

Coaxial circular array for underwater transducer application—a critical appraisal of its effectiveness

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A detailed study was carried out to observe the performance of coaxial circular array for underwater transducer applications at five different operating wavelengths. Analyses of farfield pattern, mutual interaction effects between array elements and sidelobe suppression are performed. Narrow main beams, uniform excitation velocities and suppressed sidelobes by multiplicative array techniques are observed to be suitable for the use of underwater bathymetry.

1. Introduction

Transducers used for several applications in underwater instruments like echosounder and subbottom profiling (graphical representation of depth and subbottom features) are essential for converting electrical signals to acoustic signals in water media or vice versa. Various array geometries were preferred for above purposes because of their different properties such as high gain and beam steerability etc. The coaxial circular array is well known for its simplicity of structure, and some of its properties like high gain and frequency scaling are useful for underwater bathymetric (measurement and charting of ocean depths) applications [1]. Furthermore since it provides symmetrical as well as narrow beam angles, it has been found to be superior over the array systems. In view of above, the present communication deals with the work carried out by the author on coaxial circular array arrangement of circular disk elements. Three concentric circles of different diameters were chosen on the basis of operating wavelengths. Each circle consists of eight elements; hence a total of 24 elements are distributed within the array system. Studies related to vertical farfield pattern of such an array and field frequency responses, mutual interaction effects between array elements, and sidelobe suppression techniques applicable to such an array by using Taylor Shading (for non-uniform) and as well as uniform excitation of elements are considered.

The above studies were carried out at five suitable wavelengths of operation. They are 0.5λ , 1.0λ , 1.5λ , 2.5λ and 7.5λ where λ is design wavelength. The diameter of each circular disk is assumed to be $\lambda/2$.

2. Farfield Pattern and Field Frequency Responses

The array factor $F(\theta, \phi)$ for three turn coaxial circular array (radii of the innermost, middle and outermost circles are a_1 , a_2 , and a_3 respectively) can be written as (1).

$$F(\theta, \phi) = \sum_{n=1}^3 \sum_{m=1}^8 \exp j\beta(a_n \sin \theta \cos \phi \cos (m-1)\pi/4 + a_n \sin \theta \sin \phi \sin (m-1)\pi/4).$$

Element Pattern(1)

where Element Pattern = $\frac{2J_2(\beta \bar{a} \sin \theta)}{\beta \bar{a} \sin \theta}$

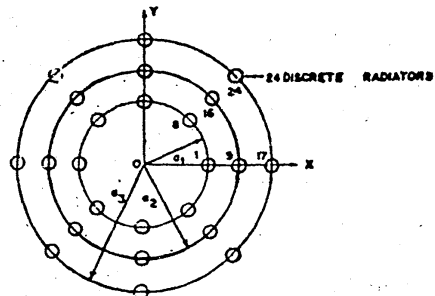


Fig 1. Geometry of the Coaxial circular Array

$J_1(\beta \bar{a} \sin \theta)$ is 1st order Bessel function of argument $\beta \bar{a} \sin \theta$ and \bar{a} is the radius of the element (in the present case it is 0.5λ). β is the operating wave number and m is the element and n is circle number.

Farfield pattern computed for the combinations of radii $a_1=4.0\lambda$, $a_2=6.0\lambda$ and $a_3=8.0\lambda$, is chosen

at different operating wavelengths of 0.5λ , 1.0λ , 1.5λ , 2.5λ and 7.5λ . Fig. 2 shows the narrowest beamwidth (2°) for an operating wavelength of 0.5λ and gradually increasing beamwidth (3.3° , 5.3° , 8.6° and 26°) at 1.0λ , 1.5λ , 2.5λ and 7.5λ . A wide beamwidth obtained at 7.5λ at 26° is no less useful for a subbottom profiler.

