Investigations on Ultrasonic Transducer Array Systems for NDE of Underwater Pipelines
Structural integrity of his shelter, defence, transportation and energy resources has been of great concern to man from time immemorial. Earliest instance of testing techniques can be traced back to the prehistoric man where a sharp tug on a vine could ensure its load bearing capacity. Though testing techniques have come a long way from that, the basic philosophy of proof testing remains the same even today. The field of Nondestructive testing (NDT) is related to other technical disciplines involving instrument development, health physics, laser technology, medicine, process control, corrosion monitoring and nuclear power. Some of the nondestructive testing techniques available today are, radiography, magnetic particle tests, magnetic flux
leakage technique, ultrasonic testing, neutron radiographic technique, liquid penetrant
technique, remote field eddy current technique, leak testing, acoustic emissions, visual
inspection and holography [1].

Ultrasonic testing technique is found to be the best suited for underwater applications.
Electromagnetic waves get easily attenuated in water hence cannot penetrate. The
use of ultrasound for nondestructive characterisation of metals and other materials was
one of the first applications of ultrasound and dates back to the 1950s. The detailed
properties of materials that can be measured with ultrasound include microstructure,
surface characteristics, elastic properties, density, porosity, mechanical properties,
process characteristics and flaws. Ultrasonic waves transmitted may take the form of
longitudinal, shear and surface waves. Wave characteristics include ultrasonic
velocities and frequency dependence of ultrasonic attenuation/absorption. Specific
reaction occurring within a tested material may include ultrasound reflection,
transmission, refraction, diffraction, interference, scattering and absorption. In applying
ultrasound to testing, the characteristics of the radiation source that can be
manipulated include wave type, frequency, bandwidth, pulse shape and pulse size.

Ultrasound is the only technique that is applicable to a wide range of materials
compared to other nondestructive characterisation methods such as liquid penetrant
examination, magnetic particle, eddy current testing and radiography [2]. Of the
various Non Destructive Evaluation techniques, ultrasonic method plays a vital role in
defect detection, characterisation, estimation as well as in medical diagnostics and
therapy. The success of an ultrasonic nondestructive testing application depends on
the selection of the best qualified transducer, with optimum frequency response, pulse
width and shape. Some of the applications of ultrasound are in detection of fluid flow, liquid level, viscosity, density, proximity and material thickness. Industrial applications are in cleaning, drilling, emulsifying, soldering, welding as well as in some security systems to detect intruders. In surgery it is used in extracorporeal lithotripsy, for breaking up gall stones into fragments. Ultrasonic density sensors are used in density measurement of lime slurries, for the purpose of adjusting pH. These sensors can be fully immersed in an agitated slurry, without the sensor surface being coated or clogged. The suspended solids present in the slurry attenuate the ultrasonic beam. Ultrasonic waves transmitted from a transducer gets reflected or scattered at a surface or discontinuity which can be received by another transducer. The time elapsed between the transmitted and reflected signal is a measure of the distance of the discontinuity or crack. The amplitude of the reflected signal is proportional to the dimension of the defect.

1.1 HISTORICAL DEVELOPMENT

Ultrasonic testing of defects in solid materials was first proposed by Sokolov in the year 1929[1]. In 1931 Mühlhäuser obtained the first patent for an instrument working with the shadow method. Kruse, Meyer, Bock, Czerlinsky, Götz and Shraiber have also been working with transducers made from piezoelectric quartz plates. During the second world war, ultrasonic instruments designed by Berthold and Trost were used for the first practical testing of steel boiler plates. After the second world war, the companies ACEC of Charloi, Belgium and Dr. Lehfeldt and Co. of Heppenheim, Germany started the production of ultrasonic instruments using the shadow method.
The experiments for imaging methods were started in the 1930s with Pohlman cell being the first to transform the sound pressure into visual image. A complete device using this cell, the Schallsichtgerät was developed with a large visual field of 500mm. It was used to test steel plates. Ogura et al. Cunningham and Quate have used the principle of the Pohlman cell in 1972 with a frequency of 1000 MHz for ultrasonic microscopy. Sokolov in 1936 introduced the relief method in which the image of the ripples generated on the water surface by the reflection of high intensity ultrasound by immersed specimen, can be observed with special illumination. In the 50-100MHz range it is used in commercial applications as an ultrasonic microscope (SLAM-scanning laser acoustic microscope) or sonomicroscope by Sonoscan, USA.

