Soft Acoustic Metamaterials

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logenetic relationships and genomic divergence dates between Neandertals, Denisovans, and modern humans. Alternatively, the older mitochondrial divergence date of ~1 million years may reflect the input of a more ancient Asian population, or that all the dates are overestimates resulting from the temporal dependency of molecular rates, and the erroneously low rate produced by the distant chimp-human external calibration (*13*).

We thus infer that *H. floresiensis* was an endemic species whose lineage originated at least 1 million years ago, restricted to a small region of Wallacea, whereas the Denisovans probably arrived during the mid-Pleistocene (after 600,000 years ago) and spread more widely in the region. The Denisovans east of the Wallace line may be represented by the Philippines Callao specimen, or have not yet been recognized. Other enigmatic hominin remains in Asia—from Narmada (India) and Dali, Jinniushan, Maba, and Xujiayao (China)—may represent the apparently once more extensive Denisovan population, or perhaps yet other species.

The Denisovan genome reportedly also contains a small contribution from another archaic population, whose source is currently unknown (*6*, *7*). Did the Denisovans interbreed with a more ancient species, such as *H. erectus* or *H. antecessor*, or perhaps a late surviving *H. heidelbergensis* in Asia (*14*)? Given the uncertainties in the molecular dates, the genomic divergences may be compatible with a recent model suggesting that modern humans, Neandertals, and Denisovans are a trichotomy that originated from the widely dispersed Middle Pleistocene species *H. heidelbergensis*, perhaps around 400,000 years ago (*14*). The fragmentary and disparate nature of the East Asian fossil record provides only tantalizing glimpses of a diversity of hominin groups. Similarly, the apparently widespread distribution of early hominins across Wallacea, exemplified by the finds from Flores and the Philippines, raises the issue of whether they could even have extended to the Sahul shelf and regions like New Guinea and Australia (see the figure).

Why did gene flow between Denisovans and modern human populations occur primarily east of Wallace's Line and not on the Asian mainland? Given that intentional dispersal to Wallacea required the use of watercraft, the first modern human groups encountering the established Denisovan populations were likely to have been of very limited size. Either interbreeding may be more likely under these circumstances, or any interbreeding that does occur is more likely to be preserved as a signal in descendants. The genomic evidence suggests that gene flow from the Denisovans may have been largely male-mediated, providing some clues about the nature of the interactions (*4*). In addition, rapid dispersal by modern humans into tropical Wallacea is likely to have led to exposure to a wide range of new pathogens, such that disease resistance alleles obtained through hybridization with native populations may have been selectively advantageous (*15*). The first groups of modern humans leaving Africa, which were also presumably of limited size, similarly appear to have interbred during initial encounters with established Neandertal populations in western Asia (*16*). An anticipated wealth of new genomic data are set to further illuminate the nature of these interactions between Neandertals, Denisovans and modern humans, as well as the extent and possible functionality of the DNA that was exchanged.

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MATERIALS SCIENCE

Soft Acoustic Metamaterials

Soft materials that embed small resonators in a host material can dampen or focus sound.

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Resonance phenomena occur with all types of vibrations or waves and may play a part in spectacular events, such as the collapse of structures—for example, the fall of the Broughton suspension bridge near Manchester in 1831 (*1*). Indeed, the oscillations of a structure submitted to harmonic excitation reaches its maximum amplitude at the resonance frequency ω_0 of the system. At low driving frequencies ($\omega < \omega_0$), its response is in phase with the forcing but becomes out of phase just beyond ($\omega_0 < \omega$). Such an out-of-phase response has been exploited with "locally resonant materials" (*2*). The proposed strategy is to embed a large enough collection of identical mechanical resonators in a passive structure to control wave propagation. These features are used to reach unusual macroscopic behaviors such as ultradamping of noise or negative refraction for imaging (*3*).

The macroscopic frequency-dependent effective parameters (effective mass density ρ_{eff} and bulk modulus κ_{eff}) of such a composite can be easily derived if the resonators are much smaller than the incident acoustic wavelength. In the out-of-phase regime ($\omega_0 < \omega$), ρ_{eff} and κ_{eff} may exhibit negative values. As illustrated in the figure, a negative mass density means that a volume element V_0 of the composite accelerates (vector a) in the opposite direction to the driving force F as $F = (\rho_{eff}V_0)a$ (see the figure, panel A). A negative bulk modulus implies that the composite expands upon an isotropic compression as $\Delta P = -\kappa_{eff}(\Delta V/V_0)$ (see the figure, panel B).

The effective refractive index is given by $n_{eff}^2 = \rho_{eff}/\kappa_{eff}$. When either ρ_{eff} or κ_{eff} is negative, depending on the nature of the resonators, n_{eff} becomes purely imaginary (evanescent waves), implying an exponentially decaying wave as sought for efficiently

