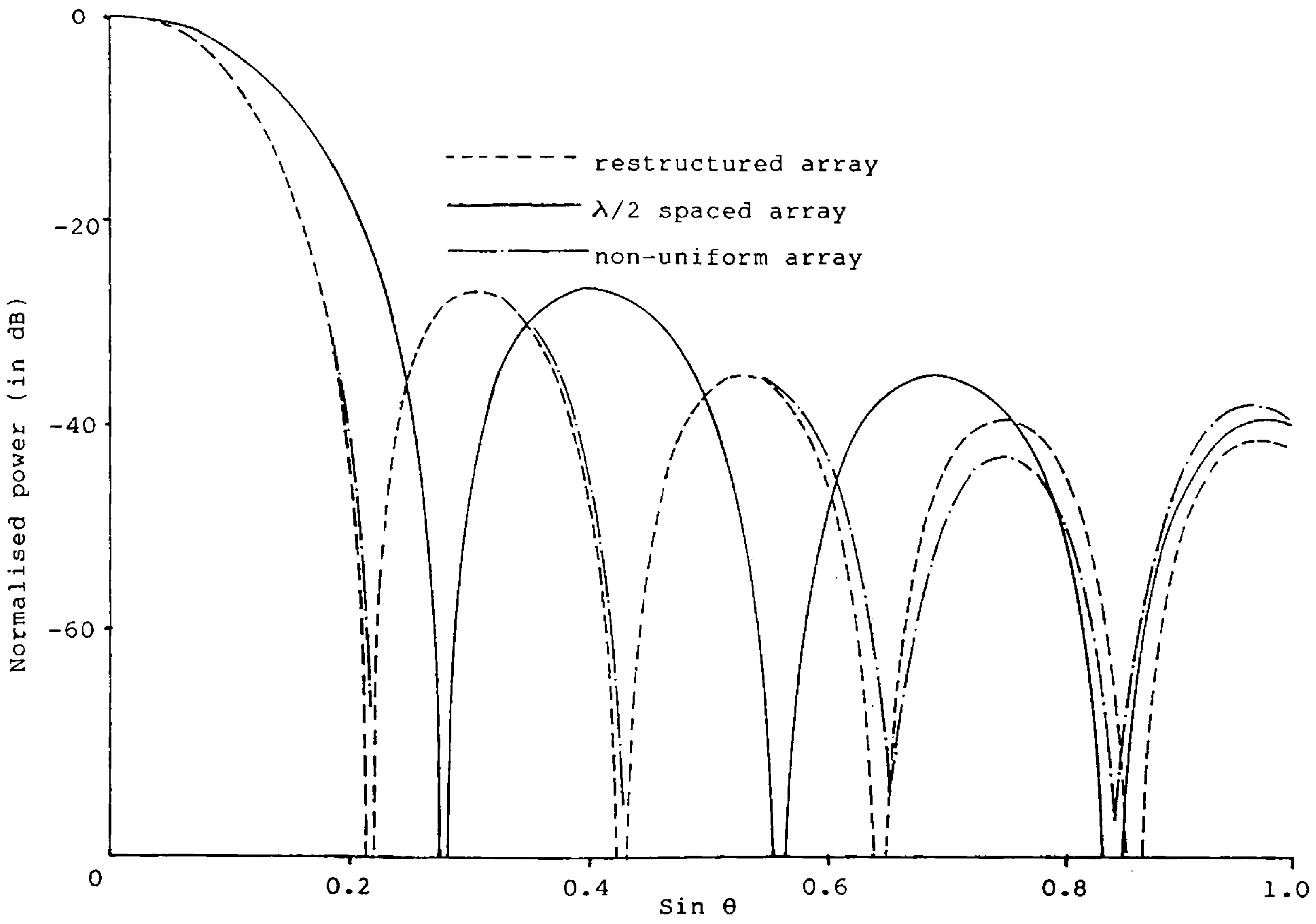


Fig.3.12: The beam pattern of 10 x 10 element planar array (at Ø = 45°)

Using the same approach, suitable set of spacings for planar arrays of circular radiating aperture have also been determined. The beam characteristics of these arrays are studied, theoretically, and a tolerable increase in sidelobe level, as in the case of square radiating aperture arrays, can be seen from the Figs.3.13 and 3.14, which are plotted with the beam patterns of 19 and 37 element circular aperture arrays. The superiority of the proposed planar arrays of square and circular radiating apertures over both conventional $\lambda/2$ spaced and restructured arrays is well evident from the tables 3.3 and 3.4, which are tabulated with the parameters having functional dependence on spatial distribution of array elements.

3.4 OPTIMALLY DISTRIBUTED PLANAR ARRAYS

The total enumeration method cannot be recommended for the design of large arrays, as it is a time consuming and tedious process. This can be overcome by using appropriate distribution formulae for predicting the suitable set of spacings [85-87]. In this approach, the spacings between the elements is varied in accordance

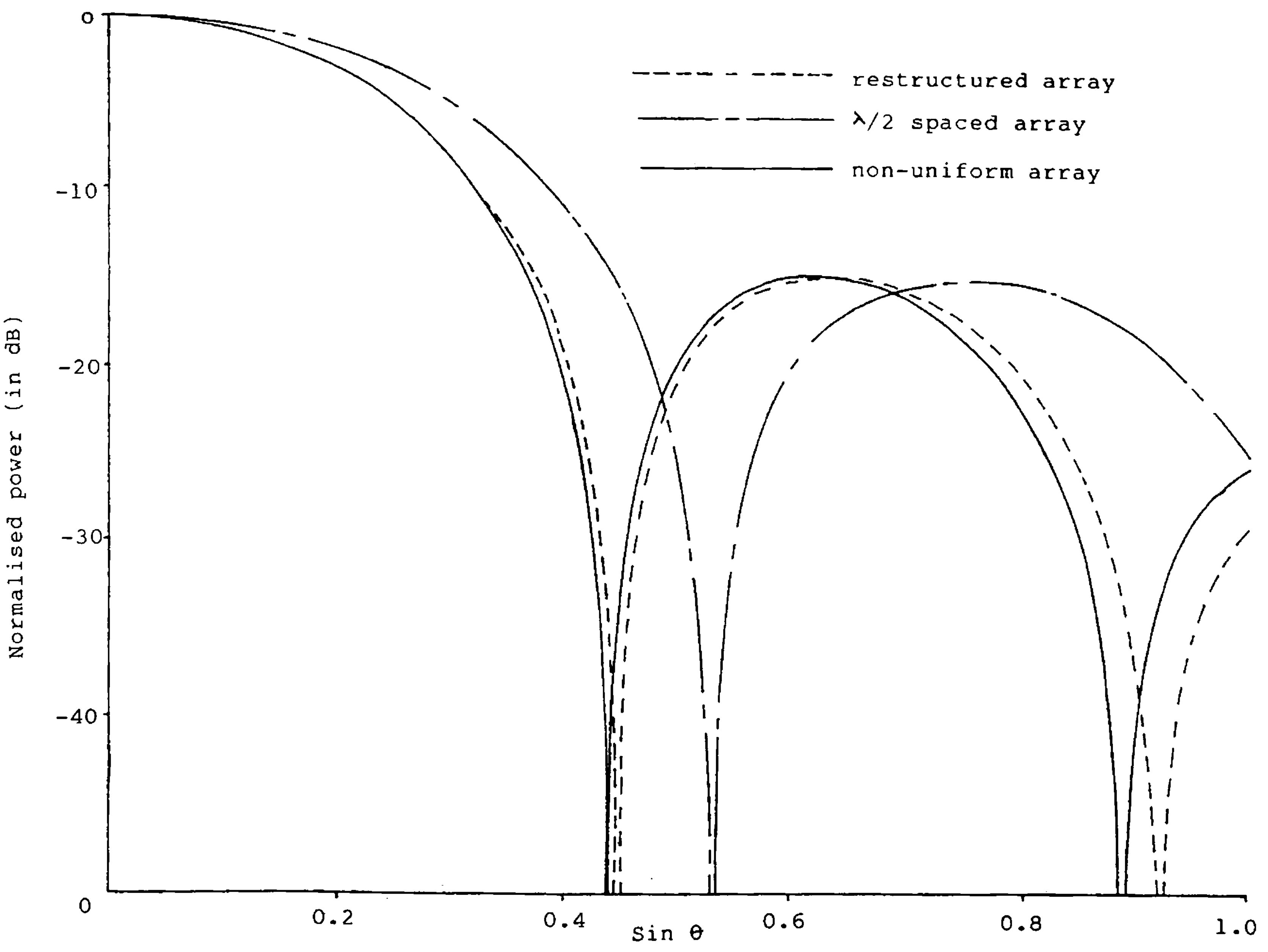


Fig.3.13: The beam pattern of 19 element circular array

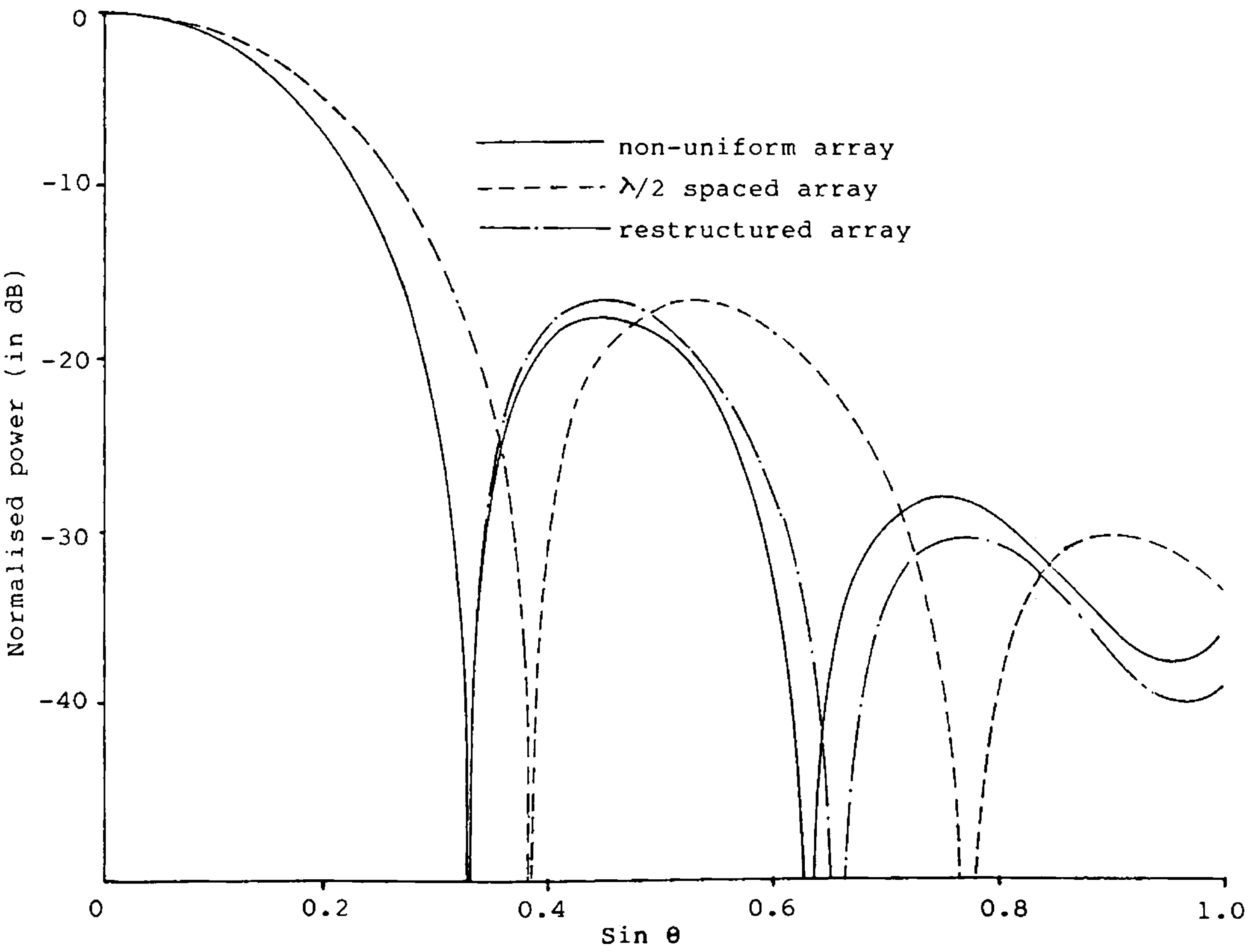


Fig.3.14: The beam pattern of 37 element circular array (at Ø = 0°)

