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UTILIZING STEADY-STATE TRAVELING WAVES IN A QUIESCENT WATER ENVIRONMENT FOR PARTICLE PROPULSION

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ABSTRACT

Using steady-state traveling waves as a propulsion mechanism emerges as a highly effective strategy for displacing particles, eliminating the need for an external fluid transfer pump. This experimental inquiry delves into the intricate application of traveling waves within a beam submerged in quiescent water, deploying two distinctive force input methods to govern particle movement acoustically. The complexity of this research lies in balancing the finesse of particle motion while concurrently imposing constraints on the number of control cycles implemented. To address this challenge comprehensively, we introduce a diverse range of control cycles tailored to manipulate particles of varying sizes. Navigating the nuanced dynamics of this system requires a sophisticated approach, prompting the adoption of the Reinforcement Learning Approach. This methodological choice empowers us to discern the characteristics of traveling waves necessary for facilitating the movement of particles with divergent sizes. The utilization of Reinforcement Learning not only refines our understanding of the intricate interplay between waves and particles but also enhances our ability to optimize control strategies in this particular context.

The significance of this research extends beyond the confines of the laboratory, resonating in various applications, with particular prominence in advancing transportation mechanisms for cells and analogous entities. By elucidating the underlying principles governing the interaction between traveling waves and particles of different sizes, the findings offer invaluable insights that can be harnessed to optimize particle manipulation techniques. This holds potential implications in biotechnology, where the precision control of particle movement is pivotal for applications ranging from targeted drug delivery to the manipulation of biological cells. Furthermore, our exploration not only contributes to the theoretical understanding of particle manipulation through traveling waves but also yields tangible practical implications. The versatility of our approach, as exemplified through the successful manipulation of particles with varying sizes, underscores its potential applicability across a spectrum of scenarios, emphasizing its broader relevance within the burgeoning field of acoustic fluids.

In conclusion, the utilization of steady-state traveling waves as a particle propulsion mechanism, as showcased in this experimental investigation, not only holds promise for the advancement of particle manipulation but also underscores its potential impact in diverse applications. Through the thorough exploration of control cycles and the strategic application of the Reinforcement Learning Approach, this research not only contributes to the theoretical knowledge underpinning acoustofluidics but also provides practical methodologies for precision particle manipulation. These advancements are poised to play a pivotal role in shaping the future landscape of biotechnology and related fields, where fine-tuned control over particle dynamics is a cornerstone for innovation and progress.

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1 INTRODUCTION

The growing demand for underwater vehicles for ocean exploration has spurred research into more efficient propulsion systems. Emulating marine organisms' swimming patterns aims to improve maneuverability and efficiency [1]. Traditional propulsion systems with many rotating parts limit overall efficiency due to maintenance requirements [2]. This study seeks to develop a propulsion method with fewer rotating parts. By inducing undulatory motions in finite structures, researchers aim to unlock new possibilities for underwater propulsion [3]. This experimental study focuses on generating propulsive forces using steady-state structure-borne traveling waves in one-dimensional beams for advanced underwater propulsion applications. The investigation into the generation of mechanical waves constitutes a foundational domain of inquiry within the realms of both physics and engineering [4]. Waves may be categorized as either traveling waves or standing waves, contingent upon whether energy propagation occurs along the direction of their propagation or is localized to specific regions. Previous studies have elucidated that the application of a singular force to a structure can induce waves that, due to impedance alterations, undergo reflection, leading to the formation of standing waves [5, 6]. Nonetheless, by stimulating the structure with two single-point force inputs featuring a phase differential, a hybrid wave may emerge, incorporating elements characteristic of both traveling and standing wave phenomena. Experimentally generating pure traveling waves within finite structures presents a notable challenge owing to the propensity for reflections at boundaries [7]. Nonetheless, recent investigations have demonstrated the successful generation of traveling waves across a spectrum of structures including strings [5, 8], beams [4, 9, 10], cylinders [6], and two-dimensional surfaces [11]. Malladi et al. [12] have contributed to this field by devising a numerical model aimed at generating traveling waves within a 1D beam under varied boundary conditions. Subsequent experimental validation of this model was conducted using a brass beam, where piezoelectric elements were employed to impart force inputs. Additionally, experimental endeavors have been undertaken to induce traveling waves within slender two-dimensional plates, employing multiple piezoelectric actuators [13]. In general, the capacity to customize traveling waves within structures holds significant ramifications for numerous engineering domains, including underwater propulsion systems [3, 14, 15] and thermal management systems. The outcomes derived from these investigations offer crucial perspectives into wave dynamics across diverse structural contexts, fostering the potential for the advancement of engineering solutions that are both more effective and sustainable. The subsequent section delves into the experimental configuration employed in this study to induce traveling waves.

