Low-frequency water-wave bandgap of flexible metastructures

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Introduction

Surface gravity waves contain both valuable renewable energy and destructive potential, threatening coastal infrastructure. Metamaterials—artificial structures capable of manipulating wave propagation—offer new possibilities for wave manipulating. This study introduces flexible oscillating-body metamaterials (FOBMMs) composed of bottom-mounted flexible blades.

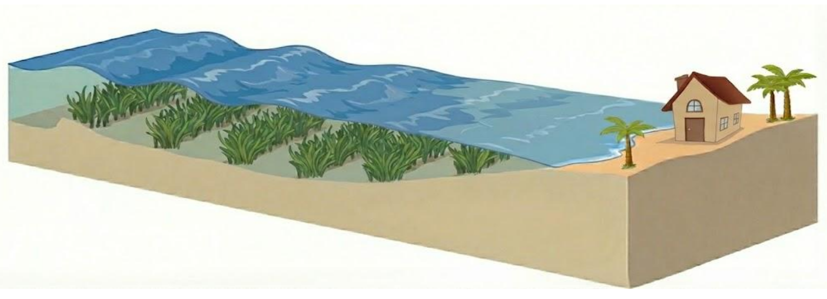

Fig. 1 Aquatic plants attenuate water waves

These blades are mounted on the seabed, resemble the swaying seaweed, and respond dynamically to the excitation of waves. These blades act as local resonators that interact strongly with incident waves, enabling low-frequency wave attenuation and the creation of broadband bandgaps, which conventional Bragg-type structures fail to achieve.

Methodology

Referring to Fig. 2, the finite metamaterial structure consists of N bottom-standing barriers, which are deployed in a fluid domain Ω with infinite horizontal extent and finite depth H.

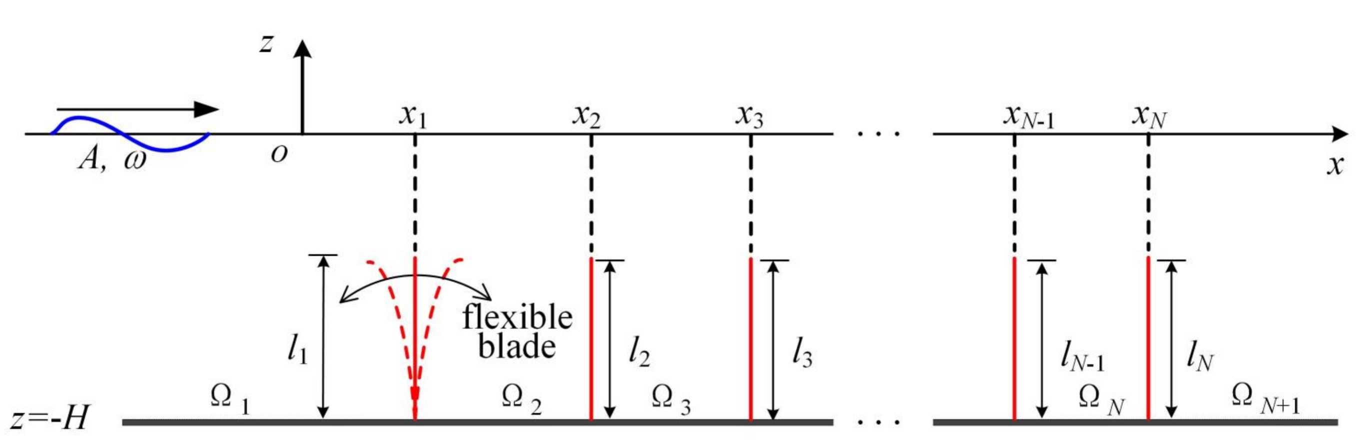

Fig. 2 Schematic diagram of a wave interacting with FOBMMs

A theoretical model describing the interaction between FOBMMs and water waves is developed by combining linear potential flow theory for water waves and Euler–Bernoulli beam theory for flexible blades.

$$E_n I_n \partial_z^4 w_n - \omega^2 \rho_n h_n w_n = i\omega\rho(\phi|_{x=x_n^-} - \phi|_{x=x_n^+}) \quad (1)$$

$$\nabla^2\phi^\chi = 0\ \forall(x,z)\in\Omega;\ \partial_z\phi^\chi = 0 \cdot\ z=-H;\ \partial_z\phi^\chi = \frac{\omega^2}{g}\phi \cdot\ z=0. \quad (2)$$

The matched eigenfunction method is adopted for the boundary value problem of wave motion and modal expansion technique is used for the initial value problem of structure motion.

$$W_{n,\zeta}(E_nI_n\kappa_{n,\zeta}^4 - \omega^2\rho_nh_n)l_n + i\omega\sum_{p=1}^{N}\sum_{L=1}^{\infty} f_{n,\zeta}^{p,L} W_{p,L} = F_{n,\zeta}^e \quad (3)$$

$$\phi_i^\chi = \sum_{j=0}^{\infty}\left(B_{i,j}^\chi e^{\lambda_j x} + C_{i,j}^\chi e^{-\lambda_j x}\right) Z_j(z),\ (x,z)\in\Omega_i \quad (4)$$

An integral-equation technique is applied to solve the unknown coefficients of velocity potential. These complex far-field amplitudes should satisfy the energy conservation equation, it reads $R^2+T^2=1$.

