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Active damping of ultrasonic receiving sensors through engineered pressure waves

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Letter

Active damping of ultrasonic receiving sensors through engineered pressure waves

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Abstract
Transducers for ultrasonic sensing and measurement are often operated with a short burst signal, for example a few cycles at a specific excitation voltage and frequency on the generating transducer. The vibration response of a narrowband transducer in detection is usually dominated by resonant ringing, severely affecting its ability to detect two or more signals arriving at the receiver at similar times. Prior researchers have focused on strategies to damp the ringing of a transducer in transmission, to create a temporally short output pressure wave. However, if the receiving transducer is narrowband, the incident pressure waves can create significant ringing of this receiving transducer, irrespective of how temporally short the incident pressure waves are on the receiving transducer. This can reduce the accuracy of common measurement processes, as signals are temporally long and multiple wave arrivals can be difficult to distinguish from each other. In this research, a method of damping transducers in reception is demonstrated using a flexural ultrasonic transducer (FUT). This narrowband transducer can operate effectively as a transmitter or receiver of ultrasound, and due to its use in automotive applications, is the most common ultrasonic transducer in existence. An existing mathematical analog for the transducers is used to guide the design of an engineered pressure wave to actively damp the receiving FUT. Experimental measurements on transducers show that ultrasonic receiver resonant ringing can be reduced by 80%, without significantly compromising sensitivity and only by using a suitable driving voltage waveform on the generating transducer.

Keywords: active damping, flexural ultrasonic transducers, mathematical analog, narrowband, ultrasound measurement

(Some figures may appear in colour only in the online journal)

All ultrasonic transducers have a bandwidth, where the transition between narrowband and wideband sensitivity is somewhat arbitrary. Narrowband transducers tend to be operated close to a resonance, via the through thickness or radial resonant modes of constituent piezoelectric elements, or through the excitation of resonant modes of a flexing plate or membrane [1–4]. In many applications, a narrowband

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transducer is excited with a relatively small number of cycles at a designated input voltage. Vibrational response is dominated by a resonant ringing phenomenon, where the component generating the ultrasonic waves, such as the flexing plate, vibrates at its natural frequency after the excitation signal has stopped. This ringing can cause significant temporally-extended waveforms in both the transmission and reception of ultrasonic pulses [5–7]. In general, this ringing can lead to a relatively long transducer response time in reception and is problematic both for situations when separate generation and detection transducers are used, and when a single transducer is used as a transceiver, where the duration of the received signal can extend into the arrival time of the next signal. It is important to reduce the ringing of a narrowband transducer, for example to improve time-of-flight measurement accuracy or enable operation of narrowband transducers in closer proximity without the risk of severe interference between temporally adjacent signals. Here, an active damping approach to limit the ringing of a receiver ultrasonic transducer is demonstrated by engineering the temporal profile of the incident ultrasonic wave on the transducer.

Damping the response of a transducer during the ultrasonic generation stage has been widely investigated, for example by exciting the transducer with an initial pulse mirrored by a second pulse in anti-phase with the first. This secondary anti-phase pulse drives in opposition to the ringing response, thereby shortening the transducer's response time. There is an inherent delay between the application of the drive signal and the time at which the vibration response of the transmitting transducer reaches a maximum amplitude, attributable to the inertia of the transducer's vibrating components. By modulating the amplitude and duration of the damping pulse to account for this change in signal amplitude over time, a greater reduction of the transmitter's response time can be achieved in comparison to the technique of implementing a pulse phase-shifted by 180° [8, 9]. This is an example of an active damping strategy. Alternative methods include using tuned shunting circuits with load impedances [10, 11], and hybrid active-passive switching circuits [12], although these are generally difficult to apply in practice. However, there is a distinct limitation in exclusively damping a transmitter transducer. The pressure waves may be temporally short, but if incident on a narrowband receiving transducer, can cause this receiver to resonate for a significant period of time, making it difficult to separate signals that have similar arrival times. This is true for transmitting and receiving transducers possessing similar dynamic characteristics such as resonance frequency, preferential for maximising the signal-to-noise ratio in the response of the receiver transducer. It is desirable to be able to reduce the ringing of the receiver, since many applications require either a set of transducers in pitch-catch configuration or a single transducer operating as both a transmitter and a receiver interchangeably.

