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Real-time implementation of Kalman filter to improve accuracy in the measurement of time of flight in an ultrasonic pulse-echo setup

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ABSTRACT

In this paper, we demonstrate a hardware implementation of Kalman filter to enhance accuracy in the measurements of time-of-flight in an ultrasonic pulse echo technique (operated at 10 MHz). Pulser-receivers and other respective circuit units are designed using off-the-shelf electronic components. The advanced reduced instruction-set computing machine processor based Raspberry Pi single board computer is used to implement the Kalman filter and control various processes. Additionally, a graphical user interface is designed using Qt software, under the Debian open source operating system. The software has capability to measure and display the time-of-flight and ultrasonic propagation velocity in a liquid under test. The designed system with the Kalman filter exhibited an extremely small error of about 0.01% in the time-of-flight measurements compared with other systems. The functionality of the developed approach to measure time of flight and thereby ultrasonic velocity with significant improvement has been discussed in this article. It was experimentally verified that by improving other parameters such as the separation between the transducer and the reflector and cell structure, significant improvement in the accuracy of ultrasonic velocity in the liquid under test is achieved.

I. INTRODUCTION

There are numerous ultrasonic velocity measurement techniques available, out of which the pulse method is highly preferred due to its inherent advantages. An ultrasonic pulse method for the propagation velocity measurement in liquids like sing-around,[1,2] pulse superposition,[3] pulse-echo overlap technique, and pulse interferometer techniques[4] has already been discussed in the literature. The main advantage of using a pulse technique is the elimination of standing waves and minimization of local heating of the sample.

The ultrasonic pulse-echo technique is the most popular, reliable, and sustainable technique among all the ultrasonic pulse techniques, for the measurement of time of flight of a pulse.[5] A pulse-echo technique is advantageous because of the use of single transducer for transmission and reception and low power delivery to the sample that avoids micro heating of sample and gives multiple echo train for better time of flight and amplitude measurements.

In the pulse-echo technique, an ultrasonic wave travels through a sample and generates the echoes each time when the oscillator is switched off.[5,6] In the typical pulse echo setup, the echo generation is by the reflector placed at the opposite end of the transducer. The setup yields a characteristic train of echoes from the transmitted pulse. The amplitude of the successive echoes decays in a characteristic manner. The amplitude decay pattern and the echo separation reveal the elastic properties of the medium. With the more accurate information of path length and successive amplitude echoes, the velocity of propagation and attenuation can be estimated with a fair amount of accuracy.[5] However, the measurement of time-of-flight between successive echoes is very critical to precisely estimate the ultrasonic propagation velocity.

Recently, significant improvements have been made in the design of pulse-echo technique for the precise ultrasonic velocity measurement.[7–10] A precise ultrasonic velocity measurement in a liquid sample can be achieved by maintaining high stability of temperature (liquid cell), better path length, higher counter resolution and frequency, and instruments with faster response time and enormous computing power.[7] Normally, in a measurement instrument, a digital counter reported variation in a counting resolution of ±1 or more.[7] However, such measurement resolution is not significant enough to generate accurate data. Hence, we anticipate that there is an urgent requirement of proper pulse-echo measurement setup with significant accuracy for time-of-flight measurements. With the advent of advanced embedded systems and their enormous computing power, it is possible to implement digital signal processing for enhancing the signal quality, accuracy, and reliability in the measurements.[11–13]

In the present work, we report hardware implementation of Kalman Filter (KF) for the precise measurement of the time-of-flight. The KF algorithm precisely stabilizes the measurements that fluctuate due to various effects such as electronic noise and environmental effects. It has been experimentally observed that the KF based system significantly enhances the accuracy and the reliability in the measurement of ToF at nanosecond level.[14,15]

