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Realization of spatio-temporal boundaries using a one-dimensional active mechanical metamaterial

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1. Introduction

Wave reflection and refraction typically occur at points where the effective parameters of a medium change discontinuously in space. On the other hand, a similar scattering phenomenon can also occur when the effective parameters of an entire medium change instantaneously at a certain time. This type of scattering is known as time reflection (TR)[1], in which two types of scattered waves emerge: one traveling in the same direction as the incident wave (later-forward wave) and the other in the opposite direction (later-backward wave). In TR, the wavelengths are conserved before and after the scattering due to spatial translational symmetry. Consequently, the total energy of the wave is not conserved as the energy is exchanged with the environment to change the effective parameters. Likewise, frequencies are also not conserved before and after the scattering. This leads to phenomena such as the wave amplification and frequency translation, have potential applications in techniques like wave filtering and noise reduction.

Furthermore, when the effective parameters of the medium vary both in time and space, the boundary is called a spatio-temporal boundary, which allows for various types of modulations to the waves. While there have been several experimental realizations of the boundaries in the time domain[2-5], there are few experimental realizations of spatio-temporal boundaries.

In this study, we aim to fabricate a device that can realize an arbitrary spatio-temporal boundary and measure the wave phenomena that occur at that boundary.

2. Experimental equipments

As shown in **Fig. 1**, we fabricate a one-dimensional active mechanical metamaterial whose effective parameters as a medium can be changed by external magnetic forces. Three wires are threaded under constant tension through 15 acrylic rods arranged in parallel, with the center wire serving as the axis of rotation. A neodymium magnet is attached to the lower end of each rod, and an electromagnet is installed in a fixed position just below the magnet. A reflective seal for motion capture is attached to the top of each rod, and the displacement of this seal is recorded by motion capture cameras to measure the waves. The 15 electromagnets are independently turned on and off at desired timing using a computer program. When an electromagnet is turned on, an attractive force acts between the neodymium magnet and the electromagnet. This reduces the effective moment of inertia of the rod.

In the ongoing experiments, after manually exciting the end rod to generate incident waves, the program is run to generate a specific boundary, and the wave motions are recorded by the motion capture cameras to analyze the wave scattering due to spatio-temporal boundaries.

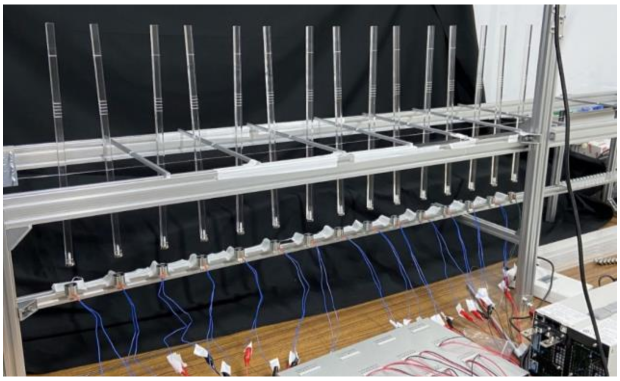

Fig.1 Overview of the one-dimensional active mechanical metamaterial.

3. Preliminary experiments and results

First, as a preliminary experiment, we tested whether magnetic force could change the effective parameters of the medium. A single pendulum is assembled using an acrylic rod with a neodymium magnet attached to the bottom. An electromagnet is also installed below the neodymium magnet. By applying the magnetic force, the period of the pendulum changed due to the change in the effective moment of inertia. The displacement of the top end of the pendulum is recorded by motion capture to derive the period. **Figure 2** shows the results. When the electromagnet is switched ON, the period decreases, and when the electromagnet is switched

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OFF, the period increases. These changes indicate the decrease and increase in effective moment of inertia, respectively. The results confirm that the effective moment of inertia of the rod can be changed by up to 38% using a neodymium magnet and an electromagnet.

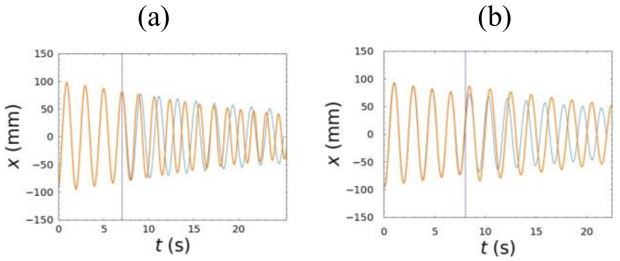

Fig. 2 Time variation of the horizontal displacement at the upper end of the pendulum. The orange curve represents the measured results, the dark blue dashed line indicates the time the electromagnet was switched, and the blue curve is a trigonometric fit of the data before switching. (a) The electromagnet switches from OFF to ON at t = 7.0 s. (b) The electromagnet switches from ON to OFF at t = 8.0 s.

4. Simulations and results

Before the experiments with the fabricated metamaterial, we run simulations with the string model to confirm TR and the scattering of waves at the spatio-temporal boundary. A commercial software COMSOL Multiphysics is used for these simulations. In the fabricated metamaterial, the effective moment of inertia of each rod varies with the magnetic force. Since the moment of inertia of each rod corresponds to the string density ρ in the string model, the wave equation of displacement $u(x,t)$ becomes

$$\frac{\partial}{\partial t}\left(\rho(x,\, t)\frac{\partial u(x,\, t)}{\partial t}\right) = S\frac{\partial^2 u(x,\, t)}{\partial x^2} \qquad (1)$$

with the string density $\rho(x,t)$ that varies in time and space and the constant tension S.

Figure 3 shows the simulation results as the series of images. TR is shown in Fig. 3(a), and the scattering of waves at the spatio-temporal boundaries of the two patterns is shown in Fig. 3(b) and Fig. 3(c), respectively. In each case, the amplitudes of the scattered waves are consistent with the scattering coefficients of later-forward waves and later-backward waves obtained by solving equation (1) under appropriate boundary conditions.

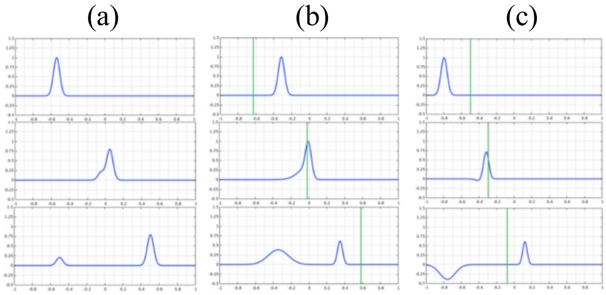

Fig. 3 (a) Waveform when the string density ρ of the entire string changes by a factor of 0.7 at a certain time. (b) Waveform when the boundary where the string density changes to 0.7 times (green line) overtakes the incident wave. (c) Waveform when the incident wave overtakes the boundary where the string density changes to 0.7 times.

5. Outlook

We are currently working on realizing the boundaries shown in Fig. 3(a)-(c) with the fabricated metamaterials and measuring the scattering phenomena at these boundaries. This study will ultimately improve our metamaterial to achieve completely arbitrary spatio-temporal boundaries, independent of the direction of travel of the incident wave and boundary, and independent of the increase or decrease in the effective parameters of the medium. If the technology that can generate arbitrary spatio-temporal boundaries is developed, it will be possible to apply modulation, such as frequency conversion and amplification, to waves in various systems.

References

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