Research accomplishments

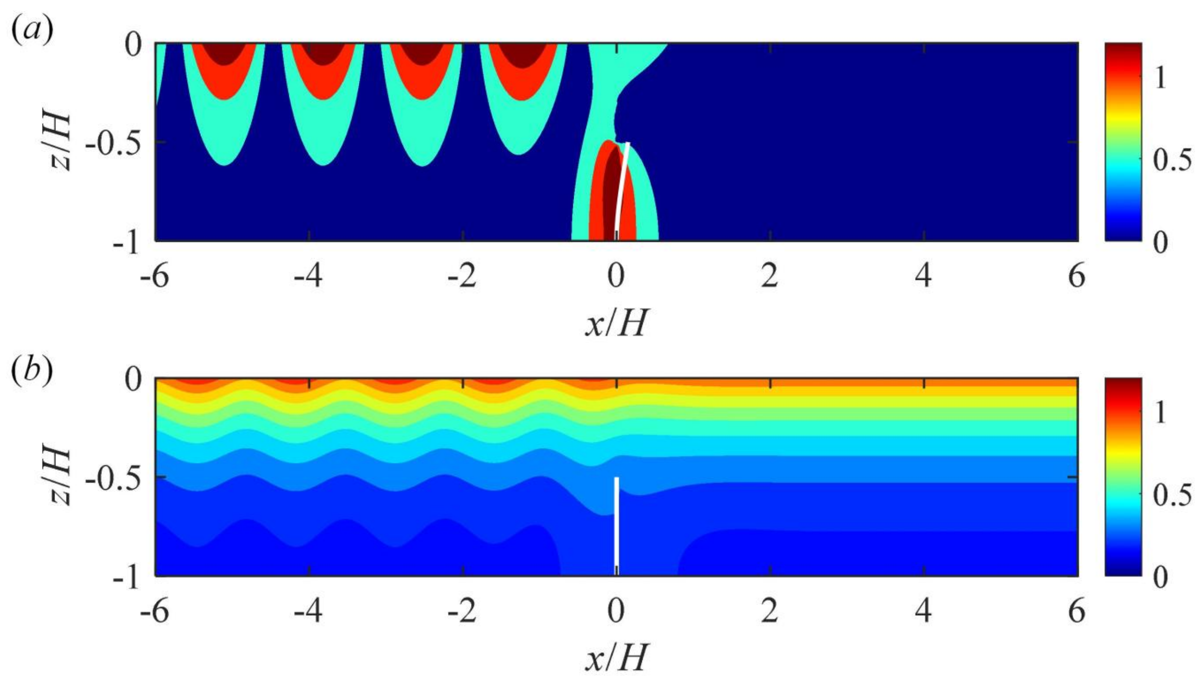

Fig. 3 Color plots of the velocity potential in the fluid domain, with the wave incident from the left inlet at resonant Frequency. (a) Flexible and (b) fixed blade

As shown in Fig. 3(a), there exists a local energy amplification around the flexible blade at the resonant frequency. This localized energy concentration corresponds to a zero-group-velocity mode within the wavenumber space indicating that wave propagation is effectively impeded due to the strong coupling between the incident wave and the resonant mode of the flexible resonator.

