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DESIGN CONSIDERATIONS OF TRANSDUCER ARRAY SYSTEMS FOR ULTRASONIC TESTING OF UNDERWATER PIPELINES

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Abstract

Ultrasonic nondestructive evaluation of ocean structures and underwater pipelines will help in preventing catastrophic failures. Probes of various types have been developed for ultrasonic NDE of underwater pipelines, which require rotational as well as linear movements for the complete inspection and evaluation. This method being a time consuming one, an attempt has been made to design an annular cylindrical array, which will reduce the probe movements as much as possible. This paper presents a study of the usefulness of such an array for underwater pipeline inspection.

Introduction

Nondestructive evaluation (NDE) is one of the most challenging fields of research and development. NDE plays a significant role in the prevention of catastrophic failures, quality control and cost savings. NDE can ensure products that are more efficient, cost effective and safer for the consumer and the environment [1, 2]. Ultrasonic NDE is a more handy technique than X-rays and gamma rays. Ultrasonics is also employed in medical diagnosis and imaging applications [3]. The potential of ultrasonic technology provides an advanced means of describing the size, population, geometry and location of material anomalies. Ultrasonic NDE technique has wide applications and a considerable economic impact. This paper describes the design and development of an annular cylindrical array, which can be used for the ultrasonic NDE of underwater pipeline flaws. The beam characteristics and gain of the proposed array are studied.

High ultrasonic frequencies in the $1 - 10\text{MHz}$ range are often desired for NDE, to achieve a reasonable resolution of flaws or cracks. It is a low power application because the ultrasonic energy explores the test material and is modified. Ultrasonic waves are introduced into the region to be tested, and are reflected at the interfaces of materials having different acoustic properties [4]. Ultrasonic testing employs the fundamental relationship of distance, velocity and time. The various techniques used for ultrasonic testing are: the pulse echo technique, the through transmission technique and the resonance technique.

The pulse echo technique is the most versatile. A short burst of ultrasonic waves is sent into the object to be tested; echoes from the discontinuities or defects are processed and displayed on a CRT, which displays their amplitude and time of flight. In through transmission, the transmitter probe is placed on one side of the object and the ultrasound is monitored using another probe. A flaw in the path constitutes a barrier for the ultrasound, casting an acoustic shadow on the receiver probe, which thus reveals the defect. The resonance method requires two adjacent resonances for thickness determination [4].

Detection of pipeline flaws

A single probe method is in widespread use for the detection of flaws, in the pulse echo method. The probe is moved around and along the pipeline in the transmit/receive mode. A narrow beam of ultrasound generated by the probe is transmitted as pressure waves...
through the coupling medium and the wall of the pipeline. A flaw present in the pipeline reflects a part of the sound energy, which is received as an echo pulse, either by the transmitting probe in the transmit/receive mode or by a separate receiving probe [5]. In this method, the probe head is required to rotate for complete inspection of the pipeline, which severely limits the speed of inspection.

These limitations can be overcome by the use of either a ring array or an annular cylindrical array. The annular cylindrical array can be seen to have improved performance.

Annular cylindrical array

The configuration of the annular cylindrical array is shown in Figure 1. It consists of $m$ n-element linear arrays (staves), arranged in a circular configuration. In the approach presented in this paper, the desired portion of the annular cylindrical array, consisting of $l$ n-element linear arrays can be energised, which will generate a focussed beam. An appropriately grouped set of the remaining staves of the annular cylindrical array will be used for receiving the echo pulse. The beam pattern $B(\theta)$ of the portion of the annular cylindrical array, consisting of $l$ staves, can be expressed to a good approximation using [6]:

$$B(\theta) = b(\theta) b'(\theta),$$

where $b(\theta)$ and $b'(\theta)$ are the beam patterns of the n-element linear array and $l$-element curved array. The value of $l$ should be typically less than 6.