Table 3.3: A comparative study of relevant transmitting/receiving parameters of various non-uniformly spaced planar arrays with that of $\lambda/2$ spaced and restructured arrays

Number of elements in the planar array	Recommended interelement spacings of the non-uniform array (in one direction) $d_1, d_2, \dots, d_{N-1}$ (in λ)	% reduction in interaction force of non-uniform array with		Peak sidelobe level (at $\emptyset$ = 45°) (in dB)			Array gain (in dB)		
		$\lambda/2$ spaced array	Restructured array	$\lambda/2$ spaced array	Restructured array	Non-uniform array	$\lambda/2$ spaced array	Restructured array	Non-uniform array
4 x 4	0.681, 0.604, 0.629	40.60	12.00	-22.60	-22.82	-21.68	13.51	14.78	14.70
5 x 5	0.769, 0.69, 0.717, 0.675	21.46	16.00	-24.08	-24.08	-23.68	15.28	17.51	17.45
6 x 6	0.643, 0.564, 0.590, 0.549, 0.60	37.62	17.15	-24.85	-24.85	-23.69	17.16	18.23	18.12
10 x 10	0.699, 0.62, 0.647, 0.606, 0.657, 0.697, 0.686, 0.684, 0.577	35.20	20.00	-25.93	-25.93	-24.42	21.73	23.70	23.72
15 x 15	0.694, 0.615, 0.642, 0.599, 0.651, 0.692, 0.681, 0.679, 0.571, 0.648, 0.625, 0.599, 0.62, 0.598	19.15	12.10	-26.26	-26.26	-25.21	25.26	27.21	27.18
20 x 20	0.689, 0.609, 0.636, 0.593, 0.645, 0.686, 0.675, 0.673, 0.564, 0.642, 0.618, 0.592, 0.614, 0.592, 0.614, 0.632, 0.62, 0.652, 0.602	26.92	13.00	-26.38	-26.38	-25.39	27.86	29.90	29.92

Table 3.4: A comparative study of the significant parameters of various non-uniformly spaced circular arrays with λ/2 spaced and restructured arrays

Number of elements in the circular array (N)	Recommended radius of the circles measured from the centre of the array $R_1, R_2, \ldots\ldots\ldots R_{m-1}$ (in λ)	% reduction in interaction force of non-uniform array with		Peak sidelobe level (at Ø = 0°) (in dB)			Array gain (in dB)		
		λ/2 spaced array	Restructured array	λ/2 spaced array	Restructured array	Non-uniform array	λ/2 spaced array	Restructured array	Non-uniform array
19	0.615, 1.06, 1.186	38.50	20.70	-14.92	-14.92	-14.95	10.49	10.92	10.89
37	0.562, 1.042, 1.13, 1.578, 1.761	47.30	31.27	-15.78	-15.78	-16.50	11.31	13.76	13.51
61	0.678, 1.197, 1.401, 1.86, 2.149, 2.429, 2.571, 2.836	34.31	16.27	-16.13	-16.13	-16.66	15.41	16.41	16.36
91	0.671, 1.161, 1.394, 1.792, 2.01, 2.393, 2.488, 2.693, 2.81, 3.21, 3.43	46.64	34.87	-16.30	-16.30	-16.64	17.13	18.08	17.95

with a specific distribution by assigning the minimum force spacing (d_{min}) as the mean and keeping the array dimension same as that of the restructured array. It is found on evaluation that the gaussian distributed array exhibits an acceptable performance, as regards to the interaction force is concerned.

Various planar arrays of square and circular radiating apertures have been evolved and its transmission characteristics are studied. These arrays do not exhibit any degradation in its beam characteristics, except for a slight increase in the sidelobe level at far outside the main beam. This is well evident from the beam patterns of 6 x 6 and 10 x 10 element square radiating aperture arrays and 19 and 37 element circular radiating aperture arrays, which are shown in Figs.3.15, 3.16, 3.17 and 3.18 respectively.

The recommended spacings of various planar arrays of square and circular radiating apertures are tabulated in Tables 3.5 and 3.6 respectively along with other parameters such as peak sidelobe level, array gain, percentage reduction in interaction force etc.

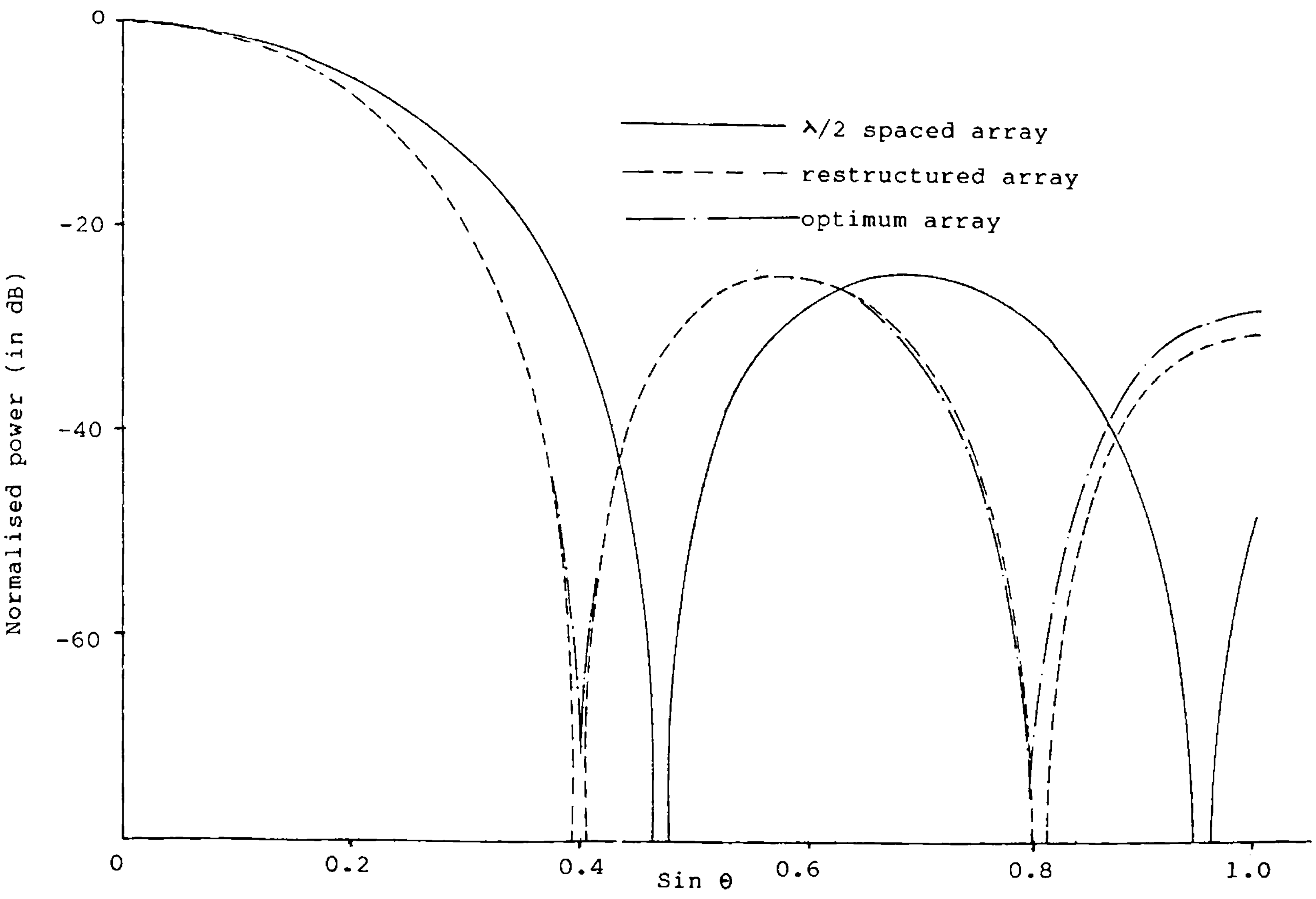


Fig.3.15: The beam pattern of 6 x 6 element planar array (at Ø = 45°)

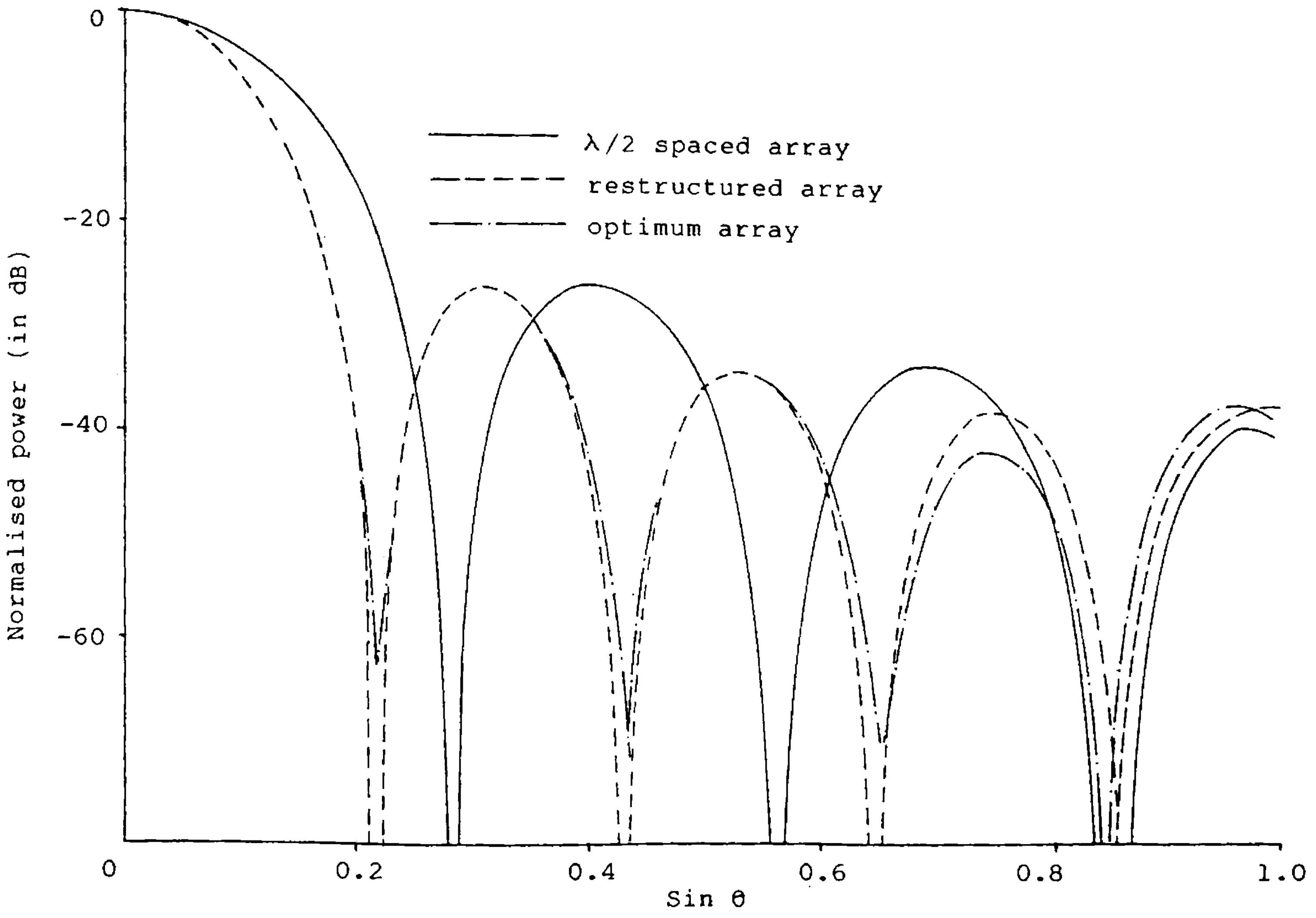


Fig.3.16: The beam pattern of 10 x 10 element planar array (at Ø = 45°)

