TEMPERATURE COMPENSATION IN ULTRASONIC RANGING SYSTEMS: AN EMPIRICAL MODEL

BY

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ABSTRACT

Ultrasonic ranging systems have for many years been used to measure the distance between two points by emitting short bursts of high frequency signals and listening to the echo. It has been used as a means of acoustic location with applications in intelligent suspension systems, modern naval warfare and measurement of echo characteristics of targets in water. The measurement of distance by ultrasonic ranging systems is characterized by the problem of the errors that arise due to variation of the speed of sound with change of temperature. In this thesis a design of an ultrasonic ranging system is made based on the temperature-distance characteristic correction technique to minimize the errors in the measurement of distance of the ultrasonic ranging system. The main objective of designing a unique temperature compensating ultrasonic ranging system to track resonant frequency drifts of ultrasonic transducer caused by variation in temperature is taken into consideration. The objective was achieved by measuring mean deviation in distances between two fixed points as the temperature changed. It is shown that the errors can be minimized by using a built-in compensator or an algorithm developed based on the deviation-temperature equations. The study is likely to significantly improve on accuracy of distance measurement using ultrasonic ranging systems whenever temperature changes occur. Applications which employ time-of-flight technique in ultrasonic auto ranging systems is best suited for this method which can be implemented by incorporating either a built in compensating system or using an algorithm for the error correction whenever there are temperature variations when measuring distance.

CHAPTER ONE
INTRODUCTION

1.1 Background

Sound Navigation and Ranging (SONAR) is a technique that uses sound propagation to navigate, communicate with or detect other objects. SONAR is used as a means of acoustic location and measurement of the echo characteristics of "targets" in water [1]. The measured travel time of SONAR pulses in water is strongly dependent on the temperature and the salinity of the water [2].

SONAR systems use frequencies that vary from infrasonic to ultrasonic. The ultrasonic frequency range is typically considered to be 20 KHz to 500 KHz, or just below the AM Broadcast band. Sounds at these frequencies are much more directional than lower frequency sounds [3]. The method of measurement of distance using SONAR is capable of easily and rapidly measuring the layout of rooms and performing length measurements in science laboratories.

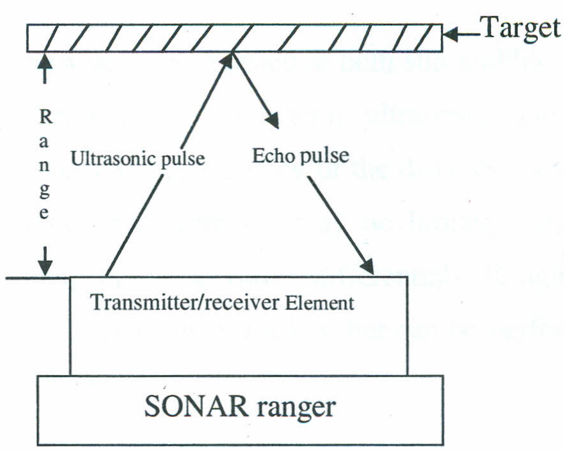


Figure1: Illustration of basic sonar operation

SONAR devices utilize Ultrasonic Ranging Systems (URS) that allow the measurement of distance between two points. Ultrasonic ranging systems operate simply by emitting a short burst of high frequency sound that is generated electronically, amplified and transmitted by a transducer and then listening for an echo (see figure 1). The signal that travels through the medium is reflected by the target object and returns to the transducer as an echo which is then received and amplified by the system electronics. The time for the round trip is then determined and provided the correct speed of sound is known, the distance to the object can be calculated[4, 5]. The distance is computed by dividing the time measured between the emission and reception by two. This division is necessary to take into account the time the sound travels towards an object from the transmitter and the time the reflected sound takes to travel from the object back to the receiver.

Ultrasonic Ranging Systems have been used in a wide number of applications, among them the walking cane for the visually handicapped, altimeters for aircrafts, camera lens focusing, intelligent suspension systems in cars, modern naval warfare, mine and obstacle avoidance, fishing and electronic dipsticks for liquid level measurement and many other industrial applications [6, 7].

Although range finding underwater is performed at both sub-audible and audible frequencies for great distances (tens of kilometers), ultrasonic range finding is used when distances are shorter and the accuracy of the distance measurement is desired to be finer. Ultrasonic measurements may be limited through barrier layers with large salinity, temperature or vortex differentials. Ranging in water varies from about hundreds to thousands of meters, but can be performed within centimeters to meters accuracy [8].

Even though measurements can be performed fairly accurately, errors that arise due to temperature variations cannot be neglected. Sound travels at approximately

331.4ms^{-1} in air but the actual speed will vary depending on temperature, humidity and pressure. It is the temperature dependence that is most significant in determination of the speed of sound [9]. Since ambient temperatures vary, the readings from the ultrasonic systems are not accurate because of these variations. In this work, a system is developed that can be used to correct errors in the measurement of distance caused by temperature variations in ultrasonic ranging systems that utilize pulse-echo time-of-flight (TOF) technique.

1.2 Objectives of the study

Main objective

The purpose of this study is to design a unique temperature compensating ultrasonic ranging system that tracks the resonant frequency drift of ultrasonic transducer caused by changes in ambient temperature of air in order to improve on the accuracy of ultrasonic ranging systems in distance measurements.

Specific objectives

The specific objectives of this study are to;

1. conduct experiments to determine relationship between distance measured by the ultrasonic ranging system and temperature.
2. obtain empirical equation(s) that can be utilized to correct the error in the measurement of the distance by ultrasonic ranging systems caused by temperature variations in air.

1.3 Statement of the problem

Variation of speed of sound with temperature, though small, may cause appreciable errors in distance measurements using ultrasonic ranging systems. Previous work has concentrated on using Laplace's velocity equation and not on methods based on actual physical measurements that can be used to minimize errors caused by variation of speed of sound with temperature in ultrasonic auto ranging systems that utilize pulse-echo time of flight (TOF) technique in their operation. The solution lies in the development of a unique temperature compensating ultrasonic ranging system that tracks and resolves the resonant frequency drift of ultrasound transducer caused by changes in ambient temperature of air to compensate for the errors in measurement of distance between two points.

1.4 Significance of the study

The results obtained in this work are likely to improve the accuracy of ultrasonic auto ranging systems that utilize TOF technique in their operation.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview and present state of knowledge

The use of sound to 'echo locate' underwater objects in the same way as bats use sound for aerial navigation seems to have been prompted by the *Titanic* disaster of 1912. The world's first patent for an underwater echo ranging device was filed at the British Patent Office by English meteorologist Lewis Richardson a month after the Titanic sank [10]. A German physicist Alexander Boehm also obtained a patent for an echo sounder in 1913 [10, 11]. Canadian Reginald Fessenden, while working for the Submarine Signal Company in Boston, built an experimental system beginning in 1912 that was later tested in Boston Harbor, and finally in 1914 from the United States Revenue Cutter Miami on the Grand Banks off Newfoundland Canada. In that test, Fessenden demonstrated depth sounding, underwater communications and echo ranging to detect an iceberg at a range of three kilometers. The so-called Fessenden oscillator, operating at a frequency 500 Hz was unable to determine the bearing of the berg due to its three-meter wavelength and the small dimension of the transducer's radiating face (less than 1 meter in diameter). The ten Montreal-built British H class submarines launched in 1915 were equipped with a Fessenden oscillator [10, 11].

Acoustic location in air was used before the introduction of RADAR (radio detection and ranging). Animals such as dolphins and bats use sound for communication and object detection. The use of sound by human beings to detect objects in water was tried in 1490 by Leonardo Da Vinci who inserted a tube into water to detect vessels by placing an ear to the tube and listening to the sounds emanating from the vessels [10, 11].

Most SONARs are used monostatically, with the same array often being used for transmission and reception as opposed to bistatic or multistatic operation in which more transmitters (and receivers) that are spatially separated are used [11].
Some research has been carried out to improve the accuracy and reliability of ultrasonic ranging devices where one known method in the monostatic operation is to cross-correlate the transmitted and received signals to determine the time-of-flight (TOF) and then perform temperature and pressure compensation based on approximations. Parabolic interpolation on the cross-correlation's magnitude is used to increase the accuracy of TOF estimation and high measurement resolutions including good noise immunity is achieved [12].

Bohn [13] presented a detailed analysis of the environmental effects of temperature and humidity on the speed of sound in which he stated that an overview of the available literature reveals serious shortcomings for practical applications. His results show that an accurate control of temperature and humidity must accompany the popular trend of splitting microseconds when time correcting sound systems and failure to do so makes precise time correction an exercise in futility.

Martin et al [14] in their paper "Ultrasonic ranging gets thermal correction" present some aspects of research activities on sensors for robots, developed at the Instituto de Automatica Industrial (IAI) and stresses the demand for greater precision in the measurement of distances using ultrasonic techniques that makes it necessary to compensate for alterations in the speed of sound in the interposed medium due to temperature variation. In the paper they describe a method for calculating this correction in order that no other external sensor is necessary. The method is based on the resonance-frequency variation of the piezoelectric elements with temperature variation. The accuracy reached with this correction was highly acceptable for most robotics applications.

The international standard algorithm, often known as the UNESCO algorithm due to Chen and Millero [15] uses pressure as a variable rather than temperature to account for errors in the measurement of the speed of sound in seawater. The original UNESCO algorithm was presented by Fofonoff and Millard [16] in 1983. The coefficients in this algorithm were recalculated in 1995 following the adoption of the International Temperature Scale of 1990.

