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Physics Procedia 63 (2015) 42 – 46

Physics
Procedia

43rd Annual Symposium of the Ultrasonic Industry Association, UIA Symposium 2014

Minimizing the excitation of parasitic modes of vibration in slender power ultrasonic devices

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Abstract

The design of slender power ultrasonic devices can often be challenging due to the excitation of parasitic modes of vibration during operation. The excitation of these modes is known to manifest from behaviors such as modal coupling which if not controlled or designed out of the system can, under operational conditions, lead to poor device performance and device failure. However, a report published by the authors has indicted that the excitation of these modes of vibration could be minimized through device design, specifically careful location of the piezoceramic stack. This paper illustrates that it is possible, through piezoceramic stack position, to minimize modal coupling between a parasitic mode and the tuned longitudinal mode of vibration for slender ultrasonic devices.

Keywords: Modal coupling; Langevin transducer; experimental modal analysis, harmonic analysis

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1. Main Text

It has been widely documented that ultrasonic devices can exhibit vibrational responses that lie outwith their linear vibrational regime. These nonlinear behaviors can be induced in the ultrasonic device through modal coupling or by the excitation of autoparametric or Duffing-like responses (Cardoni et al. 2004, Mathieson et al. 2013, Aurelle et al. 1996). Slender ultrasonic cutting devices, such as devices used in the food industry to cut textured or layered products or those utilized in surgical procedures to cut soft or hard tissue, can be prone to exhibiting such behaviors, which if allowed to manifest can lead to suboptimal performance or premature device failure.

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doi:10.1016/j.phpro.2015.03.007

Modal coupling can occur in ultrasonic devices under several scenarios; when two or more resonant frequencies are spaced sufficiently close together, when two or more modes of vibration exhibit high damping, or through a combination of the two previous conditions. This induces a vibrational response which is not dominated by a single mode of vibration, but contains characteristics of multiple modes of vibration (Ewins 2000). Typically, slender ultrasonic devices such as cutting devices, which exhibit modal coupling, are driven in a longitudinal mode of vibration. This will generally couple with a (parasitic) bending mode of vibration which manifests in the response as a combined longitudinal-bending mode of vibration, and which can induce elevated stresses in the device.

Traditionally, the piezoceramic stack of the transducer is located at or close to the nodal plane of the longitudinal mode of vibration, however, this location often lies close to the nodal plane of a neighboring mode of vibration, which under the correct conditions can couple with the tuned mode of vibration. Previous observations have indicated that the location of the piezoceramic stack in the transducer can affect the level of the response of a mode of vibration to an extent that it can be reduced if the piezoceramic stack is located in its anti-nodal plane (Mathieson et al. 2013). Therefore, this report investigates the possibility of reducing the response of a parasitic mode of vibration when a device is driven in its tuned longitudinal mode of vibration through locating the piezoceramic stack in the anti-nodal plane of the parasitic mode.

2. Investigated devices

The investigated ultrasonic devices consist of a Langevin transducer and rod horn, Fig. 1. The transducers, which are half-wavelength, consist of a titanium alloy endmass (TiAl6V4) and four PZT8 equivalent piezoceramic rings (Sonox P8), while the TiAl6V4 rod horns, either ϕ9mm or ϕ5mm, are also half-wavelength. The devices are tuned to vibrate longitudinally at a frequency between 27.0 and 30.1 kHz, however, the devices are also designed so that a parasitic bending mode of vibration is tuned at a resonant frequency close to the resonant frequency of the longitudinal mode of vibration. The devices named T1D9 and T2D5 are tuned so that the piezoceramic stack is located in the nodal plane of the parasitic mode of vibration (this location also corresponds with the longitudinal nodal plane for T1D9), while T2D9 and T1D5 are tuned so that the piezoceramic stack is located at the anti-nodal plane of the parasitic mode of vibration. The 7th bending mode was tuned as the parasitic mode that neighbors the tuned longitudinal mode of T1D9 and T2D9, while the 5th bending mode of the rod horn neighbors the tuned longitudinal mode of T1D5 and T2D5.