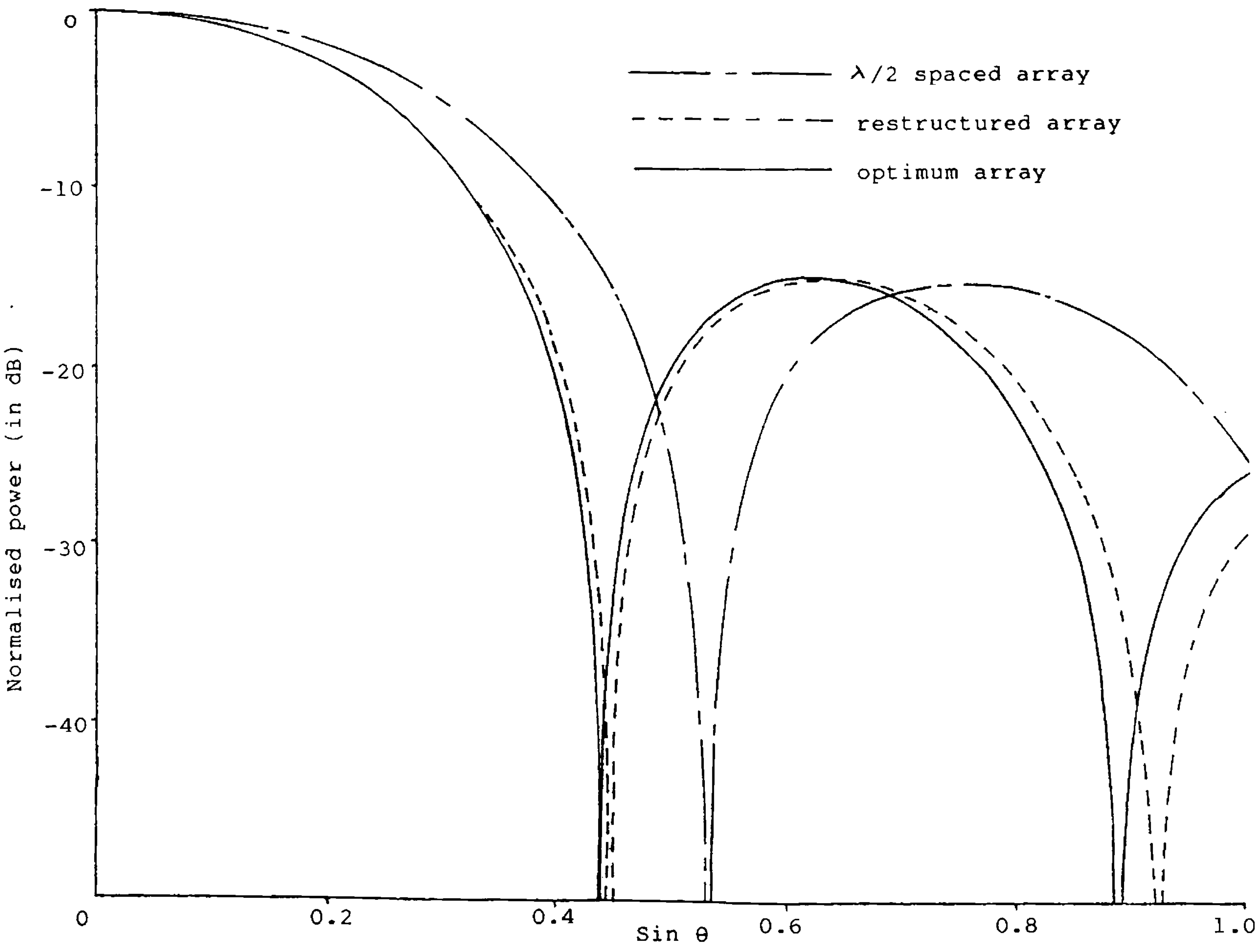


Fig.3.17: The beam pattern of 19 element circular array

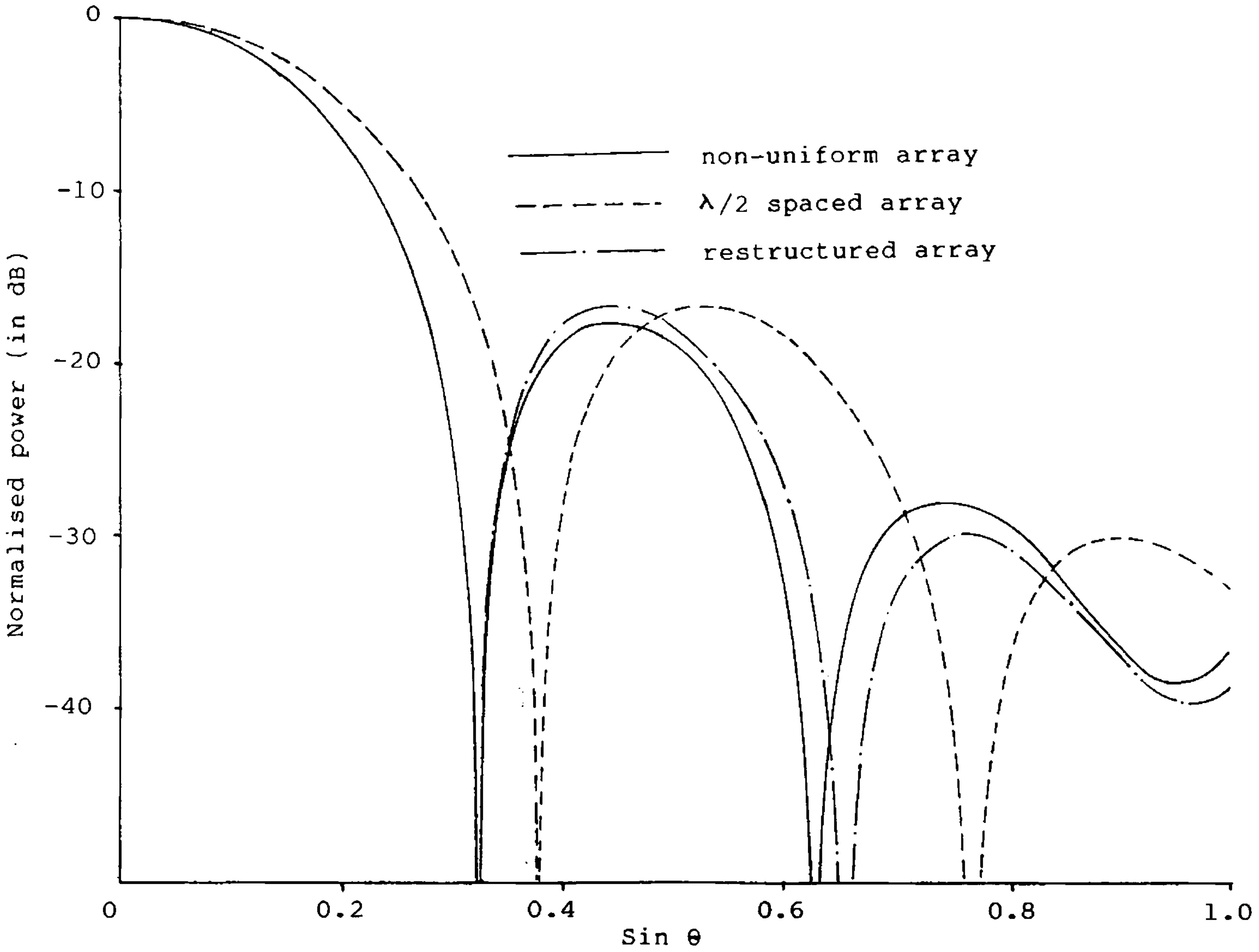


Fig.3.18: The beam pattern of 37 element circular array (at Ø = 0°)

Table 3.5: The significant parameters of $\lambda/2$ spaced, restructured and optimum planar arrays

Number of elements in in the planar array	Recommended interelement spacings of the optimally formulated array (in one direction) $d_1, d_2, \ldots\ldots, d_{N-1}$ (in λ)	% reduction in interaction force of the optimally formulated array		Peak sidelobe level (at $\emptyset = 45°$) (in dB)			Array gain (in dB)		
		$\lambda/2$ spaced array	Restructured array	$\lambda/2$ spaced array	Restructured array	Optimum array	$\lambda/2$ spaced array	Restructured array	Optimum array
4 x 4	0.646, 0.599, 0.669	44.76	18.17	-22.60	-22.82	-21.76	13.51	14.785	14.71
5 x 5	0.71, 0.664, 0.733, 0.745	18.28	12.60	-24.08	-24.08	-23.63	15.28	17.51	17.42
6 x 6	0.60, 0.553, 0.631, 0.635, 0.538	36.07	15.10	-24.85	-24.85	-23.74	17.16	18.23	18.10
10x 10	0.678, 0.63, 0.703, 0.714, 0.615 0.618, 0.614, 0.643, 0.661	29.28	12.50	-25.93	-25.93	-24.56	21.73	23.70	23.65
15 x 15	0.671, 0.62, 0.695, 0.707, 0.606, 0.61, 0.605, 0.635, 0.653, 0.603, 0.60, 0.646, 0.639, 0.62	17.52	10.35	-26.26	-26.26	-25.18	25.26	27.21	27.25
20 x 20	0.663, 0.617, 0.69, 0.702, 0.601, 0.604, 0.60, 0.629, 0.648, 0.597, 0.594, 0.64, 0.633, 0.616, 0.573, 0.647, 0.629, 0.629, 0.631	27.34	13.50	-26.38	-26.38	-25.36	27.86	29.90	29.86

Table 3.6: A comparative study of the significant parameters of various optimally formulated circular arrays with $\lambda/2$ spaced and restructured arrays

Number of elements in the circular array (N)	Recommended radius of the circles measured from the centre of the array $R_1, R_2, \dots\dots\dots R_{m-1}$ (in λ)	% reduction in interaction force of optimum array with		Peak sidelobe level (at $\emptyset = 0°$) (in dB)			Array gain (in dB)		
		$\lambda/2$ spaced array	Restructured array	$\lambda/2$ spaced array	Restructured array	Optimum array	$\lambda/2$ spaced array	Restructured array	Optimum array
19	0.620, 1.055, 1.186	40.04	22.69	-14.92	-14.92	-14.93	10.49	10.92	10.86
37	0.560, 1.04, 1.13, 1.58, 1.761	45.61	29.06	-15.78	-15.78	-16.57	11.31	13.76	13.65
61	0.681, 1.212, 1.43, 1.861, 2.094, 2.432, 2.542, 2.836	33.82	15.66	-16.13	-16.13	-16.72	15.41	16.41	16.42
91	0.702, 1.198, 1.391, 1.796, 2.143 2.382, 2.461, 2.725, 2.86, 3.135, 3.43	49.14	37.92	-16.30	-16.30	-16.56	17.13	18.08	17.92

3.5 CONCLUSIONS

It may be worth mentioning that the interelement spacings for the proposed uniform planar arrays are very close to those for the restructured uniform linear arrays which necessitates the feasibility of generating linear arrays from planar arrays. The radiation efficiency of the proposed array formats can be seen to be improved at the expense of slight degradations in the beam characteristics.

