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Technical considerations in the design of a tropical acoustic exposimeter

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The technical considerations in the design of a tropical acoustic exposimeter using the strain gauge principle are enormous.The choice of design parameters must not only be precise, but modeling should be done in such a manner as to produce a rugged, cheap, portable and sensitive device, comparable to existing designs.We have attempted to adapt the well known radiation force balance designs to conditions specifically relevant in the tropical environment.Our study has identified salient peculiarities in the requirements for desirable liquid medium, physical and isotropic properties of the cantilever materials, choice of target angle and material as well as precise electrical circuitry.The treatment of water with Sodium aluminium sulphate, use of polystyrene and duraluminium as cantilever materials and precise choice and method of mounting the strain gauges have been suggested as novel modifications for a potential tropical model.Exploiting the technical considerations outlined in this paper, drawing from experience of various authors and precise modifications in the construction of suitable cantilever arms,we attempted to develop an experimental model.Using cantilever arms made of locally available materials,namely polystyrene and duraluminium with dimensions 100 x 5 x 0.6mm and 100 x5 x 0.6mm, our design had sensitivity of 2.13mV/watt,and 1.47mV/watt respectively.The power range is given for both arms approximately 6.1watts and a detection threshold of 128mW.With slight improvements,especially in the electronic circuitary,and use of locally available materials such as polystyrene and duraluminium,our device offer prospects for a successful design of an acoustic exposimeter for use in the tropical environment.

Keywords: Technical considerations, design, strain-gauge, acoustic exposimeter, cantilever arms

INTRODUCTION

Diagnostic ultrasound has enjoyed a wide popularity in clinical medicine and is widely applied in obstetrics and gynecology (Duck F 1999), Ugwu et al (2009), gastroenterology, nephrology, paediatrics and virtually all fields of medicine (Wolf, 1998; Kurtz et al 1980; Fielding, 2004; National Cancer Institute, 2009).

In Nigeria,ultrasound has gained wide acceptance and is generally performed in many settings including obstetric and radiology departments,ultrasound and diagnostic clinics, private physicians' offices and even veterinary centers.Consequently, a large influx of ultrasound machines which are either new or pre-owned has been experienced in Nigeria. Several authors have reported surveys of acoustic diagnostic probes (Chivers 1980), Carson et al (1996),Bly et al (1986),Duck et al 1985, 1987),Duck F.A (1989a) but to the best of our knowledge, there are no recorded data on the exposimetry of diagnostic ultrasound probes in Nigeria and in the tropics.This would also be difficult,without the design of acoustic exposimeters specifically adapted for tropical use.Although several designs of acoustic exposimeters in the form of radiation force detectors exist in literature,such as those of Bindal and Kumar (1980), Bindal et al (1980), Brendel and Ludwig (1976) and CornHill (1982),no attempts have been made to develop tropical designs.

In principle,these previous designs may likely experience fluctuations in sensitivity,due to variations in ambient temperature and environmental conditions, thus necessitating a design capable of tolerating the comparatively higher temperatures likely to be encountered in

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the tropics.

The authors set out to review existing design considerations,and outline peculiar technical variations necessary for the modeling of a Tropical Acoustic exposimeter using the strain gauge principle.

The acoustic exposimeter is a radiation force detector which is based on the strain- gauge principle.It is based on the fact that the vector force associated with radiation pressure from an ultrasonic field, is found to be proportional to the ultrasonic power and independent of the ultrasonic frequency.The strain-gauge is an example of a passive transducer, which measures the variation in resistance of an electric conductor in response to a change in its geometry; specifically the induced strain. The strain-gauge is attached to a length of material which serves as a cantilever arm.The latter is clamped to a target which acts as a receptor for the radiation force exerted by an ultrasonic beam.

This force is transmitted to the cantilever arm (already laced with strain-gauges) causing its deflection and inducing a strain along the length of the arm.The strain is consequently transferred to the attached strain-gauge where it produces a resistance R on the gauge.The resistance is converted to a voltage change V using a Wheatstone Bridge circuit.The resultant voltage change can be read using a simple voltmeter.