Consider two adjacent elements A and B in the ring array, as shown in Figure 2. The path difference between A and B is

$$U = R \left\{ \sin(\theta' + \frac{d'}{R}) - \sin \theta' \right\} \sin \varphi .$$

The path difference for the $i$th element along the circumference is

$$U_{i-1} = R \left\{ \sin(\theta' + \frac{i-1}{l} d'/R) - \sin \theta' \right\} \sin \varphi ,$$

where $d$ is the inter-element spacing, $d'$ is the arc length between A and B, $R$ is the radius of the annular cylindrical array and $k = \frac{2\pi}{\lambda}$, the wave vector; $\lambda$ being the wavelength of the acoustic radiation. The total output voltage developed in the $l$-element curved array is

$$V = e^{jU_0} + e^{jU_1} + \ldots + e^{jU_{l-1}}$$

$$= \sum_{i=0}^{l-1} \cos kR \left\{ \sin(\theta' + \frac{i}{l} d'/R) - \sin \theta' \right\} \sin \varphi$$

$$+ \sum_{i=0}^{l-1} \sin kR \left\{ \sin(\theta' + \frac{i}{l} d'/R) - \sin \theta' \right\} \sin \varphi .$$

The beam pattern of $l$ elements along the circumference is

$$b'(\theta) = \left| V/l \right|^2 ,$$

and the beam pattern of the n-element linear array is

$$b(\theta) = \frac{\sin(n\pi d \sin \theta \cos \varphi)}{n \sin(\pi d \sin \theta \cos \varphi)} .$$

Hence, using [6]

$$B(\theta) = \left[ \frac{\sin(n\pi d \sin \theta \cos \varphi)}{n \sin(\pi d \sin \theta \cos \varphi)} \right]^2 \times$$

$$\frac{1}{l^2} \left[ \sum_{i=0}^{l-1} \cos kR \left\{ \sin(\theta' + \frac{i}{l} d'/R) - \sin \theta' \right\} \sin \varphi \right]^2$$

$$+ \left[ \sum_{i=0}^{l-1} \sin kR \left\{ \sin(\theta' + \frac{i}{l} d'/R) - \sin \theta' \right\} \sin \varphi \right]^2 .$$

The beam pattern for the case $n = 10$ and $I = 3$ is shown in Figure 3. The array gain of the proposed array is computed using the cross-correlation coefficients of the signal and noise. The cross-correlation coefficient for single frequency, zero time delay, unidirectional signal and the cross-correlation coefficient of isotropic noise are computed using [7].

Figure 1.
The configuration of the annular cylindrical array.

Figure 2.
Cross section of the annular cylindrical array showing the two adjacent elements A and B.

Figure 3. Beam pattern of the portion of the annular cylindrical array consisting of $n = 10$ and $I = 3$. 

Results and discussion

The effect of variation of the radius of the annular cylindrical array on its beam characteristics for \( n = 10 \) and \( l = 3 \) is given in table 1. It can be seen from the table that the half-power beamwidth, the most intense sidelobe level and the sidelobe level at 90 degrees to the beam axis remain constant, when \( R \) exceeds 40\( \lambda \).

Table 1.

<table>
<thead>
<tr>
<th>Radius ( R ) (in ( \lambda ))</th>
<th>Most intense sidelobe level (in dB)</th>
<th>Sidelobe level at 90(^\circ) (in dB)</th>
<th>3dB beamwidth (in degrees)</th>
</tr>
</thead>
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<tr>
<td>5</td>
<td>-14.84</td>
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<td>-15.14</td>
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<td>-42.19</td>
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<td>-15.36</td>
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<tr>
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</tr>
<tr>
<td>100</td>
<td>-15.40</td>
<td>-42.17</td>
<td>-14.0</td>
</tr>
</tbody>
</table>

The array performance summarised in table 2 shows the effect of the number of staves \( l \) for \( n = 10 \) and \( \varphi = \pi/4 \). Annular cylindrical arrays can be found to have better array gains, when compared to planar arrays of the same size.

Table 2.