The phase-measuring method of Hatfield, was used for thickness and velocity measurements in which the phase of an outgoing wave is compared with that of a reflected one. Kaiser put forth sound-emission analysis as a possible means of nondestructive testing of materials. Mason, Mc Skimin and Shockley made first trials to use this method. In the 1940s, materials testing by continuous waves was replaced by pulses and wall thickness measurements were carried out using the resonance method. Resonance method makes use of the fact that the resonance frequency of a plate depends on its thickness.

Resonance based instruments were later on replaced by pulse echo instruments. The transit time of the pulse gives the required information about the thickness of plate or location of flaw for wall-thickness measurements. Spallanza in 1798 suggested that bats can orientate using inaudible sound signals, but this was proved only in 1938 by Pierce and Griffin. The discovery of piezoelectric effect by Jacques and Pierre Curie
facilitated the technical realisation of the pulse echo method, using quartz crystals as transmitters and receivers.

Between 1885 and 1910, Lord Rayleigh enunciated the scientific fundamentals of the propagation of sound in solids. Langevin and Chilowski between 1915 and 1917, solved the problem of detecting submarines and icebergs by using ultrasonic pulses. Though this method found many applications in measuring sea-depths, it could effectively be used for materials testing only after the rapid developments of electronic engineering during the period 1935 to 1938.

In 1940 Firestone (USA) put forward the first proposal to use pulse echo techniques for materials testing. In England, Sproule used this method in 1942. Kruse in Germany developed a pulse echo system.

In 1943, Sperry Products Inc., Danbury, USA and Kelvin and Hughes Ltd., London, built the first commercial apparatus for pulse echo method, based on the works of Firestone and Sproule. Though considerable success was achieved in testing large forgings using longitudinal waves at perpendicular incidence, new applications like testing of tubes and welds became feasible by transverse waves produced by filling plastic wedges to the longitudinal wave probes. Piezoceramics and piezopolymers have replaced quartz due to their higher sensitivity.

The first experiments with ultrasonic holography were carried out by Greguss, Mueller, Sheridan and Thurstone in 1965 and 1966, after the invention of the laser optical holography.
In 1974, Mezrich and his collaborators invented a scanning method with lasers using interferometry. A very thin metallic foil immersed in a cell filled with liquid, forms one of the twin mirrors of Michelson interferometer, which can follow the particle movement in an ultrasonic wave. A laser beam scans its surface to produce an image. This is the principle used in ultrasonovision. In schlieren method, the optical refractive index of transparent media is modified by the pressure oscillations of ultrasound. This finds application in imaging the sound fields and propagation of sound in liquids or transparent models of specimen.

Piezoelectric scanning displays the amplitude and transit time of the echo from the specimen, like the human body, at each probe position. Dussik in 1942, Wild and Neal in 1951, Donald in 1955, Suckling and McLean in 1955 have contributed to this development. These were mechanical scanning devices, which are very slow. Bradfield in 1954 proposed the phased array in which the beam is electronically tuned, this was later on used by Somer in 1968. Improvements have been made to obtain real time images for medical diagnostics etc.

The SAFT-UT or the Synthetic Aperture Focusing Technique for Ultrasonic Testing is the latest development in digital image systems. In the early 1970s Quate et. al, and Korpel et. al, developed ultrasonic microscopy for practical applications. 1974 saw the first applications of ultrasonic tomography by Greanleaf and collaborators. In the late 1980's and quite recently, developments in high frequency transducer arrays for hyperthermia cancer treatment has been reported. The conventional piezoelectric materials like quartz and ceramics are being replaced by piezopolymers and composites.
1.2 ULTRASONIC TRANSDUCERS

A transducer is a device which converts one form of energy into another. Piezoelectric transducers convert mechanical energy into electrical energy and vice versa. Piezoelectric transducers are used for underwater applications and ultrasonic nondestructive testing. Transducers solely used for reception are called hydrophones and those used as transmitters are called projectors. Linearity and reversibility are essential requirements of a transducer. In piezoelectric crystals, a mechanical stress applied to it results in the separation of the centres of positive and negative charges producing electric dipoles within the crystal which in turn induce surface charges [6]. Also when an electric potential is applied to a piezoelectric material, it changes shape. If the electric potential is alternating, a mechanical oscillation is produced in the piezoelectric material. Quartz, Lithium sulphate, Barium titanate, PZT (Lead zirconate titanate), Lead Niobate and PVDF (Polyvinylidene fluoride) are some of the piezoelectric materials.

