Carbon nanotubes tune up

A. N. Cleland

Electromechanical resonators are components in many technologies. A nanometre-size version — a resonating carbon nanotube — has now been created that can be tuned over a range of frequencies.

The simplest stringed musical instrument is the bow, similar to a hunter's bow — a string stretched on a frame so that, when plucked, it resonates and produces a note whose pitch is determined by the string's tension. On page 284 of this issue, Sazonova *et al.*[1] demonstrate a nanometre-scale version of a musical bow by exciting and detecting mechanical resonances in a carbon nanotube suspended between two gold electrodes. The authors show that they can tune the resonance frequency, or pitch, of the nanotube by varying a gate voltage, which serves as both an electronic tension adjustment and a means of exciting the vibrations. The vibrational frequencies of the nanotube are more than a thousand times higher than the audible range, so the tones produced cannot be heard. However, in an elegant demonstration of the diverse capabilities of carbon nanotubes, Sazonova *et al.* have used the nanotube itself as an electronic detector — one that can 'hear' its own motion.

As well as their uses in music, mechanical resonators are key to many technologies, serving for instance as clocks and electronic filters in radio receivers and mobile phones. Quartz mechanical resonators are commonly used in thin-film processing as monitors of film thickness, capable of measuring the mass of a film that is only one atomic layer thick. Work is under way to develop similar micromechanical resonators for mass spectrometry[2,3], with the aim of measuring mass at the single-molecule, or even the single-atom, level. Efforts are also being made to observe and use mechanical resonators at the quantum limit[4,5] — the extremely small-energy limit, where the energy of motion of the resonator can take on only discrete values, rather than the continuous range allowed in the higher-energy classical regime. For such applications, desirable features would be resonance frequencies in the megahertz to gigahertz (10^6–10^9 Hz) range, together with small mass and compact size; tunability is also a much sought-after capability.

Carbon nanotubes — with diameters of only a few nanometres, a controlled chemical
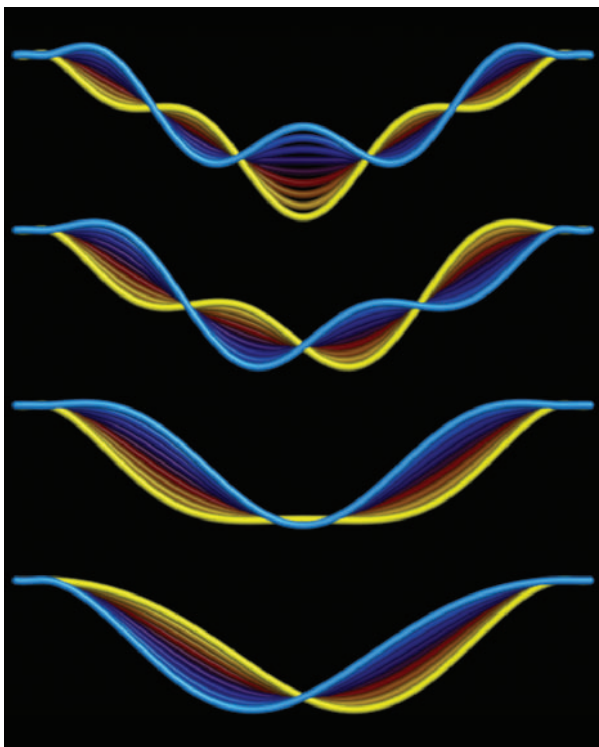
Figure 1 **Good vibrations. These simulations show the first four resonant modes of a carbon nanotube, which is clamped at each end. Sazonova *et al.*[1] have detected such vibrations, and have demonstrated their tunability over a range of frequencies — like the strings of a violin.**

make-up, intriguing electrical properties and extremely high strength and stiffness — may prove very useful as mechanical resonators. Their low mass and ability to withstand large tensile stresses indicate that they may have the potential to operate at very high resonance frequencies, and over an enormous tuning range. Nanotubes free of defects might also achieve very low mechanical loss, corresponding to a high mechanical quality that would be of great value in both timing and sensing applications. Much effort has therefore been devoted to exciting and detecting mechanical resonances in carbon nanotubes — but without much success. Sazonova *et al.*[1], however, at last provide a clear demonstration of the detection and tunability of both single and multiple resonances — tones and overtones — in carbon nanotubes (Fig. 1).

