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Reducing ring-down time of pMUTs with phase shift of driving waveform

Xinxin Liu [a], Xuying Chen [a], Xianhao Le [a], Yong Wang [a], Changju Wu [b], Jin Xie [a,*]

[a] The State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou, China
[b] School of Aeronautics and Astronautics, Zhejiang University, Hangzhou, China

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ABSTRACT

This paper proposes a method to reduce ring-down time for piezoelectric micromachined ultrasonic transducers (pMUTs) through phase shift. The proposed driving form can effectively improve the effective emission time to transmitting time (Tx time) ratio and decrease the ring-down time, which contributes to shorten the blind area in pulse-echo ultrasonic distance measurement. The phase shift method effectively restrains the pMUT's ring-down vibration within 20 nm in air and 15 nm in water swiftly. Consequently, the ring-down time can be saved from 45.9~206 μs in air and 78.9~130.1 μs in water respectively. The suppressed ring-down can sharpen the echo envelop for better location applications. Detection of the precise vibration stop time based on time constant of pMUTs is useful for measurement with high accuracy.

1. Introduction

With the rapid development of microelectromechanical systems (MEMS) technology, micromachined ultrasonic transducers (MUTs) based on capacitive (cMUTs) [1] or piezoelectric (pMUTs) [2] have advantages of low power consumption and small size. The ultrasonic time of flight (TOF) method has been widely used in medical imaging techniques, fingerprint sensors, rangefinders and et al [3–6]. There are two basic modes for TOF range finding: continuous wave (CW) mode and pulse-echo (PE) mode [7]. Narrowband CW systems suffer from multipath fading which will cause large range errors [8]. Although frequency modulated continuous wave (FMCW) excitation can overcome the problem, it requires very high dynamic range since the transmitted signal interferes the return signal [9]. Compared with CW, PE excitation needs lower average output power, but the transmitting pulse and return echoes must be separated in time [10]. This avoids the dynamic range and multipath problems existing in the CW systems. Uncertainty due to variations of temperature and humidity can be compensated by adding temperature and humidity sensors to the ultrasonic system [11].

However, when the transducers work in pulse-echo mode, they act as both emitters and receivers at the same scanning process. The Tx time will definitely be added to the TOF results and cause blind zone as shown in Fig. 1. The blind zone is a disabling interval for avoiding couple of emission and reception stage defines the nearest area to transducers. The MUTs have higher quality factors (Q) and better match of acoustic impedance than the traditional transducers, which results in the side effect so that a longer time is needed for vibration stop after excitation. Suppression of ring-down vibration can not only shorten the blind area but also improve the effective emission time to Tx time ratio. In addition, the echo signal can be sharper which is of great importance in echo envelope fitting [12]. Many efforts have been made to shorten the blind area such as adapting emission power and amplifier gain, shunting with loading resistance and optimizing encode [13–18], but none of them can precisely calculate the stop time of vibration, and some of them need complex configuration.

In this paper, a phase shift method is proposed to decrease the blind area and significantly suppress the ring-down. The optimized waveform based on phase shift can effectively shorten blind area and enhance the effective transmission time of the pMUTs. In addition, this method can be applied for most of the ultrasonic transducers.

* Corresponding author.
E-mail address: xiejin@zju.edu.cn (J. Xie).

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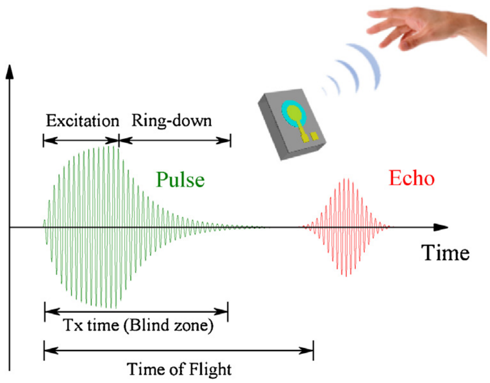

Fig. 1. Illustration of pulse-echo mode and the cause of blind zone.

2. Design and theory

Vibration of a pMUT is described by a one-degree-of-freedom lumped parameter model, as shown in Fig. 2 [19]. According to Newton's second law, the damped simple harmonic motion without environment force F_t and environment damping R_r can be written [20] as

$$M_{eff}\frac{d^2\xi}{dt^2}+R_m\frac{d\xi}{dt}+K_{eff}\xi=0 \tag{1}$$

where R_m is mechanical resistance of the system and ξ is the displacement of the system. The general solution of Eq. (1) is

$$\xi=A_0e^{-\beta_0 t}\cos(\sqrt{\omega_0^2-\beta_0^2}t+\varphi_0) \tag{2}$$

where $2\beta_0=\frac{R_m}{M}$, $\omega_0=\sqrt{\frac{K_{eff}}{M_{eff}}}$.

