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ACCURATE DISPLACEMENT MEASUREMENT BASED ON THE FREQUENCY VARIATION MONITORING OF ULTRASONIC SIGNALS

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Abstract - This paper introduces a different approach to the measurement of the time-of-flight of ultrasonic signals. Frequency variation monitoring and recording is used to determine accurately the arrival time of the ultrasonic signal. A high speed Digital Signal Processor (D.S.P.) is used for both: transmission and direct measurement of the frequency of the incoming signal in every single period and with an accuracy of about 0.1%. The proposed configuration offers small size and low cost solution to displacement measurements with a remarkable performance in terms of accuracy, range and measurement time.

Keywords: ultrasonic transducers, frequency variation, displacement measurement

1. INTRODUCTION

Ultrasonic transducers are widely used in a variety of applications and in technological areas with significant differences in performance characteristics, operating environment, specifications, etc. Ultrasonic instrumentation and measurement systems can be found in applications varying from distance measurements to non-destructive testing of materials, medical imaging and robot navigation. In a large number of these applications the measurement technique is facing actually a time measurement problem. The main effort is to estimate accurately the propagation delay of the ultrasonic wave-front as it travels from the transmitter to the receiver, or, as it is usually described the "time-of-flight" of the ultrasonic wave. Ultrasound based measurement of distance, etc, has been recognized for some years now as the most simple and inexpensive answer to typical applications of non-contact distance measurement. There are actually only two main drawbacks for this method; the poor resolution and the rather strong sensitivity to temperature (0.17%/°C in the air). The variety of applications of the ultrasonic time-of-flight measurement has been increased over the years including nowadays various high performance areas like robot navigation, chemical analysis and non-destructive testing. As a result of the stronger requirements for the performance of the systems used in these applications, certain new techniques have been proposed, aiming to improve accuracy and reliability of measurements and to diminish the measurement time. These techniques include, besides the classical threshold comparison (known as pulse echo threshold method), other, more complicated, approaches like frequency modulation, multiple frequencies transmission, cross-correlation and neural computing [1-5, 7, 8, 10]. Most of them are based on complicated calculations or procedures performed by automated computerized systems. Although more accurate these techniques are also more expensive and certainly less flexible due to the complicated hardware and/or software involved.

Hardware configuration is usually based on PCs or on single chip microcomputers (micro-controllers) since they offer versatility in implementing different measurement techniques and low cost. Yet, in most cases the micro-controller is used rather to implement a certain processing algorithm for increased accuracy, than to measure the actual time delay accurately. This is mainly because of the relatively low frequencies of the clock of micro-controllers. A different approach is reported in this work; A high speed DSP micro-controller is used to measure directly the frequency of the incoming signal and this can be done in a fast and accurate way (within one single period and with an error of 0.1%). The proposed system is presented along with illustrative examples of the possible capabilities for analysis of the incoming signal and accurate measurement of the time-of-flight of the ultrasonic waves.

2. THE PROBLEM

The classical method for the measurement of the propagation delay (time-of-flight) of the ultrasonic signals is the well-known pulse echo threshold method. A short burst of pulses is driven to the transmitter and then the received signal (echo) is compared to a certain amplitude level. The distance between the transmitter and the object is evaluated from the equation:

$$d = \frac{1}{2} \upsilon_{sound} \; t_{flight} \tag{1}$$

This is the most simple and low cost implementation of an ultrasonic ranging system suffering of course from poor resolution. There is a number of good reasons for this drawback, besides the expected (more or less) noise problems, and the inherent delay in the response of the transducers. A major limitation is caused by the fact that if one single period of the wave-front is not detected (missed due to amplitude attenuation or for any other reason), this results to an error of about 8.5mm. A simple and common improvement is to employ a dual comparator (detecting on both positive and negative parts of the incoming signal) in order to reduce the possible minimum error to a semi period (or about 4.5mm). This error is mainly caused by the variable attenuation of the amplitude of the incoming signal (depended on the distance to be measured). This is an inherent problem of the method, since the detection technique is based on amplitude comparison. In fact, the received echoes reach the threshold level some time after the exact beginning (added delay), making the target to appear slightly farther away than it actually is. This error could be easily avoided if the added delay was constant, but amplitude changes produce deviations. To quantify this error it is useful to model the echo waveform as a damped sinusoid:

$$V(t) \approx V_0 t^n e^{-ht} \sin(\omega t + \varphi) \quad (2)$$

In this mathematical model [4], n, h, φ, ω are transducer dependent parameters, ω is the undamped angular resonance frequency of the transducer. On the other hand, echo amplitude change with distance x due to beam spreading and attenuation:

$$V(x) = V_0 \frac{e^{-\alpha x}}{x} \quad (3)$$

where α is the coefficient of attenuation in air.

It has been suggested that, if the threshold level was made variable matching (3) with $x = \upsilon_{sound}\, t$, the echo produced by a target at different distances would give constant added delays. However, there are other causes of echo amplitude variations which cannot be easily modeled, such as the size and orientation of targets. Therefore, when large echo amplitude variations are to be expected, the error due to the added delay for which no compensation can be made, is half the rising time *Tr* of the waveform. This error is usually larger than a wavelength and for typical transducers operating in the range of 40 KHz it can reach 1cm.

Numerous other techniques have been reported in the literature, aiming to improve the reliability and accuracy of the time-of-flight measurement. Our approach is that with the increased capabilities of modern high-speed micro-controllers, it is possible to monitor accurately the desired characteristics of the incoming signal, and therefore there is no longer need to employ complicated methodologies. In order to present this approach we shall describe first briefly the basics of the problem; the task is to measure the propagation time of the ultrasonic wave. Now the main problem is, that although we know exactly the starting time (transmission), we do not have a clear (reliable) way to identify the arrival time. This is the critical point of the whole measurement procedure; to employ a method that offers a clear triggering based on a characteristic (any characteristic) of the incoming signal. The identification of the arrival needs not to be done within a given period (i.e. the first or the second of the received signal), what is really needed is the reliable identification of the event.

One way to improve detection reliability is for example to try to drive the transmitter-receiver system with such a waveform so that a clear peak appears at the output. This method, proposed by Grimaldi and Parvis [6], results to a considerable improvement in the identification procedure and consequently to an improved accuracy when there are no large variations of the measured distance. Yet, there are two main drawbacks in this method: a) it is also based on amplitude comparison (so it suffers from the attenuation effects) and b) there is a need for a specialized (custom designed - arbitrary) driving signal, which requires a certain hardware. The amplitude comparison method should be avoided if possible, since there is a strong amplitude attenuation effect present in the system. Another very interesting approach is to ignore practically the amplitude of the incoming signal and to try to identify the arrival event by detecting a frequency change. This is a promising technique since it is insensitive to amplitude attenuation and noise problems. Moreover, as it will be shown in the experimental results, the transducers are responding faster (or at least with the same speed) to frequency changes than to amplitude changes. The driving signal is a commonly used short burst of pulses of two different frequencies in a Binary Frequency Shift-Keyed mode (BFSK). Frequency changes are detected by monitoring the phase of the incoming (received) signal versus time. This method was originally used in the ultrasonics field by Webster and is known as phase digitizing [5]. All major drawbacks of the other methods do not appear in this one, with the exception of the time needed to identify the frequency change.

Our approach is essentially the same as the previous one, with one significant difference: the considerable reduction of the measurement time. The proposed configuration is implementing a technique for fast measurement of the frequency value (within one single period). It is monitoring the frequency changes in a fast and accurate way, and consequently capable of identifying the arrival event in the same way. Moreover, it can be used as a tool for experimental analysis of the overall system (transducers, etc) in the frequency domain. The DSP micro-controller is used to measure directly each period of the received signal and convert the period value to frequency value. Frequency monitoring of the incoming (received) signal is used to identify the arrival event and to mark the arrival time accurately.

