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**Research Article**

# Evaluation of Different Methods on Time of Flight Calculation

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**Abstract**

Instrumentation and measurement have become a very important field in the developing industry. This development reveals requirements such as minimization of measurement errors. Accurate measurement of flow and consumption is a significant process to avoid wrong billing and entanglement for water utilities. This paper presents an ultrasonic Time-of-Flight (TOF) estimation algorithm evaluation for liquid or gas flow rate measurement applications for electronic smart meters. Transducers, as a piezoelectric material, are employed in flow measurement industry, and generate ultrasonic sound waves against pressure. Reciprocal located transducers in a flow medium are triggered to obtain ultrasonic sound waves in both flow direction. Due to the small distance between transducers and speed of sound in flow medium, TOF calculation becomes a challenging process. Equivalent circuit model of a transducer is implemented on MATLAB/Simulink environment numerically, and both upstream and downstream signals, which are the transit waves between transducers and named in order to triggering order, are obtained. Firstly, behavior of an excited transducer is evaluated on simulation environment, and a random signal, which simulates measurement noise, is employed to mimic the real-world conditions. Problem definitions and proposed algorithms given in the literature are investigated, and candidate TOF measurement algorithms are selected. Each method is implemented. Afterward, obtained transit waves are employed with the conventional method to compute TOF at each zero-crossing point. To improve the measurement performance, a cross-correlation based method is proposed for TOF estimation process, and results are compared to conventional method-based measurements. Possible future directions of the study are indicated.

**Keywords:** Ultrasonic time of flight, ultrasonic flow meter, cross-correlation, flow measurement.

# Uçuş Süresi Hesaplamasında Farklı Yöntemlerin Değerlendirilmesi

**Öz**

Enstrümentasyon ve ölçüm gelişen endüstride oldukça önemli bir alan haline gelmiştir. Bu gelişim ölçüm hatalarının eniyilenmesi gibi gereklilikler ortaya çıkartmaktadır. Akış ve tüketimin doğru ölçümü, yanlış faturalandırma ve sular idaresinde meydana gelebilecek karışıklıkları önlemede önemli bir süreçtir. Bu çalışmada, elektronik akıllı sayaçlarda sıvı veya gaz akış hızı ölçüm uygulamaları için ultrasonik uçuş süresi (TOF) hesaplama algoritmalarının değerlendirilmesi sunulmaktadır. Transdüserler, bir piezoelektrik malzeme olarak akış ölçüm endüstrisinde kullanılır ve basınca karşı ultrasonik ses dalgaları üretiler. Bir akış ortamında karşılıklı olarak yerleştirilmiş transdüserler, her iki akış yönünde ultrasonik ses dagaları üretmek amacı ile tetiklenir. Transdüserler arası kısa mesafe ve akış ortamında sesin yüksek hızı nedeniyle, TOF hesaplaması zorlu bir süreç haline gelmektedir. Bir transdüserin eş değer devre modeli MATLAB/Simulink ortamında nümerik olarak uygulanmakta ve transdüserler arası geçiş dalgaları olan ve tetiklenme sırasına göre isimlendirilen yukarı/aşağı akış sinyalleri elde edilmektedir. İlk olarak, tetiklenmiş bir transdüserin davranışı benzetim ortamında incelenir ve gerçek dünya koşullarını taklit etmek için ölçüm gürültüsünü benzeten bir sinyal kullanılır. Literatürde verilen problem tanımları ve önerilen algoritmalar incelenir ve aday TOF ölçüm algoritmaları seçilir. Seçilen her yöntem

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gerçeklenir. Daha sonra elde edilen geçiş dalgaları, her sıfır geçiş noktasında TOF değerini hesaplamak için geleneksel yöntem ile kullanılır. Ölçüm performansı arttırmak için çapraz korelasyon tabanlı bir TOF tahmin süreci metodu önerilir ve sonuçlar geleneksel yöntem tabanlı ölçümler ile karşılaştırılır. Çalışmanın gelecekteki olası yönleri paylaşılmıştır.

**Anahtar Kelimeler:** Ultrasonik uçuş süresi, ultrasonik sayaç, çapraz korelasyon, akış ölçümü.

# 1. Introduction

In flow rate and velocity measurement, ultrasonic flowmeters (UF) are extensively used devices (Çengel and Boles, 2015) due to it's advantages as follows; i) Easy to install (Rajita and Mandal, 2016), ii) No pressure drop (Lynnworth and Liu, 2006), iii) No moving parts (Mousavi et al., 2020), iv) Measuring reverse flows (Chen et al., 2020). UF devices measure the ultrasonic wave flight time, also known as Time-of-Flight (TOF), to compute the flow rate of fluid (Peng et al., 2018). For this process, transducer components are employed. Transducers are piezoelectric materials which provide bipolar transformation between electrical signals and sound-waves (Chen et al., 2021). A flowmeter consists of two transducer (A and B) which are triggered sequentially. Firstly, transducer A is triggered to generate the ultrasonic wave called upstream signal in fluid, and transmit to transducer B. Secondly, transducer B is triggered, after the upstream signal is read, to generate another ultrasonic wave called downstream signal, and transmit to transducer A. TOF difference (TOFD) of upstream and downstream signals may be determined to compute the direction and velocity of flow on an embedded system (Uchiyama et al., 2019).

