Vibrations in materials with granularity

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SUMMARY

The nature of a *wave* depends on its physical origin, and in this thesis the focus is on mechanical ones. Perturbations propagating in space and time within a medium (*i.e.*, *mechanical waves*) usually transfer energy between distant points but, for small enough vibration amplitude, do not involve a lasting displacement of the elementary constituents of the medium. The building blocks, however big or small, instead *vibrate* around their rest positions. Coupling of the elementary constituents of the medium enables a vibration of one constituent to induce an oscillation in another one, constituting an emergent wave. The wave made out of vibrations is the *elementary excitation* available in a mechanical system and therefore determines its properties and response to external probing.

Imagine now that there are imperfections in the medium, which change the local properties of the material. The classical picture of solid state physics is that as the amount of disorder due to the imperfections is low, one can think of the vibrational properties of the system in terms of coherent waves of the perfect system that are scattered by the imperfections. In this way of thinking, the amount of scattering simply increases with increasing disorder. However, this perturbative picture is too naive. It was found already over 50 years ago for electronic systems that in the presence of sufficient disorder, the waves can get *localized* in a region of space. This leads to fundamental changes in the mechanical, thermodynamic, static and dynamic properties of such systems.

In this thesis we deal with *materials with granularity* — materials consisting of particles large enough that the temperature does not play any role in the dynamics of the system. We study their vibrational properties that are strongly influenced by several types of disorder — geometrical, mass and interactional.

One type of system we study are models for granular materials (also foams, colloidal glass, etc). These are packings of soft frictionless repulsive particles that interact only when in contact. Starting from a dilute system, as we increase the density, these systems *jam* into *rigid* structures that resist shear stress before starting to flow. For simplest possible particles — spheres — these model systems show scaling behavior as a function of the distance to this *jamming point* and have been extensively studied over the past decade. The vibrations in these systems have many outstanding features compared to the familiar condensed matter systems, and therefore offer crucial insight into structure of jammed systems. This knowledge may also throw new light on glasses, which still pose numerous long-standing puzzles.

In Chapter 2 we focus on of packings of soft frictionless ellipsoids of revolution near jamming, asking how the change of the shape of the particles influences robustness of the physics around the jamming point. We find that at the jamming transition for ellipsoids, as distinct from the idealized case of spheres, there are many unconstrained and non-trivial rotational degrees of freedom. These constitute a set of zero-frequency modes that are gradually mobilized into a new rotational band as ellipticity increases. Quite surprisingly, this new band is separated from zero frequency by a gap and lies below the onset frequency for translational vibrations. We find that the presence of these new degrees of freedom leaves unaltered the basic scenario that the translational spectrum is determined only by the geometry of the packings.

Chapter 3 is dedicated to the localization of vibrational modes of frictionless sphere packings. There we introduce a new method, motivated by earlier work on non-Hermitian quantum problems. This method works well both in the localized regime, where the vibrational waves are localized within the system, and in the regime where modes are extended throughout our finite system. The latter is especially important because it is known that disorder leads to localization of waves in $2d$, which can however be observed only if the system is large enough. For this regime we derive the scaling relations for the localization properties by using the tools of Random Matrix Theory, a well known method for dealing with randomness in disordered systems.

The second type of systems we study in this thesis are clusters of interacting bubbles. The collective dynamics of such a cluster is relevant for underwater noise damping and absorption with the help of bubble clouds or curtains, the (repelling) effect of bubble curtains on fish schools, for the sound production of colonies of snapping shrimp, and for submarine detection, ultrasound diagnostics with ultrasound contrast agents, for shock-wave lithotripsy, and for other industrial applications. In these systems the volume oscillations of individual bubbles in a cluster are acoustically coupled. It is therefore obviously important to probe the response of bubble clusters to external forcing by sound modes in the liquid.

In Chapter 4 we look at the collective oscillations of a bubble cloud in an acoustic field, using concepts and techniques of condensed matter physics. Compared to the vibrational model of jammed solids, the bubbles can interact even when they are far away from each other, and can also dissipate energy causing damping of waves. For large enough clusters, the collective response is often very different from that of a typical mode, as the frequency response of each mode is sufficiently wide that many modes are excited when the cloud is driven by ultrasound. The reason is the strong effect of viscosity on the collective mode response, which is surprising, as viscous damping effects are small for single bubble oscillations in water. Localization of acoustic energy is only found in the case of substantial bubble size polydispersity or geometric disorder. The lack of exponential localization for weak disorder is traced back to the long-range interaction potential between the individual bubbles.