3. THE SYSTEM

The configuration of the proposed system is based on the capabilities of accurate time measurement of modern micro-controllers. The usual series of microcontrollers can not be used in this application mainly because of their relatively low frequency of operation (clock frequency) which affects the accuracy of time measurement within one single period. They can not offer the required fast and accurate frequency measurement. A high performance system may therefore be built only on a more powerful microcontroller. Larger systems (personal computer type, etc) are avoided for practical reasons; the overall measurement system should be cost-effective and small sized. The PSP56002 single chip digital signal processor seems to offer an excellent solution. This unit is a 24 bit, 80MHz DSP micro-controller with internal RAM (adequate for this application). The timing measurement technique employed by the DSP56002 is based on a free running 24bit counter driven by a 40MHz clock (counter's clock is half of the microcontroller's nominal frequency of 80MHz) as shown in fig. 1. At the beginning of each period a 24 bit Timer Control/Status Register (TCSR) generates an interrupt which loads the content of the free-running counter to a 24bit Timer Count Register (TCR).

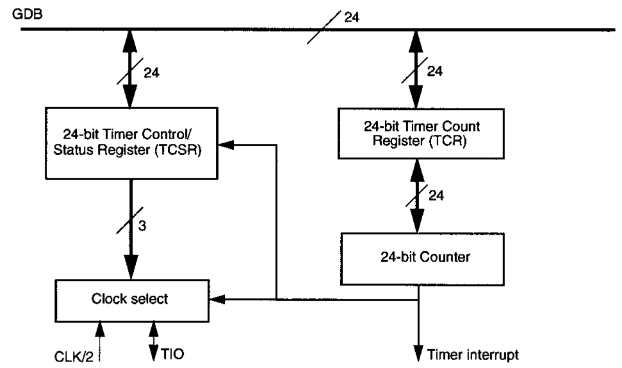

Fig. 1. DSP56002 timer system

The user's program can read the TCR and subtract consecutive values of the counter to determine the time between two events (i.e. from the beginning of a period of the received signal till the beginning of the next one, that is the exact time of a single period).

As we can see in fig. 2, if T_{INm} is the value of m period, f_m the value of frequency of this period, C_m the number of the counted pulses by the counter of the timer and T_{clock} the period of the timer clock, then:

$$T_{INm} = C_m \, T_{clock} \tag{4}$$

and the frequency value may then be derived from the number of clock pulses counted within one period:

$$f_m = \frac{1}{T_{INm}} \Leftrightarrow f_m = \frac{1}{C_m} \frac{1}{T_{clock}} \Leftrightarrow f_m = \frac{1}{C_m} f_{clock} \tag{5}$$

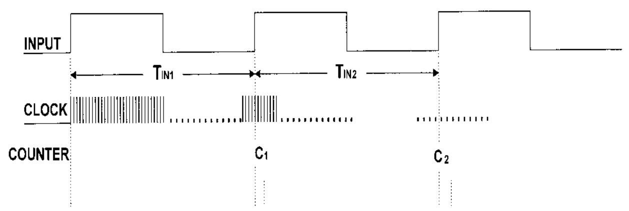

Fig 2. Measurement process of the signal period

The accuracy of this measurement is depended on the clock frequency (or period) value, which for our case is 40MHz (or 25nsec). This value results to an accuracy of 0.1% for the measurement of the frequency of the 40 kHz ultrasonic signal. The proposed practical configuration of the measurement system is shown in fig. 3.

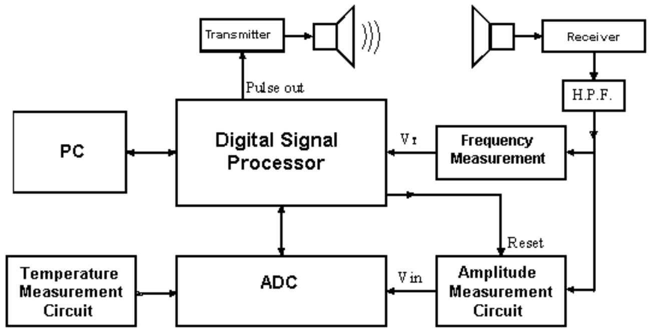

Fig.3. Experimental configuration of the proposed measurement system

The microcontroller is driving the ultrasonic transmitter with a precisely determined pulse train. This means that the frequency (or actually the period) of each consecutive pulse sent to the transmitter can be controlled, along with the total number of the pulses and the amplitude of the pulse train.