In his paper on "Study on Ultrasonic Ranging System Design", Deng [17] presents an ultrasonic ranging system which can be used to measure distance using time difference location method with a voice broadcast system. In his design measurement accuracy is improved by temperature compensation using known algorithms. The voice broadcast is used to make the design more extensive in application.

Chia-Chang et al [18] at the IEEE transactions on instrumentation and measurement in October 2001, present "A method for short or long range Time-of-Flight Measurements using phase-detection with an Analog Circuit", whose accuracy is further improved by compensating for variations in the speed of sound due to temperature changes. This compensation is performed by measuring the temperature of the air between the transducers at each step of temperature change using a thermistor and then applying Laplace's equation to calculate the speed of sound.

Researchers have proposed various methods of compensating for the variation of the speed of sound with temperature leading to various approximations. An overview of available literature however, reveals shortcomings, for practical applications, of methods that minimize errors caused by variation of speed of sound with temperature [13].

2.2 Sound waves and their velocity dependence on temperature

Basically, there are two common principles used to determine distance using ultrasonic waves [19, 20], namely Phase shift and TOF.

The phase shift method consists of measuring the phase-shift between continuously transmitted and received signals. The measured phase shift, θ, is proportional to the distance, d. These quantities are related by;

$$2\pi d = \theta\lambda \tag{1}$$

where λ is the wavelength, θ is angle of phase difference in radians and d is the measured distance.

The limitation in this method is that the measurable distance range, without ambiguity, is only from zero to one wavelength. For instance, at 20 °C, a system operating at 40 kHz would only measure, without ambiguity, distances up to 0.0086m, which is quite small for most applications [21]. The ambiguity occurs because a given phase-shift does not correspond to a unique distance. To solve this problem one needs to know the integer number of wavelengths within the distance to be measured.

The second method is mainly used for distances greater than a wavelength. In a transmitter-receiver configuration, the TOF is the time that an ultrasonic wave takes to arrive at the receiver. It is related to the distance d between transmitter and receiver by;

$$d = V_s t_f \tag{2}$$

where V_s is the speed of sound in the medium and t_f the time of flight.

Sound is produced in a material medium by a vibrating source whose waves constitute alternate compression and rarefaction pulses traveling in the medium. A longitudinal wave in a fluid can be described either in terms of the longitudinal displacement experienced by the particles of the medium or in terms of the excess pressure generated due to the compression or rarefaction. Thus the speed of a sound wave is given by;

$$V_s = \sqrt{\frac{B}{\rho}} \tag{3}$$

where V_s is velocity of sound in the fluid, B the bulk modulus of the fluid and ρ the mass density of the fluid.

Hence the velocity of a longitudinal wave in a medium depends on its elastic properties and inertial properties of the medium. On the other hand, Newton's formula for speed of sound in a gas is given by;

$$V_s = \sqrt{\frac{P}{\rho}} \tag{4}$$

where P is the pressure and other symbols have their usual meanings.

Laplace suggested a correction to Newton's formula and suggested that Newton's formula reads;

$$V_s = \sqrt{\frac{\gamma P}{\rho}} \qquad (5)$$

where $\gamma = \frac{C_p}{C_v}$ with C_p and C_v the molar heat capacities at constant pressure and constant volume respectively and other symbols have their usual meanings.

In the simplest (one-dimensional) case the propagation of displacement of a sound wave in direction x can be described by a linear wave equation of the type;

$$\frac{\partial^2 \xi}{\partial t^2} = V_s^{\,2} \frac{\partial^2 \xi}{\partial x^2} \qquad (6)$$

where ξ is the displacement of particles of the medium from their rest positions and V_s the phase velocity.

Equation (6) is a partial differential equation of second order in both time and space and has an infinite number of solutions. Sound oscillations are very fast so heat transport and temperature compensation between places of heating (due to compression) and cooling (due to expansion), which are separated by a half wavelength, cannot be effective. Hence, sound propagation generally can be considered as an adiabatic process [22]. In liquids, velocity of propagation (V_l) depends on the modulus of compression K or on the adiabatic compressibility $\kappa\left(\kappa = K^{-1}\right)$given by;

$$\frac{1}{K} = \frac{1}{V}\frac{dV}{dP} \qquad (7)$$

where V is the volume and P is the pressure, dV is the change in volume and dP the change in pressure.

The velocity in the liquid is given by;

$$V_l = \sqrt{\frac{K}{\rho_l}} \qquad (8)$$

If shear forces are not taken into account, V_l is independent of frequency (no dispersion). The adiabatic equation that is valid if the medium is an ideal gas is given by [22];

$$PV^{\gamma} = constant \qquad (9)$$

and the bulk modulus of elasticity given by;

$$\frac{1}{B} = \frac{1}{V}\frac{dV}{dP} \qquad (10)$$

Using equations (3), (9) and (10), the equation for velocity of sound in air is obtained as;

$$V_s = \sqrt{\frac{\gamma p}{\rho_g}} \qquad (11)$$

Using the ideal gases relation, the equation relating density to temperature becomes;

$$\frac{p}{\rho_g} = \frac{p_0}{\rho_0}\frac{T}{T_0} = \frac{p_0}{\rho_0}\left(1 + \frac{T - T_0}{T_0}\right) \qquad (12)$$

where P_o is the pressure at some reference temperature, T_0.

The velocity of sound in gases becomes a function of absolute temperature independent of pressure, the relationship is expressed by;

$$V_s = \sqrt{\gamma \frac{p_0}{\rho_0}}\sqrt{1 + \frac{T - T_0}{T_0}} \qquad (13)$$

For air in the range of room temperature, one can use the approximation;

$$V_s = 331.3\left(1 + \frac{T - T_0}{2T_0}\right) \qquad (14)$$

Most available ultrasonic sensor systems generally calculate distance using the time-of-flight (TOF) method [23, 24]. The distance d to a reflecting object is calculated by;

$$d = \frac{V_s t_0}{2} \tag{15}$$

where, V_s is the speed of sound and t_0 the round-trip time-of-flight.

The TOF method produces a range *value* when the echo amplitude first exceeds the threshold level after transmitting [25]. In spite of a simple method like this, information obtained by the ultrasonic sensor is influenced by the characteristics of the sensing system and the environment [26, 27].

2.3 Performance factors that affect ultrasonic sensor model

Information supplied by an ultrasonic sensor is noisy, partial and often spurious. To develop decision procedures that satisfy the actual state of affairs encountered in the operation of an ultrasonic ranging system, it is important to analyze the total performance of the model by integrating performance factors such as target characteristics and environmental phenomena [28- 31].

2.3.1 Atmospheric attenuation

The signal power of an acoustic wave decreases with distance from the source. This decrease of signal power with distance is defined by the spherical-divergence attenuation factor which follows the inverse square law given by equation (16) [32];

$$I = \frac{I_0}{4\pi R^2} \tag{16}$$

where, I is the Intensity (power per unit area), I_o is the maximum (initial) intensity and R the distance.

The maximum detection range for an ultrasonic sensor is dependent on both the emitted power and frequency of the emitted signal: the lower the frequency, the longer the range. The maximum theoretical attenuation for ultrasonic energy can be approximated by equation (17) [32];

$$a_m = \frac{f}{100} \tag{17}$$

where a_m is the maximum attenuation in dBm^{-1} and f the signal frequency in KHz. For example, for a 20-KHz transmission, a typical attenuation factor in air is approximately 0.0656 dBm^{-1}, while at 40 KHz losses run between 0.1968 and 0.2952 dBm^{-1}.

There is also an exponential loss associated with molecular absorption of sound energy by the medium. The relationship is given in equation (18) [32];

$$I = I_o e^{-2\alpha R} \tag{18}$$

where α is the attenuation coefficient for the medium.

Combining the spherical-divergence attenuation factor (equation (16)) and molecular-absorption attenuation factor (equation (18)), results in the governing equation for intensity as a function of distance from the source [32]. This governing equation is;

$$I = \frac{I_o e^{-2\alpha R}}{4\pi R^2} \tag{19}$$

In this expression, intensity falls off with the square of the distance from the source. The expression does not, however, take into consideration any interaction with the target surface whose characteristics influence the echo received by the transducer. These characteristics are identified as target reflectivity and the characteristics of the medium in which sound propagates where the twin factors of temperature variation and noise are investigated [33].

2.3.2 Target Reflectivity

To measure the distance using a transmitted sound signal, it needs to be reflected. When sound waves strike a surface it is reflected provided that the dimension of the reflective surface is large compared to the wavelength of the sound. The wavelength is significant because it determines the size of the pulse and waves having wavelengths comparable to the dimensions of the reflective surface are cancelled by edge effects.

A target surface that is hard and smooth attenuates the signal less than one that is soft and rough. A weak echo can therefore result if a sound wave strikes a surface which is soft and rough, thus reducing the precision and operating distance of an ultrasonic sensor.

The object size and inclination also has effects on target reflectivity since a large object has more surface area to reflect the signal than a small one. The surface area recognized as the target is generally the area closest to the sensor. The inclination of an objects' surface facing the ultrasonic sensor affects how the object reflects. The portion perpendicular to the sensor returns a stronger echo. If the entire object is inclined at a very great angle, the signal can be reflected away from the sensor such that a very weak echo is detected or no echo is detected at all. Thus, the totality of all energy incident upon a target object is either reflected or absorbed. The directivity of the target surface determines how much of the reflected energy is directed back towards the transducer. Since most objects scatter the signal in an isotropic fashion, the returning echo again dissipates in accordance with the inverse square law, introducing an additional $4\pi R^2$ term in the denominator of equation (19). In addition, a new factor K_r must be introduced in the numerator to account for the reflectivity of the target [34]. The governing equation for intensity therefore becomes;

$$I = \frac{K_r I_o e^{-2\alpha R}}{16\pi^2 R^4} \tag{20}$$

where K_r is coefficient of reflection.

