Chapter 18
Experimental-Based Investigation of Standing and Traveling Waves in a Petri Dish using Piezoelectric Actuation

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Abstract This study experimentally investigates the vibrational behavior of a circular Petri dish to characterize and control standing and traveling wave fields through piezoelectric actuation. Harmonic excitation was applied using four piezoelectric stacks, and out-of-plane surface motion was captured with a Scanning Laser Doppler Vibrometer (SLDV). The resulting frequency response functions (FRFs) were analyzed directly to extract modal parameters including natural frequencies, damping ratios, and mode shapes. Based on these experimentally derived characteristics, a two-point excitation scheme was developed in which actuator pairs were driven simultaneously with prescribed phase offsets. The results show that excitation at natural frequencies produced standing waves, while driving between resonances with a 90° phase difference yielded traveling waves. Additionally, the actuator configuration determined the wave type: adjacent actuators generated rotational traveling waves, whereas diagonally opposed actuators produced translational patterns. These findings demonstrate how FRF-based experimental modal analysis can be used to design phase-controlled excitation strategies that selectively generate and tune wave kinematics in thin circular structures. The outcomes establish a foundation for Petri-dish-based platforms capable of precision particle transport, fluid manipulation, and resonant sensing applications.

Keywords Traveling waves · Standing waves · SLDV · Two-point excitation · Petri-dish

Introduction

Mechanical waves are commonly categorized by how they transmit energy—either as traveling waves or standing waves. In standing waves, energy remains localized to specific spatial regions, whereas traveling waves transport energy through the medium. This distinction is crucial in dynamic systems analysis and has broad applicability across disciplines. In biological settings, many aquatic organisms and microorganisms employ traveling-wave kinematics for propulsion, reflecting principles shared with structural dynamics and fluid–structure interactions. Over more than five decades, wave-based locomotion has been extensively studied. Traveling waves underpin flagellar and ciliary motion in microorganisms [1, 2, 3, 4, 5, 6, 7] and undulatory swimming in fish [8, 9, 10, 11, 12, 13], inspiring engineered systems ranging from robotic locomotion [14, 15, 16, 17, 18, 19] and bio-inspired propulsion [20, 21, 22, 23] to biomechanical structures such as the cochlea [24, 25, 26, 27, 28, 29], where wave propagation is central to function. Beyond biological and bio-mimetic systems, traveling waves are also exploited to reduce skin-friction drag on aerodynamic surfaces [30, 31, 32, 33] and to enable non-prehensile transport at micro and macro scales via controlled surface actuation [34, 35]. Given this significance,

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multiple strategies have been developed to generate traveling waves in finite structures, including strings [36, 37, 38, 39, 40, 41, 42, 43], beams [44, 45, 46, 47, 48], plates [49, 50, 51, 52, 53, 54], rings [55, 56], and rigid-walled circular acoustic ducts [57, 58]. Bucher et al. [56] showed that exciting a structure at two locations with a 90° phase difference, at a mean frequency between adjacent modes, induces directional traveling waves. Malladi and Avirovik [34, 44, 46] extended this two-point approach to piezo-augmented one-dimensional beams under varied boundary conditions, demonstrating theoretically and experimentally that both frequency and phase govern wave formation, beyond a fixed 90° offset at the mean frequency. In parallel, alternative control strategies have been explored. Blanchard et al. [38, 39] investigated passive suppression in fixed strings using a spring–dashpot attachment, revealing localized damping that can yield coexisting traveling and standing components through complex modal behavior and enabling passive confinement via proper tuning. Motaharibidgoli et al. [47] proposed a one-point excitation with a spring–damper to generate hybrid modes in Euler–Bernoulli beams and to distinguish and optimize traveling versus standing response. While effective on linear beams, single-point actuation is less practical on small, symmetric platforms, where mounting and achieving consistent directionality from a single source are sensitive to alignment and coupling.