II. EXPERIMENTAL

A. Pulser-receiver module

Figure 1 shows a block diagram of the in house designed pulser-receiver module in the pulse-echo setup, operated at 10 MHz. Here, Raspberry Pi 3 is used for computation, controlling the unit, implementation of KF, data acquisition, analysis, and storage. A RF oscillator is designed using a 10 MHz crystal oscillator. A user selectable pulse repetition frequency from 100 Hz to 6.26 kHz is generated using a subsequent division of same pulses. The output of repetition rate generator drives a monostable multivibrator IC 74221 having an adjustable time constant and defines the time duration for which 10 MHz RF will be transmitted through the sample. The output of the monostable multivibrator is fed to the AND gate, whose second input is driven by using the RF oscillator. Hence, the output of the AND gate provides a 10 MHz RF pulse with a user selectable pulse repetition frequency of 100 Hz–6.26 kHz. It is further fed to a transistor 2N2219 based amplifier via a digital isolator ISO7420, which is used to isolate digital and analog signals to avoid noise coupling. A voltage of 52 V pulse tone burst is employed to excite the piezoelectric transducer (PZT) (disc) for generation of ultrasonic waves.[16] The used PZT transducer was of 10 mm diameter (Concord Transducer and Instrument Co., New Delhi, India), with a wrap around solder arrangement. At the receiver section, a high voltage pulse arrester is designed using a 1N4148 diode combination to avoid damage at the receiver section. The received low amplitude echoes are amplified using an LM7171 OP-AMP amplifier at multiple stages. A SMB5819 diode peak detector circuit is incorporated to convert positive peak signal echoes in single pulse format and wave shaped by using OP-AMP 358. Finally, detected echoes are fed to one of the terminals of comparator designed using LM7171 OP-AMP and the other terminal is connected to the output of high precision 20 bit DAC1220. Here, the Advanced Reduced Instruction-Set Computing Machine (ARM) processor controls the pulser-receiver unit, implementation of KF, data storage, and analysis. The display and keyboard enhance the user flexibility and interaction.

B. Time-of-flight measurement

Ultrasonic velocity of propagation in a medium under test is estimated by measuring the time-of-flight between two successive echoes over a fixed path length. It is accomplished by a 32-bit counter, IC 74LV8154, having a clock frequency of 32 MHz. The DAC1220 output voltage is adjusted at the

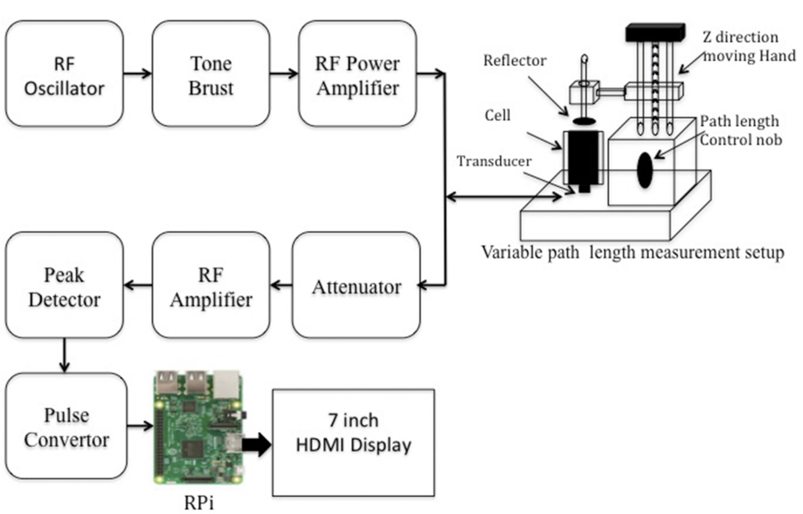

FIG. 1. Block Diagram of designed pulse-echo setup with pulser-receiver module operated at 10 MHz.