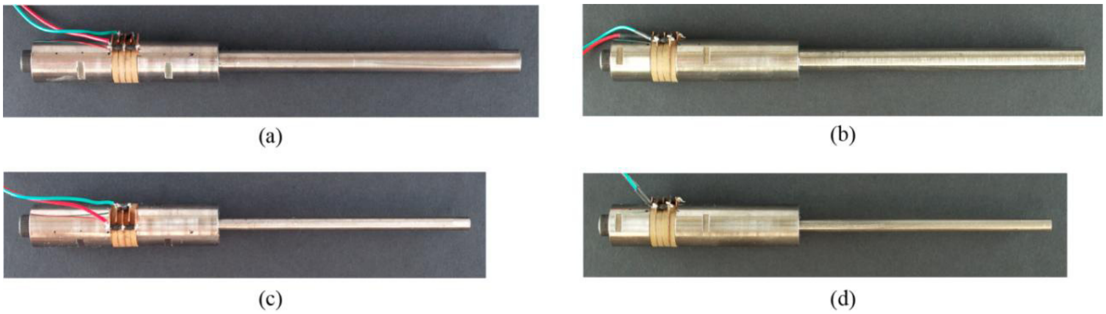

(a) (b) (c) (d)

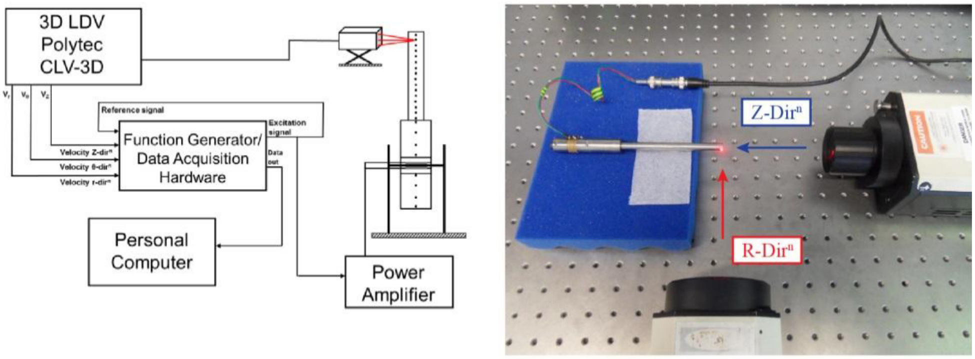
Fig 1: Full-wavelength devices; (a) transducer 1 with ϕ9mm rod horn (T1D9), (b) transducer 2 with ϕ9mm rod horn (T2D9), (c) transducer 1 with ϕ5mm rod horn (T1D5) and (d) transducer 2 with ϕ5mm rod horn (T2D5)

3. Device characterization

3.1. Resonant frequency and mode shape identification

The resonant frequencies and corresponding modes of vibration of the devices were identified in the frequency range of 0-80 kHz using experimental modal analysis (EMA), Fig. 2(a). To facilitate this, the devices were excited with a random excitation signal at low power by a function generator inbuilt to the data acquisition hardware

(DataPhysics Quattro) and then amplified through a power amplifier (QSC RMX 4050HD). A 3D laser Doppler vibrometer (LDV) (Polytec CLV-3D), was used to measure the velocity responses over a grid of points located on the surface of the devices and the acquired frequency response functions, with a resolution of 1.6 Hz, were recorded using data acquisition software (Signal Calc ACE, DataPhysics). The frequency response functions were imported to modal analysis software (ME'ScopeVES, Vibrant Technology), where the modal parameters of modal frequency and mode shape, were identified from the model. Lastly, the mode shapes were visualized using a 3D model that represented the geometry of the devices.



(a) (b)

Fig. 2: (a) Schematic of EMA, and (b) LDV configuration during harmonic analysis

3.2. Harmonic analysis

The devices were excited close to the frequency of the tuned longitudinal mode via bi-directional frequency sweeps. It has been widely reported in the literature that piezoelectric material properties vary with changes in temperature, with the subsequent effect that this influences the behavior of the ultrasonic device (Aurelle et al. 1996, Mathieson et al. 2013). To ensure that heating within the piezoceramic stack did not significantly influence the response, the devices were excited under constant voltage conditions with a burst-sine signal which had a fixed length of 4000 cycles. This excitation interval was sufficient for the device to achieve steady-state conditions, but minimized heating within the stack. Furthermore, a time delay of 2.5 seconds was incorporated between successive bursts to allow for any residual heat to dissipate.

The devices were excited at five voltage levels between 2 V_{peak} and 10 V_{peak} with a frequency increment step of 2 Hz. The sinusoidal excitation signal was generated by a function generator (Agilent 3322A) which was amplified through a power amplifier (HFVA-62). A 1D LDV (Polytec OFV 3001 with OFV 303 sensor head) was used to measure the axial (Z-direction) velocity response of the rod horn while a 3D LDV (Polytec CLV 3000) was used to measure the radial (R-direction) velocity response at the free end of the rod horns, Fig. 2(b).