CHAPTER 4

DEVELOPMENT OF AN AUTOMATED ARRAY GAIN CONTROL SYSTEM

Chapter 4

DEVELOPMENT OF AN AUTOMATED ARRAY GAIN CONTROL SYSTEM

4.1 INTRODUCTION

The design criteria of sonar projector arrays of various radiating apertures with reduced acoustic interaction effect and thus having improved radiation efficiency have been considered and the results and inferences of these investigations have already been brought out. It is evident from the outcome of the investigations already carried out on linear and planar arrays that the optimum spacings (d_{min}) proposed for each and every array are not same. As the non-uniform array is formulated by assigning these optimum spacings as mean, the element configurations of these arrays are also varying depending on the number of elements in the array. Thus, it seems impossible to generate optimum arrays of lesser number of elements from an array of large number of elements, without sacrificing its transmitting characteristics. A method is proposed, in this chapter, for generating such optimum subarrays from large arrays without sacrificing much of its transmitting/receiving characteristics.

If an N element linear subarray is to be switched from an M element linear parent array, it can take any of the (M-N+1) possible combinations of elements. Thus the effective interaction forces acting on all these combinations have to be computed along with its beam pattern and the best suited combination can be selectively generated.

To illustrate this, the generation of various subarrays from a 50 element linear optimum array is considered. The location and relevant array parameters of various subarrays (SBA) that can be generated from the 50 element linear parent array is shown in Table 4.1.

4.2 GENERATION OF SBA FORMATS

The proposed subarrays can be generated by selectively switching the appropriate elements from the parent array, using a programmable switching system. The greater the number of radiating elements in the SBA format, the higher will be the array gain and hence the maximum achievable range, and the more will be the

Table 4.1: The location and relevant parameters of various subarrays (SBA_1 (4 element), SBA_2 (5 element), ... etc.) that can be generated from a 50 element linear (n_1, n_2, n_3, ... n_{50}) parent array

Number of elements in the subarray	Minimum force spacing (d_{min}/λ)	Location of the subarray in the parent array	% reduction in interaction force of the proposed subarray with		Array gain (in dB)		
			$\lambda/2$ spaced array	Restructured array	$\lambda/2$ spaced array	Restructured array	Subarray
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
4	0.643	n_{20}- n_{23}	68.14	21.69	6.02	6.925	6.91
5	0.707	n_{27}- n_{31}	28.64	8.74	6.99	8.275	8.11
6	0.595	n_{34}- n_{39}	56.75	18.94	7.78	8.45	8.52
7	0.656	n_1 - n_7	48.50	29.68	8.45	9.51	9.48
8	0.697	n_{24}- n_{31}	47.52	9.29	9.03	10.34	10.18
9	0.621	n_{31}- n_{39}	46.13	27.89	9.54	10.42	10.39
10	0.656	n_1 - n_{10}	53.37	21.93	10.00	11.10	11.07

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
11	0.686	$n_{31} - n_{41}$	40.34	20.94	10.42	11.70	11.17
12	0.630	$n_{33} - n_{44}$	52.80	24.36	10.79	11.74	11.59
13	0.659	$n_{27} - n_{39}$	46.36	27.48	11.14	12.28	12.14
14	0.684	$n_{34} - n_{47}$	41.21	9.35	11.46	12.76	12.38
15	0.637	$n_{9} - n_{23}$	31.66	7.85	11.76	12.77	12.78
16	0.662	$n_{16} - n_{31}$	41.93	10.96	12.04	13.21	13.19
17	0.624	$n_{26} - n_{42}$	39.36	19.08	12.31	13.23	13.25
18	0.643	$n_{22} - n_{39}$	49.87	24.18	12.55	13.60	13.61
19	0.662	$n_{19} - n_{37}$	35.56	15.95	12.79	13.95	13.92
20	0.627	$n_{23} - n_{42}$	37.07	6.61	13.01	13.97	14.02
21	0.646	$n_{19} - n_{39}$	41.62	21.27	13.22	14.30	14.28
22	0.662	$n_{24} - n_{45}$	47.01	21.83	13.43	14.60	14.45

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
23	0.633	$n_{19} - n_{41}$	40.05	19.45	13.62	14.81	14.61
24	0.649	$n_{1} - n_{24}$	38.74	10.12	13.80	14.90	14.88
25	0.621	$n_{13} - n_{37}$	32.16	9.61	13.98	14.91	15.10
26	0.637	$n_{17} - n_{42}$	39.80	12.43	14.15	15.17	15.18
27	0.649	$n_{13} - n_{39}$	38.63	17.49	14.31	15.42	15.38
28	0.662	$n_{18} - n_{45}$	37.50	9.89	14.47	15.66	15.52
29	0.640	$n_{11} - n_{39}$	35.24	12.87	14.62	15.67	15.66
30	0.684	$n_{21} - n_{50}$	38.97	14.11	14.77	16.10	15.83
31	0.630	$n_{11} - n_{41}$	34.34	12.05	14.91	15.89	15.86
32	0.643	$n_{16} - n_{47}$	41.47	16.08	15.05	16.12	16.12
33	0.653	$n_{10} - n_{42}$	34.56	12.00	15.19	16.32	16.22
34	0.633	$n_{11} - n_{44}$	43.36	19.26	15.31	16.33	16.32

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
35	0.643	$n_{13} - n_{47}$	35.75	13.76	15.44	16.51	16.50
36	0.656	$n_{13} - n_{48}$	41.25	16.59	15.56	16.70	16.62
37	0.637	$n_3 - n_{39}$	39.33	18.51	15.68	16.71	16.76
38	0.646	$n_8 - n_{45}$	45.72	23.00	15.79	16.89	16.846
39	0.656	$n_{10} - n_{48}$	30.55	6.72	15.91	17.05	16.96
40	0.637	$n_{11} - n_{50}$	38.26	13.09	16.02	17.07	17.077
41	0.649	$n_2 - n_{42}$	35.18	12.93	16.12	17.24	17.18
42	0.657	$n_4 - n_{45}$	36.31	7.51	16.23	17.40	17.28
43	0.640	$n_3 - n_{45}$	35.65	13.60	16.34	17.41	17.39
44	0.650	$n_1 - n_{44}$	35.39	9.11	16.44	17.55	17.47
45	0.656	$n_6 - n_{50}$	30.01	6.02	16.53	17.69	17.59

perturbation arising from the acoustic interaction effect ie., the SBA_1 format is characterised by minimum array gain and interaction and SBA_n has the maximum gain and interaction. These subarrays can be generated in the increasing order of array gain (number of elements) from the parent array depending on the scenario being encountered, with the help of a microprocessor based switching system, the design details of which are described in the next section.

4.3 DESIGN DETAILS OF THE MICROPROCESSOR BASED SWITCHING SYSTEM

An 8085 microprocessor based trainer kit marketed by M/s.Dynalog Microsystems is used for accomplishing the selective switching of various subarray formats and its schematic block diagram is shown in Figure 4.1 [89]. The block diagram of the proposed switching system is shown in Figure 4.2. The transducers are connected to the microprocessor through various output ports and is described in section 4.4. A signal generator whose output is amplified by a power amplifier is used to drive the transducer elements. The same array is used for both transmitting and