<table>
<thead>
<tr>
<th>Number of staves in the array ( l )</th>
<th>Most intense sidelobe level (in dB)</th>
<th>3dB bandwidth (in degrees)</th>
<th>Sidelobe level at 90(^\circ) (in dB)</th>
<th>Array gain for ( \theta = \pi/4 ) ( \varphi = \pi/2 ) (in dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-13.90</td>
<td>14.2</td>
<td>-26.17</td>
<td>9.79</td>
</tr>
<tr>
<td>3</td>
<td>-15.40</td>
<td>14.0</td>
<td>-42.17</td>
<td>10.13</td>
</tr>
<tr>
<td>4</td>
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<td>13.6</td>
<td>-30.53</td>
<td>10.23</td>
</tr>
<tr>
<td>5</td>
<td>-20.50</td>
<td>13.2</td>
<td>-35.67</td>
<td>10.39</td>
</tr>
</tbody>
</table>

Taking into account the design considerations and the acoustic impedance match to water, piezo-film transducers are being evolved for the performance evaluation of the proposed array. Diametrically opposite set of staves can be used as transmitting and receiving arrays.

Conclusions

The half-power beamwidth and the sidelobe levels of annular cylindrical arrays remain unaffected beyond \( R = 40\lambda \). Annular cylindrical arrays are seen to have better gain and array performance.

Acknowledgements

The authors gratefully thank the authorities of the Cochin University of Science and Technology for providing the necessary facilities to carry out this work and the Ministry of Human Resource Development, Government of India, for financial assistance.

References


(Received 23 June 1991)

Multilayered transducer structures offer the potential for greater performance in terms of increased acoustic power and improved reception characteristics. In earlier work, a multidimensional modeling approach was presented, that was shown to provide a means of accurately predicting the in-air electrical impedance characteristics of a range of different laminated transducer structures [J. Acoust. Soc. Am. 97, 3299(A) (1995)]. These prototype devices have since been encapsulated with polyurethane rubber ready for in-water acoustic testing. This paper presents a theoretical and experimental analysis of both the transmission and reception performance characteristics of this group of multilayered devices. The effects of intermediate bondlines and electrode layers will be considered in terms of changes to both the device's sensitivity and its resonant frequency. Transducer performance will be assessed via the standard figures of merit, TVR and FFVS, in conjunction with its pulse-echo transient response. Theoretical predictions from the multidimensional model are in good agreement with experimentally obtained values. The polyurethane encapsulant was found to have detrimental effects on overall transducer performance. Beam profiles for the laminated devices have been recorded experimentally and are compared to the responses of their single-layer counterparts. [Work sponsored by the Office of Naval Research.]

3:45

2pE1A. A reinforced Neoprene rubber boot for the barrel-stave extensional projector. Dennis F. Jones (Defence Res. Establishment Atlantic, P.O. Box 1012, Dartmouth, NS B2Y 3X7, Canada)

The Class I barrel-stave extensional projector is a lightweight and compact underwater sound source that is well-suited to low-frequency sonar and oceanographic applications. By modifying a few of the parts used in the Class I projector, a high-power Class II or broadband Class III barrel-stave projector can be constructed, which is testimony to the versatility of the basic barrel-stave design. These projectors require gaps, between adjacent staves, that are sufficiently wide for free-stave vibration at the operating drive levels and water depths. Gap widths of about 1 mm are typical. A rubber boot is stretched over the projector to inhibit the ingress of seawater through the gaps. However, since the gap widths and boot wall thicknesses are similar, the boots can be forced into the gaps by hydrostatic pressure, causing significant variations in the pressure, causing significant variations in the projector performance parameters with water depth [D. F. Jones and M. B. Moffett, J. Acoust. Soc. Am. 93, 2305(A) (1993)]. To minimize these variations, a new rubber boot, with reinforcements in the vicinity of the gaps has been fabricated and tested on a Class II barrel-stave projector. Measured results showing performance stability with depth are presented.