Complementing structural approaches, surface acoustic waves (SAWs) [59, 60, 61] and broader acoustofluidic platforms [62, 63] enable biocompatible manipulation of micro/nanoparticles and cells, achieving on-chip transport [64], focusing, separation [65], and mixing [66]. Acoustic tweezers—spanning standing/traveling, bulk/surface, and streaming-driven modes—offer precise trapping, patterning, and translation from extracellular vesicles to single cells and small organisms [67, 68, 60, 69]. Despite an extensive body of work, direct implementations on standard Petri dishes—ubiquitous in cell and microbiology laboratories—remain limited, owing to constraints imposed by their circular symmetry, small footprint, and requirements for mounting, sterility, and optical access. These gaps motivate Petri-dish-centric strategies that preserve biocompatibility while delivering reliable wave directionality.

This study adopts an experimental framework that leverages modal analysis to estimate the traveling-wave fields that can be generated on standard Petri dishes for *in situ* microparticle transport, separation, and mixing in culture-relevant media. Guided by identified mode shapes and resonance frequencies, we determine drive frequency and phase relationships; accordingly, a two-point excitation scheme is proposed to achieve stable phase control and reliable wave directionality on circular substrates. While full realization of the traveling-wave fields is not presented here, the methodology and design parameters established in this work specify the conditions under which such fields are achievable. This preliminary effort provides the foundation for future tasks involving both single- and multi-particle control, including targeted transport, selective separation, and programmable mixing.

Experimental Setup

In this study, a borosilicate glass Petri dish served as the test specimen for modal analysis. Four PiezoDrive stack actuators were positioned on a 5cm grid, each mounted 2mm off-center relative to the dish, which was supported by half-sphere holders. The actuators were powered by a PiezoDrive PD200X4 amplifier with a gain of 20V / V and were driven using OptoScan software, which simultaneously scanned the dish surface during testing. The Scanning Laser Doppler Vibrometer (SLDV) provided the chirp excitation signal to the actuators and used their voltage outputs as the reference channel (see

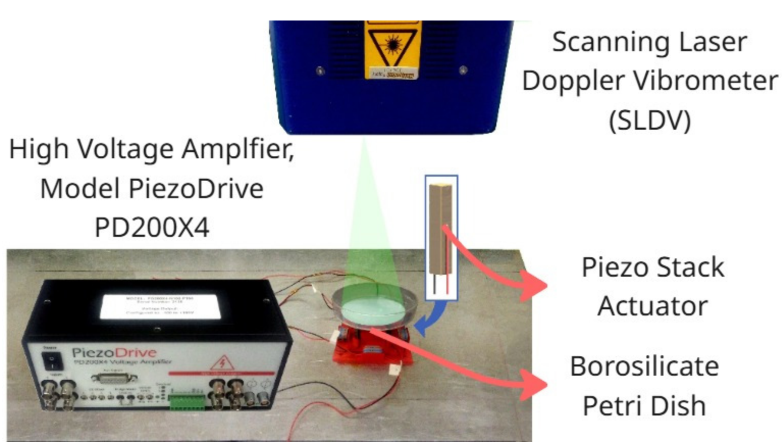


Fig. 1 Experimental setup for Petri dish modal analysis

Figure 1). The Petri dish was kept enclosed, with its lid secured to the base using double-sided tape. A circular piece of reflective tape was placed on the bottom surface to enable vibrometer measurements. For potential follow-up testing, an additional piezo actuator was fixed inside the dish. A 448-point circular mesh was defined in the OptoScan software on the dish base, consisting of 50 radial lines and 9 concentric rings. To account for the added actuator, three points were removed and nine were shifted. Modal data were collected at all 448 points for each stack actuator, resulting in four independent modal analyses.

The chirp input had an amplitude of 0.1 V, swept from 0–2000 Hz, and a duty cycle of 80%. Measurements were acquired at a maximum frequency of 50 kHz with 102,400 spectral lines, corresponding to a spectral resolution of 488.281 mHz and a sampling rate of 128 kS/s, satisfying the Nyquist criterion. Data collection was triggered at 0.05 V on the leading edge with a 1% pre-trigger factor. At each scan point, seven averages were recorded with a 0.01 s delay between acquisitions, and a rectangular window was applied during signal processing.

Data Driven Model for Traveling Wave Generation

After obtaining the frequency response functions (FRFs) of the petri-dish, each measurement point provides four responses, one from each stack actuator.