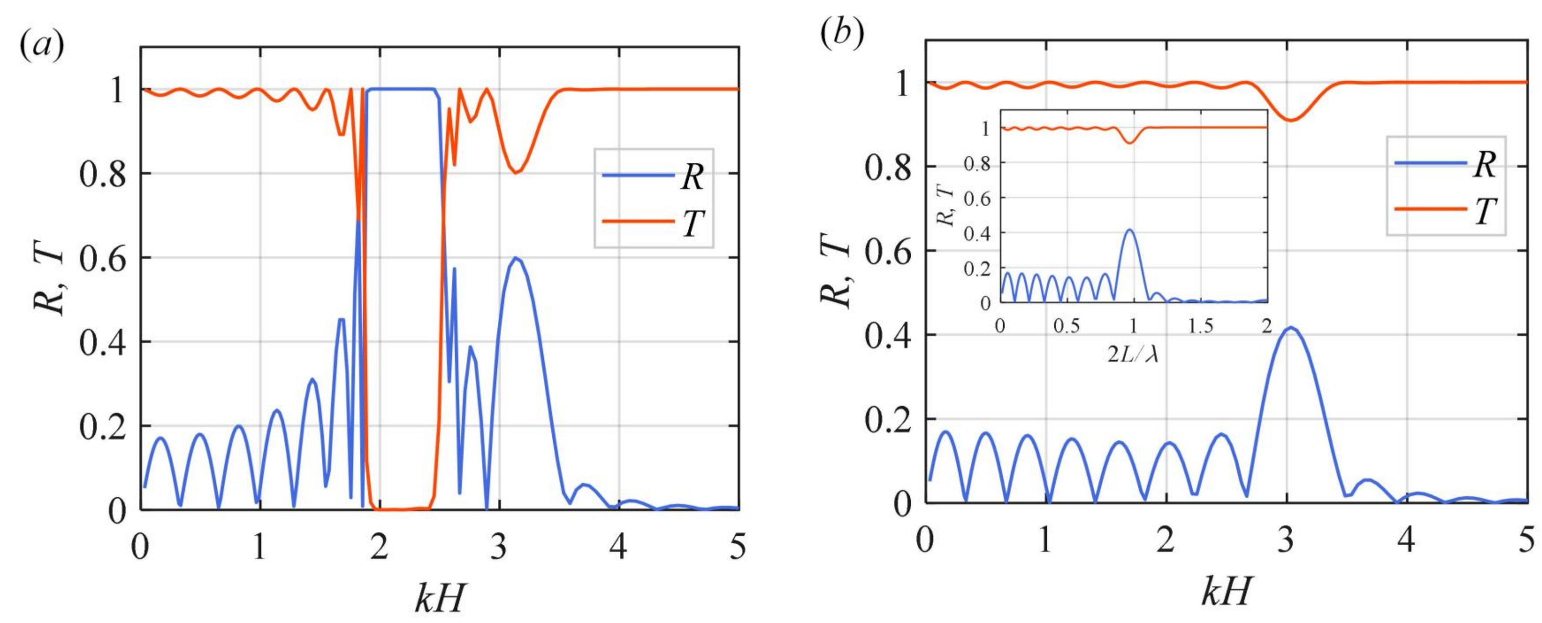

Fig. 4 Wave reflection and transmission coefficients versus wave frequency for (a) periodic flexible blades and (b) periodic fixed blades.

Fig. 4(a) demonstrated a low-frequency LR bandgap in flexible blade array, and there are Bragg resonance in the fixed blade array as indicated in Fig. 4(b).

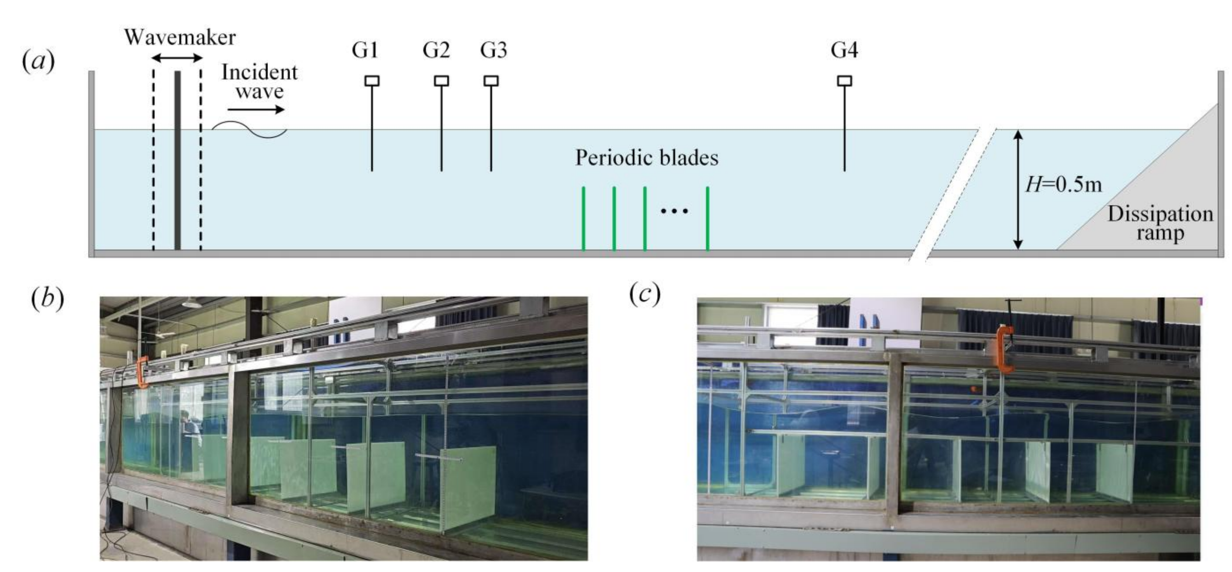

Fig. 5(a) Schematic diagram of the testing facility, experimental setup, and physical model; Experimental photograph of the (b) flexible and (c) rigid blade array.

The experimental facility and physical model are delineated in Fig. 5. Experiments confirmed significant wave attenuation when flexible blades resonate with incident waves.

Conclusions

- Developed a metamaterial system capable of attenuating long-period, low-frequency water waves.
- Revealed the local resonance mechanism of flexible blade resonators and its role in wave suppression.
- Created broad and tunable low-frequency bandgaps by periodic flexible resonators.
- Experimentally evaluated the performance of flexible blades compared with equivalent rigid structures.