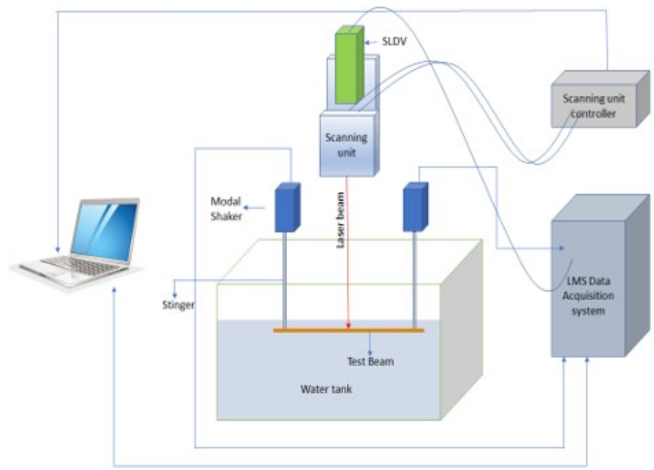
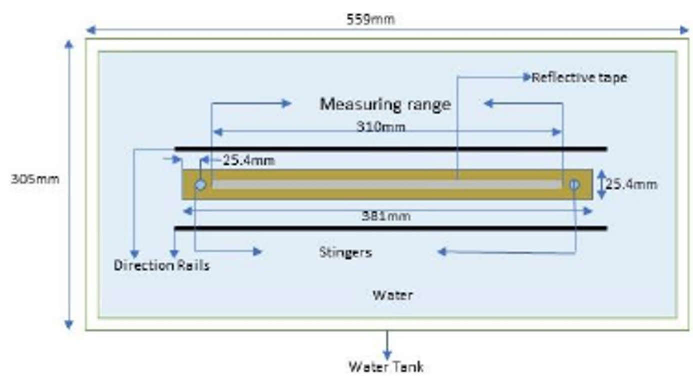
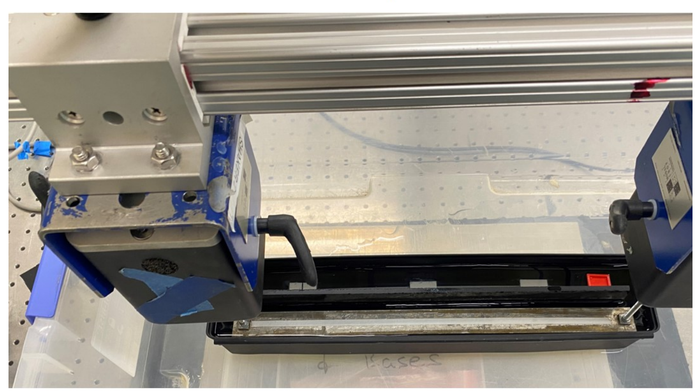


FIGURE 1: Schematic Diagram for Experimental Setup for SBTW generation and modal analysis



a)



b)

FIGURE 2: Beam Setup in Water

2 UNDERWATER MODAL TESTING

2.1 MODAL TESTING SETUP

The illustration presented in Figure 1 delineates the process of generating traveling waves within a one-dimensional beam. The Figure 4 shows an experimental setup designed and crafted using 80:20 aluminum structures to provide robust support for the modal testing equipment. Within this framework, a Polytec PDV 100 single-point laser vibrometer and two Modal Shop smart shakers are securely held in place. To simulate a tranquil underwater environment for testing purposes, a black container was utilized. Inside this container, an arrangement was implemented to establish a direct pathway for the object to traverse the water's surface. Anchored to the two shakers using a 254 mm threaded rod imposing pinned-pinned boundary conditions on, a 6061 Aluminum beam measuring 381mm x 25.4mm x 0.635mm completes the setup. To avoid residual stresses in the beam, it is crucial to guarantee correct alignment between the shakers and the beam during modal analysis [16]. As a result, it was crucial that in this arrangement, the separation between the two shakers and the two test beam holes coincide, which is illustrated in Figure 2a). With this alignment, the force coming from the shakers through the stingers is guaranteed to be exactly perpendicular to the beam's surface. An essential component of this testing is water height. The damping, mass, and stiffness acting on the aluminum beam would all rise as the water height above its surface increased. Thus, following a few attempts, the water's surface height above the beam was kept constant at 8 mm. Below the beam, the water's depth measured 34 mm. The height of water above the beam is depicted in Figure 3 .