The basis of active damping in reception is to use an engineered pressure wave to activate the receiving transducer and subsequently damp its vibration response to produce temporally shortened signals. The method presented here shows how resolution can be improved by temporally shortening the received signal rather than increasing the signal-to-noise ratio, demonstrating this exclusively in the time domain, with no requirement for computing fast Fourier transforms, and is distinct from pulse shaping which involves additional signal processing. The concept of shortening the response time of a narrowband acoustic or ultrasonic transducer by engineering a sound wave is a novel method suitable for conducting time-of-flight measurements with increased time resolution, vital for applications including nondestructive testing, flow metering and the medical sector.

Active damping in reception is demonstrated here by using the narrowband flexural ultrasonic transducer (FUT), which exploits the bending modes of a metallic plate to generate and detect ultrasound in fluid-coupled applications without the need for acoustic impedance matching [13, 14]. A piezo-electric element is adhesively bonded to the underside of a vibrating plate, secured inside a metallic housing, typically sealed at the rear with silicone. The FUT's dynamic performance has been previously reported [15, 16], where the vibration behaviour of the system is dominated by the properties of the plate, considered as edge-clamped [1, 17]. Active damping in reception will also enable the FUT to be exploited in a wider range of applications, through improved measurement sensitivity. Despite the focus on the FUT, this technique is compatible with narrowband transducers exhibiting the ringing phenomenon.

In addition to modelling the FUT behaviour and resonant frequency by finite element analysis [1], it can also be predicted using a classical mechanical analog consisting of effective parameters of mass M attached to a dashpot in parallel with a spring, with damping factor C and stiffness K respectively [5, 15]. The system is represented by equation (1), where $f(t)$ is a driving function that could be provided by a voltage source when acting as a generator, or an incident pressure wave when acting as a detector.

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t). \qquad (1)$$

The underlying physics of the FUT are complex and can only be properly modelled by finite element analysis. In measurement applications one often requires an ultrasonic pulse with a short time duration, so the key aim is to reduce the temporal duration of the signal on the receiver. Conventional methods for damping the response of either an ultrasonic transmitter or receiver usually employ the use of passive mechanical damping within the transducer or passive electrical damping within or outside the transducer, and rely on the consistency of backing layers bonded to the piezoelectric, or consistent component characteristics used in electrical damping circuits. The method described here is a different way of achieving damping on the receive sensor, which may be preferable as it puts fewer requirements on consistent assembly and performance of assembled transducers, a familiar challenge for transducer manufacturers.

Previous work on FUT established the validity of using solutions to the simple mechanical analog model [5, 15], that can also be found in other sources. One can write the following relations in equation (2) for the FUT's resonant frequency
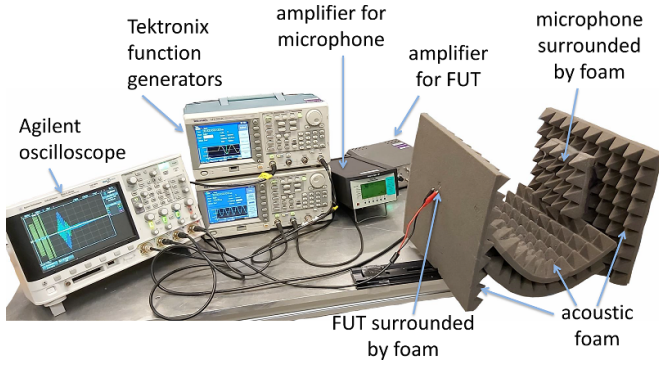
Figure 1. Photograph of the set-up for monitoring the T_X response.