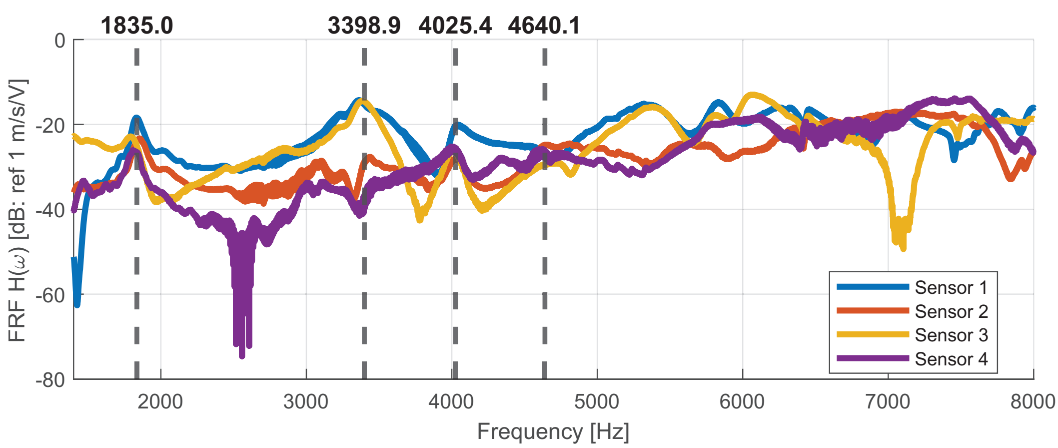


Fig. 2 Frequency response function (FRF) highlighting resonant peaks corresponding to natural frequencies

These FRFs can be arranged as

$$\mathbf{H}(x_i,\,\omega) = \begin{bmatrix}\mathbf{H_1} & \mathbf{H_2} & \mathbf{H_3} & \mathbf{H_4}\end{bmatrix}, \tag{1}$$

where $\mathbf{H}(x_i,\,\omega) \in \mathbb{C}$ denotes the FRFs at point x_i for a given frequency ω, and $\mathbf{H_1},\ \mathbf{H_2},\ \mathbf{H_3},\ \mathbf{H_4}$ represent the responses associated with actuators 1 through 4.

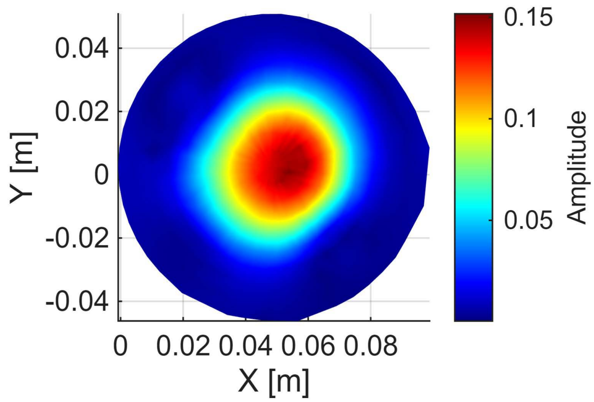
It is well established in prior work [56, 46, 70, 71] that traveling waves can be generated through two-point excitation. This is achieved by driving both actuators at a frequency located between two adjacent natural frequencies while maintaining a 90° phase difference. Under these conditions, the operational deflection shape (ODS) becomes a superposition of the individual actuator responses, with the enforced phase offset serving as the key mechanism that promotes traveling-wave formation.

For two-point excitation, the input to actuator 1 is given by $V_1 = A_1 \sin(2\pi f t)$, and the input to actuator 2 by $V_2 = A_2 \sin(2\pi f t \pm \phi)$. The combined excitation, which yields a traveling wave, is expressed as

