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Nonlinear characterization of half and full wavelength power ultrasonic devices

Andrew Mathieson[a], Niccolò Cerisola[b], Andrea Cardoni[c]*

[a]School of Engineering, University of Glasgow, G12 8QQ, UK
[b]Mectron S.p.A, Carasco, 16042 GE, Italy
[c]Pusonics S.L., 28500 Arganda del Rey (Madrid), Spain

Abstract

It is well known that power ultrasonic devices whilst driven under elevated excitation levels exhibit nonlinear behaviors. If no attempt is made to understand and subsequently control these behaviors, these devices can exhibit poor performance or even suffer premature failure. This paper presents an experimental method for the dynamic characterization of a commercial ultrasonic transducer for bone cutting applications (Piezosurgery® Device) operated together with a variety of rod horns that are tuned to operate in a longitudinal mode of vibration. Near resonance responses, excited via a burst sine sweep method were used to identify nonlinear responses exhibited by the devices, while experimental modal analysis was performed to identify the modal parameters of the longitudinal modes of vibration of the assemblies between 0-80 kHz. This study tries to provide an understanding of the effects that geometry and material choices may have on the nonlinear behavior of a tuned device.

Keywords: Power ultrasonics; EMA; Nonlinear behavior

1. Main text

It has been known, since the 1960s, that ultrasonic devices when driven under high vibrational levels near resonance exhibit nonlinear dynamic behaviors which can influence device performance (Albareda et al, Aurelle et al, Kumehara

* Corresponding author. Tel.: +34 918 70 68 82.
E-mail address: a.cardoni@pusonics.es

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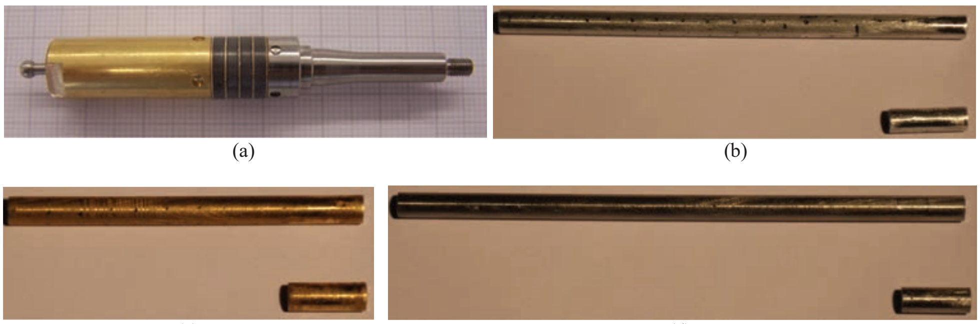
et al, Mathieson et al (2013), Mathieson et al (2015), Negishi, Umeda et al). These behaviors manifest in ultrasonic devices through shifts in resonant frequency, hysteresis loops, harmonic responses, and modal interactions. The source of these phenomena can be directly related to the presence of high stresses and strains within the power ultrasonic device whilst under high amplitude vibrational conditions.

The presence of nonlinear behavior has been extensively studied in materials used in the manufacture of ultrasonic devices. Notably, piezoceramic elements, which are employed in transducers to convert electrical energy into mechanical motion, possess vibrational thresholds above which exhibit nonlinear characteristics (Albareda et al, Aurelle et al, Negishi, Umeda et al). Furthermore, piezoceramic materials are prone to heating which also facilitates the manifestation of nonlinearities.

Although piezoceramics behave nonlinearly at relatively low excitation levels, this is not a unique source of nonlinear behavior in power ultrasonic devices. Tuned tool geometry and material of manufacture, along with connections or fastening points between components are also known sources of nonlinear behavior (Kumehara et al, Mathieson et al (2013), Mathieson et al (2015)). To differentiate between the mechanical sources of nonlinear behavior from those stemming from heating within the piezoceramic elements, an experimental technique has been employed which separates nonlinear behaviors originating from high stresses and strains from those due to elevated temperatures.

2. Transducer assemblies

Rod horns were tuned using finite element analysis (FEA) (Abaqus, Dassult Systèmes) to form half or full wavelength assemblies in conjunction with a commercial power ultrasonic transducer used in surgical procedures, Fig. 1(a). The half wavelength assemblies were tuned to vibrate in the first longitudinal mode of vibration, while the full wavelength assemblies were tuned to operate at the second longitudinal mode of vibration. To investigate the influence that material selection has on the behavior of the rod horns, three sets of horns were manufactured using different alloys, Fig. 1. The length of the rod horns and corresponding mechanical quality factor, Q_m, of the tuned assemblies (calculated using $\sqrt{2}$ peak method) can be seen in Table 1 (Stansfield (2002)).