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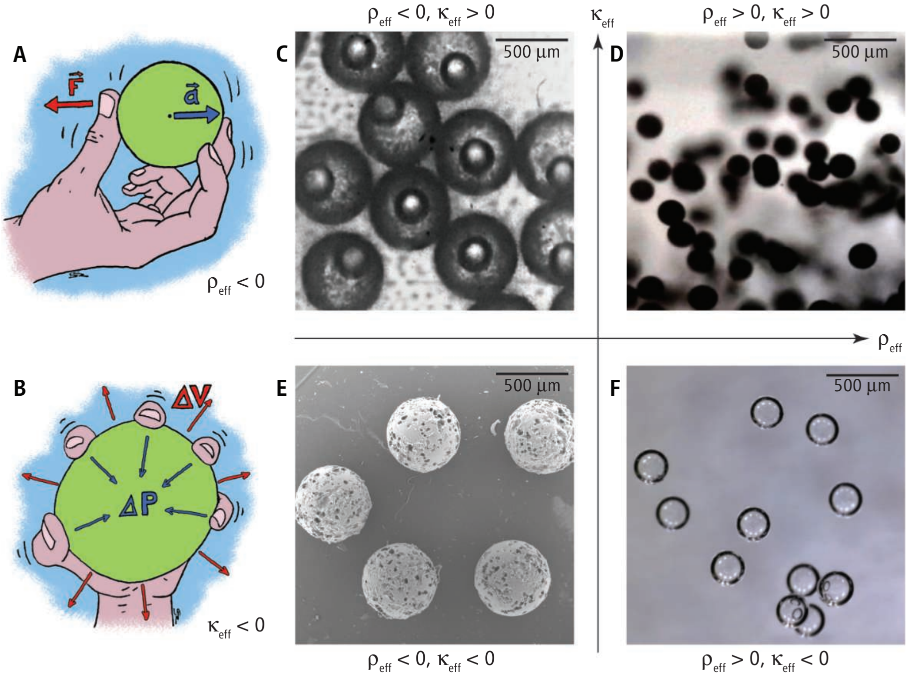

Features of acoustic metamaterials. (**A** and **B**) Schematic illustrations outline the dynamic behaviors of locally resonant materials with negative-valued effective parameters submitted to harmonic excitations. (A) The acceleration *a* of a material possessing a negative effective mass density ($\rho_{eff} < 0$) is opposite to the driving force *F*. (B) A material possessing a negative effective bulk modulus ($\kappa_{eff} < 0$) supports a volume expansion ($\Delta V > 0$) upon an isotropic compression ($\Delta P > 0$). (**C** to **F**) Classification of various locally resonant materials in the (ρ_{eff}, κ_{eff}) plane in terms of the sign of the effective mass density and the bulk modulus, made of various resonant inclusions: (C) core-shell particles, (D) "slow-oil" droplets, (E) polymer porous beads, and (F) air bubbles.

blocking low-frequency sound. For example, the dipolar resonance of core-shell particles induces a negative mass density (*2*), whereas the monopolar resonance of Helmholtz resonators implies a negative bulk modulus (*4*). Otherwise, negative refraction requires both ρ_{eff} and κ_{eff} to simultaneously exhibit negative values at the same frequency (*5*), which leads to a negative index (propagating waves) as sought for subwavelength imaging (*6*). Several resonant structures satisfying these two conditions have been proposed that benefit from simultaneous monopolar and dipolar resonances of two types of inclusions (*7*). Alternatively, another promising route is the exploitation of strong Mie-type resonances (the wavelength of the sound wave propagating within the scatterers being comparable to their size) of a single type of particles. The speed of sound within these particles should be very low in comparison with that of the host matrix in order to achieve a "double-negative" acoustic metamaterial (*8*).

Most of the reported experimental realizations in the audible domain have been for long-wave sound insulation by means of two-dimensional (2D) panels made of millimeter-scale, handmade resonators (*9*). For other applications, such as subwavelength imaging, the achievement of a negative-refraction flat lens (*10*) calls for the manufacture of 3D resonant structures, which is far from obvious in the megahertz frequency range required for echography (e.g., ultrasonograms). Indeed, for ultrasound, the characteristic size of the resonators should be reduced to the micrometer scale, for which mechanical engineering becomes inadequate for a massive production of calibrated objects. Soft-matter methods, such as microfluidics, chemical formulation, or self-assembly, can be used to fabricate resonators with various shapes, structures, and compositions.

Such an approach requires the manipulated objects to be fabricated in soft phases like fluids, gels, or soft solids. Recently, millifluidics has allowed the production of core-shell particles with a submillimeter size (*11*) (see the figure, panel C). Otherwise, microfluidics is well adapted for an accurate control of both the size and the geometry of liquid inclusions, especially structured in a complex way (*12*). Recently, it allowed the production of highly monodisperse emulsions (see the figure, panel D) exhibiting a wide array of multipolar Mie resonances (*13*) that result from the sound-speed contrast between fluorinated-oil droplets (~500 m/s) and a water-based host matrix (~1500 m/s). However, much higher sound–speed contrasts are required to enhance Mie-type resonances (*3*), and current efforts now focus on the synthesis of "ultraslow" inclusions, that is, dense yet soft particles.

Such requirements should be satisfied with a mesoporous material, in which the bulk modulus is strongly reduced (i.e., the material becomes softer) by the presence of a large amount of air cavities. This approach achieves a nonzero mass density because the mass of the solid skeleton, whereas the air bubbles contribute only to the negative bulk modulus (see the figure, panel F). Possibilities are offered by silica aerogels—well known for possessing a very low speed of sound (<100 m/s) (*14*)—or porous polymer materials, because they can be shaped as spherical beads (see the figure, panel E) using microfluidics (*15*).

Such "soft" approaches also offer the possibility to mold the fluid metamaterials in any possible shape thanks to its liquid or gel-like state. Another advantage is the ability of these fluid resonant structures to be highly responsive to any external fields (e.g., magnetic, electric, and shear) that can tune the material properties. This approach paves the way toward the realization of responsive and tunable acoustic metamaterials.

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