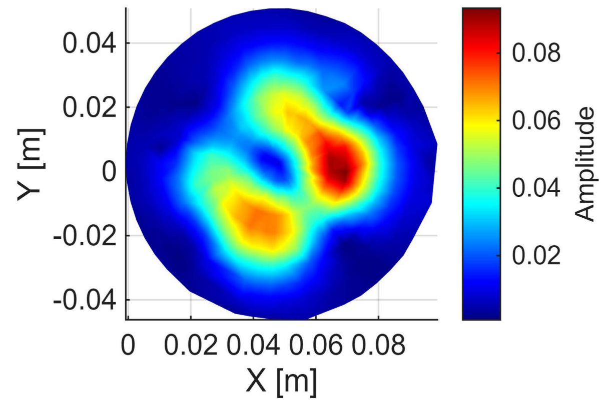
$$\mathrm{TW} = A_1 \sin(2\pi f t) \ \pm\ A_2 \sin(2\pi f t \pm \phi), \tag{2}$$

where A_1 and A_2 are the excitation amplitudes, f is the frequency, t is time, and ϕ is the phase difference, equal to 90° for an ideal traveling wave. In contrast, standing waves occur when excitation is applied at a natural frequency. Under this condition, the actuators respond either in-phase (0°) or out-of-phase (180°), dictated by the symmetry of the corresponding mode shape. To confirm whether the procedure generates a traveling wave, the FRF-based data-driven model is used to construct the ODS of the petri-dish when two of the four stack actuators are excited simultaneously, as described in Equation (2). The ODS is obtained from the real part of the velocity response,

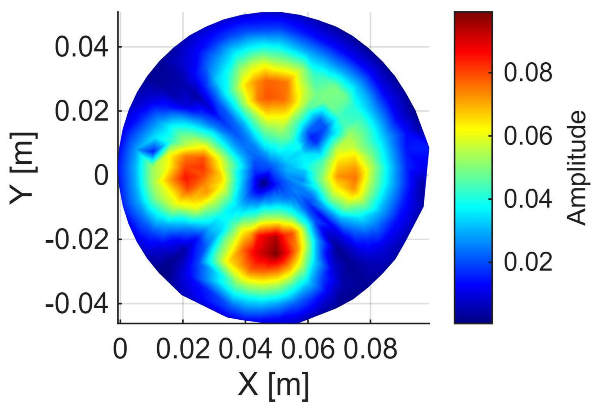
$$\mathbf{v}(t) = \mathrm{Re}\big(\tilde{v} e^{\iota \omega t}\big)\,, \tag{3}$$



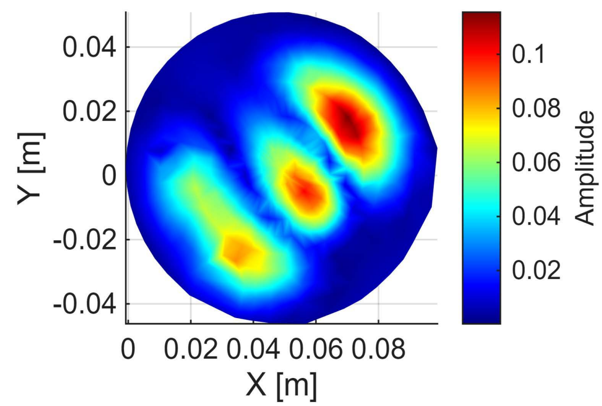
(a) Modeshape of the Petri-dish at 1835 Hz



(b) Modeshape of the Petri-dish at 3398.9 Hz



(c) Modeshape of the Petri-dish at 4025.4 Hz



(d) Modeshape of the Petri-dish at 4640.1 Hz

Fig. 3 Modeshapes of the Petri-dish at selected frequencies

where $\mathbf{v}(t)$ denotes the velocity at a point over time t, and $\tilde{v}$ is the complex velocity response due to two-point excitation. Combining Equation (1) and Equation (2), $\tilde{v}$ can be expressed as

$$\tilde{v}(x_i) = \begin{bmatrix} \mathbf{H_1} & \mathbf{H_2} & \mathbf{H_3} & \mathbf{H_4} \end{bmatrix} \begin{Bmatrix} A_1 e^{\iota \phi_1} \\ A_2 e^{\iota \phi_2} \\ A_3 e^{\iota \phi_3} \\ A_4 e^{\iota \phi_4} \end{Bmatrix}, \tag{4}$$

where A_1, A_2, A_3, A_4 are the excitation amplitudes applied to the actuators, and $\phi_1, \phi_2, \phi_3, \phi_4$ are their respective phase angles. In this study, actuator pairs $(1\text{–}2)$, $(1\text{–}3)$, and $(1\text{–}4)$ are considered, with only two actuators excited at a time. For simplicity, the voltage amplitudes are fixed at unity, while the phases are assigned as $0°$ and $90°$ for the respective actuators. The resulting standing and traveling wave patterns are presented in Figure 3 and Table 1, respectively, in the following sections.