As for the measurement of TOFD signal, related literature is investigated (Willigen et al., 2021; Sun et al., 2021; Huang and Young, 2009; Angrisani et al., 2006; Gueuning et al., 1996; Demirli and Saniie, 2001; Andria et al., 2001; Barshan, 2000). Willigen et. al. (2021) proposed different excitation signal characteristics to minimize measurement zero-flow error. Sun et. al. (2021) proposed an interpolation based method to increase measurement accuracy of TOF signal. Huang and Young (2009) defined a temperature problem on TOF measurement, and designed a novel self compensated TOF measurement syste. Angrisani et. al. (2006) proposed a discrete Kalman filtering based method on TOF measurement process, and reliability of the system is investigated. Gueuning et. al. (1996) combined the conventional method and phase-shift method, and performed experimental studies to investigate the performance of the proposed system. Demirli and Saniie (2001) proposed a parametric generalized echo model based method to estimate the actual TOF value. Andria et. al. (2001) proposed to use wavelet and short time Fourier transform to determine the enveloped signals, and applied pulse detection algorithms for measurement process. Barshan et. al. (2000) employed threshold, correlation, curve-fitting, and sliding-window based measurement methods, and compared to results considering the different error evaluation metrics.

This paper represents a comparison of different methods on computation of TOF value of the streams. Firstly, a RLC equivalent model of transducer is employed to mimic it's dynamics and behavior as given in Willigen et al (2021). Numerical implementation and analysis of the model is performed on MATLAB/Simulink environment. Nonlinear and complex dynamics of the transducer model are evaluated. According to the evaluations, necessary implementation conditions of the proposed method are determined. Equivalent circuit parameters are changed to generate phase-shift on signals. This phase-shift provides the upstream and Downstream signals. Afterward, these signals are contaminated by a noise signals to mimic the real system conditions. A sample cross-correlation function, threshold method and Nth zero-crossing method are applied to signals to investigate the time domain performances of the proposed methods. TOF measurement results of the three methods are compared, and results are given.

Remaining parts of the paper are organized as follows; i) In Section 2, related equivalent model of the transducers, TOF measurement process and proposed method are explained, ii) Section 3 represents the results of the proposed method based TOF measurement, and it's performance evaluations, iii) A brief summary of the paper, necessary findings of the proposed method, and possible future directions of the study are indicated in the Section 4.

# 2. Material and Method

## 2.1. Transducer Equivalent KLM-model

A simple KLM-model is employed in order to observe complex dynamics of a transducer in simulation environment (Krimholtz and Leedom, 1970) (Figure 1).

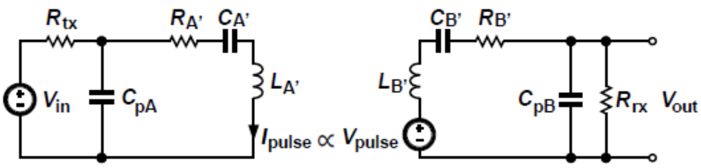


*Figure 1. KLM electrical equivalent circuit of a transducer.*

Transducer equivalent model consists of a transmitting circuit including a resistor $R_{tx}$ and a voltage source $V_{in}$. $R_{rx}$ resistor is employed as the receive circuit impedance. To mimic the cable capacitance and transducer waveform and phase features, $C_p$ is considered for the modelling process. Separated parts of the KLM-model represents the upstream transducer A and downstream transducer B. Proportionality between $I_{pulse}$ and $V_{pulse}$ represents the transition of the ultrasonic wave from one transducer to another. $V_{in}$ signal is employed as the excitation signal of the streaming transducer, and chosen as a single pulse signal. $V_{out}$ signal is considered as the overall output signal of the model which represents the received ultrasonic stream waveform.

## 2.2. Simulation of Equivalent Transducer Model

Numerical analysis of the KLM-model is performed on MATLAB/Simulink environment. Related model component parameters are chosen from Willigen et al. (2021) (Table 1).

*Table 1. Implementation of electrical circuit model parameters.*

| $R$ | $L$ | $C_A$ | $C_p$ | $C_B(U)$ | $C_B(D)$ |
|---|---|---|---|---|---|
| $20\Omega$ | $46\mu H$ | $139pF$ | $0.55nF$ | $139pF$ | $130pF$ |

A phase-shift on upstream signal is obtained by setting the capacitor $C_B$ to be 5% mismatch. Thus, downstream signal is achieved. A zero mean unit variance white noise is added to the stream signals as measurement noise. Amplitude of this noise is assumed to be 10% of the signal amplitudes (Figure 2).

