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Andrew Feeney, Lei Kang, George Rowlands, and Steve Dixon

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Dynamic characteristics of flexural ultrasonic transducers

Andrew Feeney

Centre for Industrial Ultrasonics, Department of Physics, University of Warwick, Coventry, West Midlands, CV4 7AL, UNITED KINGDOM; a.feeney@warwick.ac.uk

Lei Kang, George Rowlands and Steve Dixon

Department of Physics, University of Warwick, Coventry, West Midlands, CV4 7AL, UNITED KINGDOM; l.kang.1@warwick.ac.uk; g.rowlands@warwick.ac.uk; s.m.dixon@warwick.ac.uk

The flexural ultrasonic transducer is a robust and inexpensive device which can be used as either a transmitter or receiver of ultrasound, commonly used as proximity sensors or in industrial metrology systems. Their simple construction comprises a piezoelectric disc bonded to a metal cap, which is a membrane that can be considered as a constrained plate. Flexural transducers tend to be driven with a short voltage burst of several cycles at a nominal resonant frequency, in one of two vibration modes. The physics of their vibration response has not been thoroughly reported, and yet an understanding of their operation is essential to optimise application. The vibration behaviour of a flexural transducer can be discretised into three principal zones, comprising a build-up to steady-state, steady-state, and a natural decay, or ring-down. This discretisation can be used to develop mathematical interpretations of the flexural transducer response. Through a combination of experimental methods including laser Doppler vibrometry, and the development of a mechanical analog model, the response mechanisms of flexural transducers are investigated.

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1. INTRODUCTION

The flexural ultrasonic transducer (FUT) is a sensor used primarily for proximity measurements and industrial metrology systems. There are air-coupled ultrasound sensors available, some of which are configured as arrays[1,2]. The FUT is composed of a driver, generally a piezoelectric ceramic disc, attached to a metallic cap membrane. A typical FUT is shown in Figure 1(a), fabricated from aluminium. Driver excitation generates a bending of the metal membrane, which produces the desired ultrasound signal. The FUT can be employed as both a projector or a receiver of ultrasound, and its resonant frequencies are strongly dependent on the cap membrane material and the physical dimensions, principally the cap membrane diameter and thickness. The most common cap membrane materials include aluminium, stainless steel, and titanium, based on their relative robustness in operation, and their elastic properties which enable ultrasound signals to be generated between 20 and 100 kHz.

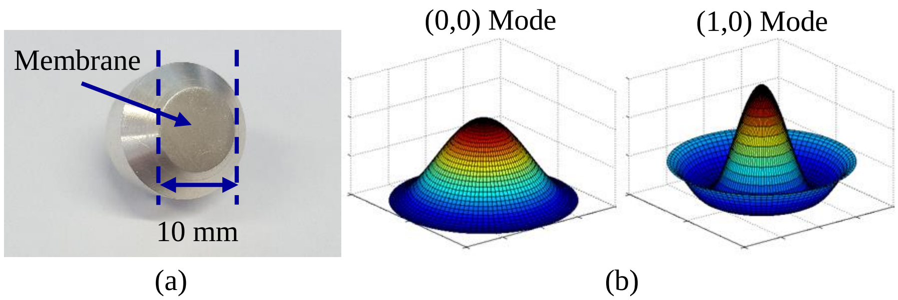

Figure 1: (a) A flexural ultrasonic transducer, and (b) the (0,0) and (1,0) axisymmetric vibration modes.