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

Fig. 1. (a) Commercial surgical transducer; (b) 6082 aluminum alloy rod horns; (c) brass rod horns; (d) 316 Stainless steel rod horns. The longer rod horn when assembled with the transducer forms a full wavelength power ultrasonic device. The shorter rod horns when assembled with the transducer form a half wavelength device.

Table 1. Rod horn length and Q_m of transducer-rod horn assemblies.

	Full wavelength assembly		Half wavelength assembly	
	Length (mm)	Q_m	Length (mm)	Q_m
6082 Aluminum alloy	95	1228	16	492
Brass	60	955	13	316
316 Stainless steel	110	337	13	311

3. Identification of modal parameters

The frequencies and mode shapes of the first, second and third longitudinal modes of vibration of the half wavelength assemblies, as well as the first to fifth longitudinal modes of vibration of the full wavelength assemblies were predicted through finite element analysis (FEA) and identified by experimental modal analysis (EMA).

3.1. Experimental setup

EMA of the tuned devices was performed by exciting the devices with a random excitation signal output by a function generator built in to the data acquisition hardware (Data Physics Quattro) and passed through a power amplifier (QSC Audio RMX 4050HD). The vibration velocities were measured over a grid of points located on the ultrasonic device using a 3D laser Doppler vibrometer (Polytec, 3D CLV-3D), while the detected frequency response functions, with a frequency range of 0 and 80 kHz, were recorded though Signal Calc ACE data acquisition software (Data Physics Corp) before the collected data was imported to modal analysis software ME'ScopeVES (Vibrant Technology Inc) and the resonant frequencies and corresponding modes of vibration were extracted.

3.2. Identified modal parameters of rod horn assemblies

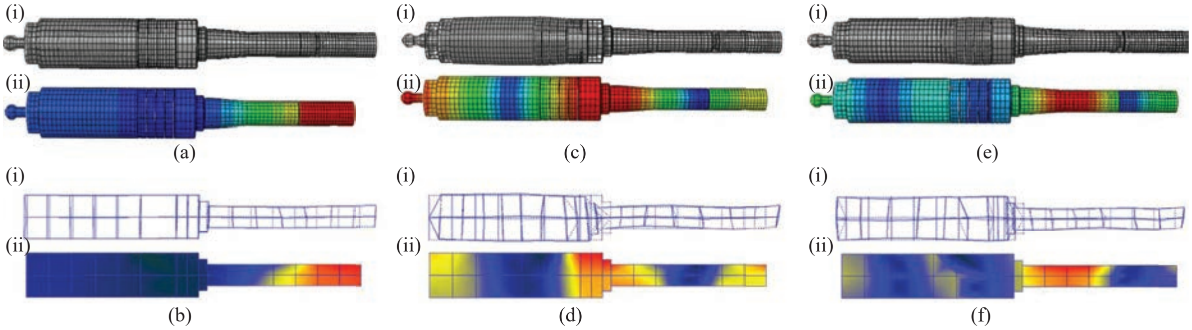


Fig. 2. Longitudinal modes of vibration for the half wavelength stainless steel rod horn-transducer assembly. (a) FEA: 1st Longitudinal mode of vibration; (b) EMA: 1st Longitudinal mode of vibration; (c) EMA: 2nd Longitudinal mode of vibration; (d) EMA: 2nd Longitudinal mode of vibration; (e) FEA: 3rd Longitudinal mode of vibration; (f) EMA: 3rd Longitudinal mode of vibration; (i) Deformed mode of vibration; (ii) Contour plot; blue through to red represents contours of low to high displacement amplitude.

Table 2. Predicted and measured resonant frequencies of the rod horn-transducer assemblies.

