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Time-based Acoustic Displacement Transducer

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Abstract: The purpose of this research is to design and test an acoustic linear displacement transducer operated in a time-based measurement. A standard computer system supported with a sound card has been used in order to realize the measurement, process, and store data. The operation principle of the proposed transducer is summarized as follows. The acoustic transmitter (speaker) which is fixed at one end of a resonance tube generates a pulse signal with specific parameters and then the pulse travels within a glass tube (filled with air) and is reflected from the other end of the resonance tube, which is a part of a movable spindle. The time of the reflected signal will be measured using an acoustic receiver (MEMS or electrolyte microphone) which is located at a specific distance from the speaker. A mathematical representation and experimental tables describing the relationship between displacement and the time of the reflected signal will be illustrated.

Keywords: Displacement Measurement, Standing wave, Phase Shift, Time Delay, IOT.

1. Introduction

Measurement of dimensions, displacements and deformations are widely used in modern industrial automation. Displacement measurement plays a great role in various industrial applications [1]. The role of displacement transducers in industrial measurements is also great because when measuring many mechanical quantities such as force, pressure, and torque, they are first converted to displacement and then transferred to an electrical quantity.

Devices for measuring displacement are widely used in various systems of automatic regulation and control. The use of such devices is a typical example of how to determine the dimensional changes and deviations of part shapes during the process of sorting and processing to regulate the position and movement of various objects. Measuring devices used in engineering and instrument manufacturing, used in the processing of parts, is mainly intended for measuring small displacements (less than 1 mm); measuring devices for measuring large displacements is used to measure the positions of different objects, liquid levels and in other similar cases [2].

Displacement transducers are used in industry to measure distance of objects and related parameters such as displacement, velocity and vibration [3]. For this purpose, measuring displacement transducers are classified by the range of their inputs. The first class of small displacement transducers (up to 2-3 mm for linear and 2-3 ° angular displacements) is utilized. The second class contains large displacement transducers (up to several meters for linear displacement and 25-40 revolutions for angular displacements). Various types of measuring transducers are used for measuring displacement such as rheostat, strain gauge, inductive sensors, capacitive sensors, radiation transducers and acoustic transducers [4].

Inductive sensors are widely used in the industry for measuring movements in the range of tenths of a micrometer to units of decimeters, as well as for measuring other physical quantities that are converted into movement. This is due to the significant advantages of inductive sensors such as the simplicity of design, reliability, high sensitivity, significant output power, protection from external electric and magnetic fields [5]. An example of a well-known inductive sensor is Linear Variable Differential Transformer (LVDT) [6], a transformer with a mechanically controlled core. A sinusoidal voltage of constant amplitude is applied to its primary winding. On the secondary windings, an alternating voltage is induced. A core of ferromagnetic material is inserted into the cylindrical hole between the coils. In this case, the core does not touch the windings. Two secondary windings are included in the anti-phase. When the core is located in the center of the transformer, the output signals of the secondary coils mutually cancel each other, so there is no voltage at the transformer output. Moving the core away from the central position leads to a change in the magnetic fluxes in the secondary windings. As a result of the resulting unbalance, the output voltage appears. The change in magnetic fluxes occurs due to a change in the magnetic resistance of the space between the coils. On the basis of what has just been mentioned, it follows that the magnitude of the flux linkage is determined by the axial position of the core. In the linear working region, the amplitude of the induced signal is proportional to the displacement of the core. Therefore, the output voltage contributes to the measurement of movement. The output of the LVDT not only shows the amount of movement, but it also displays its direction. The direction of movement is determined by the phase angle between the reference and output voltages. The reference voltage is produced by a stabilized generator.

Capacitive displacement transducers operate on the principle of a capacitor, which is formed by two plates separated by a dielectric. The change in the size of the plates, the distance between them or between them and the dielectric causes a change in capacitance.

With respect to the capacitance change, several types of capacitive sensors are found in industry such as capacitive proximity sensor and the capacitive proximity switch. These sensors are capable of detecting the target at some distance from the instrument.

Capacitive transducers are used to measure angular and linear displacements, linear dimensions, level, forces, humidity, concentration, etc. They can be structurally made with plane-parallel, cylindrical, pin electrodes, with or without dielectric between the plates.