Detecting the motion of such structures was a stumbling-block in previous attempts because of the small sizes and high frequencies involved. Here[1], the nanotubes' motion was detected using the variation in their electrical conductance as they moved through the electrical field of the gate electrode. However, because the nanotubes' high electrical resistance made it difficult to extract the direct signal (that at the resonance frequency), the authors used the nonlinearity in this electrical response to demodulate the signal to more easily detected audio frequencies. This is analogous to what happens in a radio receiver, where a MHz-frequency carrier is demodulated to extract the superposed audio signal. Resonance frequencies ranging from 5 to 150 MHz were excited and detected. Each resonance could be tuned by varying the gate voltage, thus varying the nanotube's tension; tuning was achieved in some cases over more than one octave. And some of the nanotubes displayed at least three different resonances, corresponding to overtones of the fundamental vibration mode, all of which were externally tunable.

One disappointment in the results is the low resonance quality factor, *Q*. The highest *Q* values measured were about 200. This means that, once a nanotube is set vibrating, half of the initial energy of motion is lost within about 200 oscillations. A tuning fork, with a significantly higher *Q* value than this, loses much of its energy by exciting sound waves in the air around it (which allows the listener to hear it). But the highest *Q* values for the nanotubes were measured in a vacuum, eliminating sound waves as a possible channel for energy loss. When the ambient pressure was increased to just under 1% of atmospheric pressure, Sazonova *et al.*[1] found that the *Q* value was significantly reduced. Whether the small *Q* — and thus the large loss — is due to contamination of the nanotube surface, to friction within its structure, or to the loss of vibrational energy in the mechanical supports, is clearly a topic for further investigation.

But Sazonova and colleagues' achievement provides a clear direction for future work: to understand the mechanical properties of carbon nanotubes; to develop

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applications for these smallest of resonators; and, possibly, to further advance our understanding and control of mechanical-energy loss. Future efforts may add multi-stringed instruments to the present device — and perhaps, in time, arrive at a full symphony orchestra.

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Cell biology

Myosins meet microtubules

Margaret A. Titus

A central part of the machinery of cell division is the spindle. The creation and operation of this structure seem to require a component of the cell's infrastructure not previously associated with it.

A shocking thing has happened in the world of the cytoskeleton, the complex of proteins responsible for cell shape and movement. One of the most important structures it forms is the spindle, which ensures the faithful delivery of replicated chromosomes to daughter cells following cell division. Spindle assembly was once believed to be the sole responsibility of the cytoskeletal components known as microtubules, and their associated motor proteins (the dyneins and kinesins). The paper by Weber *et al.* on page 325 of this issue[1] now shows that the process depends — in some circumstances at least — on another cytoskeletal component, actin, and an associated motor protein, a member of the myosin family, which can bind directly to microtubules.

A spindle is necessary for both meiosis, the form of cell division that produces gametes for sexual reproduction, and mitosis, cell division for growth. Working with unfertilized eggs, or oocytes, of the amphibian *Xenopus*, Weber *et al.* show, surprisingly, that one of the members of the highly diverse family of myosins, myosin-10 (Myo10), is involved in both spindle assembly and the subsequent positioning of the nuclei during meiosis.

The view that the spindle depends solely on the microtubule cytoskeleton arose from experiments showing that up until its final act — the creation of daughter cells via a process called cytokinesis — cell division was a myosin-free event. Early studies[2,3] looked at only one form of myosin, Myo2. But subsequent work[4] demonstrated that mutants lacking other myosins (such as types 1, 5, 6, 7 and 15) can undergo mitosis perfectly well.

The first hint of direct interaction between a myosin and microtubules came from an initially puzzling observation[5,6] — that in a certain cell type, Myo5, known as a motor that powers organelle transport, localizes to microtubules as well as to the centrosome (a structure from which the spindle develops), in addition to being present in regions where actin resides. Consistent with these observations, it later emerged that Myo5 binds directly to microtubules *in vitro* with high affinity via its tail region[7].