The dynamic characteristics of the FUT have only recently been subject to detailed investigation. The cap membrane of the FUT is designed to vibrate in the axisymmetric modes of vibration, examples of which are displayed in Figure 1(b), adapted from MATLAB simulation[3]. The axisymmetric modes of vibration are the fundamental modes of a flexural transducer. The (0,0) and (1,0) modes are shown in Figure 1(b), where the (m,n) nomenclature refers to the nodal radius and diameter respectively[4]. There are hence higher-order modes of vibration which can be utilised, such as the (2,0) mode. In practical use, the FUT is subjected to a signal at a specific voltage and drive frequency, usually as a burst sinusoid. This signal generates the mode of vibration at the resonant frequency defined during the design stage. An amplitude-time response spectrum is generated with three distinct zones[5], depending on the temporal length of the excitation signal. An example of this spectrum is shown in Figure 2.

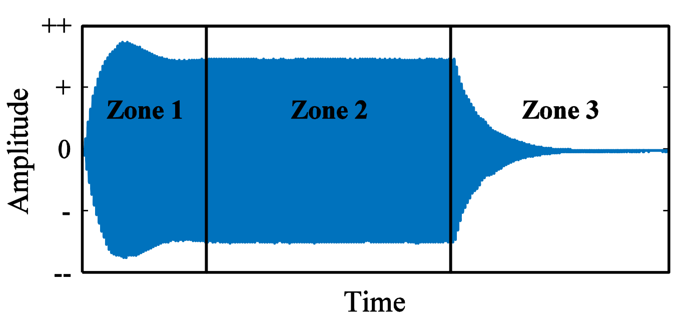

Figure 2: The discretised zones of FUT vibration response, showing a progression to steady-state followed by resonant ring-down, divided into three regions.

The first zone exhibits the progression of the amplitude of the ultrasound signal towards steady-state, as a function of time, the second zone is steady-state, and the third zone is a natural or resonant decay of the FUT vibration after the input signal has been switched off. Excitation signals which are temporally too short can produce amplitude-time spectra dominated by the first and third zones, since steady-state is not reached. Thus far, there has been little treatment of the physics of the first zone in the literature. In Figure 2, the over-shoot of the vibration amplitude in the first zone has been provided to demonstrate the response of the FUT when operated off-resonance.

This study reports on the latest developments in the vibration analysis of the FUT, demonstrating improved understanding of its dynamic characteristics. The dynamic response of a commercial-type FUT (Multicomp) is investigated in this research, in air at ambient conditions, using laser Doppler vibrometry (LDV), supported by a mathematical model. This research is essential for the development of FUTs which can operate at higher frequencies, greater than 100 kHz, and in hostile environments of high pressure and temperature. It is anticipated that these high frequency FUTs, or HiFFUTs, will be employed in a wide range of industrial applications, such as gas flow metering, and in flexural-type arrays in development[6].

2. VIBRATION AMPLITUDE MEASUREMENTS

The measurement and analysis of the FUT vibration dynamics was undertaken using LDV. Each commercial FUT possesses a nominal fundamental (0,0) mode resonant frequency of 39.5 ± 1.5 kHz. The vibration response of the FUT for different drive frequencies was measured using laser Doppler vibrometry (LDV, Polytec OFV-5000). Drive conditions are important to define properly. A signal with too short a temporal length may not generate the desired steady-state. An example of this is demonstrated in Figure 3, where a burst sinusoid input signal with a drive frequency of 40 kHz, input voltage of 10 $V_{P\text{-}P}$, and 10 cycles has been applied to a FUT. The vibration response of the FUT in this case was measured through LDV.

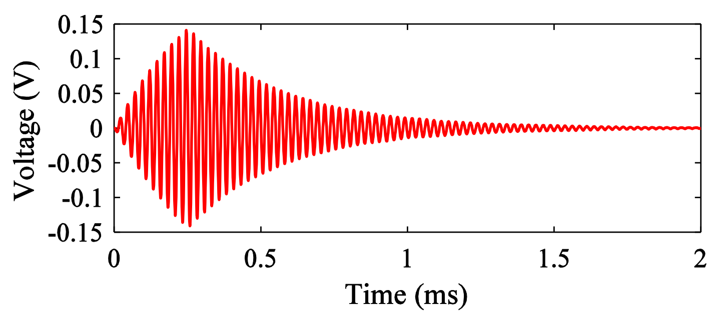

Figure 3: FUT Amplitude-time spectrum from LDV, with a 10 cycle burst at a drive frequency of 40 kHz.