4:00


The prebreakdown corona phase of a spark discharge in salt water produces a measurable acoustic pulse. This pulse is produced by the formation and collapse of a vapor bubble. The plasma has a multiphonged shape, and it creates a bubble with a corresponding acoustic pulse. The rate of formation of plasma fringes may be a fractal dimension of the size of the discharge. A fractal model of the growth of the corona discharge can be used to connect the variables of voltage, current, and bubble wall acceleration. The dependence of the acoustic and electrical response and thus the fractal dimension of the corona growth on liquid conductivity, and applied voltage are investigated. The acoustic data are used to infer the bubble wall acceleration while the current-voltage data are measured directly and used to determine the total resistance of the plasma. The corona is formed by the application of high-amplitude electric fields to a set of electrodes that are immersed in the liquid. [Work supported by the Office of Naval Research under Grant No. N00014-94-1-0550.]


130th Meeting: Acoustical Society of America 2903
Transient Pressure Variation of Pulse Excited Ring Array for Pipeline Testing

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Abstract

An ultrasonic transducer array comprising a selectively energised section of a ring array concentric to the test pipeline, with the ultrasound focused on its contour is used for underwater pipeline inspection. Beam characteristics, sidelobe levels and effective acoustic pressure of the array is evaluated. The transient response as well as the continuous wave effective acoustic pressure of a section of the ring array is computed for different configurations. A comparison of the acoustic pressure field of the ring array with a linear array demonstrates the focusing effect of the ring array for such applications.

INTRODUCTION

Ultrasound transducers find major applications in flaw detection and medical diagnosis. A large number of ultrasonic probes have been developed suitable for various applications[1]. Generally single probe transducers are being used for inspection and detection of flaws in underwater pipelines, but a substantial time saving in the inspection can be achieved by using suitable arrays. Investigations on phased array configurations as potential applicators for ultrasound hyperthermia cancer therapy are also in progress[2]. By adjusting the driving signal to each array element, the focused beam of the phased array can be translocated to the desired region, thereby eliminating the mechanical movement of the applicator that must be continuously moved[3]. Fabrication of ultrasonic arrays is feasible using integrated circuit and hybrid construction techniques.

Generally used NDE techniques are the reflected pulse and the beam obscuration techniques. In the reflected pulse amplitude technique, the amplitude of the reflected pulse is affected by defect type, shape, size, orientation and diffraction of ultrasonic beam and also the test piece geometry, surface conditions and material characteristics. Successful and reliable defect detection can be achieved, taking into account, diffraction around the edges of the defect, distance from the surface of detection, consistent acoustic coupling and formation of standing waves [5,6].

The pressure field of short pulse transducers have been evaluated using the convolution as well as Fourier transform technique[4]. Turnbull, Foster, Ebbini etc have carried out valuable studies on ultrasound phased arrays as promising tools in biomedical imaging. Convolution and Fourier transform techniques have been employed for the prediction of the field of a short pulse device as reported by Stephanishen, Freedman, Robinson, Foster, Hunt etc., [4,7-10]. Pulsed two dimensional transducer arrays suited for medical imaging have been studied by Turnbull and Foster [3]. In a narrow band or continuous wave excited two dimensional array system, the pressure distribution is computed as the product of axial pressure distribution, element factor and array factor. The transient field is obtained as the convolution of the ultrasound waveform with the impulse response of the acoustic source. Another approach using the Fourier transform technique has been employed by Foster and Hunt, in which the pressure pulse leaving the transducer is split into its continuous wave components and allowed to propagate to the field point and then reassembled in the correct phase [4].

A widely spaced point source ultrasound ring array working in the near field was designed, by Whittington and Cox, requiring a rotation of $10^\circ$ for complete inspection of the pipe. Inspection of underwater pipelines have been carried out by single probe and twin probe transducers in the single and multiple reflection modes. The probes have to be rotated about the pipeline for complete inspection. A ring array or annular array with electronic switching reduces the need for mechanical...
rotation of the transducer probes.

