Investigation on the shock formation in acoustic energy transfer systems

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Abstract. A finite-amplitude acoustic wave distorts as it travels in a medium and eventually gives rise to the formation of a shock where the energy is dissipated proportionally to the cube of the jump in the pressure. In acoustic energy transfer (AET) systems, we note that the energy lost due to the formation and propagation of shock can significantly compromise its efficiency when operated beyond the shock formation distance (SFD). Consequently, we regard shock formation distance as an essential design parameter in designing efficient AET systems and present a model capable of predicting the SFD in the acoustic wave generated by a baffled disk with general transverse displacement in a weakly viscous fluid medium. The model's predictions are compared with the results obtained from a nonlinear finite element simulation and experiments performed elsewhere in the literature.

Introduction

AET is a transformative contactless energy transfer technology that utilizes acoustic waves to transfer energy from a piezoelectric transmitter (Tx) to receiver (Rx) [1]. AET is receiving increased attention as it outperforms conventional electromagnetic CET technologies in several critical applications. In a recent study, it was experimentally demonstrated that the interplay of acoustic and electro-elastic nonlinearities and the standing wave effects between Tx and Rx in a high powered AET system manifest in a complicated manner [2]. As such, it is beneficial to understand the consequence of individual sources of nonlinearity. Towards that objective, we investigate in this study the consequence of the nonlinear acoustic wave propagation on AET systems. In AET systems, in addition to the transfer of energy and diffraction, the decrease in excitation pressure will be aided by loss in energy due to the formation and propagation of shocks beyond SFD. As such, we note that the efficiency will be significantly compromised after SFD and regard it as an essential design parameter for high-intensity AET phenomena. In this work, we consider an axisymmetric-baffled-vibrating piezoelectric disk and develop a mathematical model by solving the Westervelt equation using a novel method of renormalization scheme up to ϵ^2-order to predict the SFD.

Results and discussion

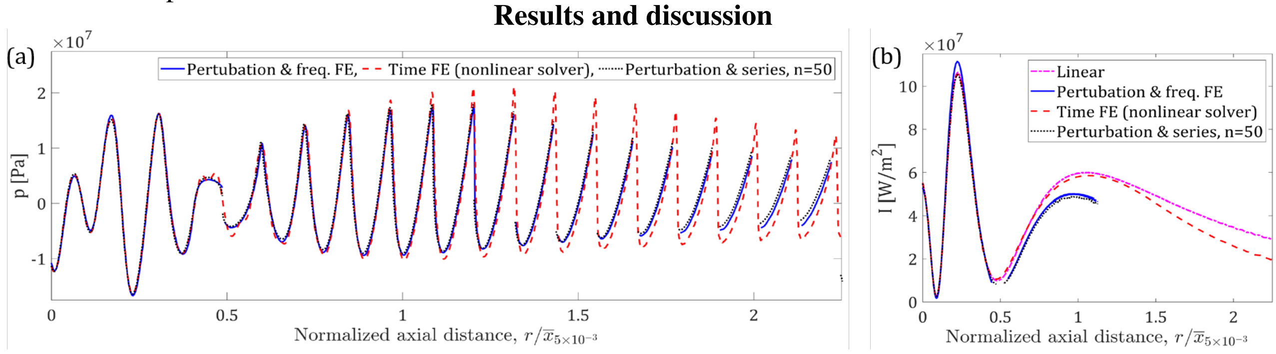

Figure 1: Comparison of steady-state axial (a) pressure waveform and (b) mean intensity obtained from time-domain FE simulation and from the model developed when p_1 and p_2 are obtained from analytical formulation (Perturbation & series, $n = 50$) and from linear frequency domain FE simulations (Perturbation & freq. FE).

The efficacy of the mathematical model developed to predict the nonlinear wave propagation and SFD is assessed by considering a piezoelectric disk submerged under-water with radius $a = 5$ mm and thickness $h = 2$ mm made of PZT$-$5H material. Figures 1a & 1b show respectively the steady-state axial pressure waveform at time $t = 1/(2f_0)$ and the mean intensity for an excitation of $\epsilon = 5 \times 10^{-3}$ at 1.005 MHz obtained using time-domain FE simulation and from p_1 and p_2 as determined from analytical formulation and frequency domain FE simulations. Here, p_1 and p_2 are respectively the ϵ and ϵ^2 order solutions in the model developed. Based on the closeness of the responses predicted, we conclude that the transformation does an excellent job in predicting the pressure distributions at closer distances. From the results, the model yields multiple solutions in a small region around $r/\overline{x}_{5\times10^{-3}} = 0.5$, and when $r/\overline{x}_{5\times10^{-3}} > 1.13$ that correspond to the formation of a shock. However, from Fig. 1b, the mean intensity predicted by the time-domain FE simulation deviates from the linear case only after $r/\overline{x}_{5\times10^{-3}} = 1.13$ suggesting it as the SFD [3], thereby validating the model's prediction. The details of the novelty in the model, comparison with experimental results, justification of anomalies, and short-comings of the model are not mentioned here for brevity and will be presented at the conference.

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References

[1] Meesala, V.C., Hajj, M.R. and Shahab, S. (2020) *Nonlinear Dynamics* 99(1), pp.249-268.

[2] Bhargava, A., Meesala, V. C., Hajj, M. R., and Shahab, S. (2020) *arXiv preprint* arXiv:2006.12691.

[3] Khokhlova, V., Souchon, R., Tavakkoli, J., Sapozhnikov, O., and Cathignol, D. (2001) . *JASA* 110,1.