1.2.1 Ceramic Transducers

Piezoelectric ceramics are available in a wide variety of elastic, electric and piezoelectric constants, which are suited for a wide range of applications. Piezoelectric ceramics can be moulded into various shapes and sizes with their polar axis directed according to the geometry and mode of vibration. Various commercial versions of PZT are manufactured in different countries [6]. Barium titanate, Lead metaniobate and Sodium niobate are also being used as transducer materials. Lead zirconate titanate has gained popularity among ceramic materials due to its strong piezoelectric effect and high Curie point.
1.2.2 Piezopolymer Transducers

PVDF is a semi crystalline polymer of molecular structure CH₂-CF₂-(CH₂-CF₂)n-CH₂-CF₂ with a nonpolar α form with antiparallel dipole chains and a highly polar β form with a parallel dipole chain. The piezofilm is stretched and poled under intense electric field. The electrodes are coated on the film by vacuum deposition. Apart from NDT transducers, piezofilm finds application in military, industry, medicine and sports utilities. Some of them are hydrophones, computer keyboards, tactile sensors, micropositioners in manipulator devices, imaging and osteogenesis in medicine, microphone and tone generators, sports equipments, acoustic speakers etc.

Some of the attractive features of PVDF as a transducer material are

* wide frequency range from 0.005Hz to 10⁹Hz
* vast dynamic range ie., sensitive from 10⁻⁸ to 10⁶psi
* low acoustic impedance
* high elastic compliance
* high voltage output of about 10 times that of piezoceramic
* high dielectric strength with a capacity to withstand strong fields(75V/µm)
* high mechanical strength and stability
* relatively low fabrication costs

All these factors together make PVDF an excellent active material for transducer design.

Piezoelectric composites of ceramic and polymeric materials are also being used for transducer fabrication. They are two phase materials in which the ceramic contributes to the piezoelectric effect and the polymer phase helps in reducing density and permittivity of the material and increases elastic compliance.
1.2.3 Radiated fields

The acoustic field distribution for sinusoidal excitation is given by the Rayleigh's integral [8] [9]. The intensity remains fairly constant in the near field, but the intensity decreases with distance from the source in the far field due to the presence of a spherical wave. The field distribution in the near field is complex, while the far field axial distribution of a disc can be expressed as the product of the spherical wave and the directivity function.

1.2.4 Focusing

A plane piston transducer produces an unfocused beam which spreads radially due to diffraction. The acoustic pressure becomes too low with distance and the beam diameter becomes too large making it difficult to obtain a good transverse definition when probing an object. Focused acoustic beams can provide a good transverse definition and high acoustic intensity at a point of interest. Focusing in a single element transducer can be achieved by shaping the transducer using a lens and in multielement transducer, focusing can be achieved by adjusting the relative phases of the signals from each element.

1.2.5 Sound levels and decibel scale

A logarithmic scale is commonly used to represent the strength of sound. In the acoustic phenomena wide range of frequencies are to be handled. The audible intensities range from $10^{-12}$ to $10$ watts/m$^2$. The decibel scale is the most generally used logarithmic scale[5]. The intensity level of a sound of intensity $I$ is defined as

$$IL = 10 \log_{10}(I/I_o)$$

$IL$ is expressed in decibel(dB) and $I_o$ is the reference intensity.

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1.3 PROPERTIES OF TRANSDUCER ARRAYS

Transducer arrays find wide ranging applications from underwater communication, target detection, mine hunting etc in the kHz range to flaw detection, imaging and ultrasonic holography in the MHz range. The advantages of using an array over a single hydrophone are

* focusing effect
* better sensitivity
* directionality
* improved signal to noise ratio

Since there are more number of elements in an array, more voltage or current is generated, improving the sensitivity than a single element exposed to the same acoustic field. The directionality of the transducer enables the identification of sound arriving at a particular direction. An improved signal to noise ratio capacitates the discrimination of isotropic noise against signals.

Different configurations and designs of arrays suited for different applications are emerging day by day such as the linear array, ring array, cylindrical section array, annular cylindrical array etc [10].

Some of the important parameters of transducer arrays are

* array gain
* shading and superdirectivity
* array beamsteering
* directivity index
1.3.1 Array gain

One of the most important factors in the detection of underwater targets is the improvement in the signal to noise ratio. This is measured by the array gain of the transducer array in decibels, expressed as a ratio of the signal to noise ratio of the array to that of a single element.