The coefficient of reflection also depends on the inclination of the reflecting surface, for a wave arriving normal to an object surface, the coefficient is given by;

$$K_r = \frac{I_r}{I_i}\left[\frac{Z_a - Z_o}{Z_a + Z_o}\right]^2 \tag{21}$$

where I_r is the reflected intensity, I_i the incident intensity, Z_a acoustic impedance for air and Z_o acoustic impedance for the target object.

Modern ultrasonic ranging systems transmit short bursts of frequencies consisting of four discrete frequencies: 8 cycles at 60 KHz, 8 cycles at 56 KHz , 16 cycles at 52.5 KHz, and 24 cycles at 49.41 KHz. Such a technique in which different frequencies are employed to increase the probability of signal reflection from the target is useful since certain surface characteristics could theoretically absorb a single frequency waveform thus preventing detection [41].

A possibility of a sudden change in the media could also be utilized in length measurements using ultrasonic ranging systems. The bigger the impedance mismatch between the two media, the more the energy that is to be reflected back to the source. In industrial phenomenon, this allows tank level measurement to be accomplished using an ultrasonic transducer in air looking down on the liquid surface, or alternatively an immersed transducer looking upward at the fluid/air interface.

2.3.3 Noise

Generally speaking, three kinds of noise will affect the ultrasonic sensor performance: environmental noise, crosstalk noise and self-generated noise. Environmental noise may occur near certain machines that generate noise signals or near discharging high-pressure air. This type of noise can be continuous and strong enough to disable ultrasonic sensors completely. Self-generated noise results from circuit components of the ultrasonic ranging system and would practically guarantee mutual interference with the main signal. Cross-talk is a particularly damaging condition because it will repeatedly cause inaccurate readings, this is so because unlike random noise, crosstalk is systematic.

2.3.4 Temperature

The velocity of sound in a medium is a function of the density and bulk modulus of elasticity of the medium. Both of these parameters change with temperature making the speed of sound in air also temperature dependent. For temperature variations typically encountered in indoor robotic ranging applications, this dependence results in a significant effect even considering the short distances involved. A temperature change over a realistic span of 16°C to 32°C can produce a range error as large as 0.31m at a distance of approximately 11m [41]. Fortunately, this situation can be remedied through the use of a correction factor based upon the actual ambient temperature, available from an external sensor mounted on the robot [41].

The possibility does still exist, however, for temperature gradients between the sensor and the target to introduce range errors, since the correction factor is based on the actual temperature in the immediate vicinity of the sensor only.

2.4 Time-of-flight measurement and estimation

Successful operations of most ultrasonic ranging systems rely on accurate TOF measurements. A pulse is transmitted and an echo is produced when the transmitted pulse encounters an object. This echo received by the system is then processed by using the speed of sound in calculating range measurements. Range information forms the basis of many applications such as object localization, classification, and tracking [19, 35–39]. Correct localization of targets using ultrasound depends on how accurately TOF can be measured and how well the speed of sound in the medium is known. Since a pulse–echo system is employed, the measurements are not significantly affected by movements of the propagation medium. The methods utilized in the measurement of TOF include thresholding, curve fitting, sliding window and optimum correlation detection [19].

2.4.1. Thresholding method

One way of measuring TOF is the thresholding method where the TOF is found by determination of the time t_{ot} at which the echo amplitude waveform first exceeds a preset threshold level τ, (See figure 2 below).

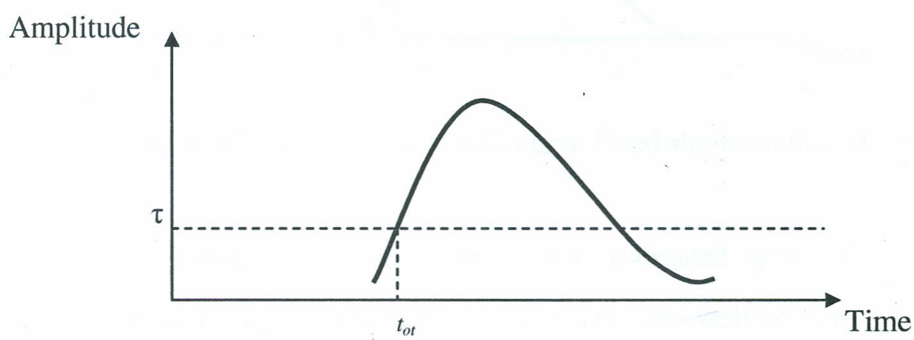


Figure 2: Thresholding method (threshold level is τ)

Assuming Gaussian noise, τ is usually set equal to 3–5 times the noise standard deviation. In current practical ultrasonic systems, with this choice, the threshold level turns out to be between negative 20 to negative 35 dB below the peak of the pulse [19].

2.4.2 Curve-fitting method

Another TOF estimation method is curve fitting, in which a nonlinear least-squares method is employed to fit a curve to the onset of the ultrasonic echo in order to produce an unbiased TOF measurement, (See figure 3 below).

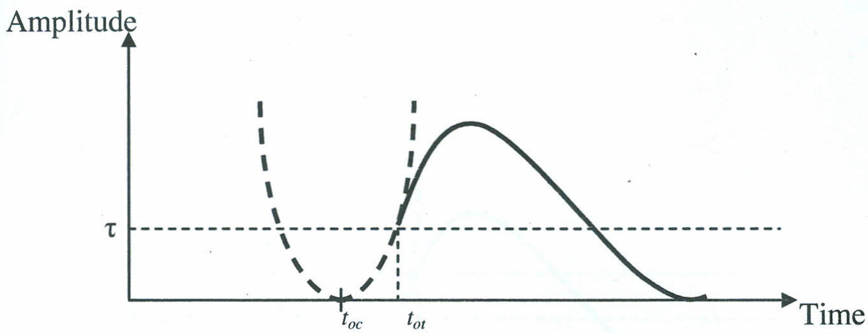


Figure 3: Curve fitting (parabolic curve fitted shown in dotted lines)

A parabolic curve of the form $a_o(t-t_{oc})^2$ is estimated to fit at the envelope around the rising edge of the echo signal. It has been verified that this is a good approximation [19]. First, initial estimates of the two parameters a_o and t_{ot} are obtained. The initial estimate for t_{ot} is found by simple thresholding, and a_o which essentially determines the eccentricity of the parabola is estimated from the second derivative approximation of the vertex form of the equation of the parabola around the threshold point. These parameters are used to initialize an iterative numerical procedure namely the Levenberg–Marquardt nonlinear least-squares method [19]. In simulations and experiments, samples of the echo signal, taken around the threshold point, have been used to estimate the parameters a_o and t_{oc} of the best-fitting curve. The value of t_{oc} finally obtained, which corresponds to the vertex of the parabola, is the TOF obtained using the curve fitting method. This value usually falls to the left of the thresholding estimate, and reduces the bias considerably. There is, however, a simpler variation of the curve-fitting method which does not require the nonlinear iterative procedure. In this method, two different threshold levels are set, and a parabola is fitted to the two samples of the signal at which the threshold levels are exceeded, (See figure 3 below).

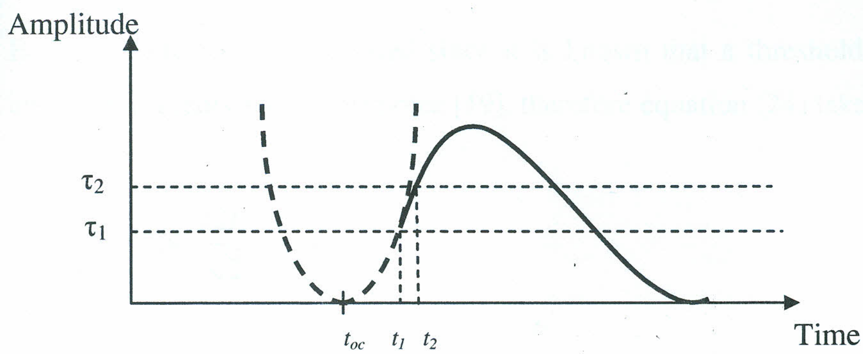


Figure 4: Curve fitting using two threshold levels

For example, if τ_1 and τ_2 are the two threshold levels ($\tau_2 > \tau_1$) and t_1 and t_2 the times at which these thresholds are exceeded then the parameters a_o and t_{oc} of the parabola $a_o(t-t_{oc})^2$ passing through these points can be solved from the following two equations:

$$\tau_1 = a_o(t_1 - t_{oc})^2 \qquad (22)$$

$$\tau_2 = a_o(t_2 - t_{oc})^2 \qquad (23)$$

Eliminating a_o from both equations (22) and (23) we obtain the following expression for the TOF, t_{oc}:

$$t_{oc} = \frac{\left(\sqrt{\frac{\tau_2}{\tau_1}}\right)t_1 - t_2}{\left(\sqrt{\frac{\tau_2}{\tau_2}}\right) - 1} \tag{24}$$

Equation (24) can be simplified since it is known that a threshold ratio τ_2/τ_1 of about 2 represents a suitable choice [19], therefore equation (24) takes the form

$$t_{oc} = \frac{\sqrt{2}t_1 - t_2}{\sqrt{2} - 1} \tag{25}$$

Equation (25) thus represents the simplified version of equation (23) used in estimating the time-of- flight using the parabolic curve fitting method.