The formulation and computation results of array characteristics and effective acoustic pressure of a ring array for underwater pipeline inspection is featured in this paper.

PRINCIPLE

The inspection system comprises a ring array placed concentric over the pipeline and a section of \( M \) elements are selectively activated to focus the ultrasound along the contour of the pipeline. Fig.1 shows the configuration and orientation of the array about the pipeline. The array may be operated in the reflection or through transmission mode. The same section or a similarly grouped set of elements of the array may act as receivers to collect the information of the defect. The ultrasound gets reflected at the discontinuity and the reflected echo is obtained corresponding to it. In the through transmission, there is an acoustic shadow at the discontinuity. Some of the assumptions made for the computations of beam characteristics and effective acoustic pressure is that point source of elements with spacings of half the acoustic wavelength are considered. Therefore grating lobes are eliminated and interelement interaction is minimal. The amount of reradiated energy captured by the point source of elements can be neglected for all practical purposes. Finite size of the elements are to be considered when realising the array.

THEORETICAL CONSIDERATIONS

Receiving array

The beam pattern of the desired section of the receiving ring array comprising of \( M \) elements is computed as \( B(\theta) \). Plane acoustic waves incident on the transducer elements generate an electrical output. Total output voltage from the section is the sum of the weighted contributions from each element [11-12]. From Fig.2, the path difference \( U_m \) due to the \( m_{th} \) element relative to the 1\(^{st} \) element is obtained from the geometry of the array shown in Fig.2 as,

\[
U_m = R \left[ \sin(\theta' + \frac{md'}{R}) - \sin\theta' \right] \sin\phi
\]

(1)

where, \( d \) is the interelement spacing, \( d' \) is the spacing along the circumference of the array,

\[
\phi = m/4, \quad \Theta' = \sin^{-1} \left[ \frac{R}{d'} \sin\left( \frac{d'}{R} \right) \right] - \theta
\]

(2)

Hence total output voltage \( V \) can be computed as,

\[
V = \sum_{m=0}^{M-1} \cos \{ kR[\sin(\theta' + \frac{md'}{R}) - \sin\theta'] \sin\phi \}
\]

\[+j \sum_{m=0}^{M-1} \sin \{ kR[\sin(\theta' + \frac{md'}{R}) - \sin\theta'] \sin\phi \}
\]

(3)

where \( k = 2\pi/\lambda \) and \( \lambda \) is the acoustic wavelength.

Beam pattern of the receiving ring array is computed as

\[
B(\theta) = \left( \frac{V}{M} \right)^2
\]

(4)

\[
B(\theta) = \frac{1}{M^2} \left[ \sum_{m=0}^{M-1} \cos \{ kR[\sin(\theta' + \frac{md'}{R}) - \sin\theta'] \sin\phi \} \right]^2
\]

\[+ \frac{1}{M^2} \left[ \sum_{m=0}^{M-1} \sin \{ kR[\sin(\theta' + \frac{md'}{R}) - \sin\theta'] \sin\phi \} \right]^2
\]

(5)
Transmitting array

Effective acoustic pressure developed at a distance \( r \) from a simple source has been described by Leon Camp [13]. The effective acoustic pressure at a point along the contour of the pipeline for a continuous wave excited ring array is the numerical sum of the weighted contributions from the selectively energised \( M \) elements. The acoustic pressure at any desired point along the pipeline can be computed as,

\[
P = \sum_{m} A_{m} e^{j\omega \left( t - \frac{r_{m}}{v} \right)}
\]

where \( A \) is the r.m.s value of pressure at a distance of 1m, \( r_{m} \) is the path length, \( v \) is the acoustic velocity and \( \omega \) is the angular velocity. From the geometry of the array in Fig.2 the path length \( r_{m} \) is,

\[
r_{m} = \frac{z^2 + 4R(R-z)\sin^2\left(\frac{md}{R} - \phi'\right)}{2R}
\]

where \( z \) is the radial distance between the array and the test pipeline and \( \phi' \) is the angle between the field point and the central element with the center of the pipeline.

