Chapter 17
Traveling Wave Generation Through Piezoelectric Shunt Damping

A. Omidi Soroor, S. Motaharibidgoli, and P. A. Tarazaga

Abstract Having many different applications in mind, traveling wave generation in finite structures has been studied extensively by researchers in various fields. Surveying the literature suggests that most of the published work applied to finite and continuous structures is based on the notion of exciting the structure at two different locations at the same frequency with a phase shift to produce such waves. Recently, another approach has been proposed where there is only one excitation source, and the second one is replaced by a discontinuity that generates the required counterforce for reflection absorption. Thus far, this method has been experimentally verified in solid media where a perfectly tuned mechanical discontinuity, such as a spring-damper set, was leveraged. The authors herein are interested in replacing the mechanical discontinuity with an adaptive element in the hopes of widening the excitation frequency bandwidth in which this type of response is achievable within a given structural configuration. As such, a shunted piezoelectric element is adopted, thereby enabling variable stiffness and damping coefficients that can be adjusted based on the excitation frequency of the incident waves. This methodology also provides the ease of tuning the system electronically as opposed to achieving this precise tunning mechanically, which has been shown to be very difficult.

Keywords Traveling Waves · Single-Point Excitation · Shunt Damping · Negative Capacitance

Introduction

Researchers have extensively studied methods for traveling wave generation due to their various applications since 1990 [1]. These applications include but are not limited to particle transfer [2], robotic locomotion [3], and propulsion [4]. The majority of the literature is concerned with the two-point (or two-mode) excitation method for generating such waves. In this approach, the structure is excited at two locations with a frequency between two vibration modes and a phase shift between them, such that traveling waves are obtained within the space between the two exciters [5]. However, the authors have recently attempted another approach to traveling wave generation in solid media, i.e., the single-point excitation method. This idea had been previously explored by Xiao et al. in acoustic ducts [6]. In this approach, one of the exciters is replaced with a highly tuned type of discontinuity, a spring-damper set in mechanical structures, as seen in [7]. One of the primary motivations for developing this method is to mimic the observations from the mammalian cochlea, wherein the basilar membrane undergoes a similar dynamic behavior, i.e., the sound entering the ear initiates a wave on the basilar membrane that travels towards its apex without any reflections [8].

A recent study [9] by the authors has suggested that adopting a mechanical discontinuity to generate the required counterforce for the incident wave reflection cancellation might not be a feasible solution as it may not address a wide excitation frequency bandwidth. The discontinuity has to be specially tuned to the excitation frequency, restricting the ability to address a large bandwidth solution. Therefore, in the present study, the authors introduce an adaptive solution to address an excitation frequency range similar to the basilar membrane responsiveness in the audible frequency range. As such, piezoelectric materials are chosen to replace the spring-damper set implemented in the prior works. In the following section, the details of this solution, as well as some of the preliminary results of a pilot study conducted by the authors, are presented and discussed.

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Methodology

The present method uses piezoelectric patches shunted with RC circuits instead of the mechanical discontinuity introduced in [7] and [9]. Figure 1 depicts the schematic of the proposed traveling wave solution.