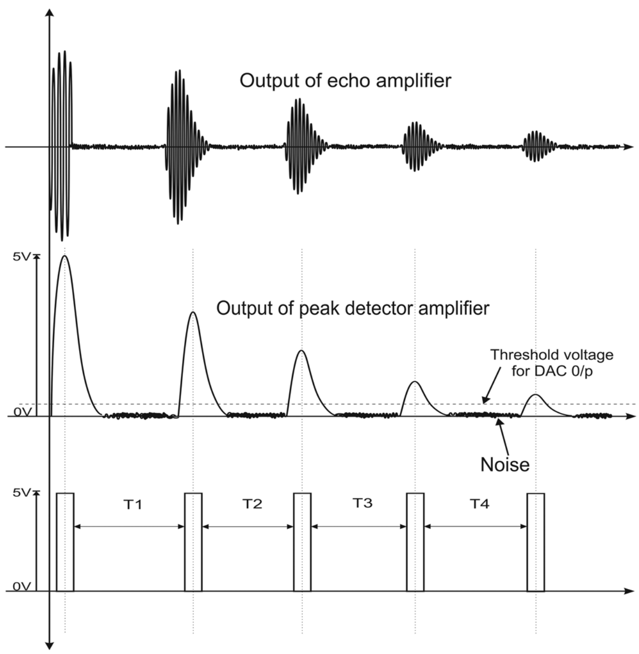

FIG. 2. Conversion of ultrasonic echoes to the single short pulse suitable for the ToF measurement.

threshold level and compared with the peak detector output to obtain the resultant output of echo pulses in a sharp pulse form at the output stage of the comparator. The threshold voltage helps to avoid noise signal comparison for better stability. Figure 2 shows conversion of ultrasonic echoes to the single short pulse for digital measurements. T represents the time interval between echoes pulses.

C. Implementation of Kalman filter

In the present work, a linear KF is implemented to extract signal from noise. Indeed, KF operates recursively on streams of noisy input data to produce a statistically optimal estimate of the underlying system-state.[14,15] The developed KF is adaptive and autotuned as per changes in the process input to the measurement system. KF is implied on the time-of-flight measured using the 32 bit counter output.

The KF also known as a linear quadratic estimation (LQE) and it is an algorithm that uses series of measurements over observed time, containing statistical noise and other inaccuracies, and produces estimate of unknown variable that tends to be more accurate than those based on the measurement alone.[14,15] It estimates a process using a form of feedback control, i.e., the process state at some time and then obtains feedback in the form of (noisy) measurements.[15] As such, the equations for the KF fall into two groups: time update and measurement update equations. The time update equations are responsible for projecting the forward (in time) current state and error covariance estimates to obtain *a priori* estimates for the next time step. The measurement update equations are responsible for the feedback, i.e., for incorporating a new measurement into *a priori* estimate to obtain an improved posteriori estimate. The time update equations can also be thought of as predictor equations, while the measurement update equations can be considered as corrector equations.

In fact, the final estimation algorithm resembles to that of a predictor-corrector algorithm for solving numerical problems.

The specific equations for the time and measurement updates are shown below.

Time update equations:

$$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_k, \tag{1}$$

$$P_k^- = AP_{k-1}A^T + Q. \tag{2}$$

Measurement update equations:

$$K_k = P_k^- H^T \left(HP_k^- H^T + R\right)^{-1}, \tag{3}$$

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-), \tag{4}$$

$$P_k = (1 - K_k H)P_k^-. \tag{5}$$

Here, Q is the process noise covariance and R is the measurement noise covariance. $n \times n$ matrix A relates the state $X_{k\text{-}1}$ at the previous time step to the state X_k at the current step. Matrix B relates the optional control input u_k to the state X_k. Matrix H relates the state X_k to the measurement Z_k. P is the error covariance, but P_k^- is the priori estimate error covariance, and P_k is the posteriori estimate error covariance.

1. Kalman filter simulation

In the present work, our aim is to estimate a constant from the noisy measurements. As the signal is invariant for process noise, hence, it is preferred to set a very small value (even zero) for Q (process noise covariance). Also, the state of the original (noise-free) signal does not change from step to step, hence A considered as 1. There is no control input, thus u = 0. Our noisy measurement is of the X_k state directly, H = 1.