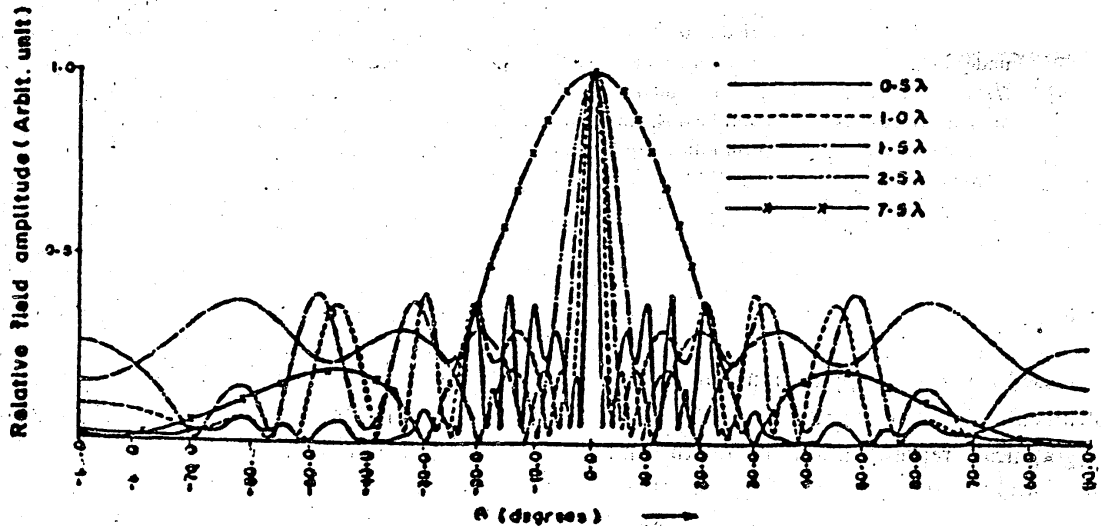


Fig. 2. Vertical Power Pattern for a Coaxial Circular Array

3. Mutual Interaction effects between Array Elements at different wavelengths

Sherman [2] emphasised the importance of the acoustic interaction among radiators and stressed the need for working out such an effect with suitable mathematical analysis. Later on Wang [3] and Pritchard [4] developed the method of computation of such an effect which has less accuracy and is cumbersome as it involves more computation time. Chakraborty [5] had employed a modification in Pritchard's techniques which reduces computer time considerably while maintaining the accuracy.

The complex excitation pressure across the s th radiator is

$$[P_s] = [V_s] [Z_s] \quad \dots(2)$$

Let the reference pressure at the s th radiator be equal to unity so eqn. (2) can be rewritten as,

$$[V_s] = [Z_s]^{-1} \quad \dots(3)$$

Assume $Z_{s,l}$ is the mutual impedance between s th & l th radiators of coaxial circular array

$$Z_s = \sum_{l=1}^{24} Z_{s,l} \quad \dots(4)$$

The self impedance of each radiator of circular disk radiator 0.5λ is given when $s=1$

$$Z_{s,s} = \rho_0 \pi \bar{a}^2 [i - J_1(2\beta \bar{a})/\beta \bar{a}] + jH_1(2\beta \bar{a})/\beta \bar{a} \quad \Omega \text{ (MKS)} \quad \dots(5)$$

where $J_1(2\beta \bar{a})$, $H_1(2\beta \bar{a})$'s are 1st order Bessels and Struve functions respectively of $2\beta \bar{a}$. ρ_0 is the characteristic impedance of the medium. Mutual impedance $Z_{s,l}$ can be presented, when $s \neq l$, as

$$Z_{s,l} = \rho_0 \pi \bar{a}^2 2 \sum_{p=0}^{\infty} \sum_{q=0}^{\infty} (p+q+0.5) \pi^2 p! q! (q/d_{s,l})^{2p+q} J_{p+1}(\beta \bar{a}) J_{q+1}(\beta \bar{a}) H_{2p+q}(\beta d_{s,l}) \quad \Omega \text{ (MKS)} \quad \dots(6)$$

p, q are the no. of iterations. $H_{p+q}^{(2)}(\beta d_{s,i})$ is spherical Hankel function of second kind. $d_{s,i}$ is interelement spacing.