At the other end, an analog interfacing circuit is employed to provide the same microcontroller with the appropriate input information (about the received ultrasonic signal). At the input, right after the ultrasonic receiver there is an analog signal conditioning section, which is formed by a controlled amplifier and a high pass filter (used to reduce possible low-frequency interference). Then the input signal enters two different paths: a frequency measurement path with a specially designed high-speed comparator, and an amplitude measurement path with a maximum value circuit. From the first path the microcontroller gets the information about the duration of each consecutive period and from the second the digital data corresponding to the value of the amplitude for this period. As shown in fig. 3, the basic analog circuit is a high-speed comparator, which triggers the timing input of the micro-controller at the exact time instants of the beginning of each period of the received signal. The measurement of the amplitude of each period of the incoming signal is not actually used in the described application for the reasons mentioned earlier in this work (attenuation). It has been included in the system though for the following two reasons mainly:

- the amplitude measurement section is needed for other options of the same system like the mautomated calibration and self-testing procedure.
- the information about the amplitude is used by this system to validate the frequency measurements. This means that this information is helpful for the estimation of the time window when an input signal is detected and therefore frequency analysis is useful. It should be noted that it has no effect on the time-of-flight measurement, and it is not needed in practical applications where a certain frequency variation pattern (modulation) is applied. It is not necessary, but very useful as an additional tool for the experimental analysis of the transducer-receiver setup.

On the amplitude measurement path, a precision half wave rectifier followed by a Sample-and-Hold circuit drives the A/D converter with the maximum value of each period (that is the amplitude value of each period). The accuracy of the amplitude measurement is mainly depended on the A/D converter, which is a 10bits parallel output converter with 900nsecs max conversion time and 800KHz sampling rate. The final figure for the accuracy of the measurements of the amplitude of each period of the incoming signal is about 5mV (or 0.1%).

4. EXPERIMENTAL RESULTS

The practical configuration of fig. 3 has been experimentally built and operated via a serial interconnection with a personal computer. The frequency values were temporarily stored in the microcontroller's memory (along with all other required information, i.e. time) and transferred right after the end of each measurement to the PC for analysis. There is actually a serial bidirectional, communication between the micro-controller and the personal computer. The PC is not needed for the measurements but it is used as a user-friendly interface to control the measurements sequence and analyze the output information. In a practical application all tasks can be performed by the micro-controller and the output information (the value of the time-of-f light or the distance) can be either directly displayed locally, or transferred to any other computerized system.

The experimental system has been tested first with an input signal of 40kHz coming directly (without ultrasonic transducers) from a high performance generator (HP3325B). The output information as shown in fig. 4 and fig. 5 illustrates system's frequency measurement capabilities.

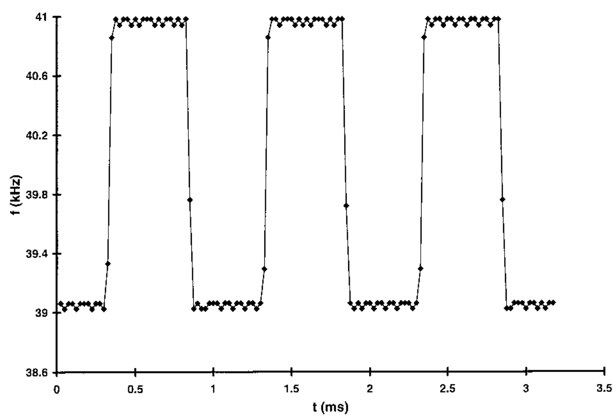

Fig. 4. Frequency response of a BFSK modulated signal from a generator.

