Characterization of nonlinear electro-elastic behavior of piezoelectric receiver in ultrasound acoustic energy transfer systems

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Abstract. A scheme based on the approximate solution determined by the method of multiple scales is proposed for the identification of nonlinear material parameters of a piezoelectric disc. The theoretical approach is experimentally validated to determine these parameters through dynamic electrical actuation. The identified material parameters are then used to investigate the nonlinear electro-elastic behavior of the disk, used as a receiver, in an ultrasound acoustic energy transfer system.

Introduction

Contactless energy transfer techniques are pivotal in the development, use, and reliability of low-power sensors, control devices and communication networks in applications where wired electrical contact is dangerous or impractical. The ultrasound acoustic energy transfer (UAET) has the advantage of being noninvasive when compared to other well-studied methods. UAET method is based on the reception of acoustic wave by a piezoelectric receiver, which converts the mechanical energy induced by incident acoustic waves to electrical power output. To date, most research investigations have been concerned with modeling and proof-of-concept experiments in the linear regime [1, 2]. The linear analysis will fail when the amplitude of elastic strains in the receiver induced by the acoustic waves exceeds a specific threshold where linear assumption fails and when induced strains couple nonlinearly with the electric field generated by the receiver. Any model in this regime must account for the nonlinear interactions between strains induced and the corresponding electric field. As the nonlinear material properties of piezoelectric materials are not well documented in the literature, we present a parameter identification strategy and illustrate the analytical response of the piezoelectric receiver subjected to a spherical acoustic source in water.

Mathematical modeling

Parameter identification strategy

We develop a parameter identification strategy by determining the approximate solution of the governing equation to an electrical excitation with the method of multiple scales [3]. As such, we determine the governing equation of the first mode using quadratic and cubic stiffness material nonlinear parameters as

$$\ddot{q}+\omega^2 q+2\mu_1\dot{q}+\delta_1 q^2+\delta_3 q^3+\hat{\theta}V\cos\left([\omega+\sigma]\,t\right)=0 \tag{1}$$

Figure 1: Experimental setup with a piezoelectric disk whose surface velocity is measured by laser vibrometer.

where q, ω, μ_1, $\hat{\theta}$, and σ are respectively the temporal displacement, natural frequency, damping, effective coupling coefficient of the first mode and σ is the detuning parameter. The forcing frequency is written as, $\Omega=\omega+\sigma$. δ_1 and δ_2 are the parameters that govern the quadratic and cubic material nonlinearity. The steady state amplitude response relation to be employed towards the identification of δ_1 and δ_2 obtained by solving equation 1 with the method of multiple scales is determined as

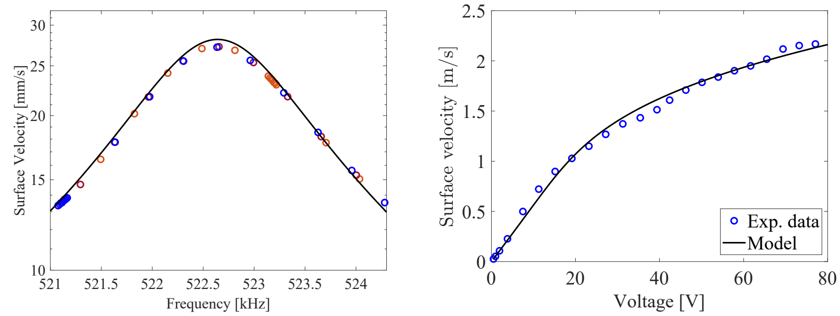
$$\frac{a^2\left(9a^2\delta_3\omega^2-10a^2\delta_1^2-24\sigma\omega^3\right)^2}{36V^2\omega^2\hat{\theta}^2(\sigma-2\omega)^2}+\frac{16a^2\mu_1^2\omega^4}{V^2\hat{\theta}^2(\sigma-2\omega)^2}=1 \tag{2}$$

where $q\approx a\cos\left(\Omega t+\gamma\right)$ and γ is the steady state phase different between excitation and the receiver response.

Results and discussion

Experimental results - parameter identification

Figure 1 shows the experimental setup with a modified lead zirconate - lead titanate (piezoelectric material, PIC-181) disc manufactured by Physik Instrumente [4] operating in thickness mode in free-free boundary conditions. An electrical excitation is induced by a Keysight 33500B signal generator which is fed to E&I amplifier. The disc's surface velocity is measured by Polytec laser vibrometer and is acquired by NI DAQ system as shown in figure 1. Figure 2(a) shows the comparison of experimentally measured surface velocity of the disk in a frequency sweep at input voltage of 500 mV, with the linear response of equation 1. The parameters of natural frequency, damping ratio and electromechanical coupling coefficient are identified by a least squares curve fit of the linear response. Figure 2(b) shows the saturation phenomenon observed in the surface velocity as the excitation voltage amplitude increases from 500 mV to 77 V at 522.5 kHz. Figure 2(b) also shows a decent agreement of the trend predicted by the identified nonlinear parameters using equation 2 and the experimental data. This procedure can be used to characterize the nonlinear behavior of both the receiver and the transmitter disks in UAET systems.

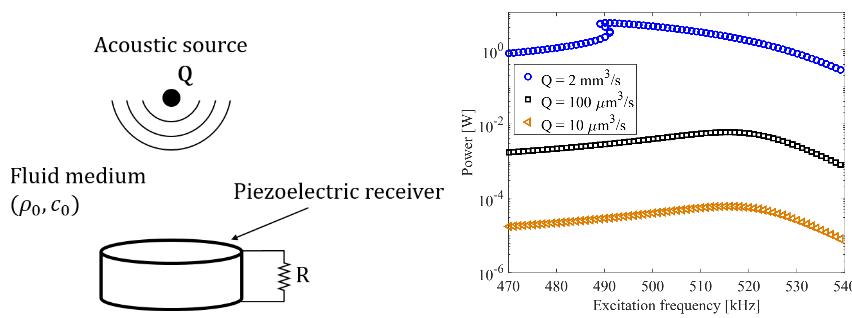


(a) (b)

Figure 2: Comparison between experimental data (markers) and model prediction (solid line) for (a) linear, and (b) nonlinear frequency response of the transducer with identified parameters.

Electromechanical response of receiver to an acoustic excitation

We model the electromechanical response of the piezoelectric disk receiver in free-free boundary conditions submerged in water and excited by a spherical acoustic source as shown in the figure 3(a). Supplementing the previous literature where a linear constitutive relation is employed, and following Meesala et. al [5], we consider the nonlinear parameters identified and study their effect on the response. Figure 3(b) shows the power generated by the receiver for source strengths is set to 10μ m^3/s, 100μ m^3/s and 1mm^3/s as predicted by the method of multiple scales. As shown in figure 3(b) the softening material nonlinearity shifts the peaks towards right in the frequency response, but it is not very significant for the source strength considered.



(a) (b)

Figure 3: (a) Schematic of the piezoelectric receiver and (b) power generated by the receiver as predicted by the method of multiple scales for a very low load resistance of $R = 1$ Ohm.

Conclusions

The material nonlinear parameters of an ultrasound acoustic energy transfer receiver are identified experimentally by employing a parameter identification strategy which is based on the approximate solution determined by the method of multiple scales. The effect of the identified material nonlinear parameters of the receiver on the energy transfer characteristics excited by a spherical source is illustrated.

Acknowledgments

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