2.4.3 Sliding-window method

The third method for measurement of TOF considered in this study is the sliding window method, whose use for ultrasonic signals was first suggested by Barshan and Ayrulu [40]. The method originates from the double thresholding detection originally developed for radar signals, and is used to make detection more robust to noise. In this method, a window of width N is slid through the echo signal one sample at a time and at each window position, the number of samples which exceed the preset threshold level τ are counted. If this number exceeds a second threshold m, then a target is assumed to be present and a TOF estimate is produced. The advantage of the method is its robustness to noise spikes, since the target detection is based on at least *m* samples exceeding the threshold, instead of a single one as in simple thresholding. This way, noise spikes of total duration less than *m* can be eliminated. The performance of this method therefore depends on the window length *N*, the second threshold value *m*.

2.4.4 Optimum correlation detection

The optimum correlation detection method for estimating TOF utilizing matched filter techniques have been used widely to improve the accuracy of TOF measurements in applications such as target localization and identification [41]. A matched filter contains a replica of the echo waveform and is employed to determine the most probable location of the echo in the received signal [19, 40]. The computer implementation of this procedure is time consuming because of the required correlation operation, even when realized in the frequency domain. Since the shape of the echo waveform usually changes during propagation due to attenuation, and also varies with target type, size, location, and orientation, a large number of templates for the expected signal must be stored for the correlation operation. Another fundamental problem with this method is the inherent time delay involved since classical correlation detection requires that the *entire* echo be observed before an estimate is produced. Hence, when working in real time, this method is only suitable for distant objects when the echo duration is negligible compared with the travel time. For nearby targets, or in applications where only the leading edge of the signal is available [19, 40], for instance, when the signal levels are saturated, the estimate must be made at the beginning of the observed echo using methods such as those earlier described. Nevertheless, this method serves as a useful basis for comparison with the other methods.

The first three methods mentioned are suboptimal but fast and simple to implement in real time. These methods are compared with the optimal correlation detection method which maximizes signal to noise ratio (SNR) by Barshan [19]. SNR is taken as the ratio of the maximum amplitude of the echo signal to the amplitude of noise standard deviation. Overall, the three simple and fast processing methods of thresholding, curve fitting and sliding window provide a variety of attractive compromises between measurement accuracy and system complexity [19]. In this study the simple thresholding method was used.

CHAPTER THREE

METHODOLOGY

3.1 General procedure

In this work, the influence of temperature on ultrasonic ranging systems that utilize TOF technique in their operation was investigated and the deviation-temperature characteristic of an ultrasonic ranging system obtained experimentally. The deviation-temperature characteristics were obtained by varying the ambient temperature using heaters and observing the distance measured by the ultrasonic ranging system. The average temperatures along the path of sound were measured using thermocouples connected to a Fluke 2285 data logger. The characteristics obtained in the study were then utilized to find a correction equation for the errors in the measurement of the distance caused by temperature variations.

3.2 Design strategies

The design of a temperature compensated ultrasonic system is multifaceted in approach since the system encompasses both analog and digital electronic subsystems, computer hardware and software and also incorporates a transducer working on the principle of mechanical vibrations, which may be a piezoelectric or capacitive electrostatic transducer. The interactions between the various subsystems need to be considered in a parallel fashion in order to achieve synergy. Potential conflicts need to be analyzed and overall system performance optimized at system level. To achieve an optimum design, there is need to look at the several parameters that may affect the performance of such a system.

3.2.1 Absorption of ultrasound in air and reflection from the target

The accuracy of all distance measurements using ultrasound depends on the shape and size of the reflecting surface. Objects with surfaces that are small compared to the wavelength of the signal emitted by the system and are positioned at a wide angle to the acoustic axis of the transducer can be almost impossible to detect. Because of this, maximum reflectivity is achieved when an ultrasound signal is directed towards flat surfaces, perpendicular to the acoustic axis and is of sufficient size to produce a satisfactory echo signal. In addition there is an exponential loss in signal strength with distance, due to attenuation of sound in air thus the signal power varies exponentially. Due to surface geometry, the phases of reflected waves can also interfere with each other resulting in production of large variations of the echo signal (comparable to the effect called 'speckle' in laser optics). This interference is frequency dependent. If the echo is weak at one frequency, there are other frequencies at which the echo would be strong. High reflective reliability for this design was provided by use of multiple-frequency signal transmitted by the transducer. This technique in which different frequencies are utilized to increase the probability of signal reflection from the target was employed in this study.

3.2.2 Ramp gain

The ultrasonic ranging system responds only to echoes from objects that are in a given solid angle around the transmitter axis that is within the acceptance angle. The acceptance angle is determined by the acoustic lobe pattern of the transducer. The system also varies amplification with distance because a constant amplification would severely limit the operating range. Since the roundtrip time for the signal is proportional to the distance, the amplification increases as a function of time. This time variable gain is adjusted to the objectives of the system. (See appendix 4). Large amplified signals improve the accuracy of the distance determination.

3.2.3 Noise

A major requirement of the system was to filter extraneous noise. Noise may be thought of as frequencies different from the four frequencies produced by the transducer : 8 cycles at 60 *KHz*, 8 cycles at 56 *KHz* , 16 cycles at 52.5 *KHz*, and 24 cycles at 49.41 *KHz*., or glitches or spikes either externally generated and detected by the transducer or internally generated by the electronics. This requirement was met by a built in inductor-capacitor (LC) filter, bias current compensation preamplifier circuit and an integration capacitor that continuously discharges so that noise spikes do not have a cumulative effect and cause inaccurate readings.

3.3 Material selection and experimental set up

There are many parameters that can be used as a basis for selecting an ultrasonic system for the type of work carried out in this study. Six parameters were used in selecting an ultrasonic system suitable for this work. These were beam angle, sensitivity, noise immunity, bandwidth, range and simplicity. Components of such a system comprise the ultrasonic ranging system, the acoustical transducer and the electronic circuit.

3.3.1 Ultrasonic ranging system

The electronic circuit powered by a 6V direct current (DC) supply has a digital circuit with a crystal controlled clock that generates the ultrasonic frequencies. The analog circuit amplifies the echo which is then detected by the digital circuit to produce a signal proportional to the received echo. The amplifier has a self adjusting sensitivity over the entire range of the system. This means that the amplification increases as a function of time. This time variable gain is adjusted to the objectives of the system such that even with small echoes, large amplified signals are used to improve the accuracy of the distance determination.

The transmitted signal and the received echo determine the time measured by system which is directly related to distance. A 420 KHz clock allows accurate measurement of this time. The switching voltage applied to the circuit causes it to transmit and receive repeatedly, providing a new measured time each cycle. After each cycle, the system measures the time and converts it into distance. The block diagram and schematic diagram of the ultrasonic ranging system are shown in figure 5 and figure 6 respectively.

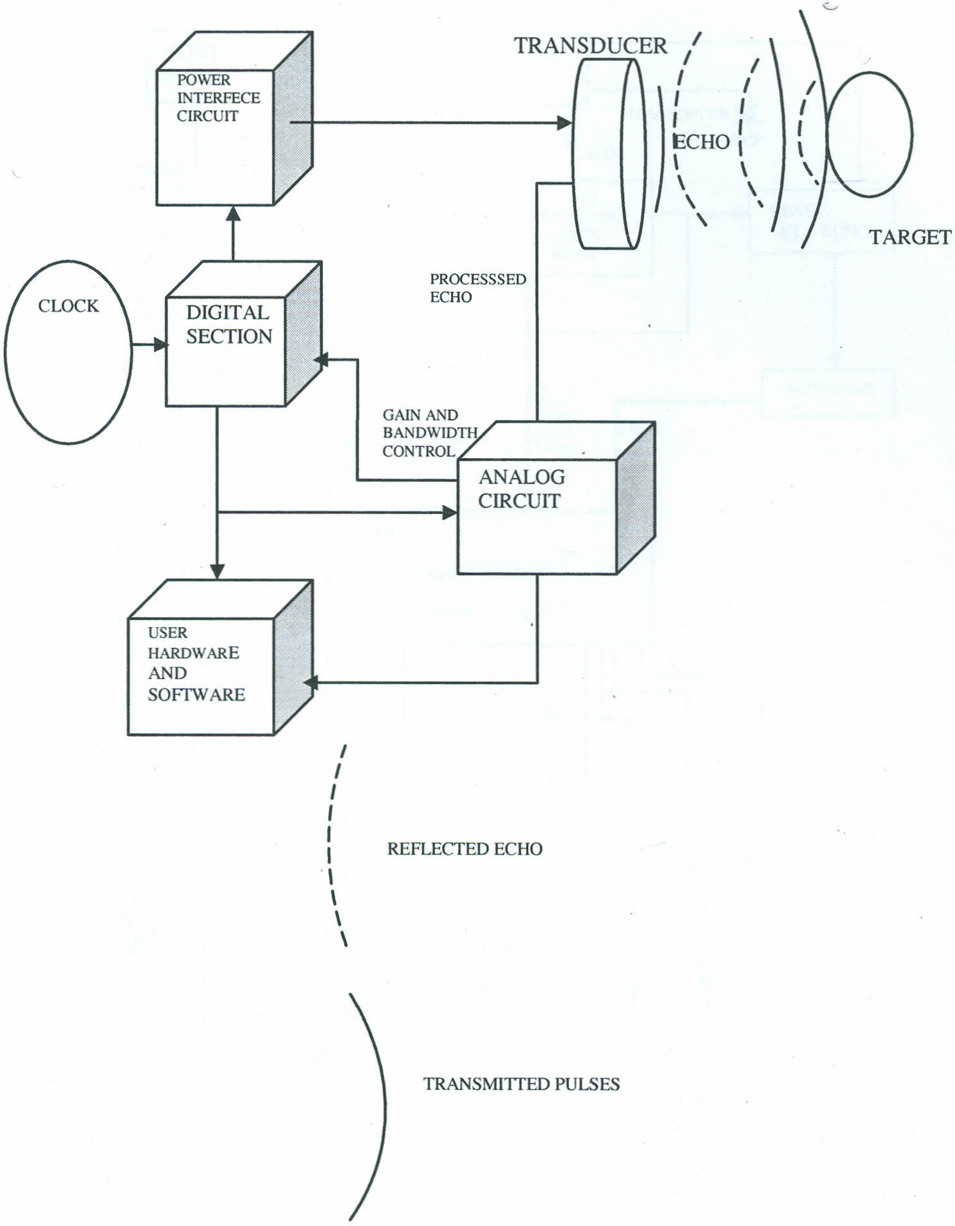


Figure 5: Block diagram of the ultrasonic ranging system [43]