Results

The analysis focused on the frequency range of 1400–5000 Hz, within which the Petri dish exhibited four natural frequencies associated with standing waves and three frequencies where traveling waves were observed. These natural frequencies were identified directly from the measured frequency response functions (FRFs), and the corresponding wave types are summarized in Table 2. The operating deflection shapes (ODSs) were then evaluated under three actuator combinations to characterize the vibration patterns across the dish. The measured FRF for standing waves is shown in Figure 2, where resonant peaks indicate the four natural frequencies. The associated mode shapes are presented in Figure 3, which follow the expected behavior of circular plates. The FRF highlighting the frequencies corresponding to traveling waves is given in Figure 4. In this case, the regions between resonant peaks were used to identify three traveling-wave frequencies. The corresponding ODSs for these traveling modes, measured under three different actuator pairings, are shown in Table 1.

Clear trends emerged across the different actuator combinations. When actuators were positioned along vertical or horizontal axes (Stack Actuator 1-2 and Stack Actuator 1-4), the resulting traveling waves exhibited rotational patterns. In contrast, the diagonal combination (Stack Actuator 1-3) produced transverse traveling waves. Increasing frequency also led to greater spatial complexity: at 4332.5 Hz, the waveforms contained more peaks than at lower frequencies, reflecting the higher-order nature of the response.

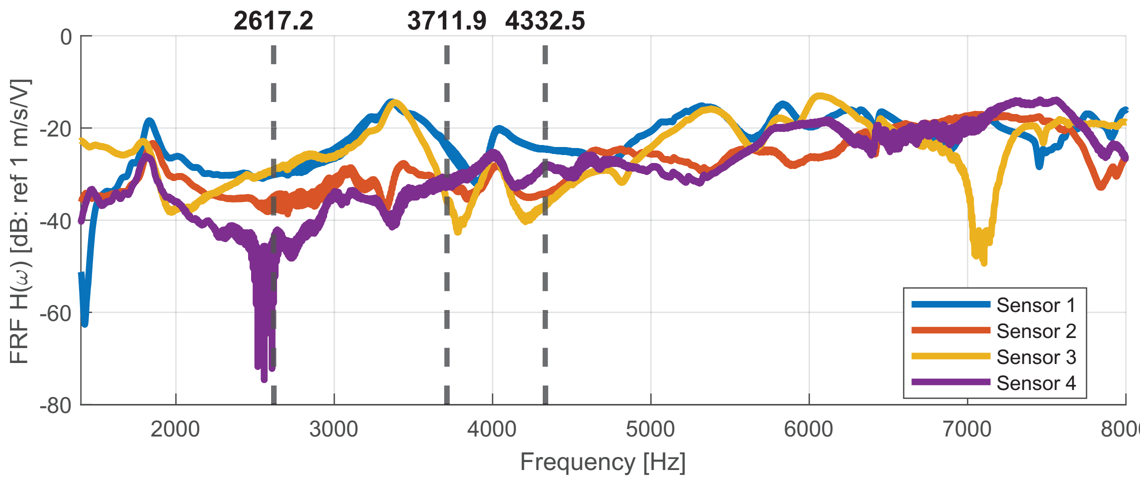


Fig. 4 Frequency response function (FRF) highlighting frequencies corresponding to traveling waves