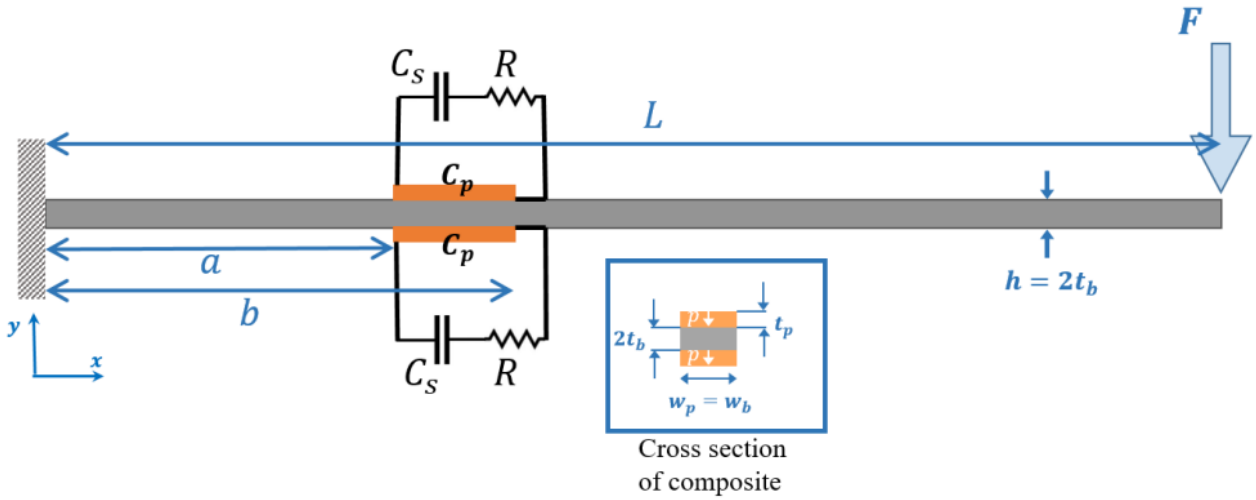

Fig. 1 Cantilevered beam with shunted piezoelectric patches [10].

In Figure 1, F denotes the harmonic excitation force. L, w_b, h, and t_b are the beam's length, width, full thickness, and half thickness. t_p and w_p represent the piezoelectric patches' thickness and width. Each piezo patch is shunted with a resistor and a capacitor with resistance R and capacitance C_s, respectively. C_p is the inherent capacitance of the piezoelectric element. The coupled electromechanical finite element formulation for the following system is developed as follows,

$$\begin{cases} M\ddot{u} + Ku = B_v V(t) + B_f F(t) \\ B_v^T \dot{u} + (C_p + 2C_s)\dot{V} + \frac{2}{R} V = 0 \end{cases}. \tag{1}$$

In Eq. (1) M and K are the mass and stiffness matrices, respectively. $\mathbf{u}$ and V are the nodal displacement vector and voltage, respectively. Finally, B_V and B_f are voltage and force influence matrices. The details regarding these matrices and vectors can be found in [10]. Interestingly, following some mathematical manipulation, it turns out that shunted piezoelectric patches induce external stiffness and damping in the system, which can be calculated as follows,

$$\bar{K} = \frac{R^2\omega^2 (C_p + 2C_s)}{4 + (R\omega (C_p + 2C_s))^2} B_v B_v^T \text{ and } \bar{C} = \frac{2R}{4 + (R\omega (C_p + 2C_s))^2} B_v B_v^T. \tag{2}$$

Using such passive electrical elements adds much more adaptability to the model compared to the cases considered in prior studies, as the equivalent stiffness ($\overline{K}$) and damping ($\overline{C}$) can be easily tuned now. Hence, with proper circuit tuning, high-quality traveling wave response can be obtained in the region between the excitation force and piezoelectric patches. In the following section, some of the preliminary results of this study are presented and discussed.

Preliminary Results

According to [7], a cost function is used to assess the wave quality in a given region. Pilot studies have suggested that optimal traveling wave response can be obtained in cases where resistive shunts are used, implying that $C_p + 2C_S = 0$. This suggests that

$$C_s = \frac{-C_p}{2}, \tag{3}$$

meaning a negative capacitance is required to meet this condition, as the piezoelectric material's inherent capacitance is positive. The cost function plot in Figure 2 asserts that a small optimal region exists where high-quality traveling waves exist for a given case. It is worth mentioning that a lower cost function value is associated with a higher quality of traveling waves.