3.3.1.1 The electronic circuit of the ultrasonic ranging system

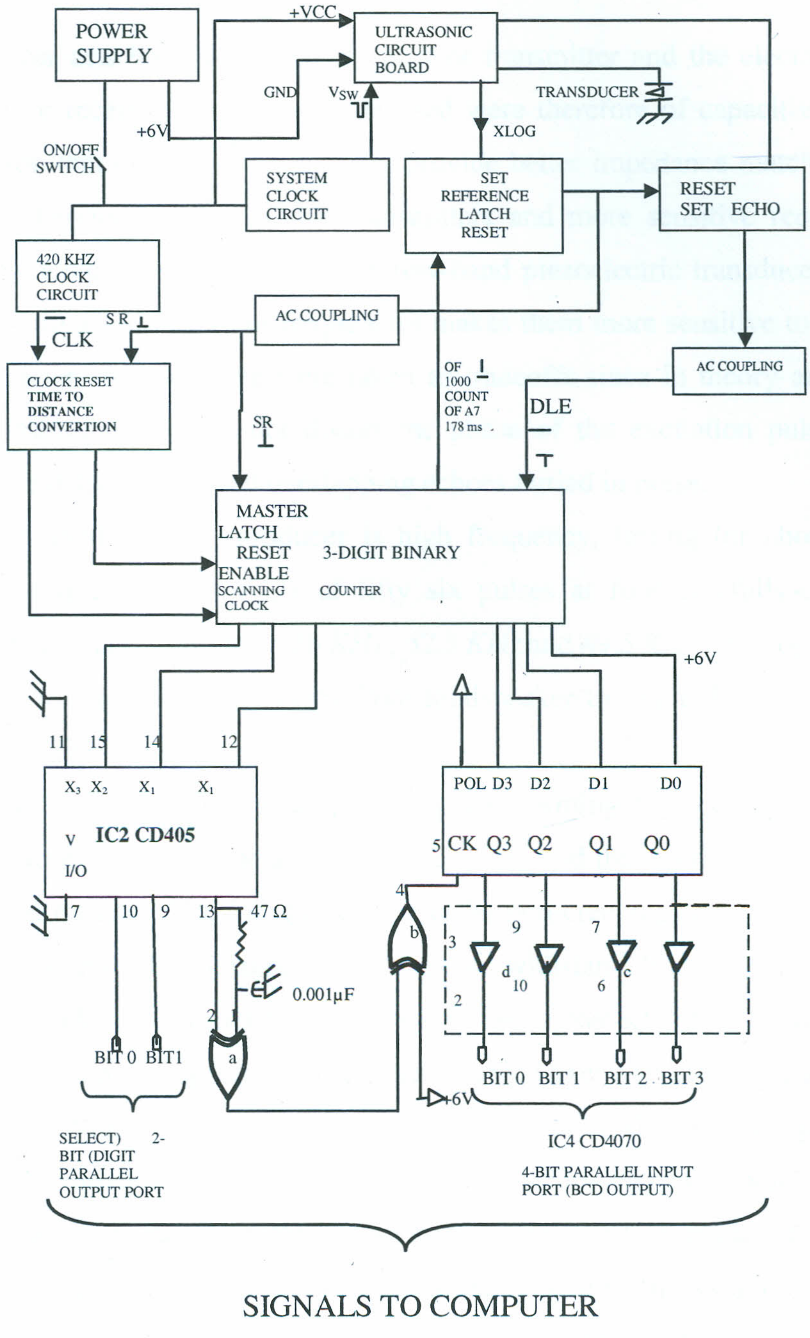


Figure 6: Schematic diagram of the ultrasonic ranging system [43]

3.3.1.2 The transducer

The transducer acts both as the loudspeaker or transmitter and the electrostatic microphone or receiver. The transducers used were therefore of capacitive type for the reason that capacitive transducers provide better impedance matching to air and are therefore more efficient transmitters and more sensitive receivers. They are broadband compared to the narrow-band piezoelectric transducers and this response to a wide range of frequencies makes them more sensitive to noise. The noise factor and the range were taken as tradeoffs since in theory an ideal broadband transducer would not distort the phase of the excitation pulse and allows for the detection of even overlapping echoes buried in noise.

The pulse emitted by the transducer is high frequency, lasting for about one millisecond and actually consists of fifty six pulses at four carefully-chosen, ultrasonic frequencies of 60 KHz 56 KHz, 52.5 KHz and 49.5 KHz. The operating mode of the transducer then changes from loudspeaker to microphone to detect the returning echo.

A special foil is stretched over a grooved plate, forming the moving element which transforms electrical energy into sound waves and the returning echo back into electrical energy. The foil chosen has to be non-creeping, elastic, yet light and extremely thin. The insulating part has to withstand high fields without punching through. The grooved metallic back plate in contact with the insulating side of the foil forms a capacitor which when charged exerts an electrostatic force to the foil. The foil is pliable and an excellent electrical conductor (see figure 7). This foil is the moving part which transforms electrical energy into sound waves, and, conversely, sound waves into electrical energy and is made of plastic (kapton) with a conductive (gold) coating on the front side and stretched over a metallic back plate (aluminium). An AC voltage of a given frequency forces the foil to move at the same frequency and to send out sound waves. With a DC bias applied externally, a steel spring transfers the voltage from the back plate and holds the foil under constant tension. The perforated front cover mechanically protects the foil with a small loss of the signal strength. In its use in ranging, the sound output has to be maximized while the phase and the distribution of the output across the transducer have to be well defined and uniform. Its diameter determines the acoustical lobe pattern or acceptance angle (or response angle). The large diameter of the transducer, the high frequency used and an accurate in-phase condition (coherence) create a narrow beam for transmission as well as reception. An analog gain circuit that feeds the transducer has a step-up transformer, thus the circuit transmits with 320V and develops a bias of approximately 140V for the receive mode.

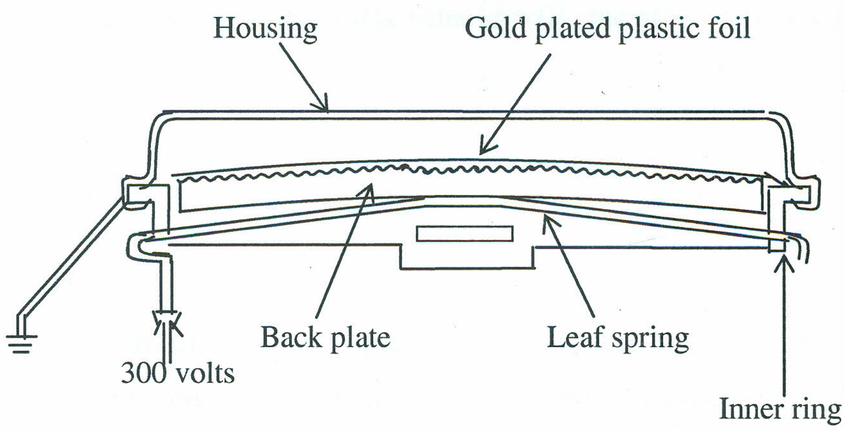


Figure 7: Transducer assembly

The major acoustical factors affecting the performance of a sonar ranging system are related to the transducer performance. To analyze transducer radiation characteristics, the transducer can be treated as plane circular piston set in an infinite baffle. The radiation characteristic function of the transducer then is given by equation (26) [31];

$$H(\phi)=\frac{J_1(kr\sin\phi)}{(kr\sin\phi)} \tag{26}$$

where $H(\phi)$ is the radiation characteristic function, $k=\dfrac{2\pi}{\lambda}$ is the wave number, r is the piston radius, ϕ is the azimuthal angle and J_1 the Bessel function of the first kind [31,41].

The interest is in the radiation pattern beam-width as a function of frequency and transducer size. The beamwidth is most commonly expressed as the angle intercepted by the points on either side of the principal axis where the radiation pattern is 3dB less than the on-axis value$(\phi=0)$, therefore it is possible to set [41]:

$$2\frac{J_1(x)}{x}=-3dB=\frac{1}{\sqrt{2}} \tag{27}$$

To solve the relationship in equation (27) requires an iterative procedure. However, a very good approximation can be achieved by expansion of the Bessel function of 1st kind to only three terms. Expanding and solving yields

$$x=1.62, \qquad \textit{where} \quad x=kr\sin\phi \tag{28}$$

Therefore the angle ϕ is found as;

$$\phi = \sin^{-1}\left(\frac{x}{kr}\right) \qquad (29)$$

This is the angle of the central axis to the -3dB point. Therefore, the 3dB full angle beamwidth is β,

$$\beta = 2\phi = 2\sin^{-1}\left(\frac{1.62}{kr}\right) \qquad (30)$$

A typical plot of transducer radius versus frequency is shown in appendix 3 and was used to determine the desired beamwidth using appropriate combinations of transducer size and operating frequency.