Fig. 4 shows the measurements of a frequency modulated input varying in a binary mode from 39kHz to 41kHz (BFSK), while fig. 5 shows a triangular frequency modulated input in the same range.

The expected error of 0.1% (40Hz) can be seen in this figure (as the fluctuation of the measured value on the two levels), along with the capability of the system to monitor sudden changes of frequency very quickly.

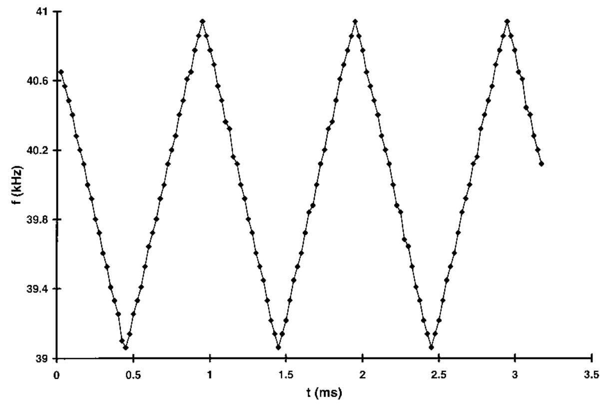

Fig. 5. Frequency response of a triangular frequency modulated signal from a generator.

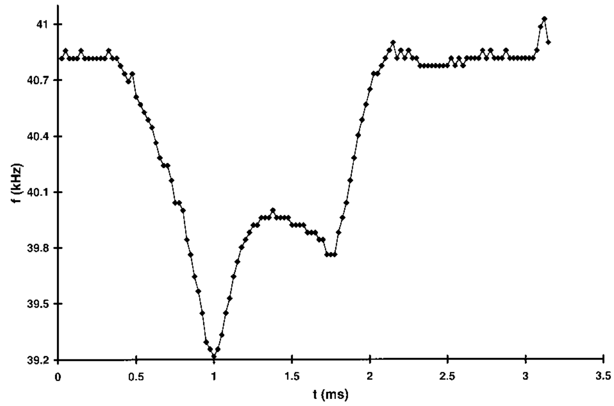

Fig. 6. Frequency variations of a BFSK modulated signal, where the frequency step is below the resonance frequency of the transducers.

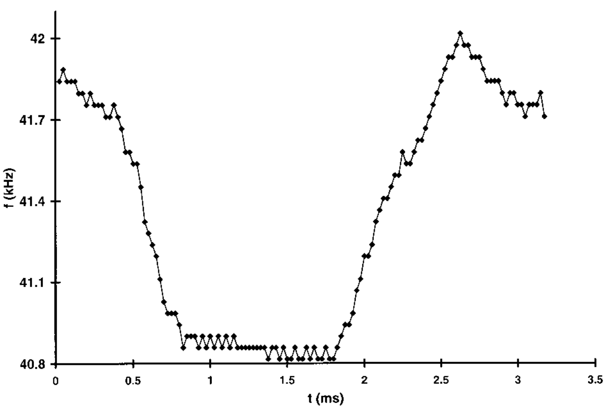

Fig. 7. Frequency variations of a BFSK modulated signal, where the frequency step is above the resonance frequency of the transducers.

The measurement system is then tested with a transducer pair placed at a distance of about 1m inside a 12cm diameter anechoic tube (with practically no reflections).

Figures 6-8 show three different cases of frequency variations of a BFSK signal monitored by this system. The frequency step is the same in all cases (1kHz), but the higher and lower frequency value is different in each of them; in fig. 6 f_{HIGH} is equal to the resonance frequency of the pair (40.9kHz) and f_{LOW} is 1kHz less (39.9kHz), in fig. 7 f_{LOW} is equal to the resonance frequency and f_{HIGH} is 1kHz higher (41.9), and in fig. 8 the resonance frequency is in the middle of the frequency step.