The FUT amplitude response shown in Figure 3 has not had sufficient time to rise towards the steady-state amplitude it would exhibit with a temporally longer signal. After the burst signal is applied to the FUT, its vibration response decays at the natural frequency of the transducer after approximately 0.25 ms. The exponential decay occurs almost instantaneously after the drive signal is stopped. It is also not possible to appropriately identify the over-shoot of the vibration amplitude in the first zone for temporally-short input signals, and so proximity to resonance cannot be assessed. Through consideration of the effects of the drive signal parameters on the amplitude-time response, an optimal drive condition can be defined.

The application of a temporally-longer drive signal with an increased number of signal cycles will generate a response spectrum where the three discretised response zones can be identified. Further LDV was undertaken on a FUT at two different drive frequencies, one at 40.5 kHz, off-resonance, and the other close to resonance, at 39.9 kHz, for an excitation of 150 cycles and input voltage of 20 $V_{P\text{-}P}$. The results in Figure 4 show the generation of the three discretised vibration response zones for a FUT, obtained by the application of an input signal to the device with a longer temporal length, with a greater number of signal cycles than were used to produce the amplitude-time spectrum shown in Figure 3. The over-shoot phenomenon is also clearly identifiable, where the vibration amplitude exceeds the steady-state amplitude in the first zone, before the second zone is generated. This does not occur when the FUT is operating at resonance, and is a characteristic indicator of the difference between the drive and resonant frequencies. Another indicator of proximity to resonance is the relative amplitude of the vibration signal, where the steady-state vibration amplitude in Figure 4(a) is greater than that exhibited in Figure 4(b).

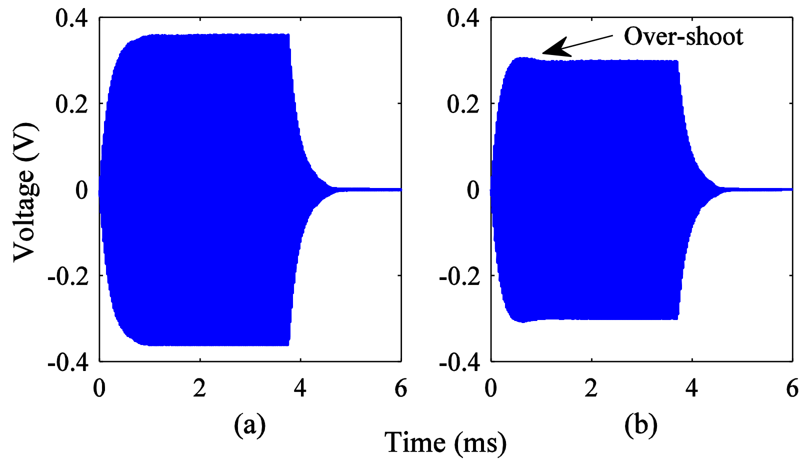

Figure 4: FUT amplitude-time spectra from LDV for drive frequencies of (a) 39.9 kHz, and (b) 40.5 kHz.

3. THE MATHEMATICAL MODEL

The experimental results presented in this study can be used to assist in the development of a mathematical model of the FUT vibration response. The FUT can be modelled as a one-dimensional underdamped spring-damper system vibrating under the influence of a sinusoidal time-dependent forcing function, where the spring-damper is configured in parallel. The equation of motion can be derived for this configuration, the solution for which will permit the simulation of the amplitude-time spectra for a range of drive frequencies. This derivation is confined to the dynamics of the first zone only, since the relationships describing steady-state and resonant decay are familiar. Based on the characteristic amplitude-time response of a FUT, as shown in Figure 2, the first zone can be considered as a switch from a zero vibration amplitude condition, to an operating amplitude condition, which is designated as the second region, steady-state. A switch in conditions can be modelled through a step function, and so the forcing function which is applied to the FUT is a convolution of the forcing and step functions. The equation of motion can therefore be expressed by Eq. (1) for the FUT.