3.3.2 Data logger (FLUKE 2285)

The instrument that was used to measure and record temperature is the FLUKE 2285 data logger. The ability to make precise measurements simultaneously is critical in this type of work as it is in many other modern technological applications. The data logger has an automatically switched multi-point measurement in conjunction with other measuring devices such as thermocouple, resistance–temperature detectors, thermistors, AC/DC voltage and strain gauges and can be used to measure temperature, voltage, current, resistance, frequency data/status, and strain among others.

The thermocouple that was chosen for this application was type J giving due consideration to its range and general application characteristics. It was connected to the HIGH and LOW input lines as follows:

- LOW: the RED wire on the thermocouple is the negative lead and was attached to the LOW terminal.
- HIGH: the positive lead (white in color for type J thermocouple) was connected to this terminal.
- SHIELD: the thermocouple that was used did not have a shield wire (two wires only) therefore a jumper was connected between LOW and SHIELD.

Thermocouples used to measure temperature of the medium (air) at several points were connected to different channels of the data logger. A pseudo channel was used to calculate the average temperature as part of a scan group of the data logger. A scan group is a collation of input channels, output channels and pseudo channels that can be programmed and monitored or scanned and recorded as a group. A pseudo channel is a channel that can be programmed by the user to perform a particular mathematical operation. A given channel may be included in any or all scan groups and may appear more than once in a list, but input channels are only measured once each time a scan is executed. Each programmed step reads an input channel, sends a value to an output channel, performs the calculations in a pseudo channel and sends a value to an output channel. Each scan group is given a channel list showing the channel data to be collected and specifying the order in which the channels within a scan group will be logged. Each scan group therefore behaves as an independent task with its own trigger conditions. To program a scan group, all of the attributes needed to spell out the conditions for triggering are entered into the system. This is the measurement technique that was used in this study in order to obtain the average temperature for the various point measurements.

3.3.3 Experiment

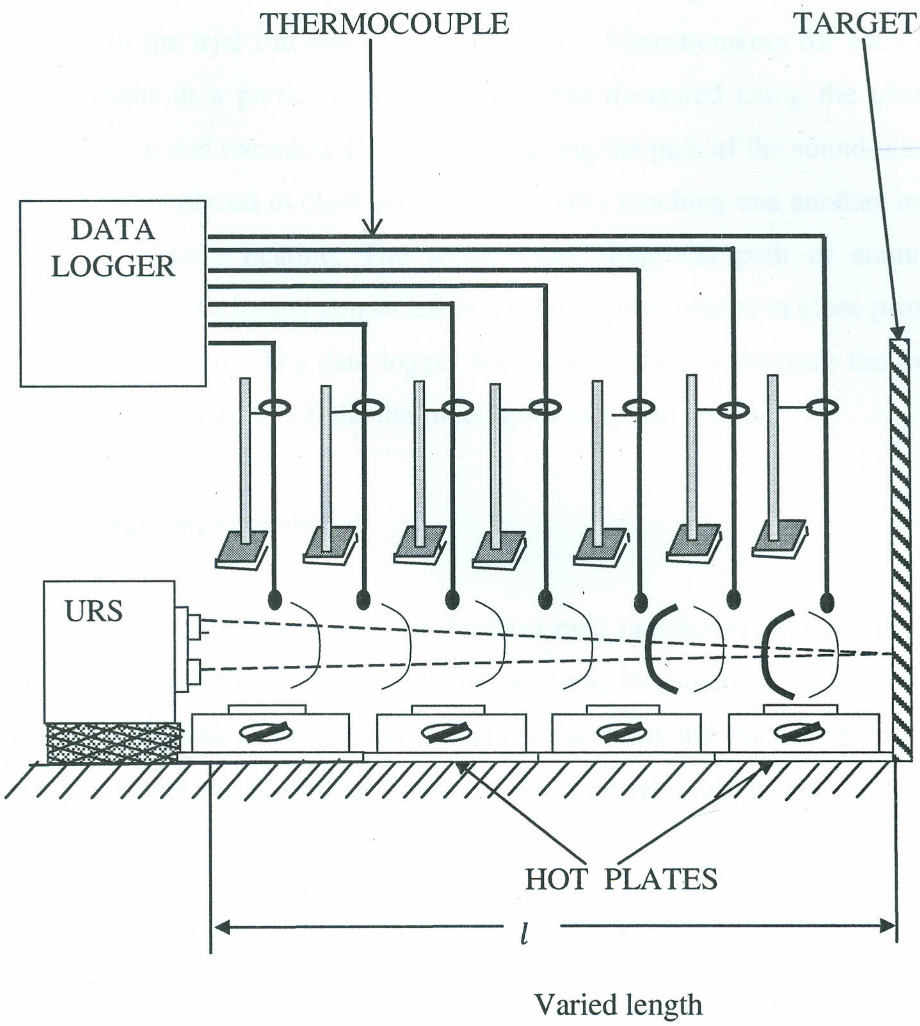


Figure 8: Experimental setup for obtaining deviation-temperature characteristics of the ultrasonic ranging system (URS)

In the setup, the beam from the ultrasonic ranging system was directed at a target (laboratory wall) directly to fall within the beamwidth of the system that is by approximating the beam to travel along the principal axis of the transducer. The distances or lengths measured were varied at intervals of 0.01 metres beginning with a length of 0.4m cm to a length of 1.0m by moving the ultrasonic ranging system, with the trial run being done at 0.36m. Measurements for each of the chosen lengths at a particular temperature were measured using the ultrasonic ranging system and recorded. Heating of air along the path of the sound was done using hot plates placed in close proximity, actually touching one another in order to achieve uniform heating. The temperature along the path of sound was recorded by the data logger connected to thermocouples placed in close proximity to the path of sound. The data logger was programmed to measure the average temperature measured by all the thermocouples as a scan group.

3.4. Design implementation

The distance readings obtained from the ultrasonic ranging system and the actual distances between the ultrasonic ranging system, measured using a metre rule were then analyzed to obtain the deviations between the measured and actual distances. Using the deviations from the characteristics, appropriate equation(s) were obtained.

CHAPTER FOUR

RESULTS AND DISCUSSION

The results presented herein are obtained from experimental data. The analysis of these results is carried out with the aim of evaluating the percentage deviations in distance measurements of the ultrasonic ranging system with variations in temperature and deriving a relationship that is used to obtain a correction equation for measured distances.

4.1 Results

The experimental data obtained from the setup are presented in Table 3. The table also shows the calculated values for the mean deviation in distance at various temperatures.

Table 1: Data for deviation obtained from the experiment also showing mean deviation at different temperatures.

Temperature ° C			**22.3**	**25.0**	**30.0**	**35.5**	**40.0**	**45.0**	**50.0**	**55.0**	**60.0**	**65.0**	**68.9**
1st length-36.6cm	**Measured length**	**1st**	35.5	35.0	34.5	34.2	33.8	33.5	33.2	32.9	32.5	32.2	32.0
		2nd	35.5	34.8	34.5	34.2	33.8	33.5	33.1	33.0	32.5	32.2	32.0
	Deviation (negative)	**1st**	1.1	1.6	2.1	2.4	2.8	3.1	3.4	3.7	4.1	4.4	4.6
		2nd	1.1	1.8	2.1	2.4	2.8	3.1	3.5	3.6	4.1	4.4	4.6
	Mean deviation		1.1	1.7	2.1	2.4	2.8	3.1	3.4	3.6	4.1	4.4	4.6
Temperature ° C			**22.3**	**25.0**	**30.0**	**35.5**	**40.0**	**45.0**	**50.0**	**55.0**	**60.0**	**65.0**	**68.9**
2nd length-40.0cm	**Measured length**	**1st**	38.4	38.2	37.8	37.4	37.1	36.7	36.4	36.0	35.6	35.2	35.1
		2nd	38.4	38.2	37.9	37.4	37.0	36.7	36.4	36.0	35.6	35.2	35.0
	Deviation (negative)	**1st**	1.6	1.8	2.2	2.6	2.9	3.3	3.6	4.0	4.4	4.8	4.9
		2nd	1.6	1.8	2.1	2.6	3.0	3.3	3.6	4.0	4.4	4.8	5.0
	Mean deviation		1.6	1.8	2.2	2.6	2.9	3.3	3.6	4.0	4.4	4.8	4.9
Temperature ° C			**22.3**	**25.0**	**30.0**	**35.5**	**40.0**	**45.0**	**50.0**	**55.0**	**60.0**	**65.0**	**68.9**