High accuracy of displacement measurements can be obtained using optoelectronic transducers. The operation principle of these transducers is based on the use of optoelectronic transmitters and receivers of optical radiation, including but not limited to raster and moire methods. In the raster method, two flat plates with parallel strokes are used. The distance between the strokes on each plate is constant, but for the two plates is slightly different. When the plates (rasters) are superimposed on one another and their transmission is observed, the zones of condensation and discharge of striations. Moving one raster relative to the other in a direction perpendicular to the strokes causes the indicated densification zones to move in the same direction.

In the Moire method, the rasters on the two plates have the same pitch, but they are located at a small angle α. to each other. When overlaying rasters and their translucence, there are light and dark bands running across the strokes and called combinational or moiré strips. Moving one of the rasters causes a much larger displacement of the Moire bands in a direction perpendicular to the direction of the raster's movement, i.e., optical reduction also occurs. The presence of optical reduction in the methods of raster and moiré makes it possible to achieve a high sensitivity to the measured movement.

The choice of the type of transducer is determined by several factors: the range of measured displacements, the static and dynamic characteristics of the transducers, the practical design, and reliability, and the output signal [7].

Most of the displacement transducers used in practice are analogue types. However, there are also digital transducers which have a built-in analog to digital converter, which provides a simple interfacing with most popular data acquisition and computer systems.

Computer technology makes the way of development of measurement and control systems more effective and less costly [7]. Nowadays, several computer systems and platforms such as Arduino, Raspberry PI and minicomputers [8] invest in measurement and control to build measurement and control systems which could be used in industrial, domestic and medical applications. Furthermore, these computer systems are considered the base of IoT (Internet of Things) and cloud computing.

The present trend in computer development could be applied to several transducers, which are capable of working in industrial environments [6, 9, 10].

In works [6, 9], the authors utilize the acoustic standing wave phenomenon to build a displacement transducer operating in both forced and resonance modes to measure displacement. The transducer is used to measure linear displacement in different ambient temperatures. The measurement setup consists of a resonance tube filled with air, a speaker attached at one end of the tube and a microphone located at the other end of the tube (which forms the movable spindle). In work [6], the authors generate an acoustic signal traveling within a resonance tube and received by microphone, and then the amplitude of received signal is measured by a computer software such as LabVIEW. In work [9], the authors apply free resonance mode of operation of a resonance tube, in which the resonance frequency generated within a tube depends on the distance between the transmitter (speaker) and receiver (microphone) of an acoustic signal. The LabVIEW software is used to measure the frequency of the signal received by the microphone.

2. Literature Review and Theoretical Background

The general name "acoustic sensors" or acoustic transducers refers to a class of very diverse devices based on acoustic measurement. The commercial use of acoustic sensors and transducers began more than 60 years ago. The most important application of these devices is the telecommunication industry, which annually uses about 3 billion of acoustic wave filters, mainly in mobile phones and base stations. Basically, these are devices that work with surface acoustic waves and serve in the transmitters as band-pass filters for both intermediate frequencies and frequencies of radio waves [11].

In addition, acoustic sensors and transducers are used in the automotive industry (torque and tire pressure sensors), medicine (chemical sensors), oil industry (gas chromatography) and many other fields (as moisture sensors, temperature sensors, etc.).

The reasons for such widespread use of this technology in industry are low cost, reliability, sensitivity and endurance of devices. In addition, some of them do not need power sources.

As a detection mechanism, a mechanical, or acoustic, wave is used. When a wave propagates within a material or on its surface, any changes in the characteristics of the wave propagation path affect the velocity and / or wave amplitudes. The frequency and phase characteristics show the change in the speed of the wave.

Sensors and transducers based on acoustic waves are extremely versatile devices whose commercial potential is only beginning to be realized. They are competitive in price, durable, very sensitive, and reliable, and even some of them are wireless and / or do not require batteries. Acoustic sensors are very convenient for use on moving objects, for example, for measuring the pressure of tires on machines or the shaft torque. In addition, acoustic sensors are desirable for remote observation of chemical evaporation, humidity and temperature. Other applications include the measurement of force, acceleration, shock wave, angular velocity, viscosity, displacement and flow, as an addition to the film characteristics. The sensors also have electroacoustic sensitivity, which allows them to determine the level of pH, ionic impurities and electric fields.