The voltage change is proportional to the resistance R on the gauge which in turn is proportional to the ultrasonic power being measured.The whole device is placed in a suitable container with liquid medium.

The above theory forms the basis for our design.

MATERIALS AND METHODS

Our method is an attempt to adapt the well known technical parameters in the modeling of a radiation force detector, specifically relevant in a tropical environment. Consequently, many basic requirements have been retained for consistency and ease of comparison. Where necessary, modifications have been introduced to achieve our overall objective.

Of the many available methods of measuring output of ultrasound probes, radiation force methods appear to be popular and had been described in literature, (Wells et al, 1964), (Hasegewa and Yosiokka,1975), (Farmery and Whittingham, 1977), (Bindal et al, 1983), (Shotton 1979) and (Kossof G, 1965).

More recently, designs based on strain-gauge radiation force detectors have been exploited by (Chivers et al, 1989), (Chivers and Anson, 1982),(Anson and Chivers, 1981a, 1981b).

The criteria for our choice of parameters is based on a well known and detailed mathematical derivation by Chivers et al (1989). The final equation which depict the sensitivity of any such strain- gauge device is reproduced below:

$\Delta V/ P = \eta = (2\cos^2\alpha/ C) (l / Єbt^2) (GVK4\varphi)$ (Chivers et al 1989)

where

η = sensitivity of the strain gauge device

α = target angle

c = speed of sound in the liquid medium

l = length of cantilever material

b = breadth of cantilever material

t = thickness of cantilever material

Є= Young's modulus of elasticity

G = Gauge factor

V = Voltage applied across the bridge circuit

K= amplification applied

φ= Factor indicating the number of gauges used in the arms of the bridge circuit

The brackets have been introduced to reflect the various contributions of the speed of sound in a surrounding medium($2\cos^2\alpha/ C$), cantilever arm dimensions and characteristics (l / $Єbt^2$) and electric circuit (GVK4φ) respectively to the sensitivity of the device.

Exploiting the above sensitivity equation, we identify four major technical parameters necessary for a workable device.

The technical parameters under consideration are as under-listed

1. Choice of suspending fluid
2. Choice of target material, geometry and size
3. Choice of target angle
4. Choice of suitable electric circuitry

1. CHOICE OF SUSPENDING FLUID

The evidence of finite amplitude effects associated with diagnostic ultrasound pulse propagation in liquids such as water has been documented previously (Duck,1991). Such effects like waveform distortion, harmonic generation, acoustic formation and associated generation of high frequency components are recognized as characteristics of non-linear propagation (Duck 1999; Duck and Starrit, 1980).

For pulsed ultrasound beams in the diagnostic range, shock formation is not only possible (Duck and Starrit 1980, Duck and Bacon 1988), but also frequently common (Duck et al 1985). Such effects become obvious when acoustic measurements are carried out in water (Duck, 1999) and may lead to significant energy loss due to excess attenuation from diagnostic ultrasound pulses (Duck and Perkins 1988); Duck and Starrit (1989).

Recalling the sensitivity equation, the first bracket ($2\cos^2\alpha/ C$) easily comes to mind. The sensitivity of any tropical device is expected to increase if the speed of sound in the liquid is reduced.

In practice, few liquids will exhibit a significantly lower ultrasonic velocity than water, and such a choice according to Chivers et al. (1989), will be limited by the fact that most fluids have frequency dependent absorption.

Water is considered as the most suitable liquid medium for standard acoustic measurements (Duck, 1999). It is non-toxic, widely available, and inexpensive and its acoustic and mechanical properties are well documented.