According to Skudrzyk [4] if the disks are separated, at greater than disk radius then eqn (6) can be reduced to

$$Z_{s,i} = R_{s,i} [\text{Sin}(\beta d_{s,i})/\beta d_{s,i} + j \text{Cos}(\beta d_{s,i})/\beta(d_{s,i})] \Omega \text{ (MKS)} \quad \dots(7)$$

where $R_{s,i}$ is real part of eqn. (5). In order to save computation time, a technique was introduced to know the actual limit of the above eqn. (6) and (7). Fig. 3 shows that $(\bar{a}/d_{s,i})^{p+q}$ (a term in eqn. 6) has become negligible beyond $p+q=1$, especially after $d_{s,i}=3.0\lambda$. So eqn. (6) was used for the case when $p+q$ (no. of iterations)=1 and upto $d_{s,i}=3.0\lambda$, otherwise asymptotic relation (7) was used.

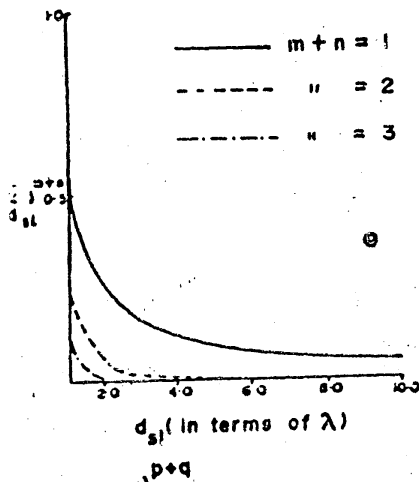


Fig. 3. $(\bar{a}/d_{s,i})^{p+q}$ for different inter-elemental distances at various $p+q$.

Above studies reveal that the values of impedances are constant for the transducer elements of the same radius, which in turn depends on operating wavelength. Fig. 4 shows that the R_s is higher upto 2.5λ and highest at 1.0λ but X_s (inductance) is the highest at 7.5λ .

The change in $|v|$ (Fig. 5) upto 2.5λ is not very significant but reaches a maximum at lowest frequency of 7.5λ . This suggests that an electrical network for suitable excitation and reception of each elements of an array can be used to overcome the effect of interaction at 7.5λ .

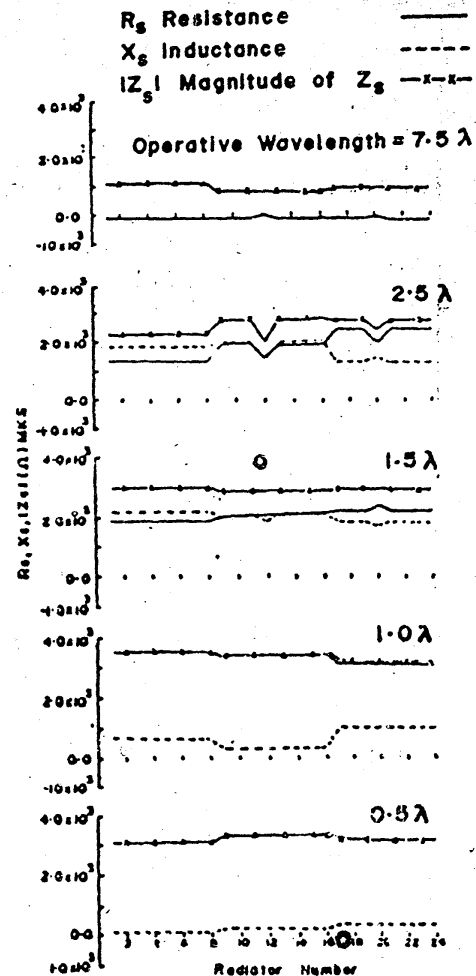


Fig. 4. Radiation resistance, inductance and magnitude of impedances for different radiators at different operating wavelengths.

4. Sidelobe suppressed Beampatterns

Beampatterns presented in Fig. 2 for uniform excitation of each disk element show the appearance of sidelobes at different operating wavelengths. It is not unknown that presence of sidelobes would create difficulties in the easy operation of the system. An application of suitable shading technique was found to be effective in reducing the sidelobe down to a desired level of -20dB [6]. In the present study, Taylor's shading approximation is used as a tool for sidelobe suppression at different operating wavelengths [7].