Furthermore, acoustic transducers based on standing wave measurement are also used in many industrial applications for measuring displacement, temperature, density and speed of rotating shaft [13-14]. The operation principle of these devices is based on the creation of a standing wave within a resonance tube. Then the measurement of the desired parameter is obtained by measuring the change of the condition of creating a standing wave. Although the author in works [6] and [9] develops displacement transducers for measuring the displacement of a spindle within a resonance tube, these works are operated by the resonance existed in the tube. This work also utilizes the resonance tube for measuring displacement. Instead of creating a standing wave within a tube, a pulse with a short duration is generated, and then the time of the phase of the reflected signal is measured.

3. Operation Principle

The operation principle of acoustic sensors is based on the radiation, reception and analysis of a direct or reflected acoustic wave. The speaker generates an acoustic signal, which is received by a receiver that converts the acoustic signal into an electrical one. A computer system is widely used to acquire and analyze the information received by the receiver.

Acoustic sensors are widely used as proximity sensors, for remote detection of various objects, for measuring distances. Currently, the market offers a wide selection of acoustic sensors in various designs, operating in different acoustic frequencies. The behavior of different acoustic frequencies in similar environmental conditions is not the same. In most cases, it will not be difficult, guided by the specifications given by the manufacturer, to select the appropriate sensor for its task. But in cases where there are malfunctions or significant errors in measurements in the operation of devices, it is necessary to make a more thorough assessment of the influence factors, such as:

- Changes in sound velocity depending on temperature and environmental properties (mainly air), - how these changes affect the accuracy of measurements and the resolution of the sensors;
- Changes in the length of the sound wave depending on the speed and frequency of sound, - how these changes affect the accuracy of measurements, resolution, minimum object size, minimum and maximum distance to the object;
- Changes in attenuation depending on the frequency of sound and humidity, - how these changes affect the maximum sensitivity distance of the sensors in the air;
- Changes in the level of external noise as a function of frequency, - how these changes affect the maximum sensitivity distance and the size of the detection object;
- Changes in the reflected echo amplitude depending on the distance to the object, the size and geometry of the surface, - how these changes affect the sensitivity distance.

In this work an acoustic sensor based on measurement of the time of reflected echo pulse is presented. The wave surface can be drawn through any point in the space covered by the wave process. Consequently, there are an infinite set of wave surfaces, while there is only one wave front at each moment of time. The wave surfaces remain stationary. The wave front moves all the time. Wave surfaces can be of any shape. In the simplest cases, they have the form of a plane or sphere.

Accordingly, the wave in these cases is called flat or spherical. In a plane wave, the wave surfaces are a set of planes parallel to one another, in a spherical wave there are a number of concentric spheres.

If a particle of an elastic medium at point 0 (Fig. 1) oscillates in accordance with the formula

$$S(t) = A_0 \cos(\omega t), \quad (1)$$

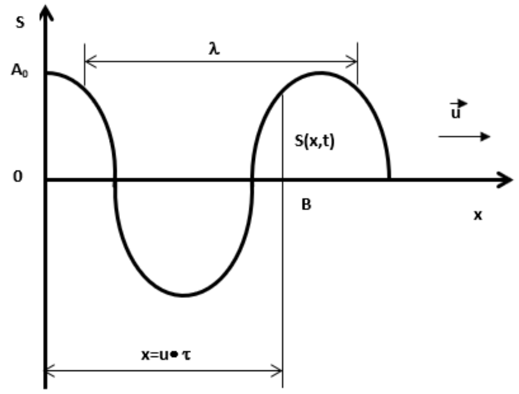


Fig. 1. The of oscillation of particles in a planar waveform

where $S\ (t)$ is the displacement of the particle of the medium from the equilibrium position; $A0$ is the amplitude (the largest displacement of the particle of the medium from the equilibrium position); t - time; T - period (time of one complete fluctuation); ω = $2\pi T$ - cyclic or circular frequency; then an arbitrary point B of the medium will come with an oscillatory motion with some time lag.

$$\tau = \frac{x}{u}, \quad (2)$$

where x is the distance over which the oscillation from point 0 to B has propagated, u is the propagation velocity of the wave (phase velocity of the wave).