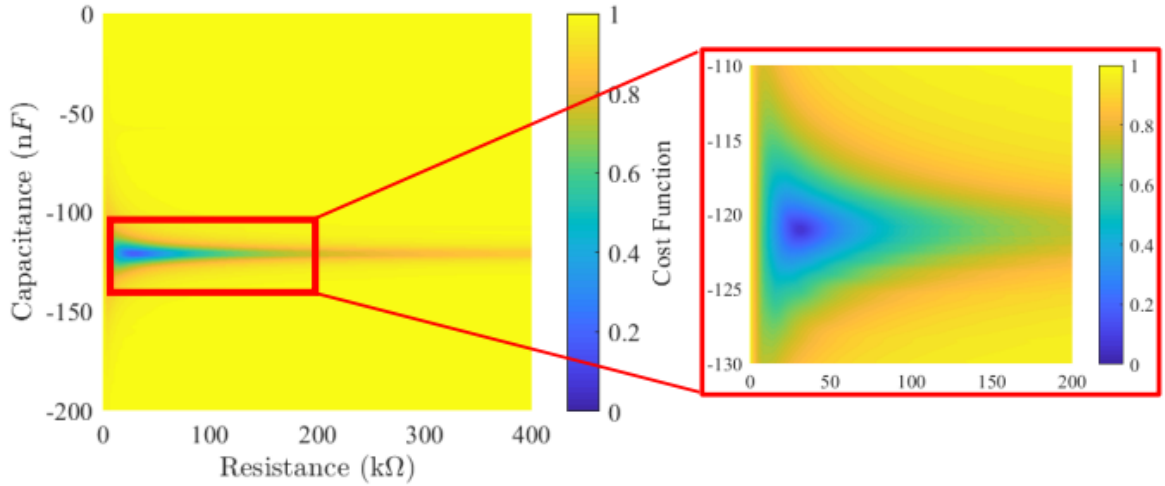

Fig. 2 Cost function contour for a case with an excitation frequency of 1700 Hz [10].

As highlighted in Figure 2, the cost function is minimized in the case where $C_s = -121\ nF$ and $R = 32\ k\Omega$. The system's response in this optimal condition is given in Figure 3.

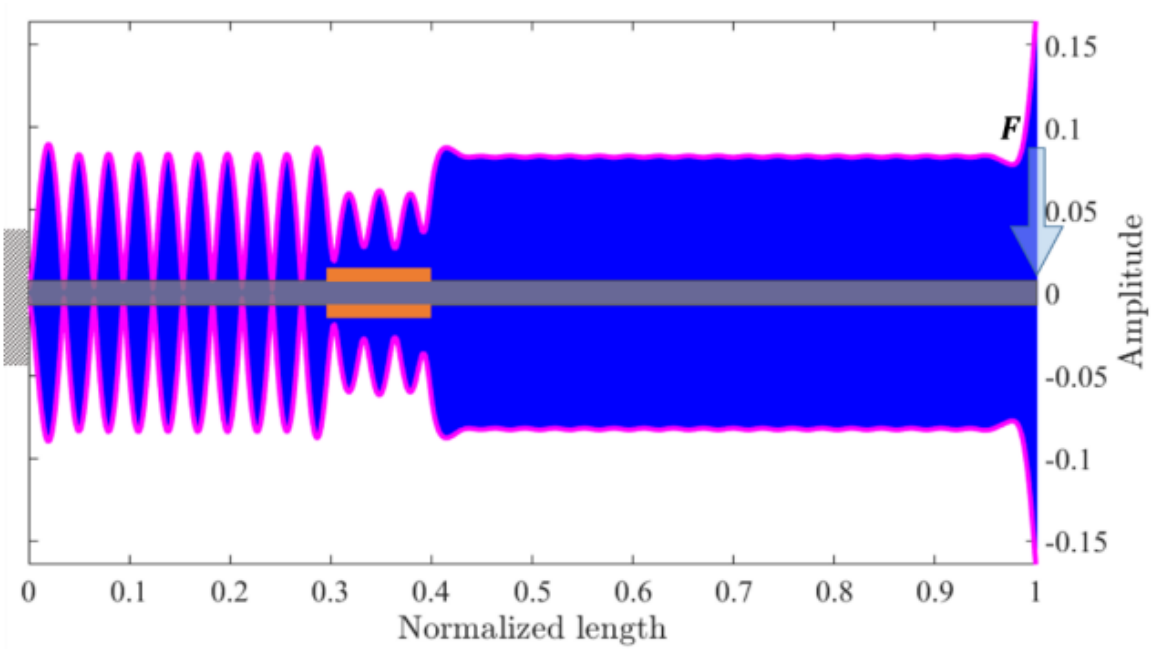

Fig. 3 Area swept by the wave and the wave envelope in the assumed optimal case [10].