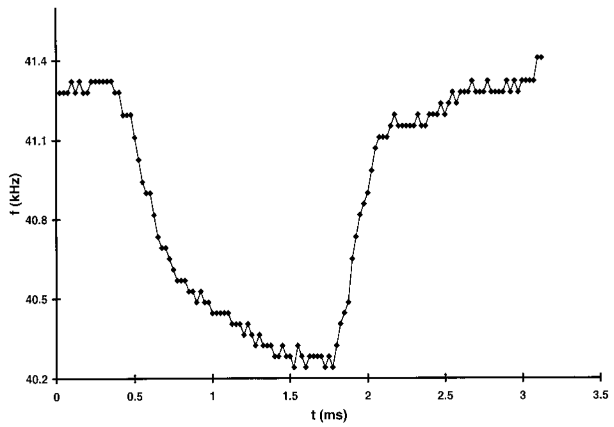

Fig. 8. Frequency variations of a BFSK modulated signal, where the resonance frequency of the transducers is within the frequency step.

From these results it is apparent that the ultrasonic transducers do not respond directly to frequency changes and their behavior is strongly non-linear. There are certain phenomena that should be considered, if frequency variations are to be used for timing (arrival time measurement) as in the case discussed in this work. Different high and low frequency values of a BFSK signal have been used as an example of the different variations that occur, in order to illustrate the importance of both requirements of the frequency measurement technique: speed and accuracy. The main drawback of the phase digitizing method (large measurement time) is apparently causing a drastic limitation on the accuracy of the timing measurements.

Fig. 9 shows the measured frequency variations for a triangular (linear) frequency modulation of the driving signal. The non-linear behavior of the transducers can be also seen in this case, but there are certainly some clearly identifiable points (peaks, slopes, etc). Fast and accurate frequency monitoring offered by the proposed method offers therefore the necessary information in order to detect a certain event and measure the arrival time of the ultrasonic wave.

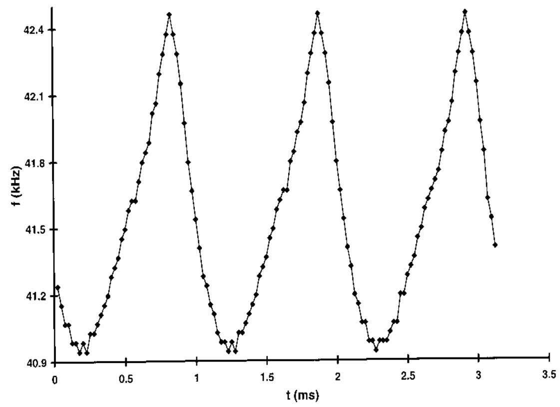

Fig. 9. Frequency variations of a triangular frequency modulated received ultrasonic signal.

The first experimental tests for this kind of measurements (the time between the transmitting and the receiving of a peak of a triangular frequency modulated pulse train) have shown a remarkable accuracy in the measurement of displacement, which reaches 0.03mm under constant temperature conditions, or under temperature compensation. This value reached the accuracy offered also by the mechanical displacement setup of the experimental system (0.02mm) and it should be noted here that this result is a directly obtained measured value - not a computer calculated statistical figure.

The above mentioned result (of 0.03mm) that measured approaches the 75ns maximum overall theoretical error of the system: 50ns for the transmission and 25ns for the reception of the ultrasonic signal. This theoretical value corresponds to a displacement accuracy of 0.0255mm.

5. CONCLUSION

The system proposed in this work is using the fast measurement of frequency of the received ultrasonic signal as an identification method for the accurate estimation of the time-of-flight. It follows from the description of the problem that the distance measurement technique based on ultrasonics is actually facing the problem of determining the arrival time of the ultrasonic wave-front accurately. Frequency modulation techniques are a good way to use for identification and fast frequency monitoring must be used for the implementation of this method. Modern DSP micro-controllers have now the appropriate clock frequencies to measure ultrasonic signals directly, accurately and within one single period. These systems therefore can measure the time-of-flight (propagation delay of the ultrasonic wave-front) directly and accurately without the need of sophisticated methodologies. The experimental results presented here indicate the novel capabilities of analysis offered by this system and the accuracy of the time-of-flight measurements.

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