$$M\ddot{x} + C\dot{x} + Kx = Fsin(\omega t).S(t_0 - t) \tag{1}$$

In Eq. (1), the effective mass, damping and stiffness terms are analogous to properties which describe the physical parameters of the FUT. The excitation amplitude, F, the angular forcing function frequency, ω, and the step function, S, are time-dependent, where t_0 is the time at which the forcing function stops. The solution to Eq. (1) is shown in Eq. (2) for $t < t_0$, with initial boundary conditions of displacement and velocity equal to zero at $t = 0$, and $S = 1$ for a vibration amplitude at a time between 0 and t_0. The derived response is a combination of the natural resonance of the FUT and the forced harmonic vibration caused by the sinusoidal forcing function, convolved with the step function.

$$x = N\,(e^{-at}cos\bar{a}t) + R(\sin(\omega t + \theta)) \tag{2}$$

The forced harmonic part of the vibration response can now be represented by a single amplitude, R. The ability of the model to accurately simulate FUT dynamic behaviour can be demonstrated, by comparing with experimental data. To illustrate, the amplitude-time response of a FUT operating with an arbitrary drive frequency of 40.5 kHz, measured using LDV and presented in Figure 4(b), was compared with a spectrum generated using (6). The results are shown in Figure 5.

The results demonstrate a very close correlation between experiment and simulation, where there is an effective overlap of the data, and specifically the signal phases and amplitudes exhibit a high level of similarity. The model has been shown to represent the dynamics of the first zone in the vibration response of a FUT with precision, including the over-shoot, and has the potential to be utilised in the design process for a range of devices based on the flexural transducer configuration. Together with the expressions which can be used to describe steady-state harmonic vibration and exponential decay, which are the second and third zones respectively, a complete set of mathematical relationships is available which can be used to accurately describe and analyse the dynamics of FUT vibration response.

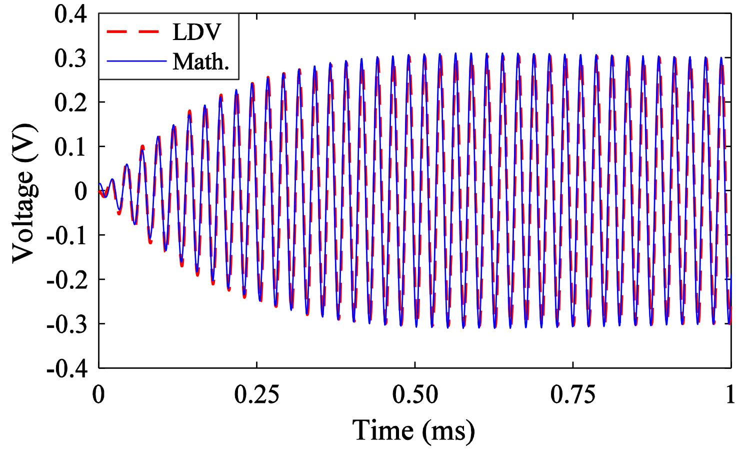

Figure 5: FUT amplitude-time spectra at 40.5 kHz in the first zone, from LDV and the mathematical model.

4. CONCLUSION

The analysis of the dynamic characteristics of the FUT has been reported in this research. Three zones in the characteristic vibration response of FUTs have been identified, and experimental vibration analysis has been applied through LDV, demonstrating the measurement of these response zones. The experimental analysis of the dynamic behavior of FUTs has been used to assist in the development of a mathematical model which can be used to accurately simulate their dynamic response. The outcomes of this research will be employed for industrial non-destructive evaluation systems.

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