Transient response

A gated sinewave signal of frequency 5.0 MHz is applied to the array for a duration of 0.2\( \mu \)s. The transient pressure \( P \), on the contour of the pipeline for the pulse excited ring array is

\[
P = \sum_{m} A_{m} e^{j\omega (t - t_{m})} \\
t_{m} \leq t < t_{m} + \tau
\]

where \( \tau \) is the pulse width and \( t_{m} \) is the time delay from the \( m^{th} \) element. The time of arrival from the nearest and farthest sources to the field point are \( t_{0} \) and \( t_{m} \) respectively. Hence the weighted contributions from all the \( M \) sources are obtained from the instant \( t_{m} \) to \( t_{0} + \tau \).

RESULTS AND DISCUSSIONS

The beam characteristics of different configurations of the point source receiving ring array of radius 3cm, with interelement spacing of \( \frac{A}{2} \) and operating at 5.0 MHz is given by \( B(\theta) \) a plot of which is shown against \( \sin \theta \), in Fig.3. The beam characteristics of a 5 element section operating at 5.0 MHz is studied for different array radii. From Table 1, it can be seen that the sidelobe levels and 3dB beamwidth are found to remain unaffected for larger radii, typically greater than 40cm.

Total effective acoustic pressure along the contour of the pipeline at any instant is the sum of the weighted contributions from all radiating set of elements. The computation of the effective acoustic pressure over a desired portion of the contour of the pipeline using a ring array of point sources is carried out for continuous and pulsed mode of excitations. The effective acoustic pressure of a ring array at the desired portion of the test pipeline is computed for continuous waves by varying the value of \( \phi' \). The pressure relative to that at \( \phi'=0 \) is computed. Variations of the acoustic pressure fields for different configurations of the array are shown in Fig.4. The focusing effect is found to be favorable for a 21 element array.

Computation of effective acoustic pressure along the pipeline for both linear and ring array of 21 elements with an interelement spacing of \( \frac{A}{2} \) and an operating frequency of 5.0 MHz shows a narrow beam generated by the ring array, thus demonstrating its focusing effect in Fig.4.

The array geometry and pipeline geometry can be optimised from the radial pressure distribution of the array. Figure 5 shows the axial pressure distribution of a 5 element section of a ring array of radius 10cm and operating frequency 5.0 MHz. The field remains steady from a distance of 3cm onwards. Therefore this array would be suitable for inspection of pipelines of radius up to 7cm.

CONCLUSION

The radial pressure distribution of the proposed array has been investigated for different array configurations from which the number of elements and array geometry can be optimised for different
pipeline geometry. A good focusing effect can be obtained by optimizing the number of elements and the radius of a ring array. Performance evaluation of the ring array shows that the sidelobe levels and 3dB beamwidth remain unaffected for radii greater than 40A. The transient response of a pulse excited ring array over the contours of the test pipeline has been evaluated.

Acknowledgements
The authors gratefully thank the Council of Scientific and Industrial Research, New Delhi, for financial assistance.

References
Fig. 1 Configuration and orientation of the ring array about the pipeline
Fig. 2 Geometrical variables used for computation
Fig. 3 Beam characteristics for different sections of the ring array
Fig. 4 Acoustic pressure field for different sections of the ring array and its focusing effect.
Fig. 5 Axial pressure distribution of a 5 element ring array

- $m = 5$  
- Frequency = 5 MHz  
- Radius of ring array = 10 cm
<table>
<thead>
<tr>
<th>Array Radius (λ)</th>
<th>Most Intense Sidelobe level (dB)</th>
<th>Sidelobe level at 90° (dB)</th>
<th>3 dB Beamwidth (degrees)</th>
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</thead>
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<tr>
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<td>100</td>
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<td>16</td>
</tr>
</tbody>
</table>

Frequency=5MHz  Radius=100λ  d=λ/2  wavelength λ=0.03cm

Table 1 Effect of radius of the array on beam characteristics of the 5 element section