2.2 EXPERIMENTAL FRF

A Single Laser Doppler Vibrometer (SLDV) was used to measure the vibrations at a single point on the beam. Siemens's LMS Data Acquisition system was connected to the SLDV and two shakers. The system was stimulated using two-force input approaches. A multi-input multi-output (MIMO) force feedback test was then carried out, using a chirp signal as the input force. Figure 6 below shows the resultant FRF.

3 TRAVELING WAVE GENERATION

The research conducted by Malladi et al. has showcased the ability to tailor structure-borne traveling waves through the simultaneous application of dual-point forces on the test structure [10]. This experimental inquiry utilized a pair of modal shakers to concurrently stimulate an aluminum beam. The voltage signals directed to these shakers were set at a frequency positioned midway between two consecutive mode shapes or resonant frequencies, maintaining a phase difference of 90 degrees. The schematic of the experimental beam model is depicted in the figure, illustrating the setup with both shakers excited at the same voltage amplitude, denoted as V, albeit with a phase difference represented by ϕ. Upon the application of forces, the structure-borne traveling wave (SBTW) emerges through the superposition of responses from each shaker. When both shakers are excited at identical frequencies, the resulting operational deflection shape (ODS) reflects the superimposed response of individual ODSs from each shaker. The pivotal element driving the generation of desired superposition and ensuing traveling waves is the maintained phase offset in the actuators' input signals.

The force input from shaker 1 is illustrated as $V_1 = A\sin(2\pi f)$, while that from shaker 2 is denoted as $V_2 = A\sin(2\pi f \pm \phi)$. Consequently, the amalgamation of these two forces to produce a traveling wave is exemplified in the following Equation (1).

$$\mathbf{SBTW} = A\sin(2\pi f) \pm A\sin(2\pi f \pm \phi) \tag{1}$$

The effectiveness of traveling waves is contingent upon the phase disparity between the voltage signals supplied to the actuators. A conventional structure-borne traveling wave comprises both traveling and standing wave components, with an improvement in the wave's quality resulting in a reduction of the standing wave contribution. The assessment of traveling wave quality is typically conducted using the cost function method, as outlined in Malladi et al.'s investigation [3].

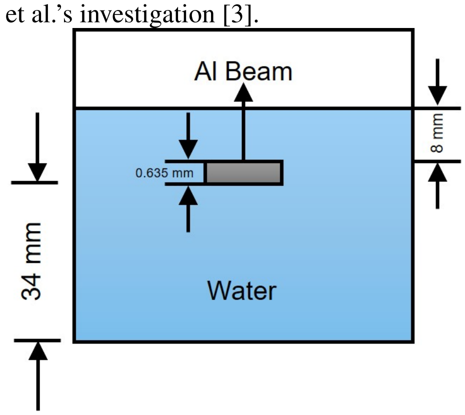
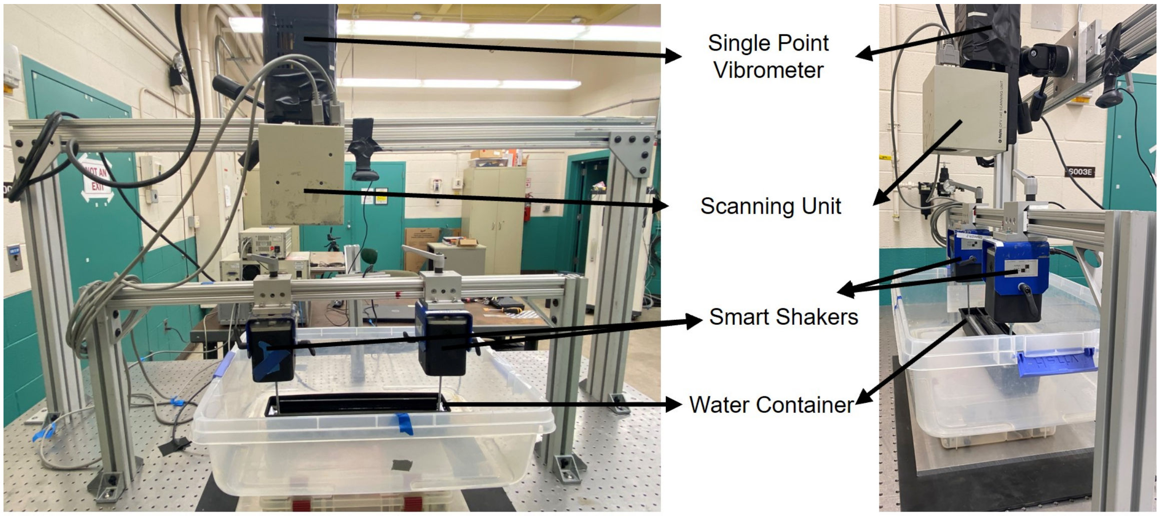


