Nonlinear granular phononic crystals and their applications

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Introduction

Phononic crystals are the analogue of *photonic* crystals for the acoustic waves. By adding scattering periodic inclusions forming a crystal inside an homogeneous host material, some ranges of acoustic frequencies are totally reflected and then forbidden in the resulting material. This creates acoustic band-gaps.

Nonlinear granular phononic crystals are composed of statically compressed chains of particles, confined in a guide, that interact nonlinearly through Hertzian contacts. [1]

Uncompressed granular crystals are called "sonic vacuum type crystals" and are incapable of transmitting linear elastic waves. [2]

History

How waves propagate in statically and dynamically loaded granular media have lead to an extensive research work since the 1980s, for example with Nesterenko, who studied the existence and interaction of solitons in packed spherical granules, using numerical methods and Shukla *et al.* who modeled the wave propagation in these media and computed it using experimental data. [3] [4]

In 2004, Daraio *et al.* designed 1D and 3D crystals made of 0.03 to 0.5 g steel spheres in a silicon or PTFE matrix and observed trains of strongly nonlinear solitary waves with amplitudes of about 0.3 N which propagate at 317 m/s which is below sound speed in air. [5]

In 2006, Daraio *et al.* showed that the non-classical, strongly nonlinear wave behavior appears in granular materials if the system is "weakly" compressed, which means that the pre-compression force is very small with respect to the wave amplitude. Oppositely, "strongly" compressed chain behavior approaches linear wave behavior. [6]

In 2011, Boechler *et al.* used granular crystals similar to the one shown on figure 1 with a defect to design a rectifier (device that allows the propagation of some frequencies only in one direction) and an acoustic switch with sharp transitions between states. [1]

The same year, Merkel *et al.* demonstrated experimentally the existence of rotational elastic waves in a 3D granular crystal composed of 27 layers of steel spheres. Those modes, observed around 100 kHz, are predicted by the Cosserat elasticity theory which accounts for the rotational degrees of freedom. [7]

In 2012, Yang *et al.* studied the propagation of stress waves in granular crystals composed of diatomic unit cells in bent elastic guides. The cells were made of 21 alternating spherical and cylindrical about 1 and 2-centimeter-long steel particles. The waves were generated by striking the particle on the top with a force of 50 to 1000 N. The pre-compression force was about 5 to 300 N. [2]

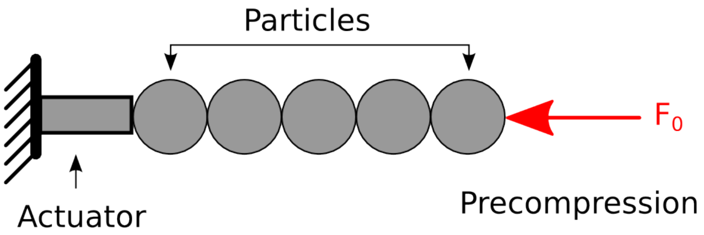

Fig. 1: Basic diagram of a pre-compressed granular phononic crystal.

Those structures possess band gaps around 5 and 10 kHz which can be tuned by modifying the pre-compression of the chain. They show highly nonlinear behaviors and propagate solitary waves. [2]

Tunability

One of the interests of granular crystals is the possibility to tune their behavior from near-linear to highly nonlinear by varying the pre-compression which changes the ratio of static to dynamic particle displacement. [1]

A simulation by Goncu *et al.* proved that the band structure of a two-dimensional granular crystal composed of silicon rubber and polytetrafluoroethylene (PTFE) cylinders could be tuned more efficiently using pattern transformation rather than changing the particles' mechanical properties, creating new gaps around 5 kHz. [8]

Daraio *et al.* demonstrated a way of tuning the solitary waves speed by a factor of two by applying the pre-compression of 2.38 N with a magnetically-induced interaction or only the gravitational preload of 0.017 N. [6]

Spadoni *et al.* numerically modeled an acoustic lens capable of generating acoustic pulses with a pressure amplitude of 675 Pa, corresponding to 57 dB, which is two orders of magnitude larger than what is reachable with linear lenses. The focal point position is tuned by varying the time and space distribution of the static pre-compression of the chains that compose the lens. Experiments using an array of steel spheres in Teflon sheets produced focused waves in a polycarbonate plate in accordance with the simulations. The wavelength is determined by the size of the particles. [9]

Applications

Nonlinear acoustic lenses can achieve better focusing and allow higher focal power than linear ones. So, they are expected to improve the performances of current devices for biomedical imaging, nondestructive testing and sonars. They could also be used to constitute nonintrusive scalpels, for cancer treatment, for example. [9]

The ability of nonlinear granular phononic crystals to behave as rectifiers or switches suggest that they could be used to control the flow of energy in several applications, such as energy-harvesting materials with frequency-dependant absorption and emission and thermal computers. Their nonlinear response allows them to change their state when small perturbations are applied, which makes them suited for sensing applications. [1]

One of the possible future direction in research about those crystal could be the ability to engineer the dispersion relation and create gaps to create tunable vibration filtering devices and systems that could be insulated from noise vibrations. [10]

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