1.3.2 Shading and Superdirectivity

A transducer array whose elements have equal weighting may produce a radiation pattern with high sidelobe levels comparable with the main lobe so that target detection is hindered. For such applications the beam pattern may be tailored by giving proper weighting or adjusting the spacing between the elements. This technique is called shading. An extreme form of shading to obtain narrow beam with arrays of limited size is termed superdirectivity [11].

1.3.3 Array Beamsteering

Beamsteering is a technique to direct the beam to a particular angle. This finds use in sonar and NDT applications. The phase of the elements are adjusted to introduce a delay between the elements so that the main lobe is directed to a desired angle.

1.3.4 Directivity index

The transmitting directivity index of a projector at a point on the axis of the beam pattern is the difference between the sound level generated by the projector and the level that would be generated by a nondirectional projector radiating the same amount of total acoustic pressure [11].
1.4 ULTRASONIC TESTING TECHNIQUES

Ultrasonic testing techniques widely being used for defect detection are the through transmission technique, pulse echo technique and resonance methods using a normal or angle beam of ultrasound. Suitable probes have to be designed considering the flaw size, sensitivity, beam divergence, penetration and resolution.

1.4.1 Ultrasonic probes

Different types of probes have been designed for different testing problems. A transmitting probe transmits ultrasound into the object, which then investigates the test material and a receiving probe receives the ultrasound which carries the information of the test object. In certain cases a single probe can be used as both transmitter and receiver [12]. In through transmission two separate probes are used for transmission and reception. In the pulse echo method the various probe configurations are the single probe, twin probe and angle probes which can be operated in the single and multiple reflection modes.

1.4.2 Through transmission technique

Material discontinuities in the path of ultrasonic waves create an obstacle for the ultrasound, through which only a small fraction of the incident energy can penetrate. Even very thin cracks of the order of a micrometer creates an impenetrable barrier to the ultrasonic waves used in nondestructive testing. An ultrasonic transmitter probe is placed on one side of the test object and a receiver probe on the other side with good coupling and alignment, and the intensity of the ultrasound received is monitored. A defect in the path of the ultrasound casts an acoustic shadow on the receiver, resulting in a drop or absence of the received signal. This reveals the
presence of the defect. Some of the requirements for successful and reliable defect detection with through transmission are the following

* The acoustic wavelength in the object must be less than the diameter of the smallest defect to be detected, because of diffraction around the edges of the defect. The minimum noticeable flaw size also depends on the distance from the surface of detection.

* A good acoustic coupling and consistent alignment of the transmitter and receiver should be ensured.

Through transmission technique is used in detection of defects in laminations etc.

1.4.3 Resonance Technique

In the resonance testing the transducer coupled to the plate is driven with continuous waves of varying frequency below its resonance. The transducer is loaded more heavily than at other frequencies when the wave passes through a fundamental or harmonic resonance of the plate. The increase of load causes a corresponding increase of driving alternating current. Thus the resonant frequency can be detected. The plate thickness can be determined knowing the acoustic velocity in the material.

This technique is used in checking the thickness of plates, sheet material, pipe wall etc. This is a time consuming process since the adjacent resonances are to be located.
1.4.4 Pulse echo technique

A short burst of ultrasound is sent into the test object and the echoes from the discontinuities, defects or boundaries of the object are amplified and displayed on a cathode ray oscilloscope. The time of flight of a pulse gives the information of the distance or depth in the object. The echo amplitude is affected by the reflectivity of the interface, its size, its orientation, distance from the probe, attenuation along the path, acoustic coupling between probe and the test surface, as well as probe characteristics.

This is the most versatile and most widely used ultrasonic method of nondestructive testing. It is used in weld testing, testing of bars, rods, sheets, pipes, rails etc.

1.4.5 Modes of display

Acoustic visualisation is much different from its optical counterpart. An optical image normally corresponds to the visualisation of the surface of an object, but most materials are at least partially transparent to acoustic waves, hence views the entire interior through which it passes and provides more information than that is optically observable. Some of the standard visualisation techniques employed in NDT and medical diagnosis are the A-Scan, B-scan and C-scan.