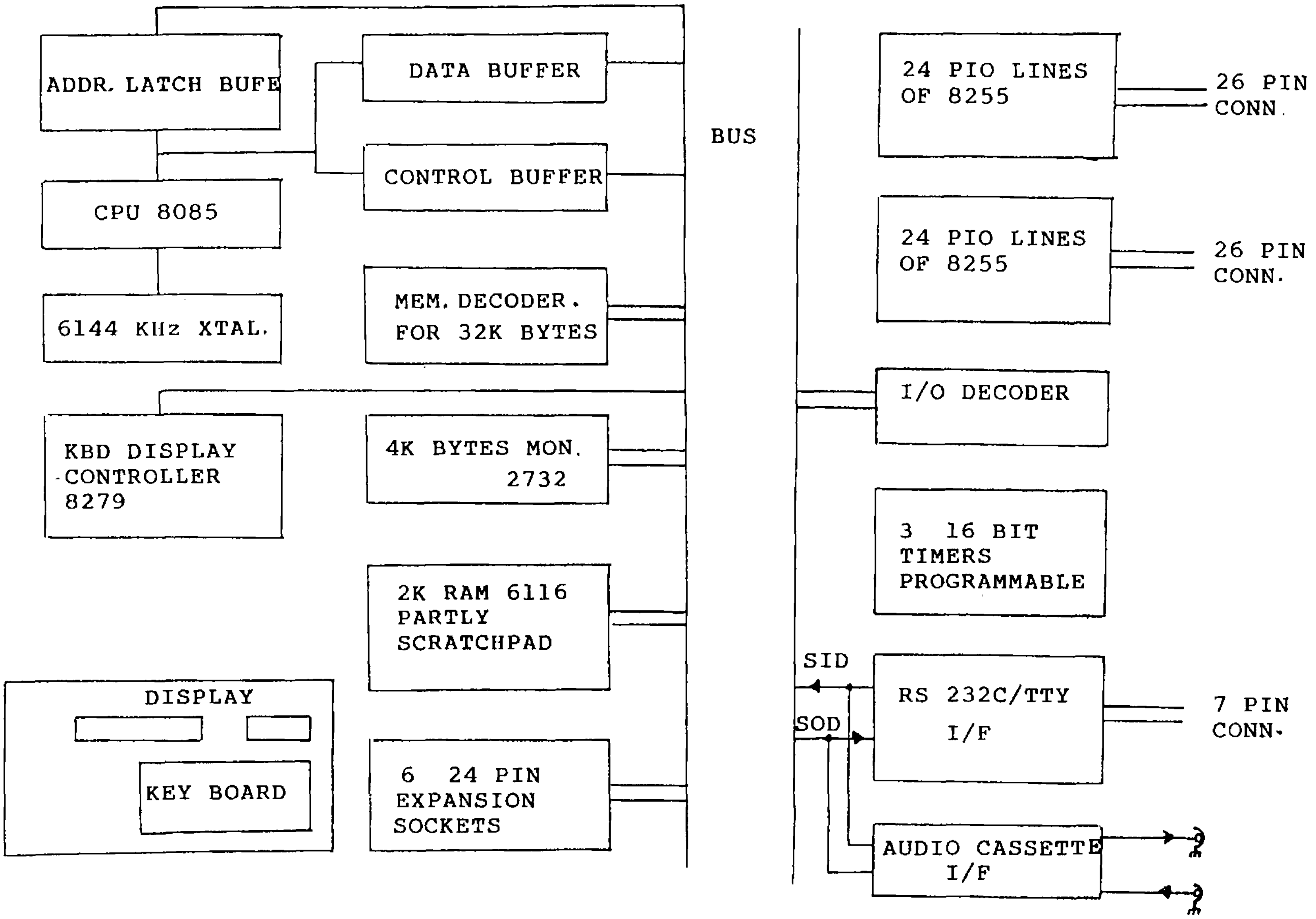


Fig.4.1: Block schematic of 8085 microprocessor based trainer kit marketed by M/s.Dynalog Microsystems
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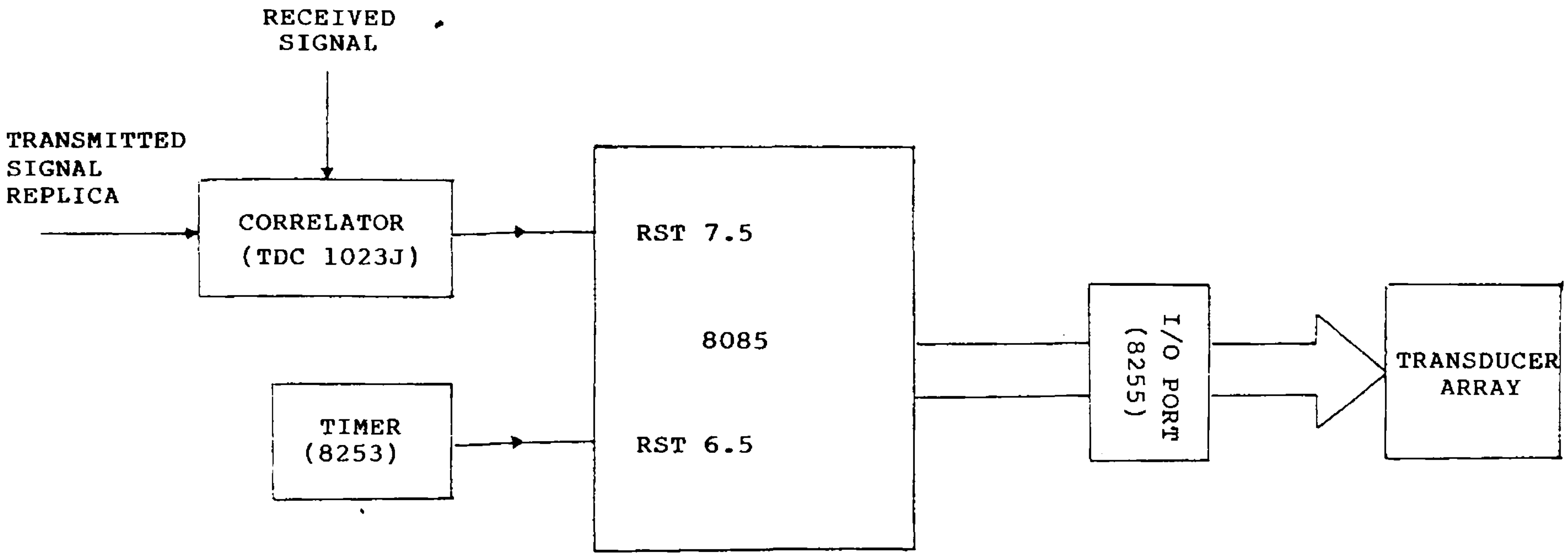

Fig.4.2: Block diagram of the proposed switching system

receiving applications and this can be controlled by using an electronic switch. The two interrupt lines of the processor, namely RST 6.5 and RST 7.5, which are connected to the timer and correlator will give necessary controls for the processor [89-96].

4.4 SWITCHING OF TRANSDUCERS

The transducer elements are connected to the microprocessor through various output ports. This is done with the help of 8255, programmable peripheral interface device. It has 24 programmable I/O pins. This chip is a very powerful tool for interfacing peripheral equipment to the microcomputer system and is flexible enough to interface almost any I/O device without the need of additional external logics. Various modes of operations are also possible [89-97].

The transducers are connected as shown in Figure 4.3. Port A and Port B of 8255 is used for switching the transducers. 8282 is used as a latching unit. The Port A (8255) is used for data transfer and Port B (8255) is used for chip selection ie., each chip (8282) can be enabled by using a single line of Port B.

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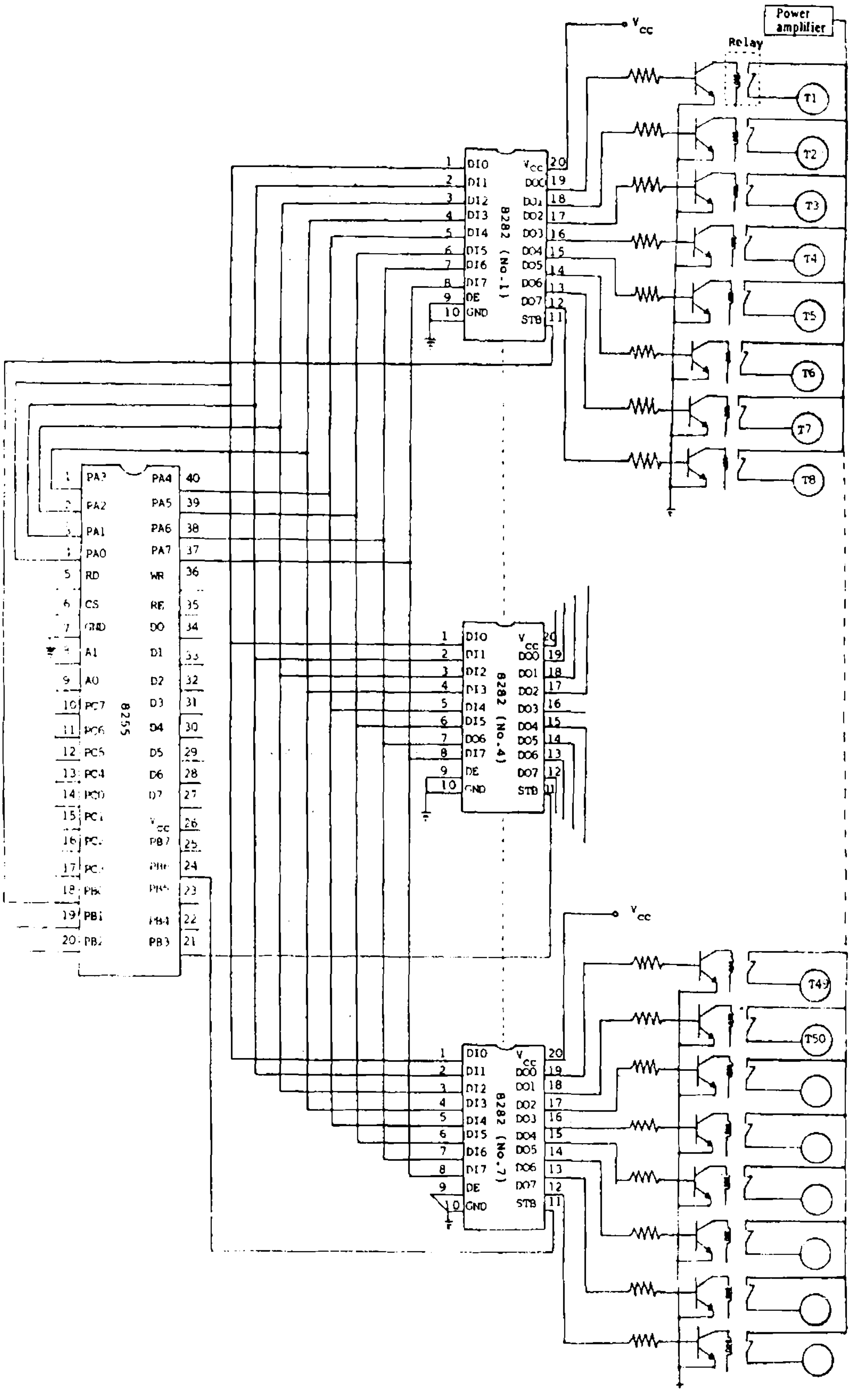

Fig.4.3: Port connections for element switching

As the 8 output pins of 8282 can be used for switching 8 transducers, seven 8282 chips are used parallely for controlling the entire 50 elements of the parent array. Thus, by keeping the required value on the data line (Port A) and by enabling the particular chip select pin (Port B), it is possible to switch any transducer in the parent array. The output of the latching unit which is used to control the transducers, through the associated transistor and relay is also shown here.

4.5 ECHO DECISION USING CORRELATOR--TDC 1023J

The correlation technique is used for detecting the presence of an echo. The magnitude of the correlation coefficient obtained by correlating the receiver output with the stored replica of the transmitted signal, is sensed by the microprocessor for decision making. This is achieved by using the digital correlator TDC 1023J of M/s.Arrow Electronics International, USA [98].

The block diagram of the correlator is shown in Figure 4.4. It can perform 64 bit correlation at 20 MHz. The digital version of the transmitted signal

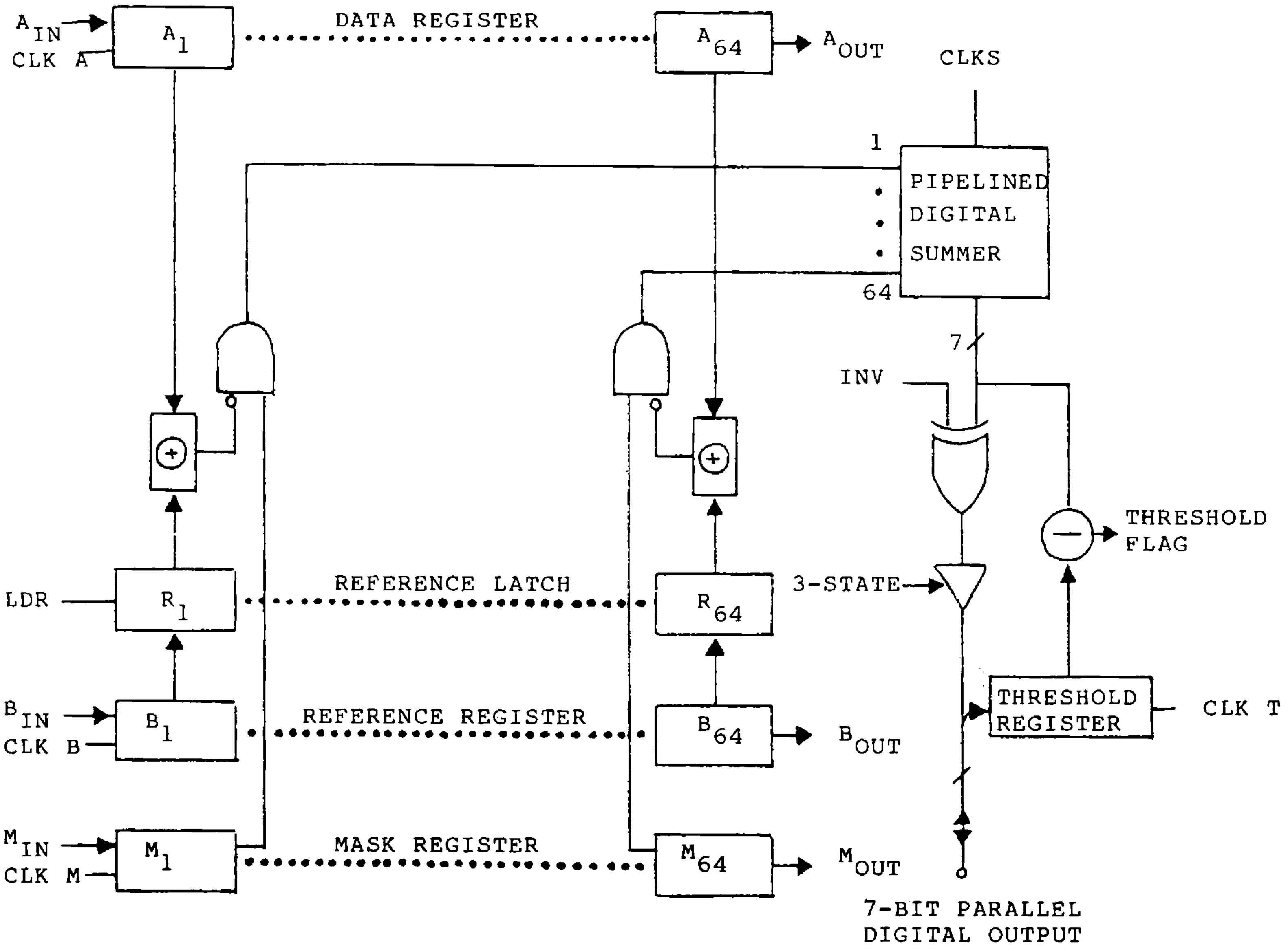

Fig.4.4: The block diagram of the Digital Correlator TDC 1023J

can be loaded into the reference register and can be transferred to the reference latch. The digitized received signal is loaded into the data register and the correlation of this with the stored replica of the transmitted signal can be taken by using clock 'S'. The correlation between the contents of the data register and reference latch is determined by comparing bit for bit using EX-NOR gates and the digital sum of this correlation bits will be represented as 7-bit binary word.