	6082 Aluminium alloy rod horn transducer assembly				Brass rod horn-transducer assembly				316 Stainless steel rod horn-transducer assembly			
	Half wavelength		Full wavelength		Half wavelength		Full wavelength		Half wavelength		Full wavelength	
	FEA (Hz)	EMA (Hz)	FEA (Hz)	EMA (Hz)	FEA (Hz)	EMA (Hz)	FEA (Hz)	EMA (Hz)	FEA (Hz)	EMA (Hz)	FEA (Hz)	EMA (Hz)
1st Long mode	29920	29014	11040	10692	22693	21657	10186	9898	24957	24868	8688	8471
2nd Long mode	48920	45582	31403	30861	47604	43860	31906	31754	48144	45046	25404	25250
3rd Long mode	81454	74784	45276	41930	78344	72530	46127	42975	82112	77229	44298	41957
4th Long mode	-	-	55217	53929	-	-	57526	56998	-	-	49140	47882
5th Long mode	-	-	71089	69212	-	-	74587	73183	-	-	66606	66072

Fig. 2 illustrates the resonant frequencies and mode shapes for the first, second and third longitudinal modes for the half wavelength assembly containing the stainless steel rod horn predicted through FE analysis and measured through EMA. Good correlation can be seen to exist between the predicted and measured modes of vibration, while Table 2 demonstrates that the predicted resonant frequencies of the longitudinal modes also correspond well with those identified through EMA. However, considering the percentage difference between the predicted and measured resonant frequencies, shown in Fig. 3, it can be observed that some longitudinal modes of vibration are better predicted than others. In both half and full wavelength assemblies, the smallest percentage difference between the predicted and measured resonant frequency was found to be the tuned mode of vibration, while, the largest percentage difference between the predicted and measured resonant frequency was observed in the second and third longitudinal modes for the half wavelength assemblies and the third longitudinal mode of vibration for the full wavelength assemblies.

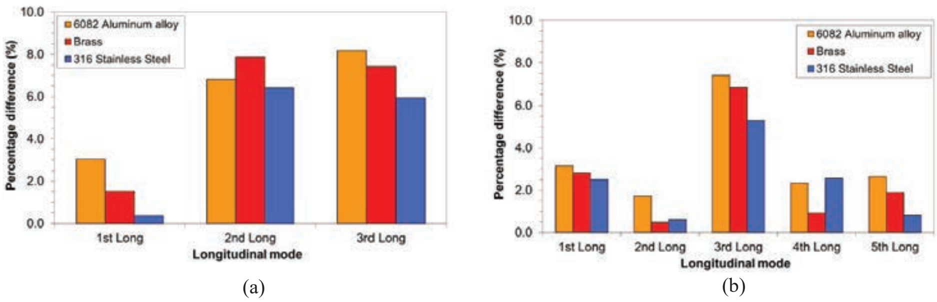


Fig. 3. Percentage difference between resonant frequencies of longitudinal modes of vibration predicted through FEA and identified by EMA for (a) Half wavelength assemblies; (b) Full wavelength assemblies.

4. Nonlinear vibrational responses

Experimental methods to separate nonlinear behaviors which stem from piezoceramic heating from those which stem from high strain or stress have been previously reported (Albareda et al, Aurelle et al, Umeda et al). The experimental technique used in this study excites the rod horn-transducer assemblies via bidirectional frequency sweeps through resonance at increasing excitation voltage levels. The devices were excited at each frequency increment by a sine burst applied for a fixed number of cycles (6000 cycles). Once steady-state conditions were reached, the vibration velocity measurements were taken. To minimize the influence of heating within the piezoceramic elements and to allow for the dissipation of residual heat, a time delay of 1 second and 10 seconds was incorporated into the experimental protocol between success bursts for drive levels of 1-10 Vrms and 10-50 Vrms, respectively.

4.1. Experimental setup

The ultrasonic assemblies were excited by a signal generated by a function generator (Agilent 3322A) which was passed through a power amplifier (QSC Audio RMX 4050HD). The velocity response of each device was measured at the free end of the rod horn using a 1D laser Doppler vibrometer (Polytec OFV3001 with CFV055 sensor head). The temperature of the piezoceramic stack was measured using a custom infrared sensor. National Instruments data acquisition hardware and interface (BNC-2110) in conjunction with Labview software coordinated the experimental protocol and data collection, while to view the time domain current and voltage responses as well as the frequency spectrum of the velocity response an oscilloscope (Tektronic DPO 7054) was used.