ω_0, and a negative decay constant for the vibrating plate of the FUT α.

$$\alpha = -\frac{C}{2M} \text{ and } \omega_0 = \sqrt{\frac{K}{M} - \alpha^2}. \tag{2}$$

The vibration response of an FUT in reception, $y(t)$, can be modelled using the transmitting FUT's response. The vibration of the transmitter's plate has been shown to directly relate to the far-field pressure it generates [15], with the pressure wave incident on the receiver modelled by $x(t)$ with appropriate amplitude and time scaling. A time delay t_s and amplitude modulation by a constant factor Δ have been imposed to account for the separation between transmitting and receiving FUTs and attenuation in the propagation medium. Here, M_R, C_R and K_R are the effective inertial, damping and stiffness parameters which can be used to characterise the vibration response of the receiver.

$$M_R \ddot{y}(t) + C_R \dot{y}(t) + K_R y(t) = \Delta x(t - t_s). \tag{3}$$

It is known that a transmitting FUT (T_X) can be excited and then damped by a sequence of two electrical pulses, where the secondary pulse acts to drive in opposition to the ringing of T_X. This research makes a significant step forward to enable the damping of a FUT in reception (R_X) via a sequence of two distinct pulses of ultrasonic air pressure, the second pulse acting in opposition to the ringing response of R_X. In this way, the full two-pulse waveform produced by T_X may have a similar or longer duration in time than the received electrical response of R_X. Due to inevitable physical variations between FUTs, and the difference in transmission and reception performance, T_X and R_X are characterised with different M, C and K parameter groups, resulting in differences in the build-up and ringdown responses of T_X and R_X. Hence, the second pulse in the ultrasonic sequence is timed to be in anti-phase with the R_X response. The experimental set-up in figure 1 shows how active damping in reception was monitored.

The T_X (Multicomp MCUSR18A40B12RS) was driven with a voltage using independent function generator channels and measured with an oscilloscope. T_X was operated in pitch-catch with a similar receiver, R_X, collinearly aligned and 220 mm apart. A calibrated microphone (Brüel & Kjær 4138A-015) measured the far-field pressure wave incident on
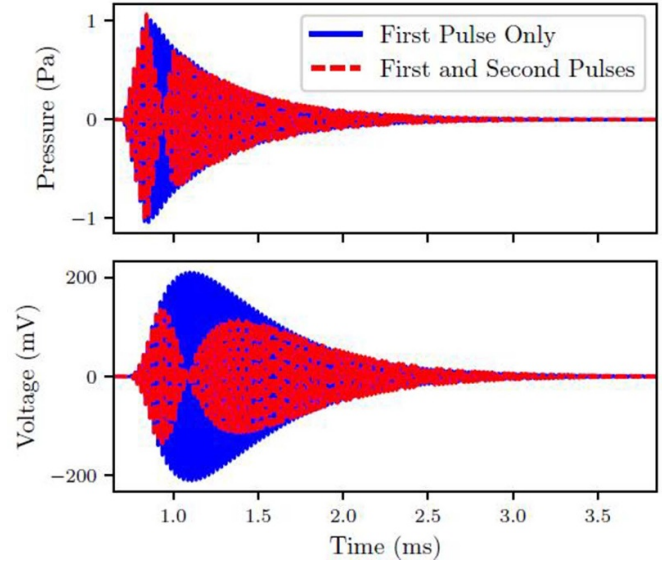

Figure 2. Far-field pressure response of T_X (top) and the amplified response of R_X (bottom) to the first two pulses of a three-pulse sequence to actively damp R_X.

R_X. Prior to active damping, T_X's resonance frequency was verified by measuring the ringdown frequency [5, 15], confirmed to be 40.0896 ± 0.0002 kHz.

An electrical pulse sequence comprising three sinusoidal tone-bursts was used to drive T_X to create a pressure waveform to actively damp R_X. This is illustrated in figure 2, where the first pulse excites T_X to produce a pressure wave that elicits a vibration response in R_X. Equation (3) is used to guide the design of a suitable sequence, which can be refined further through amplitude modifications via the experimental set-up.