Figure 3 suggests high-quality traveling waves can be obtained when the circuit parameters are optimized relative to the system configuration. Realizing the negative capacitance requires additional circuitry, which is extensively discussed in the literature [11]. Therefore, this approach is promising for improving the single-point excitation traveling waves model and relaxing the need for mechanical discontinuities such as springs and dampers in solid mechanical structures. In the last section of this extended abstract, we provide a brief overview of the ongoing research on this topic.

Ongoing Study

As the next step in the work discussed above, the authors are conducting parametric studies to understand the model's sensitivity to different parameters and configurations, e.g., unimorph or bimorph piezoelectric patch installment, series or parallel configurations of the circuitry components, etc. Efforts are being made to conduct an experimental study to verify the simulation results.

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References

1. Y. Tomikawa, K. Adachi, H. Hirata, T. Suzuki, and T. Takano, "Excitation of a Progressive Wave in a Flexurally Vibrating Transmission Medium," Japanese Journal of Applied Physics, vol. 29, no. S1, p. 179, 1990/01/01 1990, doi: 10.7567/JJAPS.29S1.179.
2. W. C. Rogers and M. I. Albakri, "Tailoring Structure-Borne Traveling Waves in Targeted Areas of a Two-Dimensional Plate for Particle Motion Applications," in ASME 2021 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, 2021, vol. ASME 2021 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, V001T07A004, doi: 10.1115/smasis2021-67804. [Online]. Available: https://doi.org/10.1115/SMASIS2021-67804
3. T. Nakamura and K. Sato, "Locomotion strategies for an omni-directional mobile robot using traveling waves propagation," in 2010 IEEE International Conference on Robotics and Automation, 2010: IEEE, pp. 3769-3774.
4. P. F. Musgrave, M. I. Albakri, and A. A. Phoenix, "Guidelines and procedure for tailoring high-performance, steady-state traveling waves for propulsion and solid-state motion," Smart Materials and Structures, vol. 30, no. 2, p. 025013, 2021.
5. V. V. N. S. Malladi, D. Avirovik, S. Priya, and P. Tarazaga, "Characterization and representation of mechanical waves generated in piezo-electric augmented beams," Smart Materials and Structures, vol. 24, no. 10, p. 105026, 2015/09/18 2015, doi: 10.1088/0964-1726/24/10/105026.
6. Y. Xiao, H. Lu, D. M. McFarland, A. F. Vakakis, and L. A. Bergman, "Inducing a nonreflective airborne discontinuity in a circular duct by using a nonresonant side branch to create mode complexity," The Journal of the Acoustical Society of America, vol. 143, no. 2, pp. 746-755, 2018, doi: 10.1121/1.5022777.
7. S. Motaharibidgoli, S. Davaria, V. V. N. Sriram Malladi, and P. A. Tarazaga, "Developing coexisting traveling and standing waves in Euler-Bernoulli beams using a single-point excitation and a spring-damper system," Journal of Sound and Vibration, vol. 556, p. 117728, 2023/07/21/ 2023, doi: https://doi.org/10.1016/j.jsv.2023.117728.
8. G. von Békésy, "Travelling Waves as Frequency Analysers in the Cochlea," Nature, vol. 225, no. 5239, pp. 1207-1209, 1970/03/01 1970, doi: 10.1038/2251207a0.
9. Omidi Soroor, A. and Tarazaga, P. A., 2025. Non-reflective traveling waves in finite thin beams: A parametric study. Thin-Walled Structures, 208, p. 112839.
10. S. Motaharibidgoli, "Generating Traveling Waves in Finite Media Using Single-Point Excitation via Passive Absorber," 2023.
11. M. Berardengo, O. Thomas, C. Giraud-Audine, and S. Manzoni, "Improved resistive shunt by means of negative capacitance: new circuit, performances and multi-mode control," Smart Materials and Structures, vol. 25, no. 7, p. 075033, 2016/06/14 2016, doi: 10.1088/0964-1726/25/7/075033.