In order to suppress the $\bar{O}-1$ sidelobes of eqn. 1, so as to achieve the desired level of inside lobes while keeping the same main beamwidth.

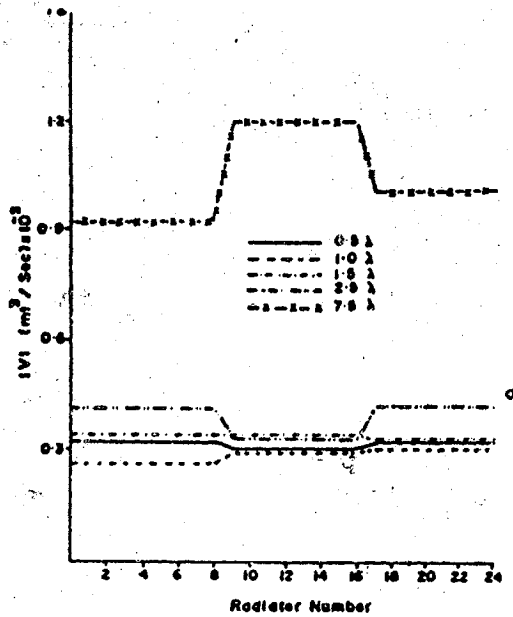


Fig. 5. Magnitude of excitation velocities with respect to radiator number at different operating wavelengths.

$$F^h(u) = F(u) \prod_{O=1}^{\bar{O}-1} (1 - u^2/u_0^2) / \prod_{O=1}^{\bar{O}-1} (1 - u^2/r_{10}^2) \quad \dots(8)$$

$$\text{where } u_0 = r_{10}^2 [A^2(\bar{O} - 0.5)^2] / [A^2(\bar{O} - 0.5)^2]$$

$$\text{and } A = \frac{1}{\pi} \text{Cosh}^{-1} 10 (\text{read, side lobe level}) / 20.$$

$F(u)$ is the pattern of Fig. 2 for $u = 2a_3 \sin \theta$, $r_{10} = 2a_3 \sin \theta_0$ obtained from Fig. 2 for the different points of null. r_{10} is $2a_3 \sin \theta_{10}$, last null angle to be suppressed. a_3 is radius of outermost circle.

From Fig. 6 it is clear that at operating wavelengths 0.5λ , 1.0λ and 1.5λ the sidelobes are suppressed well below -20dB whereas for 2.5λ and 7.5λ it is upto -16dB .

5. Sidelobe suppression by Uniform Excitation

Difficulties with the amplitude shading techniques are well known due to their degraded element sensitivity and require complex feed network. So a study related to sidelobe suppression other than usual shading techniques includes uniform excitation or reception of the array elements [8].

Amplitude tapering by means of tilting each element to a suitable angle according to different circles of the array was done. The elements of different circles were tilted at different angles (7.5° , 10° and 15° for innermost, middle and outermost circles respectively) with respect to XY plane. This revealed that there are no significant changes in sidelobes for different wavelengths at other than 0.5λ (Fig. 7) although a little reduction of beamwidth is observed with the fall of array gain. It is also realised that if tilting of element is further increased, we may obtain narrower beamwidth at the cost of reduced array gain which has the effect of aperture blocking.

So a novel method was adopted to observe the sidelobe suppressed pattern maintaining uniform excitation known as 'Multiplicative Array'. The added output of eight elements from each circle is multiplied with each other in the present case which can be expressed as

$$F(\theta, \phi) = \prod_{n=1}^3 \sum_{m=1}^8 \exp j\beta [a_n \sin \theta \cos \phi \cos(m-1)$$