The start of a second electrical pulse is timed after the first, such that the pressure wave oscillates in anti-phase with the response of R_X. The second pulse has a higher voltage amplitude and time duration than the first, to reduce the ringing of R_X towards zero in the shortest possible time. The overshoot in R_X's vibration response is then mitigated with a third pulse, designed to actively damp the remaining ringing of T_X where R_X's response is zero. It should be noted that alternative electrical pulse sequences could be applied to achieve a similar effect.

The method for actively damping R_X is achieved via the excitation of T_X with sinusoidal tone-burst pulses at the resonance frequency of T_X. An initial five cycle, 8.70 ± 0.01 V_{P-P} electrical pulse followed by a six cycle, 10.00 ± 0.01 V_{P-P} pulse with an onset time 136.57 ± 0.01 μs after the onset of the first, is used to produce an ultrasonic pressure wave that reduces the ringing of R_X to zero in the shortest time. This causes an overshoot as shown in figure 2, which is removed by a three cycle, 7.30 ± 0.01 V_{P-P} electrical pulse with an onset time 297.89 ± 0.01 μs after the first. The application of the third pulse creates a double-peaked ultrasonic waveform, with the first packet exciting a response in R_X, and the second timed to actively damp its ringing.

The total system response is shown in figure 3, with comparison to active damping methods outlined in prior research
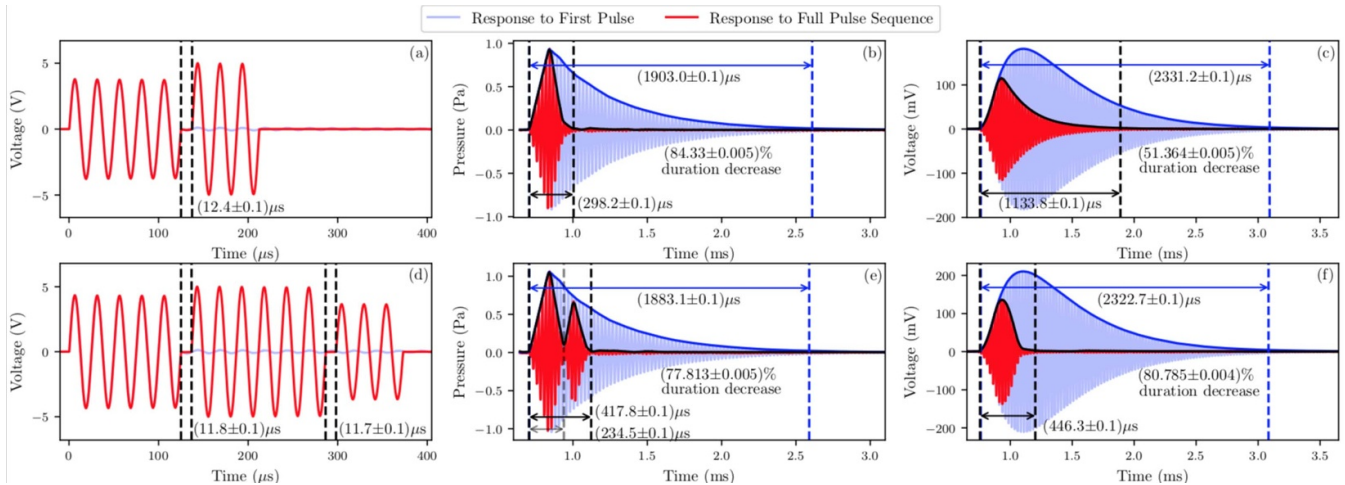
Figure 3. Comparison between active damping methods to reduce the response duration of (a)–(c) T_X, and (d)–(f) R_X, showing (a), (d) the electrical pulse sequence to drive T_X; (b), (e) the far-field ultrasonic pressure produced by T_X; (c), (f) the voltage output of R_X.