In the present case, the noise in the measured signal comprises of noise generated by various processes and measurements. But in this case, since Q = 0, the only source of noise in the model is the measurement noise (v), whose variance is R. Thus, if we estimate the variance of the measured noisy signal, then this variance will be equal to R.

Thus, before implementing the filter, the mean and variance of some input data (say the first 50 samples) are computed.

Then, computer set

$$R = \text{variance}$$

and

$$\hat{x}_0 \text{ (The initial estimate)} = \text{mean}.$$

It also needs to set the initial value of the error covariance, i.e., P_0. P quickly settles to its final "true" value, irrespective of its initial value; therefore, this choice is non-critical; hence, we choose $P_0 = 1$.

Having decided all the parameter values, the final model now becomes

Process:

$$x_k = x_{k-1} + w_k. \tag{6}$$

Measurement:

$$z_k = x_k + v_k. \tag{7}$$

The filter equations become

Time update:

$$\hat{x}_k^- = \hat{x}_{k-1}, \tag{8}$$

$$P_k^- = P_{k-1} + Q. \tag{9}$$

Measurement update:

$$K_k = P_k^-\left(P_k^- + R\right)^{-1}, \tag{10}$$

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - \hat{x}_k^-). \tag{11}$$

III. RESULTS AND DISCUSSION

To evaluate the performance of the developed model based on KF, an ARM 11 BCM2835 Raspberry pi board is used with the clock frequency of 1 GHz. The graphical user interface (GUI) is also designed in Qt on the Linux platform to perform measurement and testing. Herein, GUI provides a facility to acquire data, real time analysis, and storage. The ultimate effectiveness of the implemented KF algorithm was tested by using a uniform echo pattern.

However, several factors affect the measurement of time-of-flight; therefore, the design of sample holder is considered to be the most important and critical. Utmost care has been taken during the development of sample holder in order to minimize the factors that influence the time-of-flight and attenuation measurement. To minimize the time-of-flight measurement errors, we have designed a sample holder with the path length less than the range of near field zone, internal reflection minimized by creating grooves inside the inner cylinder; the transducer and reflector surface should be parallel and the inner wall of cylinder should be noncorrosive, so we have used Stainless Steel (SS) material; a mirror finished SS reflector is used to minimize the surface roughness of reflector. A double walled cylinder is used to maintain constant temperature of samples.

A. Precision estimation of time-of-flight using Kalman filter

During the test, a continuous input signal of 40 μs is applied, and the time interval between two echo pulses is measured with the help of counter. The counter outputs for 2000 samples are plotted, as shown in Fig. 3. The filtering action is evident from the straight line of filtered output over the measured output (Fig. 3). As can be seen from Fig. 3, the filter output disappears for the first 50 samples as this is the time during which the filter parameters are being tuned. After the tuning over the 800 samples, the KF output generates the 41.44 μs signal as represented by the red line in

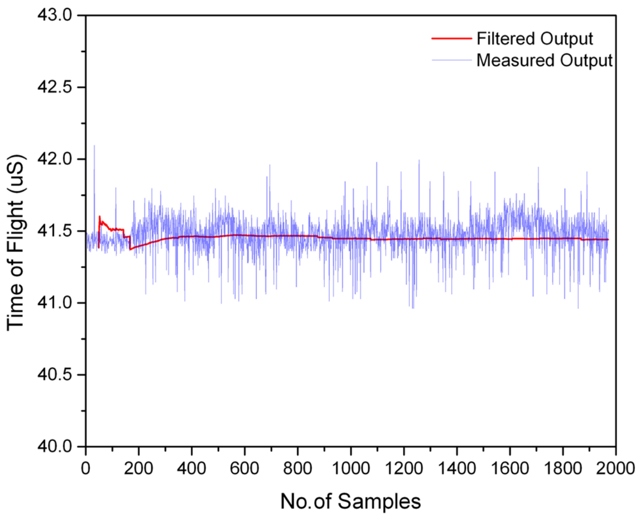

FIG. 3. Comparison of KF approach and counter for the continuous measurement of time-of-flight for 2000 samples.