Another facility is provided in this correlator for establishing a threshold value. Here, a threshold value can be loaded into the threshold register using clock 'T' and depending on the digital sum of the correlation output, the threshold flag will be activated and this can be directly used to interrupt the processor.

The digital conversion of both transmitted and received signal is done by using the A/D converter 0809 and the serial loading of these bits into the correlator is made using 74165, parallel to serial convertor [97-99]. These conversion and serial loading are controlled by microprocessor through the port 8255 are shown in Figure 4.5

4.6 SWITCHING CONTROL USING TIMER 8253

To ascertain the suitability of a particular subarray format, say SBA_1 generated from a parent array for a given scenario, this format has to be generated and retained undisturbed for a predetermined time for arriving at the echo decision. The required timing signals for performing this task are generated with the help of the timer 8253.

The usual switching time given for a particular subarray is 2 seconds. After this predetermined time, the microprocessor will generate the next subarray. If a target is detected, the system will retain that subarray for some more time, of the order of a minute, for detailed observation and tracking purposes.

The programmable timer 8253 is organised as 3-independent 16-bit presettable, down counters and all modes of operations are programmable. This counter can

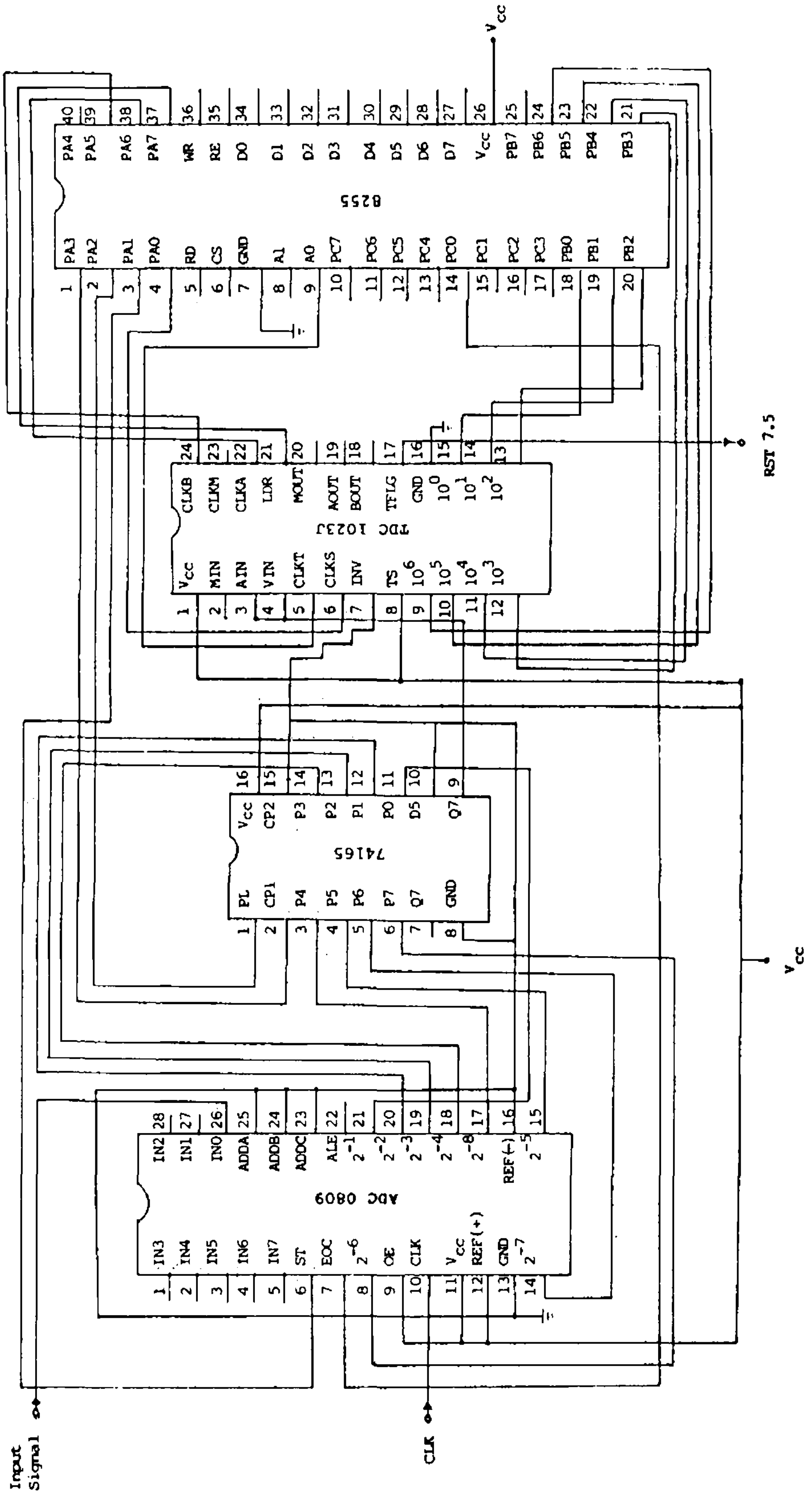

Fig.4.5: Block diagram of the echo decision subsystem

operate in either Binary or Binary Coded Decimal (BCD) and its input, gate and output can be configured by the selection of modes stored in the control word register [89].

An input signal of known frequency has to be given externally and the system clock (3.074 MHz) is selected for this. Eventhough the maximum value (FFFF H) is loaded in the counter, it can generate only a signal of pulse length 0.0213 seconds. Thus, two counters are connected serially, ie., the output of counter 1 is given as the input of counter 2 and by loading appropriate value in these counters, it is possible to generate 2 seconds and 1 minute timing signals. The connections are made as shown in Figure 4.6. The mode is selected in such a way that on termination of the counting, the output will be low for one period of input clock. The program for generating 1 minute timing signals is given in Appendix II.

4.7 SELECTIVE SWITCHING OF THE ARRAY

On initialisation, the system will first generate the SBA_1 whose array gain and interaction

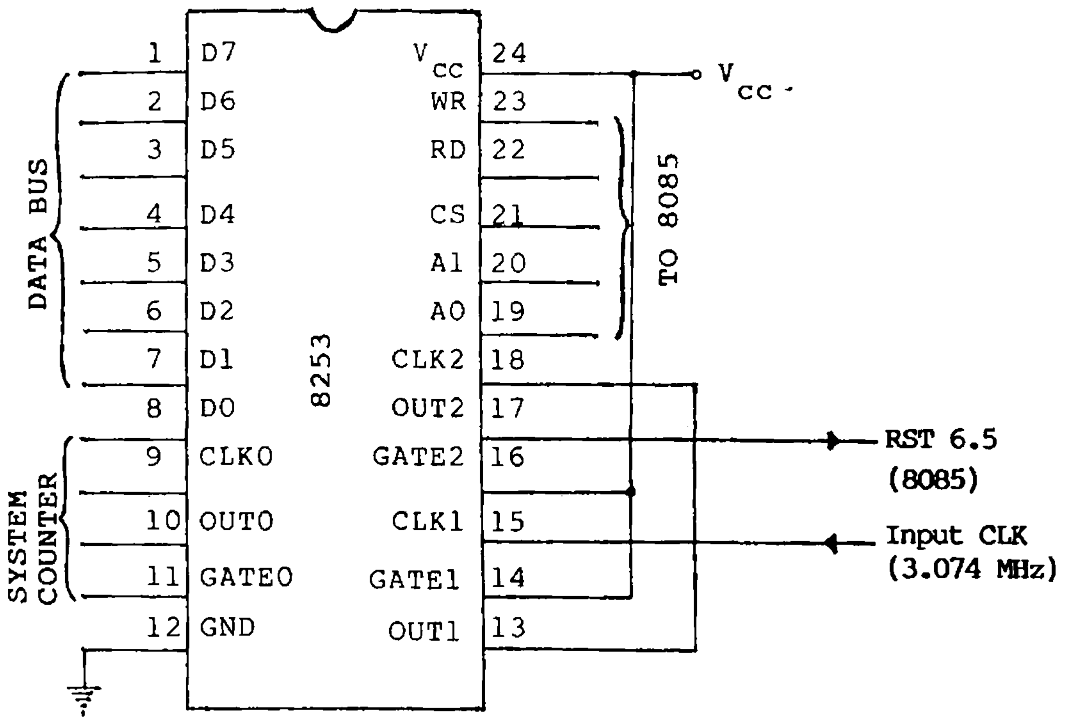

Fig.4.6: Timing signal generator

effect are comparatively low and when connected in transmitting mode, it will send a tone burst. The digital version of the transmitted signal will be stored in the reference register of the correlator. After transmitting the signal, the SBA_1 will be switched into the receiving mode and will wait for the target echo for the predetermined duration, say 2 seconds. The digitized received signal will be loaded into the data register of the correlator and the correlation of this with the contents of the reference register will be taken continuously till the next switching is performed. If the correlation value is below the correlation threshold, as fixed by the user, the 2 seconds timing signal will pull the RST 6.5 interrupt and the processor jumps to the corresponding address location and it transfers the switching control to SBA_2.

If the correlation value is well above the detection threshold, the correlator pulls the RST 7.5 interrupt and the processor suspends the generation of subsequent SBA formats. The RST 7.5 subroutine will generate the 1 minute timing signals, which facilitates detailed observation and tracking.