The most important consideration by the authors Erondu and Ogulu (2001), is the fact that water is the major component of body fluids in humans. Thus, performing experimental measurements in water as suspending fluid simulated the interaction of sonic waves with the human body. Previous authors have suggested ways of improving the sensitivity of measurements, when water is used as liquid medium. Chivers et al (1989),suggested fine-tuning by adding small weights to the stem of the target in a bid to improve buoyancy and off-set gravitational forces. Duck, (1989b) recommends that measurements be made with wave amplitude attenuated such that propagation is quasi-linear. This is achieved by either electronic or acoustic attenuation using calibrated plastic attenuators (Preston et al 1991). The unique modification by the present authors is the addition of reasonable quantities of Sodium Aluminium sulphate to water prior to measurements. This has advantage of increasing its density and reducing temperature drifts as well as improving target buoyancy. This is achieved, without necessarily affecting the speed of sound and by implication the sensitivity equation.

2. CHOICE OF TARGET MATERIAL, GEOMETRY AND SIZE

According to Chivers and Anson (1982), small target radiometers have been the subject of considerable discussion in literature as regards both practical implementation as well as theoretical and computational basis of their use.

This is because, the amplitude of the echo reflected from a scanned spherical target can be easily used as a relative measure of the pulse-echo distribution of the ultrasonic field and when combined with some other measurement techniques can be used to assess the intensity of sound, even in difficult situations.

The potential variables involved in the choice of a practical system are many and often inter-related. The crucial need must be the absolute accuracy of the calibration obtained using targets (Zieniuk and Chivers 1976a). The geometry of the target is important as this may affect the buoyancy in a liquid medium.

The spherical shape appears to have a universal acceptance. Firstly, the symmetry reduces the complexity of the mathematical analysis required. Furthermore, the shape is relatively easy to manufacture with reasonable precision. Finally, there are no sharp discontinuities in the surface, such as corners that are difficult to incorporate into the calculations in quantitative terms. Despite their advantages, some problems tend to arise in practical use of these spherical targets. These problems according to Chivers and Anson (1982a, 1982b) arise from three sources. These are namely, the finite size of the transmitting transducer, the departure of the target from an ideal rigid sphere and means to mount and move the target. The finite size of the transducer causes not only the area of the target from which scattered echoes are returned to the transducer to vary with the distance, it also confounds the principal assumption of scattering theories.

In principle, the penetration of the ultrasonic waves into the material of the target may give rise to resonance phenomenon at certain frequencies determined by the material parameters. This may vary depending on the size of the spherical target and may ultimately affect and alter the scattering pattern of the ultrasonic beam. Chivers et al (1989) predicted that the bending movement of the cantilever arm introduces a rotational movement of the target and therefore a possibility of error. They therefore suggested that a conical shaping of the target will reduce this error.

Consequently, for the purpose of consistency and possible improvement on the sensitivity of existing devices, the conical shape adopted by previous authors (Chivers and Anson 1982; Chivers et al 1989) will be maintained.

The choice of materials is critical and would be guided by their relative instability to variations in physical parameters such as cross-sectional area, temperature, density, velocity. Many authors have used various considerations. King (1934) considered the *Y*p:Ka values to be useful. *Y*p is a constant of proportionality by which the geometrical cross-sectional area of the sphere must be multiplied to give a correct force, while Ka is the acoustic radius. It is also proved that the rigid sphere of *Y*p:Ka curve is inadequate when the acoustic waves can penetrate the target. The need to obtain materials whose *Y*p:Ka curve are relatively flat has led to successive advocation of materials such as stainless steel (Dunn et al., 1977), fused silica (Hasegewa and Yosioka 1975) and even polymers (Anson and Chivers 1980). However inspite of Yp:Ka curves being available for over 50 materials (Anson and Chivers 1982), the optimum choice of material for specific measurement purpose is still difficult to define. It requires not only the calculation of the appropriate value of *Y*p but also an understanding of the way in which the uncertainties inherent in the specification of the parameters of the material are reflected in uncertainty (and thus potential accuracy) in the *Y*p calculated.

In summary, the determinant factors include availability of material whose state of purity, homogeneity and isotropic properties should vary little with their source. Furthermore, it is reasonable to assume that since the target is to be immersed in water, it should be made of a non-corrosive material at room temperature. There is also obvious need to have an adequate mechanical strength such that it allows precise machining and modeling without relaxation. Our considerations are in line with the need to have a simple portable, robust device that is relatively insensitive to vibrations (Chivers et al;1989).