The equation of the dependence of the displacement of a particle of the medium on time at point B will be written

$$S(x,t) = A_0 \cdot cos\omega(t-\tau) = A_0 \cdot cos\left(\omega t - \frac{\omega x}{u}\right), \quad (3)$$

where ω/u = $2\pi/T{\cdot}v$ = 2π/λ = k is the projection of the wave vector onto the OX axis; λ = $T{\cdot}v$ is the wavelength.

Thus, a wave propagating in the direction OX in an infinite elastic rod or an extended column of gas (air) is described by the equation of a plane monochromatic traveling wave:

$$S(x,t) = A_0 \cdot cos(\omega t - kx + \varphi_0), \quad (4)$$

where φ = (ωt-kx + φ0) is the phase of the wave, and φ0 is the initial phase.

The wave Equation (3), as well as waves of a more complex type, are a solution of the one-dimensional wave equation:

$$\frac{\partial^2 S}{\partial t^2} = \frac{1}{u^2} \cdot \frac{\partial^2 S}{\partial x^2}, \quad (5)$$

where u is the phase velocity associated with ω and k by the relation: u = ω/k = λ/T = λ·ν, where, in turn, ν is the linear frequency of the oscillations.

The phase velocity is the velocity of a certain phase value, which unambiguously characterizes the fixed state of the vibrational motion of the particles of
the medium.

The distance λ traversed by the wave (determined by the oscillation phase) during one oscillation period is called the wavelength, i.e. the wavelength is the shortest distance between adjacent particles of the medium, which oscillate in the same phase.

The oscillation frequencies ν of the particles of the medium have the same frequency as the oscillation frequency of the wave source. Waves, the frequency of oscillation of particles in which lie in the range from 16 to 20,000 Hz, are called sound waves.

Sound waves in gases and liquids are longitudinal and can propagate only in an elastic medium.

Sound waves, like electromagnetic waves, have a number of properties: interference, diffraction, reflection, etc.

The speed of sound in gases close to ideal is equal to

$$u = \sqrt{\frac{\gamma RT}{M}}, \quad (6)$$

where γ = Cp/Cv is the ratio of the specific heats of the gas at constant pressure Cp and constant volume Cv; M is the molar mass; R is the universal gas constant.

Standing waves are usually created when the incident and reflected from the obstacle are added, for example, reflected from the end of the tube containing the gas.

Suppose that two plane waves with the same amplitudes and frequencies propagate along the OX axis in opposite directions. If the origin is taken at a point at which the opposing waves have the same phase and the time is selected so that the initial phases are equal to zero, then the equation of both plane waves can be written in the following form.

For a wave traveling in the direction of the positive OX axis

$$S_1 = A_0 \cdot cos(\omega t - kx) \quad (7)$$

and for a wave traveling in the direction of the negative axis OX

$$S_2 = A_0 \cdot cos(\omega t + kx) \quad (8)$$

A standing wave is described by the expression:

$$S = S_1 + S_2 = 2A_0 \cdot cos(kx) \cdot \cos(\omega t) \quad (9)$$

The factor $A = 2A0 \cdot |\cos(kx)|$, which does not depend on the time t, expresses the amplitude of the standing wave. However, the position x could also be determined using the phase shift between the two signals S1 and S1. The phase shift expresses the time delay between the two shifted signals, as will be shown in the next section.

The phase difference of the simultaneously applied electric oscillations is measured by a microphone and it has the form: $\delta = \varphi 1 - \varphi 2 = 2\pi x/\lambda$.

The phase shift is converted into time shift using the following formula

$$t = -\frac{\delta}{\omega} = \frac{\varphi 1 - \varphi 2}{2\pi f} \quad (10)$$

The Formula (10) is used to measure the distance.

4. Design of An Experimental Setup and Testing Procedure

In this report, the length of a sound wave in air is measured by time delay which depends on the phase shift method between oscillations of the source of oscillations and oscillations in different parts of the traveling wave propagating in the air.

The experimental setup consists of the following parts: Speaker (1), Microphone (2) to measure the time shift fixed at near the speaker and parallel to it, a glass tube closed on both sides (3), Microphone (4) fixed on the spindle (5) which is freely moving along the waveguide, a measuring ruler (6).The schematic design of the transducer is shown in Fig. 2.