4.2. Results

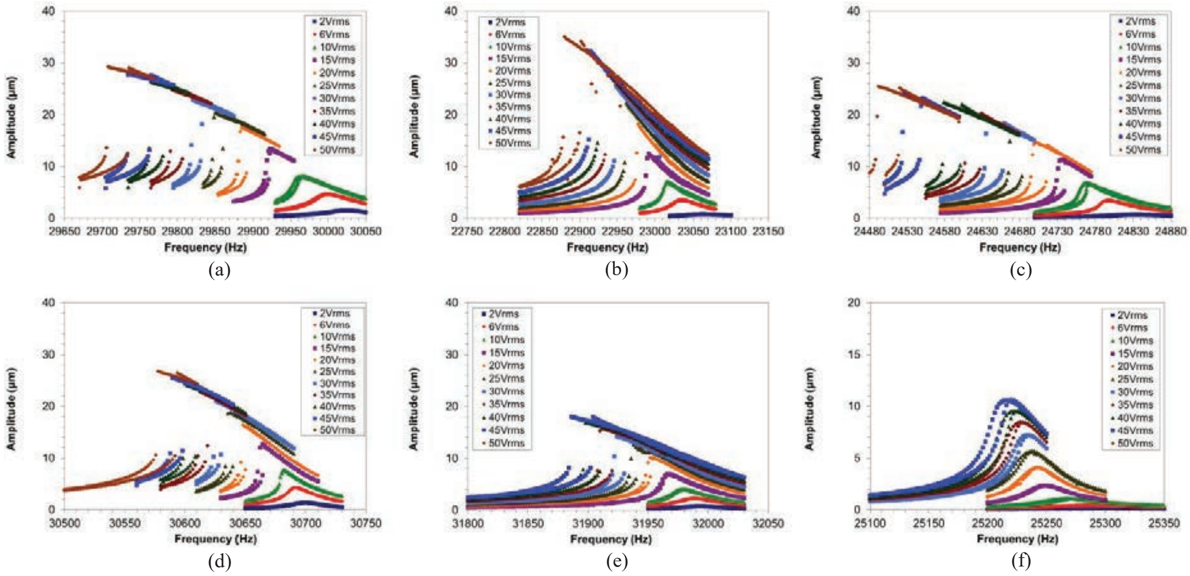


Fig. 4. Vibrational response of the rod horn-transducer assemblies. (a) 6082 aluminum alloy, half wavelength; (b) Brass, half wavelength; (c) 316 stainless steel, half wavelength; (d) 6082 aluminum alloy, full wavelength; (b) Brass, full wavelength; (c) 316 stainless steel, full wavelength.

Fig. 4 presents the response at various excitation levels for each rod horn assembly while they were excited through resonance via bi-directional sine burst sweeps. Duffing-like responses are clearly observed in the vibrational responses of all assemblies and are manifest by resonant frequency shifts, hysteresis regions and jump phenomenon. To directly compare the nonlinear behavior exhibited by each of the rod horn-transducer assemblies, the devices have been compared at an amplitude of vibration of 11 µm which are presented in Table 3.

Table 3. Frequency shift and width of hysteresis regions exhibited by the assemblies at 11 µm.

	Full wavelength assembly			Half wavelength assembly		
	Sweep up (Hz)	Sweep down (Hz)	Hysteresis width (Hz)	Sweep up (Hz)	Sweep down (Hz)	Hysteresis width (Hz)
6082 Aluminum alloy	34	36	2	101	101	0
Brass	49	56	7	73	73	0
316 Stainless steel	75	86	11	87	96	9

To allow for a direct comparison between the nonlinear responses exhibited by the different assemblies, the devices were compared at an amplitude of vibration of 11 µm. From Table 4, it can be see that the half wavelength assemblies generally exhibited larger resonant frequency shifts than the corresponding full wavelength assemblies, however, no clear trend can be identified with respect to frequency shift and rod horn material.

Hysteresis regions (difference between the resonant frequency found during the sweep up and down), were compared at the same vibrational amplitude (11 µm). Although the largest region was found to be 11 Hz, and the smallest 0 Hz, this behavior is likely to be independent of horn geometry or selected material. Likewise, the exhibition of the jump phenomenon was only observed above a vibrational amplitude of 12 µm and is likely to be independent of horn geometry and material.

5. Tightness of threaded joint

Threaded fasteners such as bolts or studs are commonly used to join ultrasonic devices as they allow quick assembly or disassembly of the component while providing a strong mechanical connection means. However, joints are complex features, which if not designed or manufactured correctly can have adverse effects on performance and reliability of ultrasonic devices (Kumehara *et al*) as well as the propagation of waves through threaded joints (Rivière *et al*).