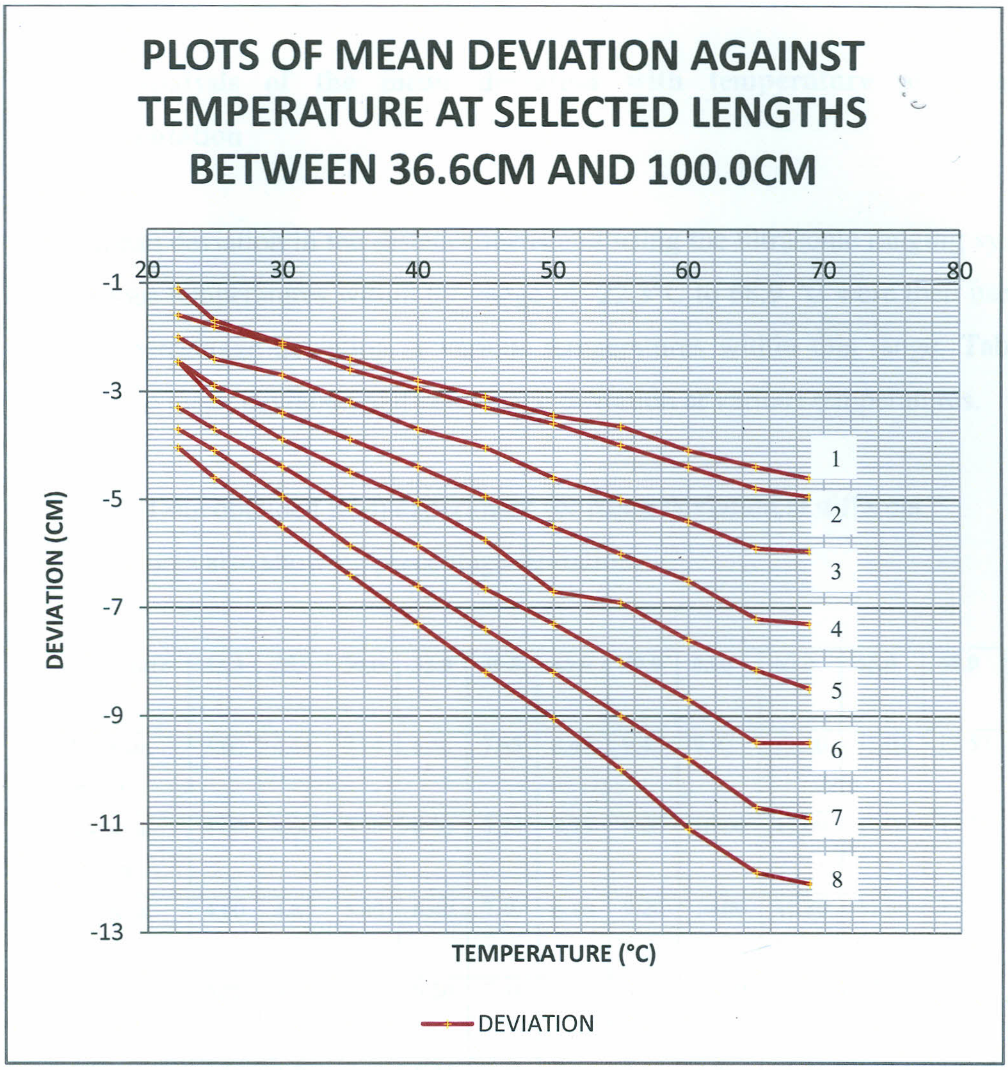
3[rd] length-50.0cm	Measured length	1[st]	48.0	47.7	47.3	46.8	46.3	45.9	45.4	45.0	44.6	44.1	44.1
		2[nd]	48.0	47.5	47.3	46.8	46.3	46.0	45.4	45.0	44.6	44.1	44.0
	Deviation (negative)	1[st]	2.0	2.3	2.7	3.2	3.7	4.1	4.6	5.0	5.4	5.9	5.9
		2[nd]	2.0	2.5	2.7	3.2	3.7	4.0	4.6	5.0	5.4	5.9	6.0
	Mean deviation		2.0	2.4	2.7	3.2	3.7	4.0	4.6	5.0	5.4	5.9	5.9
Temperature ° C			**22.3**	**25.0**	**30.0**	**35.5**	**40.0**	**45.0**	**50.0**	**55.0**	**60.0**	**65.0**	**68.9**
4[th] length-60.0cm	Measured length	1[st]	57.5	57.2	56.7	56.2	55.6	55.1	54.5	54.0	53.5	52.8	52.7
		2[nd]	57.6	57.0	56.5	56.0	55.6	55.0	54.5	54.0	53.5	52.8	52.7
	Deviation (negative)	1[st]	2.5	2.8	3.3	3.8	4.4	4.9	5.5	6.0	6.5	7.2	7.3
		2[nd]	2.40	3.0	3.5	4.0	4.4	5.0	5.5	6.0	6.5	7.2	7.3
	Mean deviation		2.4	2.9	3.4	3.9	4.4	4.9	5.5	6.0	6.5	7.2	7.3
Temperature ° C			**22.3**	**25.0**	**30.0**	**35.5**	**40.0**	**45.0**	**50.0**	**55.0**	**60.0**	**65.0**	**68.9**
5[th] length-70.0cm	Measured length	1[st]	67.1	66.8	66.2	65.5	64.9	64.3	63.6	63.0	62.4	61.7	61.5
		2[nd]	68.0	67.0	66.0	65.5	65.0	64.2	63.0	63.2	62.4	62.0	61.5
	Deviation (negative)	1[st]	2.9	3.2	3.8	4.5	5.1	5.7	6.4	7.0	7.6	8.3	8.5
		2[nd]	2.0	3.0	4.0	4.5	5.0	5.8	7.0	6.8	7.6	8.0	8.5
	Mean deviation		2.5	3.2	3.9	4.5	5.0	5.8	6.7	6.9	7.6	8.2	8.5
Temperature ° C			**22.3**	**25.0**	**30.0**	**35.5**	**40.0**	**45.0**	**50.0**	**55.0**	**60.0**	**65.0**	**68.9**
6[th] length-80.0cm	Measured length	1[st]	76.7	76.3	75.6	74.9	74.2	73.3	72.7	72.0	71.3	70.5	70.3
		2[nd]	76.7	76.3	75.6	74.8	74.1	73.4	72.7	72.0	71.3	70.5	70.3
	Deviation (negative)	1[st]	3.3	3.7	4.4	5.1	5.8	6.7	7.3	8.0	8.7	9.5	9.7
		2[nd]	3.3	3.7	4.4	5.2	5.9	6.6	7.3	8.0	8.7	9.5	9.7
	Mean deviation		3.3	3.7	4.4	5.2	5.9	6.7	7.3	8.0	8.7	9.5	9.7
Temperature ° C			**22.3**	**25.0**	**30.0**	**35.5**	**40.0**	**45.0**	**50.0**	**55.0**	**60.0**	**65.0**	**68.9**
7[th] length-90.0cm	Measured length	1[st]	86.3	85.9	85.1	84.2	83.4	82.6	81.8	81.0	80.2	79.3	79.1
		2[nd]	86.3	85.9	85.0	84.1	83.4	82.6	81.8	81.0	80.2	79.3	79.1
	Deviation (negative)	1[st]	3.7	4.1	4.9	5.8	6.6	7.4	8.2	9.0	9.8	10.7	10.9
		2[nd]	3.7	4.1	5.0	5.9	6.6	7.4	8.2	9.0	9.8	10.7	10.9
	Mean deviation		3.7	4.1	4.9	5.9	6.6	7.4	8.2	9.0	9.8	10.7	10.9
Temperature ° C			**22.3**	**25.0**	**30.0**	**35.5**	**40.0**	**45.0**	**50.0**	**55.0**	**60.0**	**65.0**	**68.9**
8[th] length-100.0cm	Measured length	1[st]	96.0	95.4	94.5	93.6	92.7	91.8	90.9	90.0	89.1	88.1	87.9
		2[nd]	95.9	95.4	94.5	93.6	92.7	91.8	91.0	90.0	89.1	88.1	87.9
	Deviation (negative)	1[st]	4.0	4.6	5.5	6.4	7.3	8.2	9.1	10.0	11.1	11.9	12.1
		2[nd]	4.1	4.6	5.5	6.4	7.3	8.2	9.0	10.0	11.1	11.9	12.1
	Mean deviation		4.1	4.6	5.5	6.4	7.3	8.2	9.1	10.0	11.1	11.9	12.1

4.2 Discussion

In our discussion, we relate the measured lengths, actual lengths and temperature by plotting graphs and then perform an analysis of the deviations by calculating the percentage deviations. A graph of the percentage deviations against temperature is plotted and a correction equation obtained from this graph.

4.2.1 Relating measured lengths, actual lengths and temperature

The lengths measured by the ultrasonic ranging system, the actual lengths and average temperatures were used to obtain the mean deviation in the distance measured using the ultrasonic ranging system at various temperatures within the range of 22.3 °C to 68.9 °C. Plots (shown in figure 9) of mean deviation versus temperature within this range were then drawn.



1.Plot for length of 36.6cm, 2. Plot for length of 40.0cm, 3. Plot for length of 50.0cm, 4. Plot for length of 60.0cm, 5. Plot for length of 70.0cm, 6. Plot for length of 80.0cm, 7. Plot for length of 90.0cm, 8. Plot for length of 100.0cm.

Figure 9: Graph of mean deviation versus temperature at selected lengths

4.2.2 Analysis of the mean deviation with temperature and design implementation

The mean deviation in the distance measured using the ultrasonic ranging system at various temperatures within the range of 22.3°C to 68.9 °C were then used to obtain percentage deviation at various temperatures within this range. Table 2 shows the mean deviation and percentage deviation at various temperatures.

Table 2: Data obtained from experiment for mean deviation at different temperatures also showing percentage deviation.