4. Results

4.1. Resonant frequency and mode shape identification

Fig. 3 presents the curve-fitted FRFs of the devices and Fig. 4 depicts the mode shapes of the longitudinal and bending modes identified from the experimental measurements. As expected, the response of the longitudinal mode dominates the neighboring bending mode, however, it can be observed from Fig. 3 that the response of the bending mode in T1D9 and T2D5 is slightly stronger than those observed in the FRFs of T2D9 and T1D5.

Other modes of vibration, 2nd and 3rd torsional (T2 and T3) as well as the 9th bending (B9) modes and the 1st longitudinal mode of the bolt, have been identified in the curve-fitted response of T1D9, while not observed in the response of T2D9. This indicates that torsional modes of vibration are not easily excited unless the piezoceramic stack is located in their nodal plane, while longitudinal modes of vibration, specifically of the bolt in this study, are also easier to excite when the piezoceramic stack is located in a nodal plane. However, it can also be observed that the 4th bending (B4) mode appears in the response of T2D9 while not in the response of T1D9. This illustrates how locating the stack in the anti-nodal plane of one mode of vibration (B7) can inherently locate it in the nodal plane of another mode of vibration.

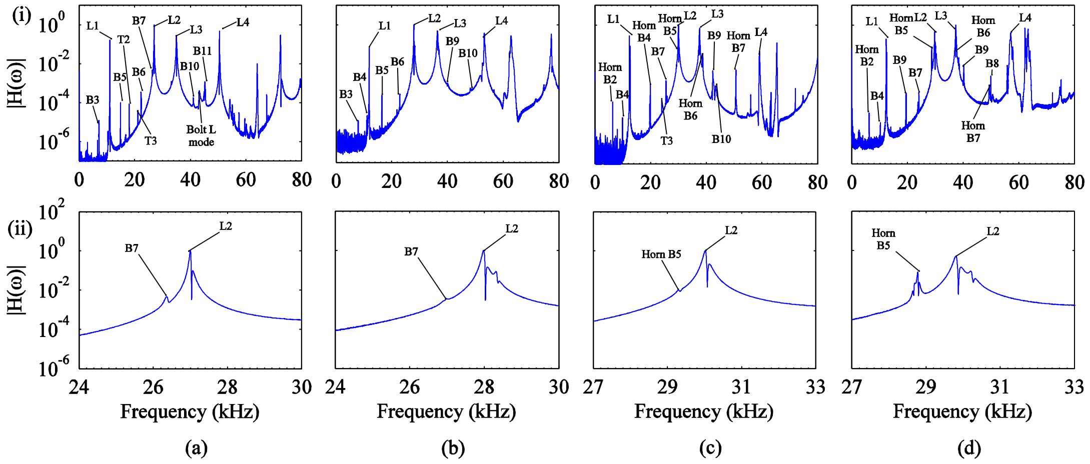


Fig. 3: Curve-fitted FRF plots, where (i) presents the full 0-80 kHz frequency range and (ii) presents an expanded region of the FRF at the frequencies of interest (a) T1D9, (b) T2D9, (c) T1D5 and (d) T2D5

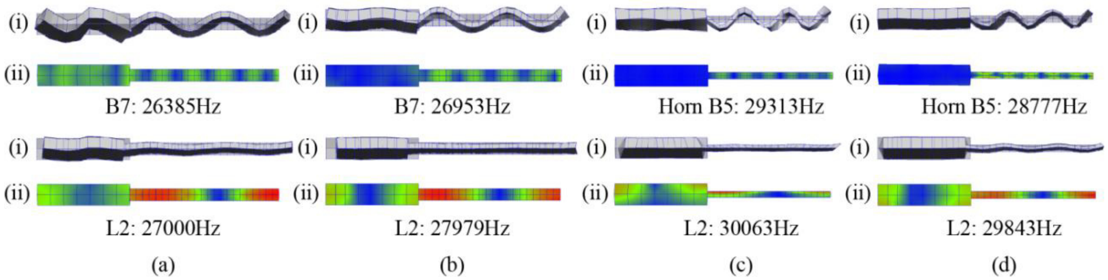


Fig. 4: Bending and longitudinal mode shapes of devices; (i) deformed and undeformed plot, (ii) contour plot, where high vibrational amplitude is depicted as red and the lowest as blue for (a) T1D9, (b) T2D9, (c) T1D5 and (d) T2D5

4.2. Harmonic analysis

As expected, the response of the transducer measured in the Z-direction, Fig. 5(i), is dominated by motion generated by the longitudinal mode of vibration. Only the longitudinal mode is detected in the responses of T1D9, T2D9 and T1D5, however in the Z-direction response of T2D5, both the parasitic (horn B5 mode) and the longitudinal mode can be detected. Measurements taken in the R-direction confirm that the parasitic mode of vibration of T2D5 is significantly more responsive than those of the other devices. Furthermore, it is considerably more responsive at the longitudinal resonant frequency. This indicates that a strong coupling is occurring between the longitudinal mode and the parasitic mode of vibration. This is confirmed by the longitudinal mode shape, identified through EMA, Fig. 3(d), as this clearly illustrates that the longitudinal mode exhibits bending responses.