$$\pi/4 + a_n \sin \theta \sin \phi \sin(m-1) \pi/4]. \quad \dots(9)$$

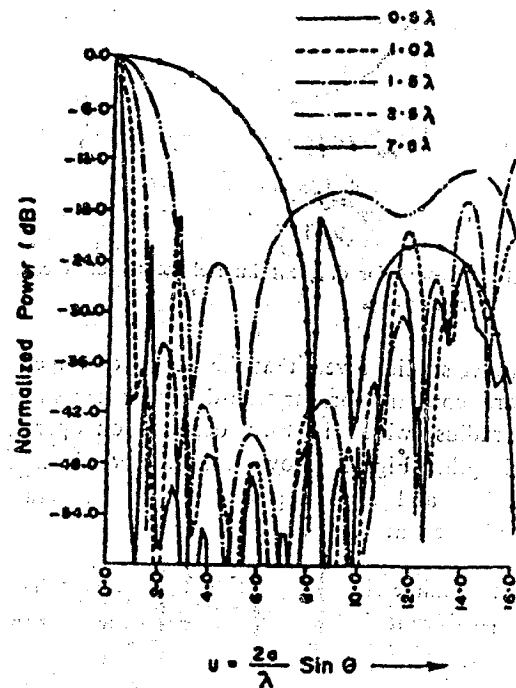


Fig. 6. Vertical power pattern for shaded (-20dB , sidelobe level) at different operating wavelengths.

It is observed from Fig. 8 that the sidelobes are suppressed well below -20 dB. The main beamwidths of 0.5λ , 1.0λ 's are the same as that of the unsuppressed pattern of the additive array (Fig. 2). For operating wavelengths of 1.5λ , 2.5λ and 7.5λ , it becomes more narrow (3.3° , 5.0° and 14°) thus making it more useful for high resolution underwater bathymetric applications.

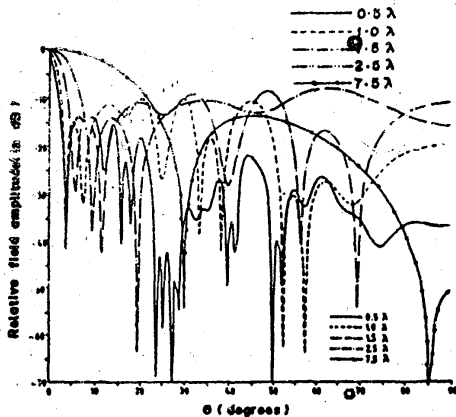


Fig. 7. Vertical power pattern for a coaxial circular array of tilted elements.

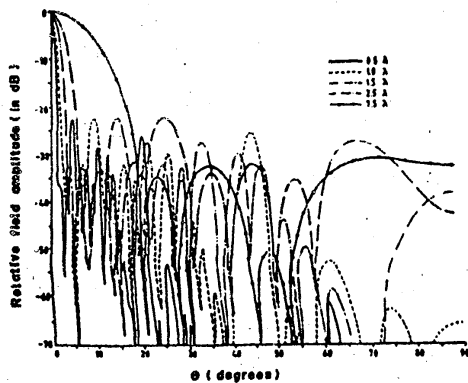


Fig. 8. Vertical power pattern for a multiplicative coaxial circular array.

6. Conclusions

Present study is devoted towards the development of design parameters of coaxial circular array for

underwater transducer applications. Sharp field pattern at five operating wavelengths are found to be useful for echosounding and subbottom profiling. Suitable analytical methods have been used to calculate mutual impedances between the array elements. Mutual impedances are higher upto 2.5λ but significantly less at 7.5λ , which may be observed from values of excitation velocities. The necessity of an additional appropriate electrical network for proper excitation is realised at operating wavelength of 7.5λ .

Observing the higher sidelobes in additive farfield patterns of the above array system, suitable shading technique was applied (Taylor shading technique) to suppress the sidelobe to a satisfactory level (-20 dB) at different operating wavelengths. But in view of non-uniform excitation of different disk elements and requirement of separate feed network complexities necessitated carrying out different sidelobe suppression techniques based upon uniform excitation. Uniform excitation with tilting element pattern was not found to be suitable whereas multiplicative array techniques were observed to be the best from the point of view of narrow beam angles and sidelobe suppressed patterns maintaining uniform excitation of each element of the array.

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