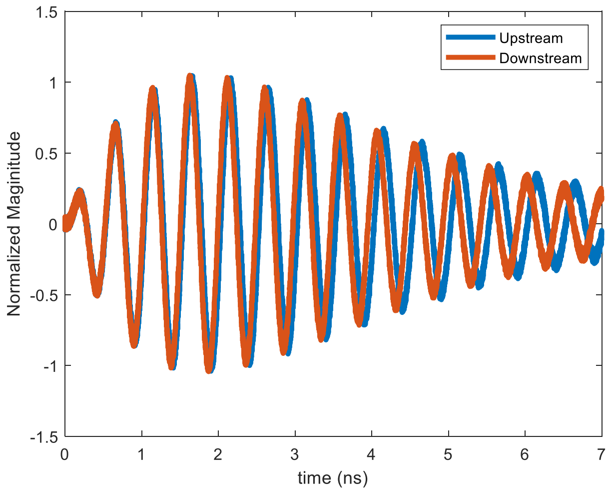


*Figure 2. Contaminated stream signals.*

### 2.3. Time-of-Flight Measurement Methods

$Nth$ zero-crossing (NZC) method is an algorithm which identifies the points where the signals are crossing the time-axis. After each of $N$ zero-crossing points of both upstream and downstream signals are determined, TOFD might be determined from the time difference related to the first zero-crossing point after a predetermined threshold is obtained. In this study, TOFD value is computed for different values of $N$.

Threshold (T) based TOFD measurement is a method which detects the time point where the stream signals are exceeding a predetermined threshold value $\tau$. Time difference of exceeding points may be determined as TOFD value of the corresponding stream signals. In this study, threshold based measurement method is repeated for different choice of $\tau$.

A sample cross-variance function might be defined as:

$$c_{y_1,y_2} = \begin{cases} \frac{1}{T}\sum_{i=1}^{T-k}(y_{1,t}-\overline{y_1})(y_{2,t+k}-\overline{y_2})\ ;\ k=0,1,\ldots \\ \frac{1}{T}\sum_{i=1}^{T+k}(y_{2,t}-\overline{y_2})(y_{1,t-k}-\overline{y_1})\ ;\ k=0,-1,\ldots \end{cases} \quad (1)$$

where $y_1$ and $y_2$ are the time series inputs of the sample cross-correlation function, $\overline{y_1}$ and $\overline{y_2}$ represent the mean of the time series, $c_{y_1,y_2}$ represents the cross-variance function, and $T$ is the number of sample points. Thus, sample cross-correlation function might be expressed as:

$$r_{y_1,y_2}(k) = \frac{c_{y_1,y_2}(k)}{s_{y_1}s_{y_2}} \quad (2)$$

where $s_{y_1}$ and $s_{y_2}$ represents the standard deviations of the time series, and $r_{y_1,y_2}$ is the sample cross-correlation. In this study, upstream and downstream signals are considered as $s_{y_1}$ and $s_{y_2}$, and TOFD measurement is performed by employing the sample cross-correlation function.

## 3. Results and Discussion

$Nth$ Zero-crossing (NZC) and threshold (T) based methods are employed for different settings, and a cross-correlation (CC) based method is considered. Table 2 indicates the results for each measurement.

*Table 2. TOFD measurement results in nanoseconds (ns).*

| $CC$ | $NZC(5\%)$ | $NZC(10\%)$ | $NZC(15\%)$ | $T(5\%)$ | $T(10\%)$ | $T(15\%)$ |
|---|---|---|---|---|---|---|
| 0.0246 | 0.0070 | 0.0070 | 0.0088 | 0.0026 | 0.061 | 0.0097 |

While the predetermined value of threshold is increased, the variation of the measurement is increasing for threshold method. However, the measurement variation is small for NZC based method while the threshold is changed. Besides, CC based measurement provides the largest TOFD value compared to other methods. Execution time of the proposed methods are computed to evaluate the algorithm performances. T method performs the related task faster. Likewise, CC based measurement method gives the most inefficient results in terms of computation time.

## 4. Conclusions and Recommendations

This study represents a numerical implementation of a transducer equivalent electrical circuit model, and TOFD measurement comparison of the methods in literature. Herein, the problem is defined and related previous works given in the literature are indicated. Firstly, the model implementation parameters are determined for the simulation works. Secondly, necessary implementation of the KLM-model is performed on the Simulink simulation environment. To simulate the both upstream and downstream transit waves, model parameters are varied in a small margin. Thus, ultrasonic waves in both flow directions may be obtained. Afterward, measurement methods, which are selected from literature, are employed to determine TOFD for different settings of; i) $Nth$ zero-crossing based method, ii) Thresholding based method, iii) Sample cross-correlation based method. Also, changes in both thresholding and zero-crossing level effects on algorithm performances are investiageted. A normally distributed random signal, which is a mimic of noise signal, is employed to mimic real-world implementation conditions. According to the results, sample cross-correlation based method gives better performance on computing the TOFD value. As the future direction of the study, a machine learning based TOFD estimation algorithm, which considers numerical and statistical features of the transit waves, may be a new area for the researchers.

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