In line with the above requirements, our target cylinder is made of Perspex while the conical part is made of brass. The brass acts as the reflecting surface as well as a barrier between water and air. The thinner the brass material, the better the actual reflection will approach the ideal. The cantilever arm should be made of materials which apart from having low Young's modulus would be resistant to corrosion (Chivers et al 1989). Several materials have been considered in literature, such as phosphor-bronze (Chivers et al 1989), brass, polystyrene and Perspex. For our tropical design, two materials have been considered, namely polystyrene and duraluminium. The choice of duraluminium in preference to phosphor-bronze is determined mainly by availability.

3. CHOICE OF TARGET ANGLE

The angle of float is considered important, since the accuracy of measurement is based on the assumption that the float is vertically displaced under the action of the ultrasonic radiation force. Considerable experimental basis for the choice of target angle has been derived by Chivers et al. (1989).

Again the equation for sensitivity comes into focus

$$\Delta V/ P = \eta = (2\mathrm{Cos}^2\alpha/ C) (l / Єbt^2) (GVK4\varphi)$$

In other words, the sensitivity of the device increases as α decreases. In practice the potential benefit of increasing Cos ^{2} α is small (Anson and Chivers 1982). It can be deduced that decreasing the target angle α above increases the sensitivity of the device. It is needful that the reflected sound does not impinge on the transducer as this would moderate the output (Chivers et al. 1989). The target angle is usually determined as the smallest value which given the geometrical arrangement of the measurement system will remove the possibility of the waves reflected from the float (target) impinging on the front surface of the transducer (Anson and Chivers 1982, Bindal et al. 1983).

In other words, all transmitted sound should be absorbed at the target area with no reflected sound returning to the transducer. For this to be possible, the distance between the transducer and the vertex of the float's conical surface should not be less than 1/2D (if D is the effective diameter of the transducer (Duck and Bacon 1988). To keep the float within the near field, the distance of the float from the transducer should not exceed $D^2/ 4\lambda$ where λ is the wavelength of the ultrasonic beam. To prevent fluctuations in the α during cantilever measurements, the surface of the target is made with reflecting surfaces, inclined at same angle to the ultrasonic beam, but are symmetrical about an axis perpendicular to the length of cantilever arm. In principle, there appears to be no uniformity in the choice of the target. The design by Perkins M.A (1989) is made from two formed 90 degrees cones of very thin metal, separated by about 2mm to form a long suspension arm, giving a pivot to target centre line radius of 12cm. Ziquri and Jones (1989), utilized a reflecting target made of glass dome and stainless steel cone of angle 90 degrees. In the design by Anson and Chivers (1982), the target consisted of an air-backed conical reflecting surface of 0.1mm thick brass at an angle of 69 degrees.

Chivers et al (1989) retained the same angle of 69 degrees. Our tropical design has retained the above angle in other to have a comparative method of calibrating the device and to maintain consistency. The above angle has other advantages of good sensitivity, positive buoyancy in water during measurements and reduced lateral movement of the target encountered in previous designs (Chivers et al 1989).

4. CHOICE OF SUITABLE ELECTRIC CIRCUITARY

The strain gauge principle was considered for the tropical design.

The strain gauge is an example of passive transducer capable of being activated by an energizing input from one or more transmiss-

ion media and in turn generates a related signal to one or more transmission systems. As earlier described, the strain gauge uses the variation in electrical resistance in wires to sense the strain produced by a force on the wires.
Both stress (force/ unit area) and strain (elongation or compression per unit length) in a member or portion of any object under pressure is directly related to the modulus of elasticity. The strain gauges may be wires, foil or semi-conductor types. The change in resistance value of a conductor under strain is more than for an increase in resistance due to dimensional changes (Kalsi, 1998).
The basic requirements for strain gauges advocated for use in tropical designs may include

1. A high gauge factor (implying high sensitivity)

2. High resistances of the gauges as this counterbalances undesirable variations of resistance in the measurement circuit

3. A low resistance temperature coefficient

4. The strain gauge should have high hysteresis effects in its response.

5. Good frequency response and linearity should be maintained within specified accuracy limits over the entire frequency range.