Table 1 Traveling wave frequencies tested across piezo actuator combinations

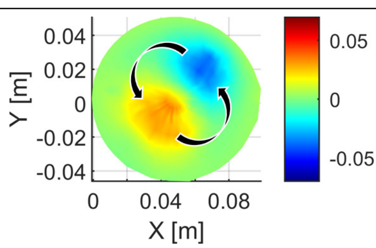
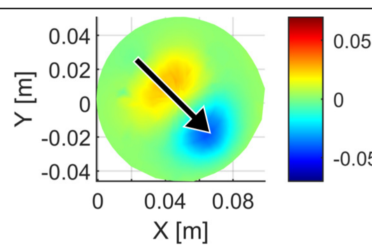
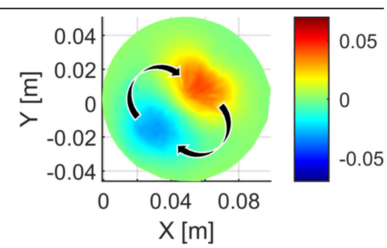
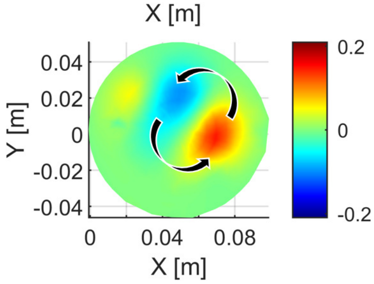
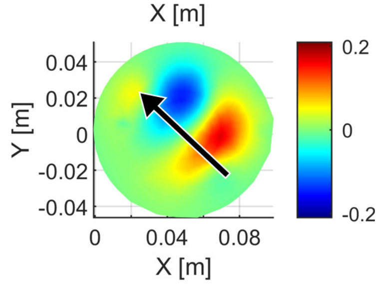
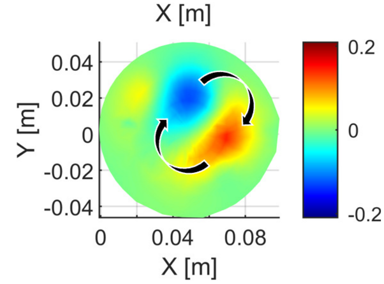
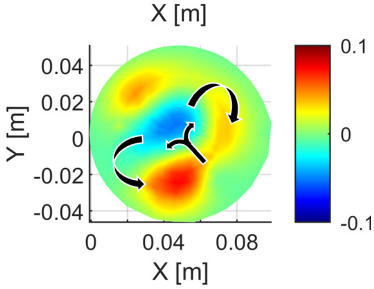
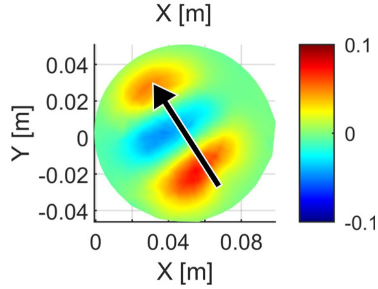
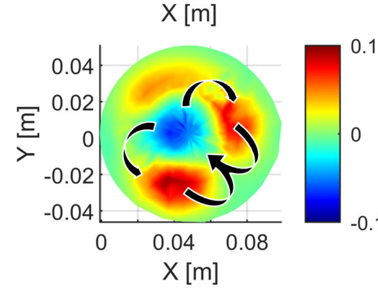
TW Frequency	Piezo Combinations		
	Stack Actuator 1–2	**Stack Actuator 1–3**	**Stack Actuator 1–4**
2617.2 Hz			
3711.9 Hz			
4332.5 Hz			

Table 2 Identified frequencies and corresponding modal or traveling-wave responses

Frequency (Hz)	Remarks
1835.0	1st mode shape
2617.2	Traveling wave
3398.9	2nd mode shape
3711.9	Traveling wave
4025.4	3rd mode shape
4332.5	Traveling wave
4640.1	4th mode shape

Conclusion

From the results, it is evident that a traveling wave can be generated on the free–free petri-dish through two-point excitation. An important observation, highlighted in Table 1, is that altering the actuator pair while maintaining the same excitation frequency and phase produces qualitatively different traveling-wave patterns. Specifically, when adjacent actuators are excited, the resulting response resembles a rotational traveling wave, whereas excitation from diagonally opposite actuators leads to a translational traveling wave. These distinctions are not only of theoretical interest but also carry practical implications. The ability to selectively generate rotational or translational traveling waves by simply varying actuator placement demonstrates a tunable actuation strategy for controlling wave characteristics. Such control opens up opportunities for employing spatially biased traveling waves (SBTWs) in future applications, particularly for manipulating particle trajectories on the petri dish. Potential extensions include single-particle transport with high precision as well as coordinated multi-particle manipulation, offering a pathway toward advanced lab-on-chip platforms and microfluidic control systems.

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Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the author(s) used ChatGPT to edit the language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

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