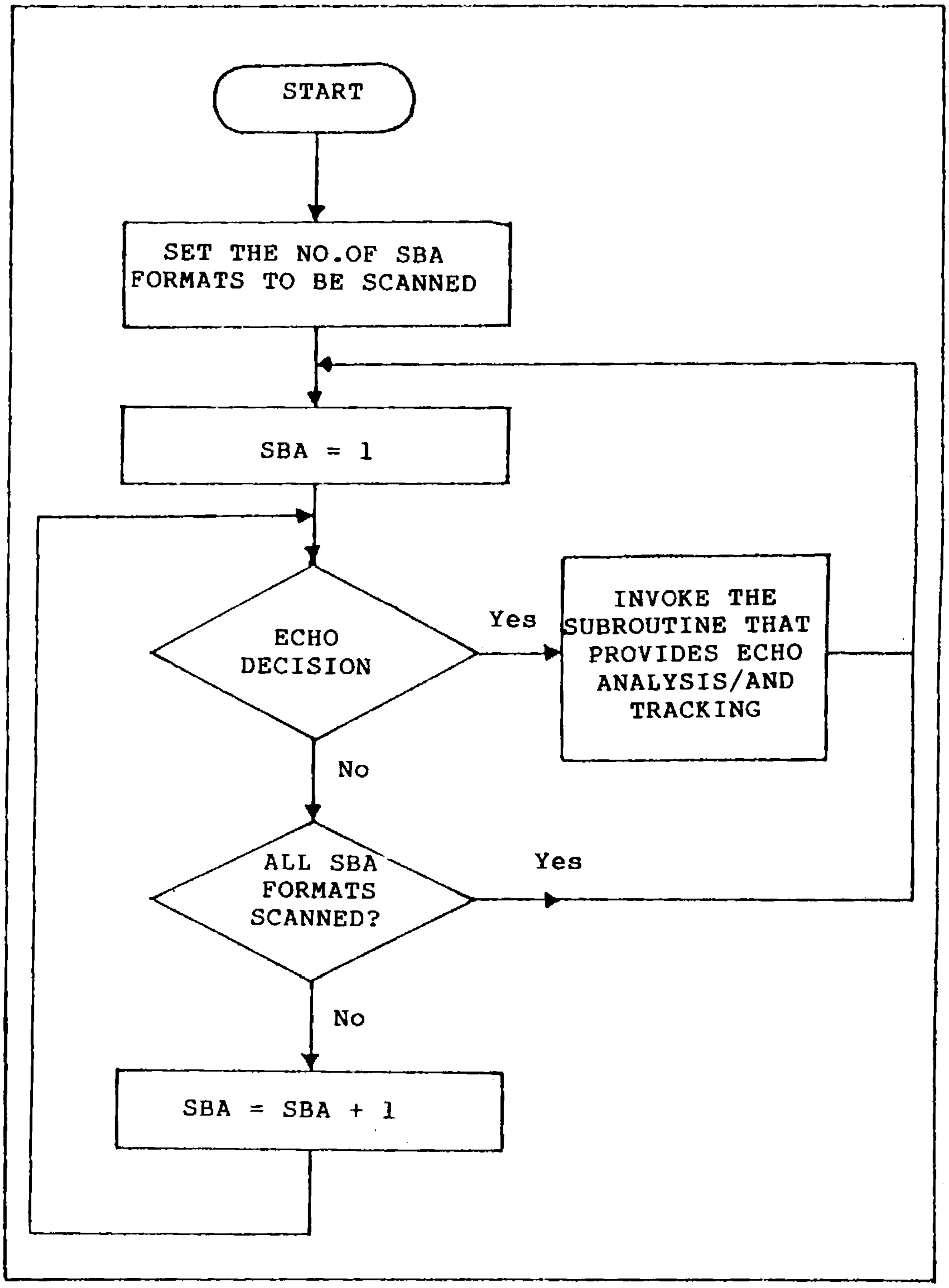

Fig.4.7: The flow chart accomplishing the echo decision

The process of checking the suitability of an SBA format for target detection is continued, by scanning from SBA_1 to SBA_n, until a target, if any, is sensed by the receiving system. When all the SBA formats are scanned completely, the system re-scans from SBA_1 to SBA_n again, until operator indicates some other sequences. The flow chart for accomplishing the echo decision is shown in Figure 4.7. The detailed machine language program for performing the switching of various SBA formats for accomplishing the decision making is given in Appendix III.

4.8 CONCLUSIONS

The capability of the switching system described here can be enhanced by using more latching units (8282) in parallel. The accuracy in analysing the echo can also be increased by connecting more correlator chips (TDC 1023J) serially.

A close observation of the results and inferences presented in this chapter clearly reveals the suitability of the proposed switching mechanism for generating the required subarray format from the given parent array, depending on the scenario under consideration.

CHAPTER 5

SIMULATION PACKAGE FOR ARRAY DESIGN

Chapter 5

SIMULATION PACKAGE FOR ARRAY DESIGN

5.1 INTRODUCTION

The transmitting and receiving characteristics of transducer arrays depend on various factors like its geometry, number of elements, source strength, relative phases of the elements etc. Array with narrow main beam and low sidelobes is desirable for a variety of applications. But these are conflicting requirements. One of the requirements can be achieved only at the cost of the other. It is the designer's choice to select the parameters depending on the nature of application.

The basic assumptions made for the theoretical predictions of the performance of an array may not be exactly correct in practical implementation, due to the electrical and mechanical limitations. Due to this, the measured array parameters are found to differ from the theoretically formulated ones. Hence, an array design package has been developed and presented in this chapter for predicting the optimum array, based on the requirements of the user, taking into account the inferences and conclusions arrived at from the studies on acoustic interaction effect experienced in different array systems.

5.2 SOFTWARE PACKAGE

In order to reduce the computational burden and to make the package more user friendly, the array design software has been split into different modules, each module carrying out a specific task. The major sub-programs will help in:

(a) array shape selection

(b) element shape selection

(c) reading in and modification of input parameters

(d) design calculations and

(e) display of results.

The modules are written in such a way that the user is prompted for all the input parameters, whenever a choice exists, and a menu is displayed showing the various alternatives [100-102]. The flow chart which facilitates the array design is shown in Figure 5.1.

5.2.1 Module I: Array Shape Selection

Interaction effect acting on an array is mainly depending on its array geometry. This effect is much pronounced in closely packed arrays and are greater for planar arrays than curved ones. For example, in a large planar array, the combined interaction from the distant transducer elements can be smaller when compared to that from the nearest transducers, while it might be negligible in a curved array [34].

This module allows the user to choose the required shape of the array from various alternatives. Initially, a menu is displayed, listing the various alternatives and prompting for the user's choice. Once the choice is made, the relevant parameters of the array are loaded into the system.

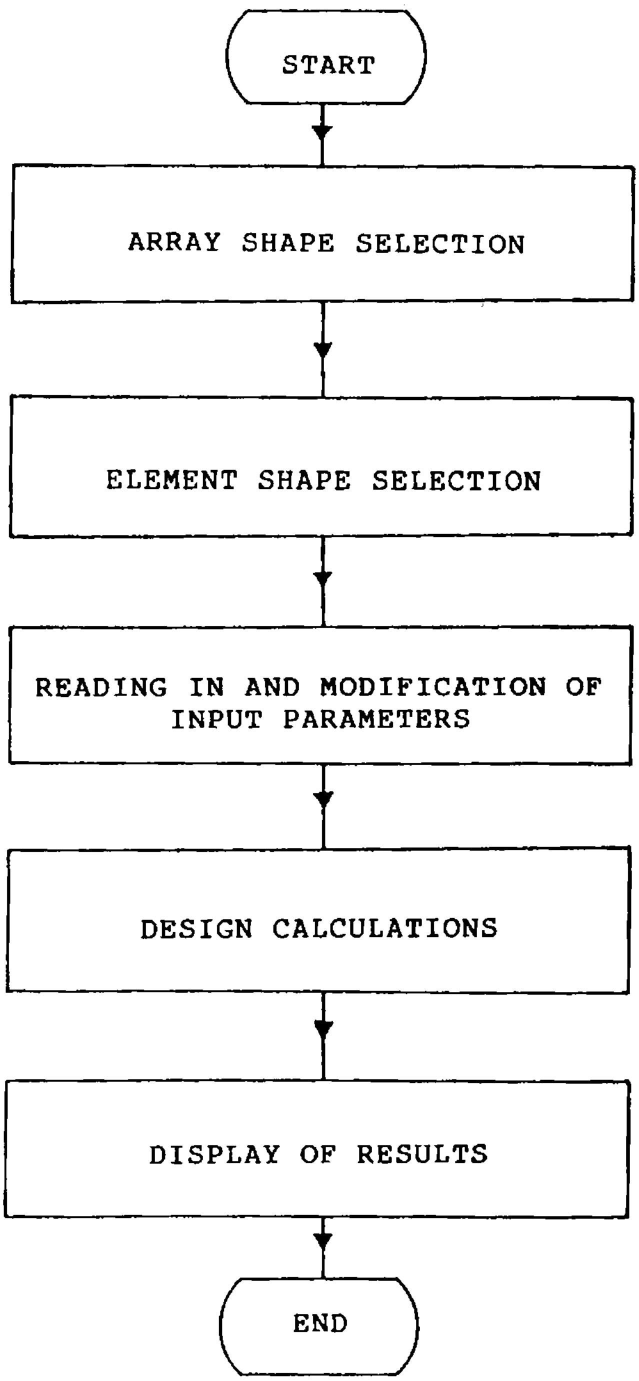

Fig.5.1: Flow chart accomplishing the array design

The shapes available in this package are:

i) linear array

ii) planar array--circular/square/rectangular
radiating aperture.

5.2.2 Module II: Element Shape Selection

From equation (2.4), it is clear that the magnitude of the interaction force is a function of the element shape. Thus, for designing the optimum array, the shape of the element should also be taken into account.

Using this module, the user can choose suitable shapes of individual transducers.

For the selection of the shapes of the transducers, three alternatives are provided. A menu is displayed, listing the various alternatives and prompting the user for the choice. The element shapes available in this package are:

1) rectangular disc
2) square disc
3) circular disc

5.2.3 Module III: Reading in and Modification of Input Parameters

Once the shape of the array and shape of the element have been finalised, the user has to feed in other relevant array parameters. The program prompts the user for each parameter.

The initial reading is done in two screens. In the first screen the program asks for the dimensions of the elements, depending on the shape of the element already chosen. For example, if the element shape chosen is rectangular disc, the program prompts the user for length, breadth and thickness of the element. In the same screen, the number of elements to be used in the array is also required to be read into the system.

In the second screen, the dimension of the array has to be specified. For example, if the shape of the array chosen is rectangular, the number of elements in the X-direction and the number of elements in the Y-direction are required for the program. If it is a circular array, the number of circles and elements in each circle are required.

Once a set of parameters has been entered and a result obtained, the user can vary any one of the input and re-execute the program to see the effect of that change. For facilitating this change of variables, the program prompts the user by displaying the dimension to be changed along with the current value in brackets.

5.2.4 Module IV: Design Calculations

This module has absolutely no interaction with the user. Once all the choices have been made and the parameters loaded, this module is invoked by the program. This module carries out all the necessary mathematical computations required to predict the optimum element configuration, satisfying the requirements of the user.

5.2.5 Module V: Display of Results

This module displays the result, once the design calculations are over. It also displays the options made by the user as well as the parameters entered along with the percentage reduction in interaction force.

The results are displayed in four screens. In the first screen, array details are displayed. This includes the number of elements, shape of the array, shape of the elements etc.

The second screen provides the optimum element configuration of the array. This gives the spacing between each and every element. This also provides an option for displaying the pictorial representation of the distribution of elements for very small arrays.

The third screen displays the beam patterns of both conventional $\lambda/2$ spaced array and optimally formulated array. This enables the designer to make a comparative study of the sidelobe levels and beamwidths of both arrays.

The fourth screen provides a comparative study of the array performances in both transmitting and receiving applications. Here, the percentage reduction in interaction force, the array gain, beamwidth and most intense sidelobe levels of both conventional $\lambda/2$ spaced array and optimally formulated array are tabulated.

5.3 CONCLUSIONS

A computer simulation package has been developed for predicting the optimum array as per the user's requirements. This package contains only limited menu for selecting the parameters. The capability of this package can be enhanced by incorporating additional facility for selecting the other factors such as material specifications, other array shapes like curved apertures, cylindrical arrays etc.