Temperature °C	**22.3**	**25.0**	**30.0**	**35.0**	**40.0**	**45.0**	**50.0**	**55.0**	**60.0**	**65.0**	**68.9**
% deviation at 36.6cm	3.00	4.64	5.74	6.56	7.65	8.47	9.42	9.97	11.20	12.02	12.57
% deviation at 40.0cm	4.00	4.50	5.38	6.50	7.34	8.25	9.00	10.00	11.00	12.00	12.38
% deviation at 50.0cm	4.00	4.80	5.40	6.40	7.40	8.10	9.20	10.00	10.80	11.80	11.90
% deviation at 60.0cm	4.08	4.83	5.67	6.50	7.33	8.25	9.17	10.00	10.83	12.00	12.17
% deviation at 70.0cm	3.50	4.50	5.57	6.43	7.21	8.21	9.57	9.86	10.86	11.64	12.14
% deviation at 80.0cm	4.13	4.63	5.50	6.44	7.31	8.31	9.13	10.00	10.86	11.86	12.13
% deviation at 90.0cm	4.11	4.56	5.50	6.50	7.33	8.22	9.11	10.00	10.89	11.89	12.11
%deviation at 100.0cm	4.05	4.60	5.50	6.40	7.30	8.20	9.05	10.00	11.10	11.90	12.10
Mean% Deviation=Δ	3.86	4.63	5.53	6.47	7.36	8.25	9.21	9.98	10.94	11.89	12.19

Using Table 2, a graph of percentage deviation versus temperature was plotted and a line of best fit obtained. The graph of percentage deviation at various temperatures within the range of 22.3°C and 68.9°C is shown in Figure 10.

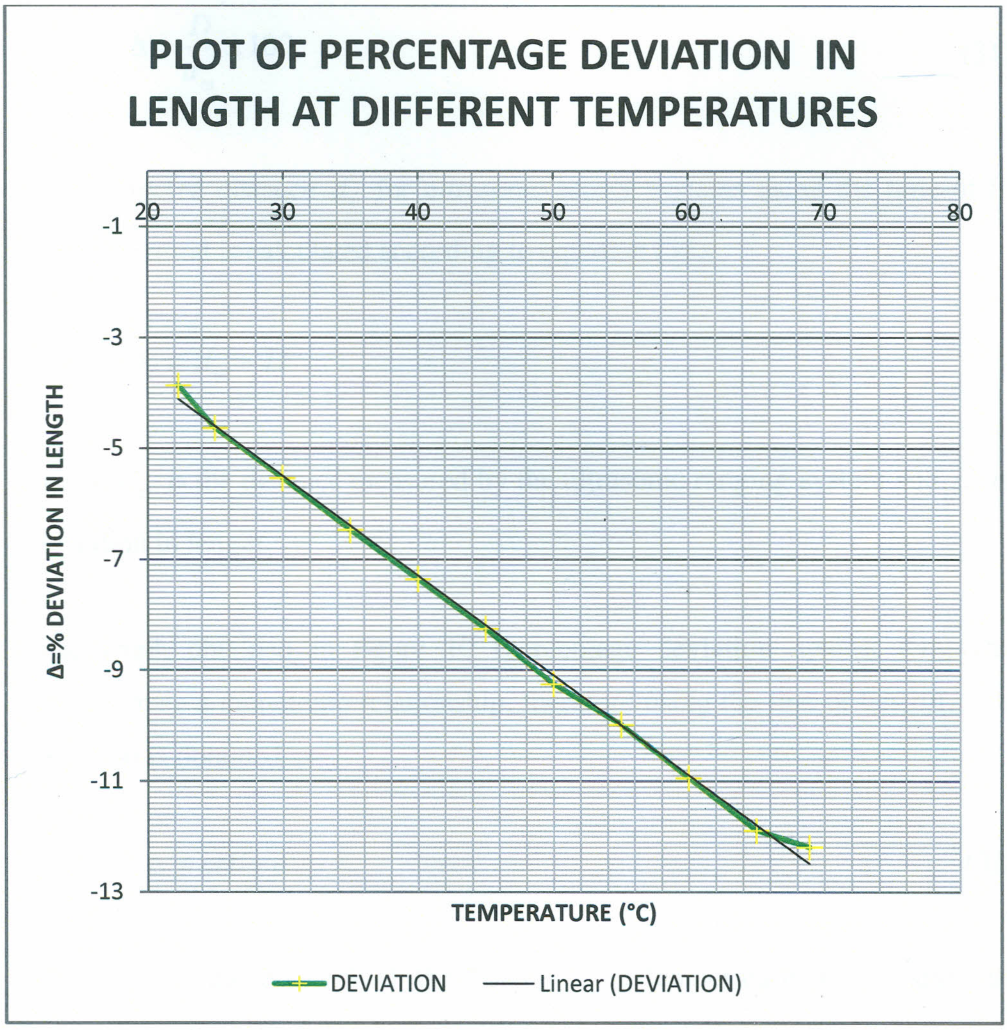


Figure 10: Graph of percentage deviation in length at various temperatures

The graph shown in figure 10 is a linear graph where the percentage deviation in length measurements can be expressed as;

$$\Delta = \frac{D}{d_m} x 100 \tag{31}$$

The corrected distance d_c for ultrasonic sensor systems using the time-of-flight (TOF) method is calculated according to equation (32);

$$d_c = d_m - D \tag{32}$$

where d_m is the distance measured by the ultrasonic ranging system and D is the deviation in length.

The graph obtained in figure 10 (percentage deviation against temperature) approximate a monotonic relationship, therefore using the line of best fit, a linear equation is obtained as;

$$\Delta = mT + c \tag{33}$$

where m is the gradient of the line, T the temperature in ^{o}C and c the magnitude of the deviation at $0^{o}C$.

If equation (33) holds outside the range of investigation (between 22.3°C and 68.9°C) then the value of c is calculated and found to be 0.04. This value is small and therefore can be ignored. At this point the corrected distance $d_c = d_m$ and temperature compensation becomes unnecessary. The linear equation (33) was therefore rewritten as;

$$\Delta = mT \tag{34}$$

Using equation (31) and equation (34) the deviation, D , is obtained as expressed in equation (35);

$$D = \frac{mT}{100} d_m \tag{35}$$

Using the results from figure 10, equation (35) was rewritten as;

$$D = \frac{-0.1873T}{100} d_m \tag{36}$$

and equation (32) for the calculation of corrected distance was found as;

$$d_c = d_m + \frac{0.1873T}{100} d_m \tag{37}$$

So that at a measured distance of say 1.00m and an ambient temperature of 30°C the corrected distance becomes 1.01m. The error in the deviation D can be evaluated using the equation for uncertainty in products whereby,

$$\delta D = \sqrt{\left(\frac{\delta T}{T}\right)^2 + \left(\frac{\delta d_m}{d_m}\right)^2} |D| \tag{38}$$

where, $\frac{\delta d_m}{d_m} = \pm 1\%$ (see appendix 6) is the fractional error in the distance measured by the ultrasonic ranging system and $\delta T = \pm 0.4^{\circ}C$ is the error in temperature measured by the 2285 Fluke data logger(see appendix 9) , so that equation (38) can be used to calculate the error in deviation. At the said distance of 1.0m and temperature of 30°C the deviation is 0.056m and the error in deviation becomes $\delta D = \pm 0.001m$. The error in the measurement of corrected distance is found by utilizing the equation for Gaussian uncertainty whereby;

$$\delta d_c = \sqrt{(\delta dm)^2 + (\delta D)^2} \tag{39}$$

So that at a measured distance of 1.0m, using equation (39) to calculate the error in the corrected distance, the error is found to be $\delta d_c = \pm 0.01006m$ which approximates the error without temperature compensation $\delta dm = \pm 0.01m$.

The results obtained for percentage deviation in distance with temperature are compared with the theoretical values calculated by Dennis Bohn [13] in his paper on 'environmental effects on the speed of sound'. The slight variations can be attributable to error in the value of the specific heat capacity ratio for the theoretical values and instrument errors in the empirical model.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this framework using the temperature-deviations characteristics, a temperature compensating ultrasonic ranging system is presented that is based on measurement of actual temperature variations in laboratory and utilizes equation (37) to compensate for errors introduced in the measurement of distance as a result of variations in temperature of air.

In this study an ultrasonic ranging system with the help of a data logger using digital signal processing techniques were effectively used to perform experiments to measure distances between two points when the ambient temperature varied. Deviations in length measurement with variation in temperature in the interposed medium (dry air) in laboratory along the equator (longitude 34° 36' 0" east, latitude 0° 1' 0" south) at an atmospheric pressure of 726.5mmHg were obtained and analyzed.

The results show that model equation (37) has been obtained for this particular system and can be used to correct for the measured distances whenever there are temperature variations within the range of room temperature to 68.9 °C. Equation (39) is used to demonstrate that the compensation introduces negligible error $(\pm 0.00006m)$ to the error in distance measurement of the uncompensated system.

5.1 Recommendations

We recommend that for future work, simulation and evaluation of the similar systems be carried out utilizing equation (37) to determine its validity and accuracy below room temperature and above 68.9 °C. To simulate and evaluate the performance of such a device, a flexible platform is needed for implementation and analysis of its performance. Lab VIEW (Laboratory Virtual Instrument Engineering Workbench) developed by National Instrument, is a graphical programming environment suited for high-level or system level design which provides such a platform. The advantage of this approach is given mostly by the flexibility and very rapid development time offered by this graphical programming software. The major hardware components include the data acquisition board (DAQ), transmitting unit, receiving unit, ultrasonic transmitter-receiver transducers and temperature measurement circuit. The system requires three analog inputs (AI) channels [42]. The first one is used to receive the temperature information, the second one is used to acquire the exciting pulses on the ultrasonic transducer, and the last one is to acquire the reflected ultrasonic echo signal thereby giving the range. Apart from the range measurement, range information can be obtained and statistical analysis done thereby obtaining the bias, standard deviation and total error, from a statistical point of view.

We also recommend that two interesting aspects of the theoretical study which are closely related to the current work be investigated: Firstly, the analysis and evaluation of phase shift based ultrasonic ranging system when subjected to thermal correction using equation (37) for small range measurements and secondly, the analysis of bias, standard deviation and total error when using other techniques of estimation of the TOF such as curve-fitting, sliding-window and optimum correlation detection.

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