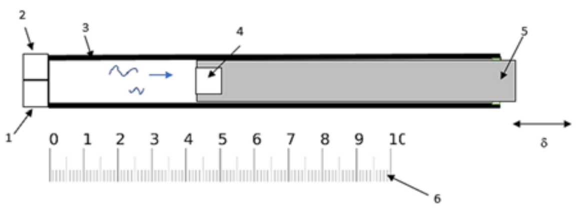


Fig. 2. The schematic design of acoustic transducer for displacement measurement.

The speaker 1 is powered by the output of a sound card which is a part of standard PC. The parameters (i.e, phase shift) of the sound wave is measured by microphone placed parallel to the speaker (Microphone 1).

The operation principle is follow. A pulse of signal is transmitted via a media and reflected by the spindle surface. The phase of reflected signal and the time shift is measured by acquiring the sound using Microphone 1.

At time t_0, the phase value φ_1 of transmitted (original signal) sound wave is ωt si measured by microphone 4, where $\omega = 2\pi\nu$ is the cyclic frequency of the oscillations.

The sound signal received by the microphone 1 placed has a phase value φ_2 equal to $\omega t - 2\pi x/\lambda$, where x is the distance between the speaker and the microphone, and λ is the length of the sound wave. The coordinate x is between the speaker and microphone.

5. Software Development

Modern programming languages and programming environments designed for developing measurement and control application software provide a wide range of tools, both for experienced programmers and for those who are not experienced programmers.

These tools allow the researchers and the students interested to create custom programs directly in standard programming languages, for example C / C++, Basic, as well as using special scientific programming languages such as MATLAB and Mathematica and LabVIEW [15].

According to the method of programming, these programming languages are divided into the following:

- Text or text-graphical programming languages of environment (Pascal, Delphi, LabWindows / CVI, Measurement Studio, Visual Basic, Visual C / C ++) that use elements of visual text programming to create user interface applications and focus first turn on experienced programmers;
- Graphical object-oriented (InTouch, "Trace Mood"), based on the use of graphic images of the automated process control system in as elements of programming;
- Graphical functionally-oriented (LabVIEW, LabVIEW / DSC, Agilent VEE), using the functional-logical principle design (drawing) and graphical representation of algorithms programs.

Graphic programming environments are easily mastered not only by professional programmers, but also by non-experienced programmers. On the one hand, modern graphical systems allow you to create programs that are almost as effective as programs written in text packages. With other parties, in most cases, graphical programs are more visible, easier to modify and debug, and faster to develop.

The main advantage of graphic programming systems is that the developer of the application, whether the engineer or technologist, can be the director himself.

LabVIEW (Laboratory Virtual Instrument Engineering Workbench) is one of the data flow programming environments that allows you to develop application software for organization of interaction with measuring and control equipment, collection, processing and display of information and calculation results, and modeling of both individual objects and automated systems in whole. The developer of LabVIEW is the American company National Instruments [16].

In this work, the author will use LabVIEW for developing the required software for data acquisition and signal processing. The flowchart of the developed software is shown in Fig. 3.

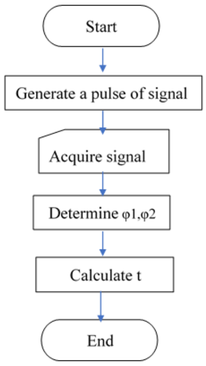
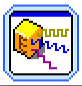
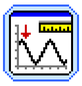
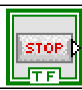


Fig. 3. Flowchart for developing software.

The flowchart illustrated in Fig. 3 can be easily converted into LabVIEW program, which is also called VI (Virtual Instrument). The program in this case consists of small programs, called subVIs or VI. These VI can be found in any version of LabView. The developed LabView Vi for receiving and processing the acquired signal is shown in Fig. 4.

The description of the main VIs is explained in Table 1.

Table 1. Description of the main VI's.