Another indication of potential microtubule–myosin interaction came from the observation that actin filaments can slide along microtubules in extracts of *Xenopus* oocytes, and that this movement is inhibited by the addition of a Myo5-binding antibody[8]. Finally, studies of the microtubule-binding domains of a plant kinesin, KCBP, revealed that a microtubule-binding domain resides in its amino terminus[9]. The region responsible was identified as the MyTH4 (myosin tail homology 4) domain, which, as its name indicates, is found in several different myosins. This finding suggested that

Figure 1 **A myosin connection. Weber *et al.*[1] show that myosin-10 (green) links microtubules (red) and actin (blue) in the meiotic *Xenopus* oocyte.**

myosins — or, for that matter, any other protein — with a MyTH4 domain might interact directly with microtubules.

Weber *et al.*[1] now show that Myo10 from the *Xenopus* oocyte does indeed bind microtubules and that it is involved in spindle assembly and positioning of the nucleus during meiosis. The carboxy-terminal tail (or non-motor region) of Myo10 contains three domains (known as pleckstrin homology domains) that bind membrane lipids, and also a region combining both a MyTH4 and a FERM domain[10]. The FERM domain is always found in association with a MyTH4 domain in myosin tails and interacts with myosin-binding partners[4]. Myo10 is found only in vertebrates. It is best known for its roles in forming the extensions at the cell edge that produce motion, and in engulfing external particles or debris[10,11], but it may also be a player in processes involving adhesion[12].

Weber *et al.* found that *Xenopus* Myo10 co-localized with microtubules along their length in oocyte extracts and, surprisingly, that it did not seem to be significantly associated with actin. *In vitro* binding assays showed that it could also bind directly to microtubules by its carboxy-terminal MyTH4–FERM domain. Unlike the case with KCBP[9], the MyTH4 domain alone bound only weakly: full binding required MyTH4 and FERM combined.

The meiotic nucleus of the oocyte typically abuts the actin-rich cortex at the cell periphery, where it is anchored by nuclear microtubules that extend into the cortex. Myo10 is localized at the edge of the meiotic spindle in the intact oocyte, in a position that would permit it to link the external spindle microtubules to the actin-rich cell cortex[1]. Microinjecti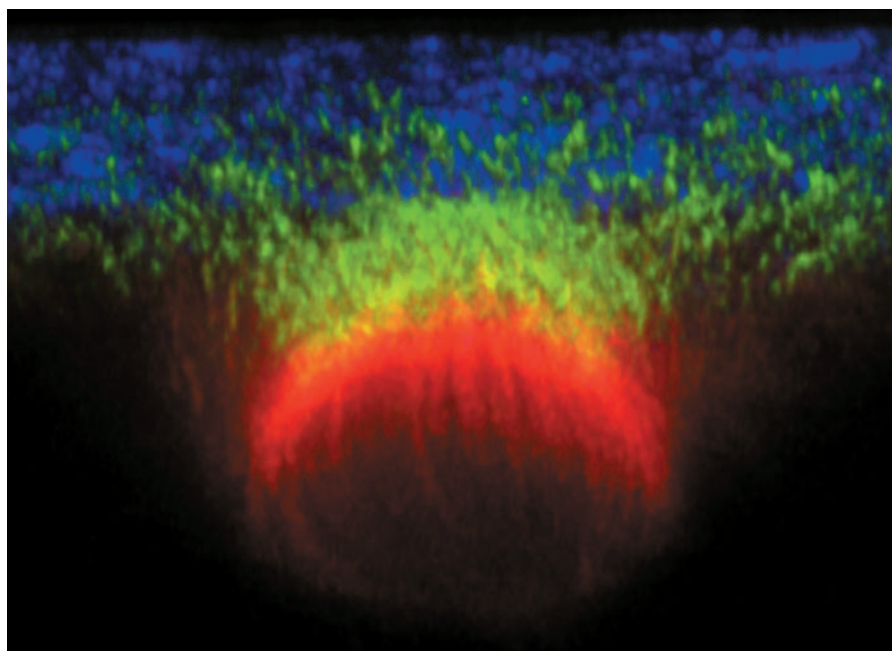on of RNA that encodes the tail