Fig. 3 and the noisy measurements are represented by blue lines where signal varies between 41 μs and 42 μs due to the error generated by the continuous measurement of counter lower bit fluctuations. The error is in nanoseconds, but it has considerable impact on the velocity measurement. The standard deviation and variance obtained using KF are 0.0202 and 0.000 409, respectively, which are extremely small as compared to counter approach as 0.6869 and 0.4718. The other method for verification of time interval is performed on digital storage oscilloscope (DSO) Tektronics TDS2014, but it has limited window resolution, which limits accuracy in the measurement. In the present case, DSO Tektronics TDS2014 window resolution is 0.2 μs; hence, it fails to perform measurement between 41.30 μs and 41.50 μs.

B. Ultrasonic velocity measurement test

The designed ultrasonic pulse echo technique based instrument with KF is tested for ultrasound velocity of propagation in standard liquids at various temperatures. The sample under investigation is placed in the liquid cell, and a Julabo ME-32 circulating thermostat maintains constant temperature with a minor fluctuation of ±0.1 °C. The observed readings and literature values are tabulated. The results of measurements carried out at 10 MHz in standard liquids for instance, water, methanol, and ethanol are summarized in Table I. Figure 4 shows the variation in ultrasonic velocity of propagation in distilled water, ethanol, and methanol for path length of 63.70 mm. As can be seen in Fig. 4, the measured values and literature values in distilled water are almost identical due to very small error percentage; thus it represents that the developed system is highly accurate and stable over the measured range. The ultrasonic velocity error percentage for samples in liquids (water, methanol, and ethanol) at different temperatures is shown in Fig. 5.

TABLE I. Ultrasonic velocity measurement at different temperatures.

Sample	T[a] (°C)	u_m[b] (m/s)	u_{KF}[c] (m/s)	u_L[d] (m/s) (Refs. 17 and 18)	Error (u_m)[e] (%)	Error (u_{KF})[f] (%)	ToF u_{KF}[g] error (Pico-sec)
Double distilled water	10.0	1446.239	1447.398	1447.270	0.071	0.008	88.43
	15.0	1464.612	1465.716	1465.931	0.089	0.014	146.69
	20.0	1481.097	1482.430	1482.343	0.084	0.007	58.49
	25.0	1495.319	1496.711	1496.687	0.091	0.001	16.04
	30.0	1508.112	1509.121	1509.127	0.067	0.001	3.98
	35.0	1519.024	1519.924	1519.808	0.051	0.007	76.32
	40.0	1527.328	1528.678	1528.530	0.078	0.009	96.82
Ethanol	10.0	1196.894	1195.795	1194.500	0.200	0.108	1082.96
	15.0	1180.121	1179.848	1178.000	0.180	0.156	1566.30
	20.0	1162.783	1161.985	1161.500	0.110	0.041	417.39
	25.0	1146.021	1145.154	1145.000	0.089	0.013	134.38
	30.0	1130.427	1129.239	1128.500	0.170	0.064	654.32
	35.0	1113.725	1112.664	1112.000	0.155	0.059	596.77
	40.0	1096.839	1095.443	1095.500	0.122	0.052	52.03
Methanol	10.0	1154.864	1153.776	1152.500	0.205	0.110	1105.93
	15.0	1138.627	1137.094	1136.000	0.231	0.096	962.10
	20.0	1120.891	1119.902	1119.500	0.124	0.035	358.96
	25.0	1104.341	1103.133	1103.000	0.121	0.012	120.57
	30.0	1087.921	1086.845	1086.500	0.129	0.031	317.43
	35.0	1071.241	1070.808	1070.000	0.115	0.038	754.57
	40.0	1054.975	1053.938	1053.500	0.140	0.041	415.58