1.5 MOTIVATION FOR THE PRESENT WORK

A lot of emphasis is laid on the structural integrity of materials during production as well as during operation. The need for evaluation of defects becomes severe as the complexity of the structure increases. Very precise and accurate methods have become essential for detection localisation and estimation of defects such as cracks
or inclusions. As inspection techniques become more and more accurate and reliable, smaller and smaller defects become detectable. Accuracy, reliability and inspection time are some of the problems encountered in testing techniques [14]. Inspection of underwater pipelines and offshore structures poses many challenges. Sophisticated unmanned systems equipped with various sensors, manipulator arms, closed circuit television camera and other tools are needed for working in the ocean environment which is too harsh for humans. There is a need to develop highly sensitive and efficient sensor systems.

Various types of probes have been developed for detection of flaw in pipes. Those commonly used are the focused probe or the single probe, which has to be moved about the pipeline. A widely spaced point source ultrasound ring array working in the near field was designed by Whittington and Cox to reduce the necessity for mechanical rotation of the probes for tube inspection [15].

The motivation to carry out this work is to develop a better ultrasonic transducer system for testing underwater pipelines. An annular ring array and an annular cylindrical array have been designed which can inspect underwater pipelines without being mechanically rotated about the pipe. The inspection time can be considerably reduced. A section of the annular ring or annular cylindrical array is selectively energised which focuses a beam of ultrasound on the pipeline. A similarly grouped section of the array can act as receivers. Then the next set of transmitters and receivers are energised and so on, thereby inspecting the whole contour of the pipeline.
1.6 BRIEF DESCRIPTION OF THE PRESENT WORK

Schematic of the work done with chapter wise details is given below.

Earlier work carried out by various authors in the field of piezoelectrics, transducers, ultrasonic nondestructive testing etc. are presented as literature survey in Chapter 2. A review of the important contributions in the field of piezoelectric materials, as well as in the design and fabrication of different transducers and transducer arrays, for various ultrasonic applications is carried out in this chapter. The revolutionary discovery of piezoelectric effect, its impact on the new generation of sensors and contribution to modern technology can be glimpsed while going through a review of the past work in this field.

The methodology adopted in the design of transducer arrays used for inspection of defects in underwater pipelines is featured in Chapter 3. Different types of ultrasonic waves, plane waves at solid liquid interface, radiated sound field and modes of display are also described. Different types of probes and inspection methods for ultrasonic testing and computation method of array gain, beam pattern and effective acoustic pressure are also depicted.

Chapter 4 highlights the formulation and computation results of array gain and beam pattern of an annular ring array and annular cylindrical array suited for pipeline inspection. The inspection system comprises an annular ring array or an annular cylindrical array placed concentric over the pipeline and selectively activated with the ultrasound focused on the contour of the pipeline. A similarly grouped set of elements of the remaining array acts as the receiver to collect the information of the defect. The array gain and beam pattern are computed for a selectively energised section of an
annular ring and annular cylindrical array. The computations are carried out for different configurations and array radius of the annular ring and annular cylindrical array. The sidelobe level and 3dB beamwidth are determined for different configurations of the array. The sidelobe level and 3dB beamwidth are found to remain constant when the array radius is $> 40\lambda$.

Chapter 5 concentrates on the formulation and computation of effective acoustic pressure of an annular ring array and an annular cylindrical array for continuous as well as pulse excited signals. An ultrasonic transducer array comprising a selectively energised section of an annular ring array or an annular cylindrical array concentric to the test pipeline, with the ultrasound focused on its contour is used for underwater inspection. The impulse response of the array $h_a(r,t)$ is computed to evaluate the effective acoustic pressure. The pressure field is evaluated as the Fourier Transform of the impulse function. The transient effective acoustic pressure is evaluated for different configurations of the array. The effective acoustic pressure at a point on the contour of the pipeline is evaluated as the sum of the contributions from individual elements. The effective acoustic pressure is determined for different configurations of the array, and by varying the pipeline radius, array radius and axial distance between the pipeline and array.

Various conclusions drawn from the outcome of the investigations are discussed in Chapter 6. An annular ring array and an annular cylindrical array are designed for inspection of underwater pipelines. Substantial reduction in inspection time and a focusing effect can be achieved using an annular ring or annular cylindrical array compared to the conventional single probe technique. The scope for further work in
this field and also the suitability of similar arrays in biomedical applications like hyperthermia cancer treatment is also discussed in this chapter.

Transducer elements have been developed using PVDF film of 110μm thickness operating in the (3,3) mode. The design, calibration and experimental set-up are discussed in Annexure I.