focusing on minimising the T_X response duration alone. Duration is defined here as the time separation between points where the envelope of the waveform crosses a threshold of 2% of its maximum value. For this comparison, T_X is driven by a five cycle, 7.60 ± 0.01 V_{P-P} sinusoidal tone-burst at its resonant frequency, followed by a three cycle, 10.00 ± 0.01 V_{P-P} sinusoidal tone-burst at T_X's resonance. The onset of the secondary damping electrical pulse is 137.19 ± 0.01 μs after the first, timed such that it drives in anti-phase with T_X's ringing response. It is evident that actively damping R_X decreases its response to a larger extent than methods focused solely on minimising T_X's response duration, with the three-pulse sequence resulting in an improvement of $29.421 \pm 0.006\%$ here. Through minimising R_X's duration, its maximum voltage output has been reduced, and a system whereby a trade-off between resolution in time and amplitude is required has been produced. However, this amplitude reduction can be expediently compensated for by electronics.

In general, a time-domain active damping solution has been presented applicable to any narrowband transducer, with no requirement for Fourier or inverse Fourier transforms. Although electrical methods also have a role in damping transducers, such as utilising FUTs with transformers, this fundamental study demonstrates active damping using three channels of a function generator, each having an output impedance of 50 Ω. More sophisticated methods of pulse sequence design are possible, including via numerical modelling for experimentally-measured M, C, and K fitting parameters. A complete mathematical model describing the response of a two-transducer system would also be valuable in the creation of a damping sequence that minimizes the duration of the receiver response. These methods will be addressed in future research.

Using FUTs, we have shown that the response time of a system of narrowband transmitting and receiving transducers can be significantly improved by using an electrical pulse sequence to generate a series of pressure wave pulses that actively damp the ringing of the receiving transducer. A carefully engineered

stimulus provided external to the narrowband receiving transducer has been used to damp it, whose membrane would otherwise continue to ring at resonance for a longer period of time after the arrival of an incident pressure wave on its active surface. In this case, that external stimulus is a modified incident pressure wave, and we have described this process as actively damping the transducer.

A three-pulse electrical sequence has produced a significant decrease in the response time of R_X compared to decreasing the duration of T_X alone. Furthermore, we presented a mathematical analog representative of the narrowband transducer system. This technique is beneficial for improving the accuracy and resolution for an ultrasonic measurement, and has significant potential for metrology, flow measurement, non-destructive testing and medical ultrasound applications. Also, even if there were distortion or dispersion features in the propagation path, there will be synchronous changes to the waveforms, meaning that the active damping in reception can still be achieved. Whilst a three-pulse electrical sequence has been used here, longer sequences could be used, or indeed more cycles could be used on the driving signal. There are in fact an infinite number of ways that this damping could be achieved through engineering the incident pressure wave, and here we have demonstrated just one approach. When determining which parameters should be used in designing a damping pulse sequence for a narrowband transducer, one needs to consider the required temporal pulse length and amplitude on the received signal. It will almost always be a compromise as it is with any other method of damping a sensor response, trading off sensitivity for bandwidth.

This method is proposed as an alternative for damping receive sensor responses that may be beneficial to use in some situations, including passive mechanical or electrical damping, and signal processing where transducer responses and the generated pressure wave are known. We are not suggesting that the technique proposed here is suitable for all transducers or measurements, and neither are we suggesting that it is suitable for situations where generation and detection transducers have

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different resonant frequencies, but one potential advantage of this approach is that it avoids the need to use passive damping, for example via sound energy absorbing backing layers which can be difficult to manufacture consistently. It is beneficial to reduce the complexity of transducer construction in terms of manufacturing cost and time, with greater performance consistency possible by reproducing the electrical driving sequence shown here. This is an entirely new philosophy for acoustic and ultrasonic sensing, for lightly damped ultrasonic or acoustic transducers of any frequency, with a broad scope across applied physics, metrology, medical, and nondestructive fields.

Acknowledgments

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