For an edge-clamped circular plate in vertical vibration, the air squeeze film damping is dominant. The damping force on the circular plate can be expressed as [21]

$$F_{air}=\int_0^a p(r)2\pi r dr=-\frac{-3\mu A^2}{2\pi h^3}\dot{\xi} \tag{3}$$

where p is the pressure in the film, $A=\pi r^2$ is the area of the plate, μ the coefficient of viscosity of the ambient fluid, h is the thickness of the film. The driving force on the circular plate is

$$M_{eff}\frac{d^2\xi}{dt^2}+(R_m+R_r)\frac{d\xi}{dt}+K_{eff}\xi=F_0\cos(\omega_e t+\varphi) \tag{4}$$

Assuming $2\beta_e=\frac{R_m+R_r}{M}$, Eq. (4) is rewritten as

$$\frac{d^2\xi}{dt^2}+2\beta_e\frac{d\xi}{dt}+\omega_0\xi=\frac{F_0\cos(\omega_e t+\varphi_e)}{M_{eff}} \tag{5}$$

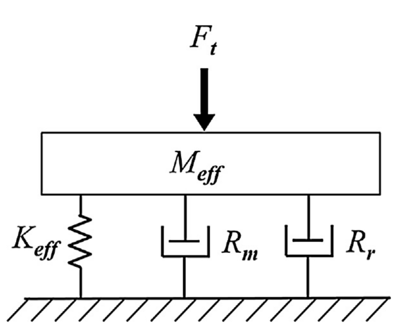

Fig. 2. Equivalent mass–spring–damper model of the pMUT.

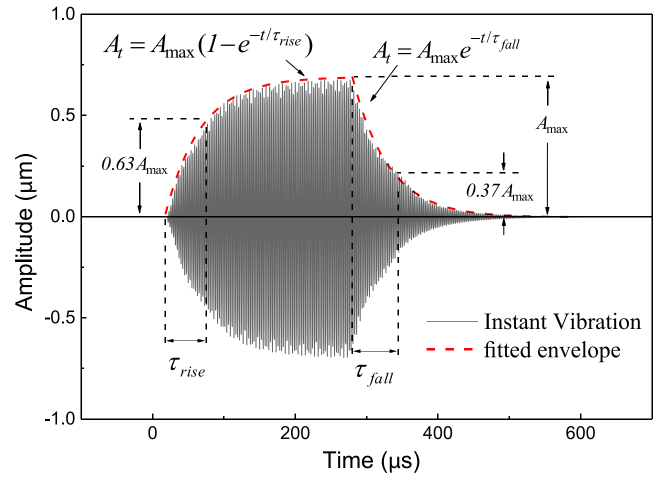

Fig. 3. Instant displacement measurement, red dash curve is fitted envelope, the vibration equations of rise and fall period are given in the chart.

The general solution of Eq. (4) is

$$\xi=A_0e^{-\beta_e t}\cos(\sqrt{\omega_0^2-\beta_e^2}t+\varphi_0)+A_F\cos(\omega_e t+\varphi_e) \tag{6}$$

where A_0 is initial position of pMUT and

$$A_F=\frac{F_0}{M_{eff}\sqrt{(\omega_0^2-\omega_e^2)^2+4\beta_e^2\omega_e^2}}$$

$$\tan\varphi_0=\frac{2\beta_e\omega_e}{\omega_0^2-\omega_e^2}$$

When the pMUT is under the force at the resonant frequency, we have

$$\omega_r=\omega_e=\sqrt{\omega_0^2-\beta_e^2}$$

Therefore, the vibration amplitude A_r at resonance is

$$A_r=\frac{F_0}{2\beta_e M_{eff}\sqrt{\omega_0^2-\beta_e^2}} \tag{7}$$

While the phase of applied force shifts half of the period after the original vibration, the resonant phase φ_r and displacement ξ_r is

$$\begin{aligned}\varphi_r&=\varphi_0=\varphi_e+\frac{\pi}{2}\\ \xi_r&=A_0e^{-\beta_e t}\cos(\omega_r t+\varphi_r)-A_r\cos(\omega_r t+\varphi_r)\end{aligned} \tag{8}$$

The instant response of the pMUT after excitation is shown in Equation (8), where A_{max} is the maximum vibration amplitude [22]. The squeeze film can be derived and this loss factor differs little with driving wave form as shown in Fig. 8. However, the mechanical resistance should be measured to get the accurate value due to the thermal damping and material damping. It is easy to derive damping factor β from fitted envelop of the measured data. The excitation envelope conforms to a logarithmic rise with time constant τ_{rise} and the ring-down envelope conforms to an exponential fall with time constant τ_{fall}. The difference between τ_{rise} and τ_{fall} is because of the induced change of mechanical damping by the external electric field.

$$\begin{cases}A_t=A_{\max}(1-e^{-t/\tau_{rise}}) & \text{Excitation}\\ A_t=A_{\max}e^{-t/\tau_{fall}} & \text{Ring-down}\end{cases} \tag{9}$$

As shown in Fig. 3, 50 cycles of 10 V pulses are applied as excitation. The vibration amplitude rises to 63% of A_{max} within the time