FIGURE 3: Schematic for Depth Measurement for Beam immersed in Water



a) b)

FIGURE 4: Experimental Setup for SBTW generation and modal analysis: a) Front View, b) Side View

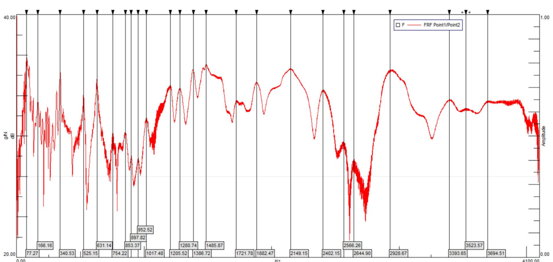


FIGURE 5: FRF measured for a point underwater on the beam

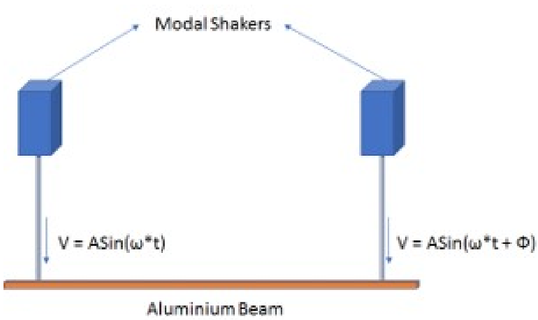


FIGURE 6: Schematic diagram for SBTW Setup using two force method

4 PROPULSION THROUGH SBTWs & IMAGE PROCESSING

Utilizing traveling wave (TW) generation, a 3D-printed object is maneuvered atop the water's surface. To induce motion in the object, structured-borne traveling waves (SBTW) are generated by employing excitation frequencies with an increased voltage range, resulting in undulating motion in the water. The object is positioned above the water's surface to illustrate its movement aligned with the direction of wave propagation.

Subsequently, the motion is captured and analyzed using a Zed2 stereo camera Figure 7 to elucidate the object's velocity under varying frequencies and excitation voltages. Additionally, several videos are recorded with alterations in wave direction to demonstrate the potential for directional control facilitated by the structural dynamics of the wave. These recorded videos undergo post-processing via blob analysis to track the object's motion over time, yielding insightful observations throughout the experimentation process.

The experimentation process involved several key steps to analyze the movement of a 3D-printed red-colored square of dimension $20mm \times 20mm \times 2mm$ weighing $2.53gm$ propelled by traveling waves. Firstly, camera calibration was conducted to obtain essential camera properties such as focal length and rotational matrices. This calibration process utilized a checkerboard pattern of 8×11 checkers with a size of $15cm$ to determine re-projection errors and establish a coordinate system. Subsequently, blob analysis was employed to analyze specific regions (blobs) within captured images, extracting features like shape, area, and position. This analysis facilitated the tracking of the object's motion over time, albeit with potential noise introduced into the coordinate system. To mitigate this noise, a Kalman filter was utilized for probabilistic analysis, predicting the object's motion in the presence of data uncertainty. This filtered data was then mapped onto the world coordinate system to assess the ob-