To investigate the effect that joint tightness has on the performance of an ultrasonic device, the half wavelength assembly containing a brass rod horn was excited through the tuned frequency at increasing excitation voltage levels using the experimental set-up in Section IV, at two different torque settings. The torque applied to fasten the rod horn to the transducer was not quantified, however, the resonant frequencies of the assembly were found at 22484 Hz (low torque) and 23065 Hz (high torque), while the corresponding values of Q_m were found to be 155.1 and 316.2, respectively. Fig. 5 presents the vibrational response for the configuration with the loose joint, and when compared with the vibrational response of the configuration containing the tight joint, Fig. 4(b), it is clear joint tightness can significantly influence vibrational response of the device. At an amplitude of vibration of 12μm the shift in resonant frequency for the configuration with the tight joint was 73Hz, while in the configuration with the loose joint was found to be 984Hz. Furthermore, at the same amplitude the width of the hysteretic regions are 0 Hz and 64 Hz, respectively.

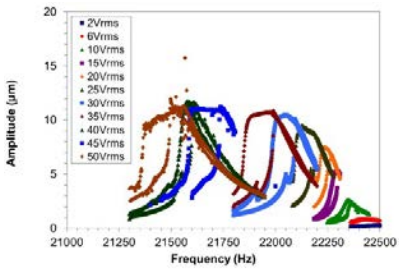


Fig. 5. Vibrational response of the brass rod horn-transducer assembly with suboptimal joint tightness.

6. Discussion

Good correlation exists between the predicted and the experimentally detected mode shapes, while the predicted frequencies of the tuned mode of vibration were found to have a difference of below 4% to those identified through EMA. However, it is also clear that this accuracy was not uniform across all longitudinal modes of vibration identified from the rod horn-transducer assemblies. The resonant frequencies predicted for the 2nd and 3rd longitudinal mode of vibration of the half wavelength assemblies and 3rd longitudinal mode of vibration of the full wavelength assemblies have a significantly larger difference from the frequencies identified through EMA. It is not possible to state with certainty why it was more difficult to accurately predict the resonant frequency of these modes of vibration, but a relationship with the location of the piezoceramic stack of the transducer has been identified. When the piezoceramic stack is located within the nodal plane, the difference between the predicted and identified longitudinal frequency is smaller than when the stack is located outwith the nodal plane. Placing the piezoceramic stack outwith the nodal plane locates the piezoceramic stack in a region where stress and strain can significantly vary across the different elements which may alter their material parameters enough to influence the resonant frequency of these modes of vibration.

Duffing-like responses were observed in all the vibrational responses of the rod horn-transducer assemblies while excited in their nonlinear regime. From previous studies, this behavior is expected (Aurelle *et al*, Mathieson (2013) *et al*, Mathieson (2015) *et al*), but no clear conclusion can be reported on the influence of rod horn material on the vibrational response of the assemblies. However, it was observed that half wavelength assemblies exhibited a greater shift in resonant frequency than the corresponding full wavelength assembly at the same vibrational amplitude. A similar observation has also been reported in half and full wavelength surgical devices (Mathieson *et al*, 2015). It is known that properties of both piezoceramic materials and metal alloys alter when exposed to elevated stress and strain (Albareda *et al,* Umeda *et al*, Campos-Pozuelo and Gallego-Juarez) and therefore the differences in the responses of the half wavelength and full wavelength devices could be accredited to an increased strain levels in the half wavelength devices. Previous research has indicated that hysteresis regions and jump phenomena are more likely to be influenced by piezoceramic materials, which are exposed to elevated drive conditions, rather than device geometry (Mathieson (2013) *et al*).

Threaded joints clearly have a significant influence on the behavior of an ultrasonic assembly. Loose joints have been shown to result lower a Q_m systems and systems that are susceptible to nonlinear vibrational responses. This is dependent on the interconnection between the interfaces of the different consistent parts of the joint, such as the bolt or end mass of the transducer and therefore the level of nonlinearity is influenced by the static forces that fasten the joint together (Rivière *et al*).

7. Conclusions

An experimental technique to investigate the nonlinear behavior of ultrasonic devices has been discussed. It was shown that nonlinearities stem from various sources including device geometry, joint tightness and driving conditions. In order to assure a stable performance of a tuned device, the impact of these parameters needs to be accounted for at the design stage.

Acknowledgements

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