6. Leads used must be materials with low and stable resistivity

7. Availability and cost of strain gauges is important in achieving a rugged and cheap device.

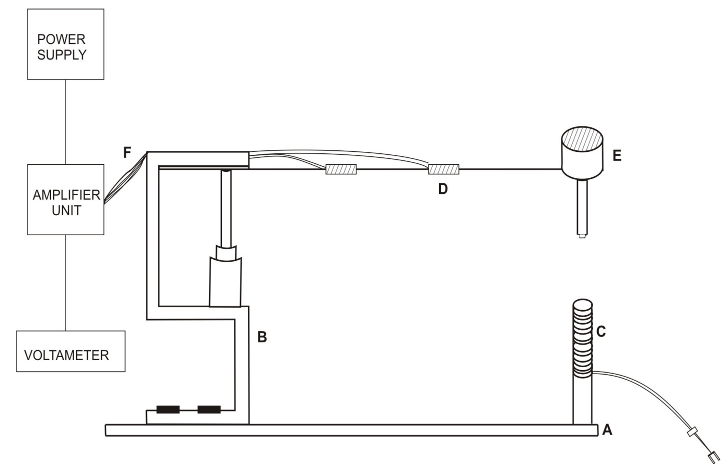
Our design utilized the foil type of strain gauges procured from RS components (Ennigma Corporation Limited, Sussex England. These have specifications as underlisted

Suppliers = RS components (Ennigma Corp. Ltd England)
Gauge length = 8mm
Temperature range = -30 to + 80^{0}C
Gauge resistance = 120Ω ± 0.5%
Gauge factor = 2.1 ±1%
Fatigue life = > 10 reversals at 1000 µstrain
Foil material = copper nickel alloy
Base material = Polyester
Temperature compensation = 23.4 x 10-6^{o}C
Stock number = 308-102

The strain gauge is connected to an amplifier with stock number 846-171. The versatile amplifier is housed in a 24-pin d.i.l package. The module is specifically designed for use with a strain-gauge bridge circuit, but may be used in application where a low drift amplifier is required. The operating temperature range between 25^{0}C to + 85 ^{0}C with a voltage of 2± 20 V dc.
During installation, each strain gauge is carefully attached to a carefully prepared cantilever arm by means of quick set adhesive. Four gauges were fixed to the arm, two on each surface, with a distance of 50mm between the gauges.
Using thin fine constantan wire grids, a parallel connection is achieved between the two gauges on separate surfaces, whereby each gauge forms one arm of a Wheatstone bridge circuit.

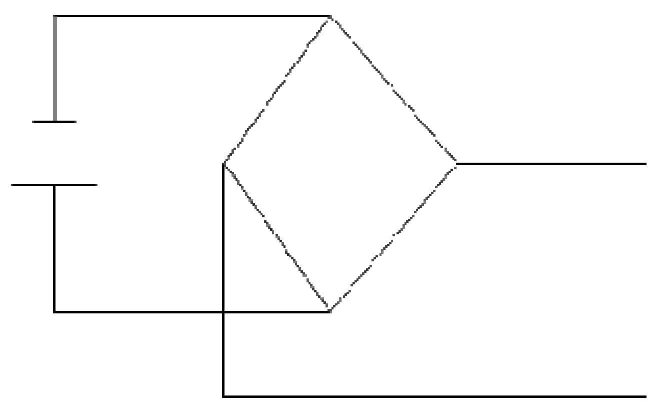
The schematic diagram is shown below:

For this tropical design, the leads from the gauges were not taken



A. BASE PLATE
B. CLAMPING ARRANGEMENT
C. ELECTROMAGNET
D. CANTILEVER ARM WITH STRAIN GUAGES
E. TARGET (FLOAT)
F. WIRE GRIDS FROM THE ARM