CHAPTER 6

CONCLUSIONS

Chapter 6

CONCLUSIONS

6.1 INTRODUCTION

This thesis addresses the design procedure to be adopted for evolving sonar projector arrays with reduced acoustic interaction among the radiating elements of closely packed projector arrays. An overview and consolidation of the results of investigations carried out on sonar projector array designs, taking into account the acoustic interaction effect, along with the highlights and scope for developments is brought out in this chapter. It has been seen that the approach presented in the preceeding chapters will be of great use in designing underwater transducer arrays, for high power applications.

6.2 BRIEF SURVEY OF THE WORK TOWARDS THE SCOPE FOR FUTURE DEVELOPMENTS

A novel, but simple technique to reduce the interaction effect in linear projector arrays is presented in chapter 2. In almost all array designs, reported in open literature, identical elements are closely spaced with an interelement spacing of about 0.5λ, where λ is the wavelength of acoustic radiation at the design frequency. From the spatial variation of interaction force, shown in Figures 2.1 and 2.2, it is evident that the force acting on the conventional λ/2 spaced array is much higher, and this can be reduced by restructuring it with some other suitable spacings, where the interaction force is less. These optimum spacings for different linear arrays and other relevant array parameters have also been worked and brought out in this chapter for validating the practicability of the restructuring of array formats, for improving the efficiency of sonar projector arrays.

The procedure that has been adopted for minimising the interaction effect in linear projector arrays has been extended to the case of planar arrays and the results are presented in chapter 3.

A microprocessor based switching system for generating various subarray formats from a 50-element linear array is presented in chapter 4. The inaccuracies in the decision making of a correlation based system can be reduced by using a digital correlator TDC 1023 J, marketed by M/s.Arrow Electronics International, USA. The accuracy can be further increased by connecting more correlator chips serially so that the register size of the correlator can be enhanced. The switching system can also be effectively utilised for beam steering by incorporating the necessary support hardware/software.

The switching system can be hooked-up to a personal computer such that higher level languages can be used for controlling the switching.

A computer simulation study has been made for predicting the optimum array as per the user's requirements and is discussed in chapter 5. Here, the software package has been formulated with minimum descriptors for selecting the parameters. The capability can be increased by incorporating additional facility for choosing the various types of elements, different materials and also large number of other shapes.

6.3 HIGHLIGHTS

The highlights of this thesis are brought out as follows:

1. A novel, but simple and effective method for evolving linear array with reduced interaction effect is presented by restructuring it with appropriate interelement spacings.

2. The impact of the proposed structural modifications on the beam characteristics has been studied and are found to be unaffected much.

3. Array gain, one of the key parameters which measures the performance of the receiving array, is found to be unaffected.

4. The radiation efficiency of the restructured and random arrays has been seen to be improved much.

5. The proposed approach for reducing the interaction effect in linear arrays is extended to the case of planar arrays also.

6. It may be worth mentioning that the interelement spacing for the proposed uniform planar arrays are very close to those for the restructured uniform linear arrays, which necessitates the feasibility of element switching with planar array.

7. A microprocessor based switching system to synthesise any desired subarray format has been suggested and developed.

8. A computer simulation study has been undertaken for predicting the optimum element configuration based on the requirements of the user.

APPENDICES

Appendix I

APPLICATIONS OF UNDERWATER SOUND

Military Applications

Sl.No.	Function	Description
(1)	(2)	(3)
1.	Acoustic Mines	Acoustic mines deployed in the sea are sensors of acoustic radiation. They explode when the acoustic level in its passband reaches a critical value.
2.	Sonobouys	Small sonar sets used for echo ranging.
3.	Submarine detection, location and tracking	Locating the submarine and observing its path.
4.	Underwater telephone	Used for underwater communication, between a ship and submarine and among submarines.
5.	Mine detonation	The acoustic mines deployed by the enemies are purposely exploded.
6.	Homing Torpedoes	Make use of moderately high frequencies.

Non-Military Applications

(1)	(2)	(3)
1.	Fish finding	Detection, location and classification of fish shoals
2.	Side scan sonar	Mapping the sea bed at right angles to ship's track.
3.	Non-destructive testing	
4.	Doppler Navigation	Doppler shift of the bottom returns determines the speed over the bottom
5.	Communication and telemetry	Transmitting information
6.	Manipulator Arms	To lay underwater cables
7.	Bathy thermograph	For measuring temperature
8.	Velocimeter	Measuring velocity of sound
9.	Diver's Aids	Small hand-held sonar sets for underwater object location by divers
10.	Acoustic flow meter	Measuring speeds of currents.

Appendix II

Program for generating 1 minute timing signal

Location (1)	OP Code (2)	Mnemonic (3)	Comments (4)
1200	3E 79	MVI A, 79	Sets-up the counter 1
1202	D3 0F	OUT 0F	
1204	3E 80	MVI A, 80	Loads the counter 1 with the count value (A980H)
1206	D3 0D	OUT 0D	
1208	3E A9	MVI A, A9	
120A	D3 0D	OUT 0D	
120C	3E B9	MVI A, B9	Sets-up the counter 2
120E	D3 0F	OUT 0F	
1210	3E FC	MVI A, FC	Loads the counter 2 with the count value (15 FCH)
1212	D3 0E	OUT 0E	
1214	3E 15	MVI A, 15	
1216	D3 0E	OUT 0E	

Appendix III

Program for performing the switching of various SBA formats for accomplishing the decision making

Location	OP Code	Mnemonic	Comments
(1)	(2)	(3)	(4)
1000	31 FF17	LXI SP, 17FF	Initialises the Stack Pointer
1003	01 0F00	LXI B, 000F	Loads the Incremental Address
1006	21 0015	LXI H, 1500	Loads Starting Address of the Switching Program
1009	3E 2C	MVI A, 2C	Loads the total number of subarrays to be generated
100B	F5	PUSH PSW	Push Stack
100C	C5	PUSH B	
100D	E5	PUSH H	
100E	3E 80	MVI A, 80	Sets-up the port 8255 (No.2)
1010	D3 0B	OUT 0B	
1012	3E 1E	MVI A, 1E	Switches SBA_1 (4 Element Array)
1014	D3 08	OUT 08	
1016	3E 04	MVI A, 04	
1018	D3 09	OUT 09	
101A	3E 81	MVI A, 81	Sets-up the port 8255 (No.1)
101C	D3 03	OUT 03	

(1)	(2)	(3)	(4)
101E	3E 00	MVI A, 00	Switching the array into transmitting mode
1020	D3 01	OUT 01	
1022	3E 76	MVI A, 76	Generates the 2 seconds timing signal
1024	D3 0F	OUT 0F	
1026	3E A0	MVI A, A0	
1028	D3 0D	OUT 0D	
102A	3E CF	MVI A, CF	
102C	D3 0D	OUT 0D	
102E	3E B6	MVI A, B6	
1030	D3 0F	OUT 0F	
1032	3E 5D	MVI A, 5D	
1034	D3 0E	OUT 0E	
1036	3E 00	MVI A, 00	
1038	D3 0E	OUT 0E	
103A	FB	EI	Enables the interrupt
103B	3E 10	MVI A, 10	Loads the threshold value for the Correlator
103D	D3 01	OUT 01	
103F	3E 00	MVI A, 00	
1041	D3 00	OUT 00	
1043	3E 01	MVI A, 01	

(1)	(2)	(3)	(4)
1045	D3 00	OUT 00	
1047	3E 00	MVI A, 00	
1049	D3 00	OUT 00	
104B	0E 08	MVI C, 08	Loop 1 begins
104D	3E 02	MVI A, 02	Initiates and Monitors A/D conversion of the transmitted signal
104F	D3 00	OUT 00	
1051	06 01	MVI B, 01	Loop 2 begins
1053	DB 02	IN 02	
1055	A0	ANA B	
1056	C2 5310	JNZ 1053	Initiates loop 2
1059	3E 04	MVI A, 04	Generates shift/load pulse of 74165
105B	D3 00	OUT 00	
105D	3E 00	MVI A, 00	
105F	D3 00	OUT 00	
1061	3E 04	MVI A, 04	
1063	D3 00	OUT 00	
1065	16 08	MVI D, 08	Loop 3 begins
1067	3E 2C	MVI A, 2C	
1069	D3 00	OUT 00	
106B	3E 04	MVI A, 04	
106D	D3 00	OUT 00	
106F	15	DCR D	

(1)	(2)	(3)	(4)
1070	C2 6710	JNZ 1067	Initiates Loop 3
1073	OD	DCR C	
1074	C2 4D10	JNZ 104D	Initiates Loop 1
1077	3E 44	MVI A, 44	
1079	D3 00	OUT 00	
107B	3E 80	MVI A, 80	Switches the array into receiving mode
107D	D3 01	OUT 01	
107F	3E 02	MVI A, 02	Initiates and monitors the A/D conversion of echo, if any, (Loop 4 begins)
1081	D3 00	OUT 00	
1083	3E 06	MVI A, 06	
1085	D3 00	OUT 00	
1087	06 01	MVI B, 01	
1089	DB 02	IN 02	
108B	AO	ANA B	
108C	C2 8910	JNZ 1089	
108F	3E 00	MVI A, 00	
1091	D3 00	OUT OO	
1093	3E 04	MVI A, 04	
1095	D3 00	OUT 00	
1097	16 08	MVI D 08	
1099	3E 8C	MVI A, 8C	

(1)	(2)	(3)	(4)
109B	D3 00	OUT 00	
109D	3E 04	MVI A, 04	
109F	D3 00	OUT 00	
10A1	3E 14	MVI A, 14	
10A3	D3 00	OUT 00	
10A5	3E 04	MVI A, 04	
10A7	D3 00	OUT 00	
10A9	C3 7F10	JMP 107F	Initiates Loop 4
1510	3E 7C	MVI A, 7C	Generates SBA_2 (5 Element Array)
1512	D3 08	OUT 08	
1514	3E 08	MVI A, 08	
1516	D3 09	OUT 09	
1520	3E 7E	MVI A, 7E	Generates SBA_3 (6 Element Array)
1522	D3 08	OUT 08	
1524	3E 10	MVI A, 10	
1526	D3 09	OUT 09	
1530	3E 7F	MVI A, 7F	Generates SBA_4 (7 Element Array)
1532	D3 08	OUT 08	
1534	3E 01	MVI A, 01	
1536	D3 09	OUT 09	

(1)	(2)	(3)	(4)
1540	3E 80	MVI A, 80	Generates SBA$_5$ (8 Element Array)
1542	D3 08	OUT 08	
1544	3E 04	MVI A, 04	
1546	D3 09	OUT 09	
1548	3E 7F	MVI A, 7F	
154A	D3 08	OUT 08	
154C	3E 08	MVI A, 08	
154E	D3 09	OUT 09	
1550	3E C0	MVI A, C0	Generates SBA$_6$ (9 Element Array)
1552	D3 08	OUT 08	
1554	3E 08	MVI A, 08	
1556	D3 09	OUT 09	
1558	3E 7F	MVI A, 7F	
155A	D3 08	OUT 08	
155C	3E 10	MVI A, 10	
155E	D3 09	OUT 09	

RST 6.5 SUBROUTINE

Program for loading the Program Counter with starting address of various subarray formats

1300	31 FA17	LXI SP, 17FA	Initialises the stack pointer

(1)	(2)	(3)	(4)
1303	E1	POP H	Pop the stack
1304	C1	POP B	
1305	F1	POP PSW	
1306	3D	DCR A	
1307	CA 0010	JZ 1000	
130A	09	DAD B	Increments the switching program address
130B	F5	PUSH PSW	Push the stack
130C	C5	PUSH B	
130D	E5	PUSH H	
130E	E9	PCHL	

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