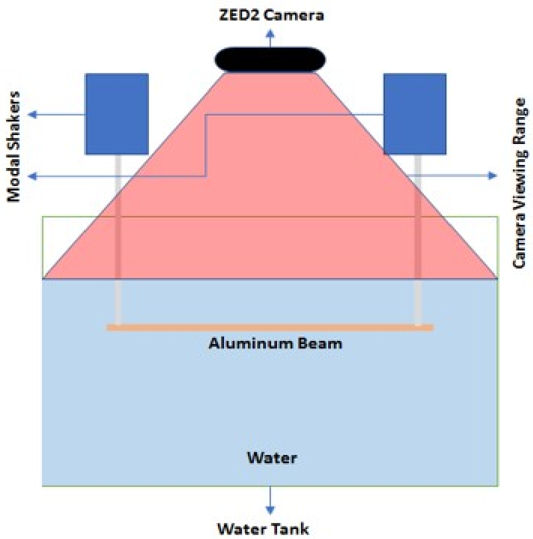


FIGURE 7: Schematic Diagram of Image Processing Setup

ject's speed and distance in real time. The experimental setup involved generating traveling waves in an underwater beam using shakers excited with sinusoidal signals. Blob analysis was performed on these videos to track the object's movement in both pixel and world coordinate systems. Additionally, displacement and velocity were plotted against time to analyze the object's motion.

5 RESULTS & CONCLUSION

In this study, we selected a blob as our object of interest and applied a structure-borne traveling wave (SBTW) at a frequency of 432.8 Hz, with an excitation voltage of $0.2V$ on the beam, maintaining a phase difference of 90°. The results obtained, as depicted in Figure 8 and Figure 9, demonstrate the effectiveness of our approach.

Our image processing techniques yielded promising outcomes, with the image tracking closely aligning with the trajectory of the particle centroid. Notably, the particle initiated motion at the 5-second mark and continued for 158 seconds, covering a total displacement of 310 mm.

These findings underscore the successful application of SBTW for controlled motion, as evidenced by the accurate tracking and significant displacement achieved within the specified duration. Such results hold promising implications for the utilization of traveling waves in various propulsion and manipulation systems, paving the way for further exploration and development in this domain.

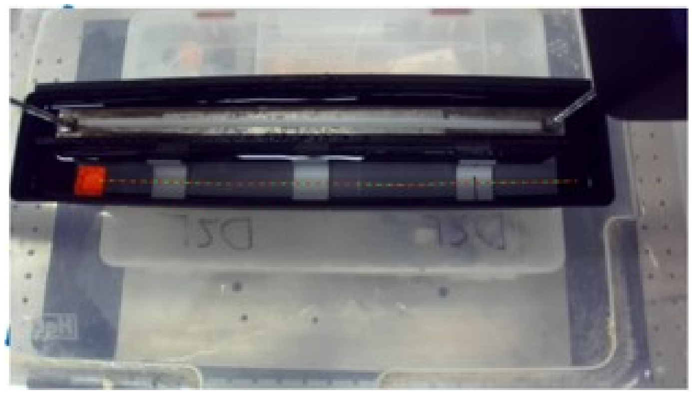


FIGURE 8: Image Processing at $432.8Hz$ with $0.2V$ applied

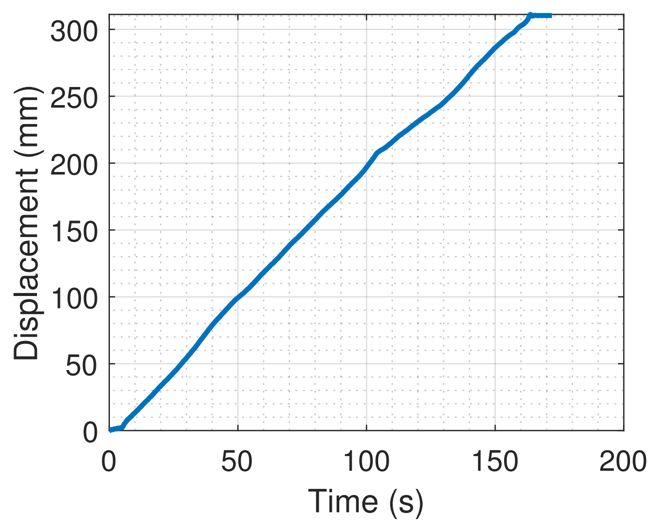


FIGURE 9: Displacement vs Time for the blob

6 FUTURE SCOPE

The ongoing research endeavors also encompass refining procedures and minimizing errors within the existing framework. As part of these efforts, the study will incorporate reinforcement learning techniques into the control feedback cycle. This integration aims to optimize the implementation of diverse traveling wave patterns with varying parameters, facilitating precise manipulation of the particle as per specific requirements. Updates reflecting these advancements will be included in the paper, underscoring the continuous evolution and potential applications of reinforcement learning in enhancing control feedback mechanisms.

7 ACKNOWLEDGEMENT

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