SCHEMATIC DIAGRAM OF STRAIN GUAGE EXPOSIMETER IN AIR



at perpendicularly to the arm as done in by previous authors (Chivers et al 1989).
Our design allows adequate but not excessive slack, so that the leads would not load the arm mechanically, and were thus taken parallel to the arm and clamped into the same pillar as that to which the stationery end of the cantilever arm was attached.
The final device is given schematically below.(figure 1)
The above device is placed inside a container filled with water treated with Sodium Aluminium sulphate, as a liquid medium.The device was tested for function, sensitivity, power range and robustness. The device was tested using 10 precision weights with values of 0.1,0.2, 0.3, 0.4, 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0grams.
The precision weights are used to represent ultrasonic power, based on the theoretical relationship between vertical weight in grams and ultrasonic power in watts. (Preston,1986). This relationship is given as 1 milliwatt = 690µgrams
Function: In order to test for the function, 8mm strain-gauges were attached to cantilever arms made of duraluminium and plastic respectively. A DC converter with voltage range of 1.5 to 12V and

maximum current of 500mA was used to provide voltage supply to the circuit, whose output is fed to a voltmeter. Precision weights are gradually introduced, to represent ultrasonic power. The presence of a deflection and digital read out of the corresponding voltage indicate function.
Sensitivity: The sensitivity of the device is defined as the output from a bridge circuit in Volts, divided by the output power.
Simply stated, Sensitivity = Volts/ watts
The sensitivity can also be derived from the slope of a graph of output in Volts against Power in watts.
Power Range: Using a null method of measuring output from a Wheatstone bridge circuit, the power range is same as the difference between the current corresponding to the smallest weight and the maximum current which can flow through the device without causing damage.
Robustness: This is inferred from the ability of the device to withstand several episodes of handling, testing and dis-assembly without significant change in function.

RESULTS AND DISCUSSION

We experimented with two cantilever arms made of locally available materials,namely polystyrene and duraluminium with equal dimensions of 100 x5 x 0.6mm (length x width x thickness). These have values of Young's modulus of elasticity,3.0 x $10^9 Nm^{-2}$ and 7.2 x $10^8 Nm^{-2}$ for polystyrene and duraluminium respectively.

Our device has a sensitivity of 2.13mV/watt and 1.47mV/watt for the polystyrene and duraluminium arms respectively.

The power range is given for both arms as 6.1 watts. The detection threshold was determined as the lowest weight producing a voltage change on the voltmeter and is given for both arms as 128mW.

The design by Perkins (1989),has a maximum sensitivity of 1 mW with a power range of about 10W. The design by Bindal et al, (1980) used a single semiconductor strain-gauge and cantilever arm made of phosphor-bronze and has a sensitivity of 30µV/watt.The modified system by Anson and Chivers (1982),used a cantilever arm made of phosphor-bronze.The maximum power was set at 2W and sensitivity was 3.6µV/W with a detection threshold of 50mW. The design by Chivers et al (1989) used phosphor-bronze and polystyrene cantilever arms. The arms showed good linearity between equivalent rate of 100mW to 8 watts. The sensitivity was 42mV/W (phosphor-bronze) and 26mV/W (polystyrene).

CONCLUSION

The technical considerations of a tropical acoustic exposimeter are enormous.The choice of design parameters must be precise and modeling done in such a manner as to produce a rugged, cheap, portable and sensitive device, comparable to existing designs. Our study has revealed salient peculiarities in the requirements for a desirable liquid medium, physical and isotropic properties of the cantilever materials as well as choice of target angle

While drawing from the experience of previous authors, various modifications in cantilever design, precise choice of strain gauges with tropical adaptability, and use of a customised electrical circuit (wheatstone bridge design) are of paramount signi-ficance.
Exploiting the technical considerations outlined in this paper,we have attempted to produce an experimental model with encouraging results.It is our belief,that the stage has been set for a proper design and subsequent modeling of a tropical acoustic exposimeter.

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