Although T1D5 also exhibits vibrational motion in the R-direction, Fig. 5(c), and the longitudinal mode shape contains a bending component stemming from the parasitic mode of vibration, Fig. 3(c), the significantly reduced vibrational response measured in the R-direction indicates that locating the piezoceramic stack in the anti-nodal plane of the parasitic mode reduces the response induced by that mode of vibration. The responses of T1D9 and T2D9 indicate similar findings. The device with the piezoceramic stack located in the nodal plane (T1D9) exhibits a larger response in the R-direction when excited at the tuned longitudinal mode than the device with the piezoceramic stack located in the anti-nodal plane (T2D9). The mode shape of the longitudinal mode of T1D9 also exhibits a bending component, Fig. 3(a), while T2D9 exhibits a limited response in the R-direction while the longitudinal mode shape does not appear to contain a bending component, Fig. 3(b).

Another behavior typical of power ultrasonic devices, stiffness softening, can also be observed in the responses as a lowering of the resonant frequency for increasing amplitude, however, as the devices were driven within a relatively low excitation range, it is not possible to fully assess the effect that the piezoceramic stack location has on this nonlinear behavior. Finally, it can be observed from the harmonic sweeps, Fig. 5, that the parasitic mode appears to be excited at two distinct frequencies, Fig. 5(a), 5(c) and 5(d). This phenomenon is known as repeated modes, or multiple modes, and can arise in devices that are nominally symmetric but possess a degree of asymmetry.

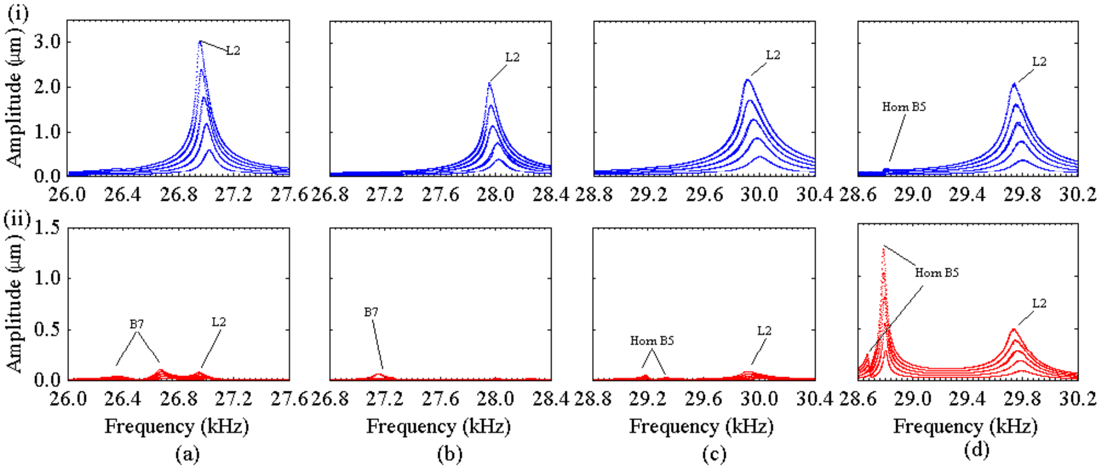


Fig. 5: Harmonic sweeps close to the resonant frequencies of interest; (i) displacement in Z-direction, (ii) displacement in R-direction for (a) T1D9, (b) T2D9, (c) T1D5 and (d) T2D5

5. Conclusions

This report has demonstrated that locating the piezoceramic stack of a slender power ultrasonic device at the anti-nodal plane of a mode of vibration reduces the vibrational response of that mode. Furthermore, locating the piezoceramic stack in the anti-nodal plane of a parasitic mode of vibration that closely neighbors the tuned mode of vibration, has been shown to reduce coupling between the tuned mode and the parasitic mode. Therefore, by implementing these findings into the design of ultrasonic devices, especially those with slender geometries, which exhibit modal coupling between the tuned mode of vibration and a parasitic mode of vibration, it may be possible to remove or minimize modal coupling and improve performance and reliability.

Acknowledgements

This project was funded by the Engineering and Physical Science Research Council (EPSRC), grant number EP/K020013/1. Thanks to Ceram Tec UK Ltd for supplying the piezoceramic material used in the transducers.

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