[a]T is the temperature of sample under study in degree Celsius.
[b]u_m is the measured ultrasonic velocity of the sample under study in meter per second.
[c]u_{KF} is the measured ultrasonic velocity with KF of the sample under study in meter per second.
[d]u_L is the literature ultrasonic velocity (Refs. 17 and 18) of the sample under study in meter per second.
[e]*Error* (u_m) is the percentage error of measured ultrasonic velocity with respect to the literature value u_L.
[f]*Error* (u_{KF}) is the percentage error of measured ultrasonic velocity with KF with respect to the literature value u_L.
[g]ToF u_{KF} error is the estimated time of flight error of measured KF ToF with respect to the literature value ToF.

Ultrasound velocity of propagation in standard liquids is calculated using equation

$$u = 2d/t, \tag{12}$$

where d is the separation between the transducer and the reflector and t is the time-of-flight. The path length is twice because wave transmits and reflects back.

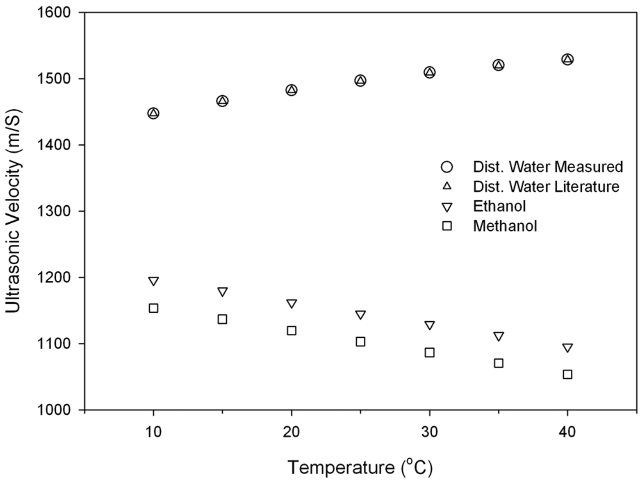

FIG. 4. Variation of ultrasonic velocity in double distilled water, methanol, and ethanol with different temperatures.

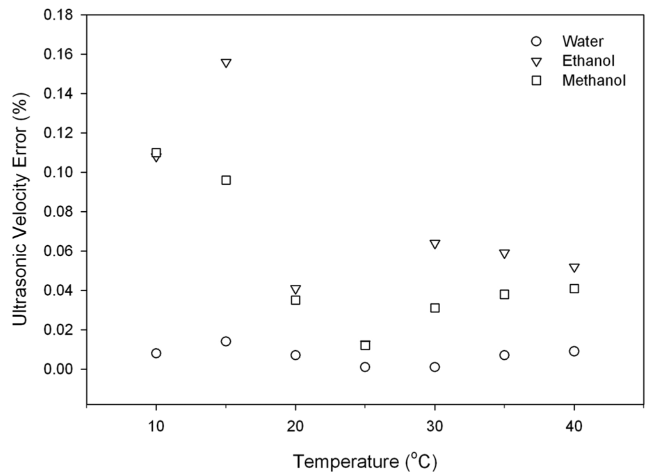

FIG. 5. Variation of ultrasonic velocity error (%) in double distilled water, methanol, and ethanol with different temperatures.

IV. CONCLUSION

The designed pulse echo system with KF has been tested for its functionality in standard liquids. It is observed that the velocity measurement has been greatly enhanced using KF implementation and particularly due to precision in the ToF measurement. It is also observed that with implementation of KF, the system significantly reduces the variations that occur due to other parameters such as noise, sudden temperature change, and transients. Thus, the method could be more effective for measurements at elevated temperatures wherein the ToF measurement is highly affected and fluctuated by external forced cooling of sample.

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