LabView VI	Description
	Acquire a sound signal by a microphone
	Generate a sound signal with specific parameters
	Measuring sound parameters: Amplitude, Phase, Frequency
	Stop program

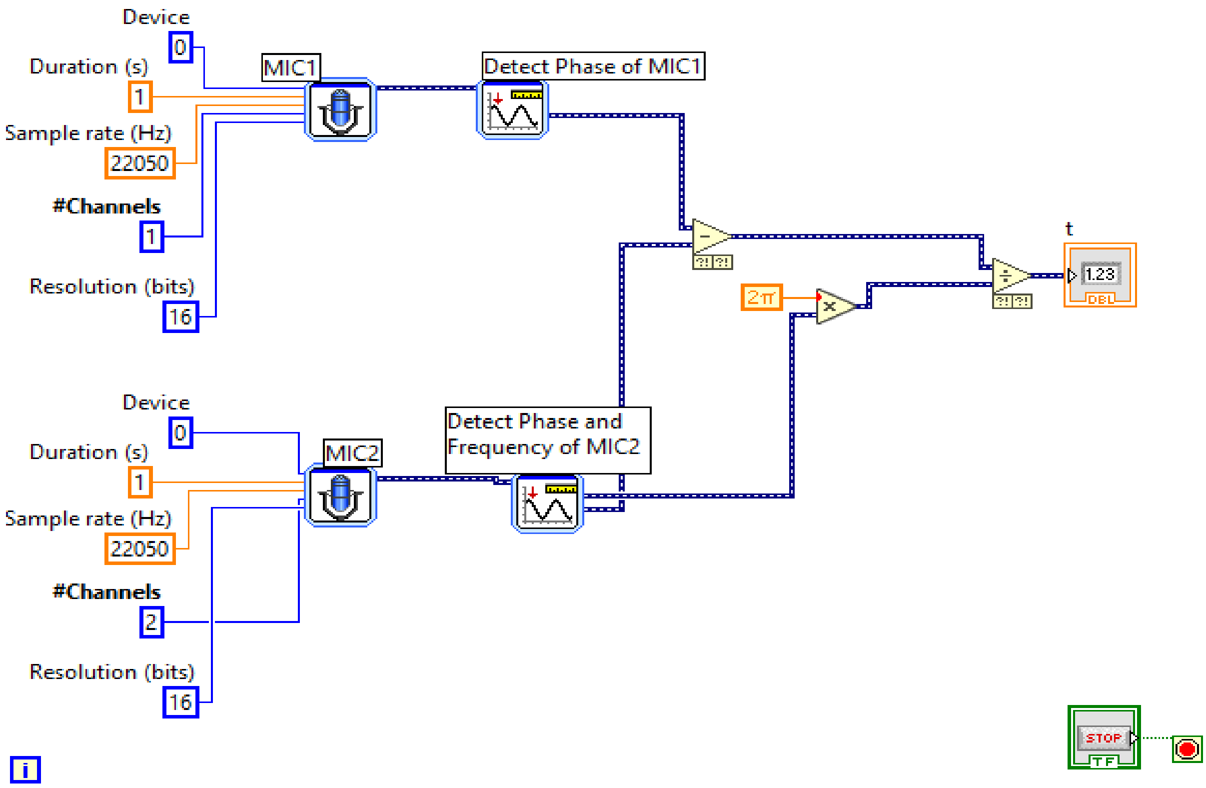


Fig. 4. The developed LabView Vi.

6. Experimental Results

The experimental results present the relationship between the measured distance and the time shift, as illustrated Fig. 5. The point 0.05 is chosen as a reference value to avoid non-linear effects that may appear in the zone near the speaker [16].

The plot of experimental results is shown in Fig. 5.

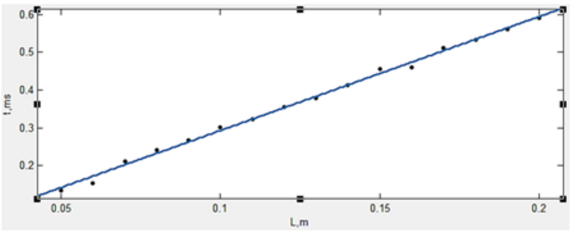


Fig. 5. The plot of experimental results.

7. Conclusion

It has been shown that a computerized transducer for displacement measurement is designed and experimented. The designed transducer is efficient, inexpensive, and multipurpose. It could be integrated with other primary non-electrical sensors and orders to get an electrical read out and to realize computer data logging and automatic positional control.

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