ering both these barriers. At the NIST facility in Boulder, Bergquist and Brent Young have developed a laser with a wavelength in the visible (563 nanometers), which has a linewidth of 5 Hz over an averaging time of 80 seconds. And, at the Max Planck Institute for Quantum Optics in Garching, Germany, a team led by Theodor Hänsch has demonstrated a technique that can step optical frequencies down to lower frequencies for easier counting of cycles. (See PHYSICS TODAY, December 1997, page 19).

What can be gained by increased accuracy? It has long been required for space navigation, especially flights into deep space, but through the Global Positioning System greater accuracy is being used to guide ships and even cars. High levels of accuracy are certainly needed for tests in fundamental physics, such as general relativity: The timing of millisecond pulsars might provide evidence for gravity waves. Also, the accuracy with which we can measure time affects the accuracy of many units derived from it. And who knows what applications could arise once the increased accuracy is there to exploit?

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Ultrahigh-Energy Sound Waves Promise New Technologies

Researchers in acoustics have long wondered whether sound waves could replace mechanical components in devices such as compressors, combustion engines and pumps; now a team of researchers in Virginia has answered—with a very loud, YES!

Perhaps because we are constantly bombarded by sound, it is easy to forget that sound waves actually represent quite small pressure variations. The sound of a jet engine a few meters away measures only about 20 Pa (about 0.0002 atmospheres). As one increases the energy going into a sound wave, nonlinear processes in the gas in which the wave propagates direct more and more energy into harmonics of the drive frequency. The harmonics distort the sound wave and ultimately form shock waves. It is these shocks that limit the amplitudes attainable. Soundwaves' low energy levels and compression ratios (defined as the ratio of the waveform's peak and minimum pressures) have limited their usefulness in high-power applications such as compressors and pumps. Accordingly, many researchers have wondered whether the acoustic saturation imposed by shock formation can be circumvented in some special circumstances.

Although acoustic saturation has been found to be inevitable (perhaps thankfully) for sound waves propagating in free space, the question of whether acoustic saturation is also unavoidable for standing waves in resonating cavities has received little attention. Recently, researchers at Macrosonix Corporation (Richmond, Virginia) have reported creating sound waves with energy densities 1600 times higher than was previously possible. According to Macrosonix founder and CEO Tim Lucas, pressures in these sound waves oscillate from peak values of up to 10 atmospheres down to hard vacuum, rendering the concept of compression ratios all but meaningless.

Two papers[1,2] presented by Macrosonix at the December 1997 meeting of the Acoustical Society of America in San Diego, California, discuss using resonator geometry to control the phases and amplitudes of harmonics in a waveform, thereby tailoring the waveform to a particular application. The researchers christened this technique resonant macrosonic synthesis (RMS). As an application of RMS, they used a specially designed resonator called a horn-cone (shaped like the bell of an elongated trumpet) to shape the waveform to avoid the discontinuity characteristic of a shock. The resulting shock-free sound waves can then be driven at much higher amplitudes.

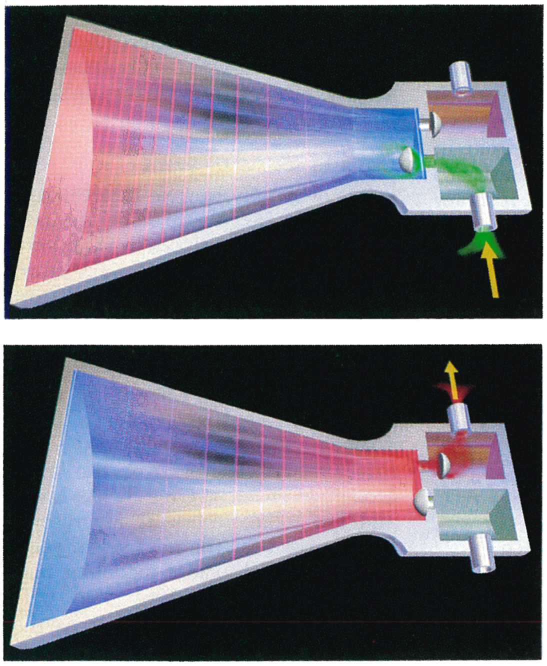
Although the idea of using resonator geometry to control sound waveforms is not new, previous advances[3] have been less dramatic. The newly synthesized sound waves are powerful enough to perform tasks that previously required mechanical components. Moreover, Lucas hopes to use RMS not only to attain high pressure amplitudes, but also to tailor the shapes and characteristics of waveforms to applications ranging from materials processing to pharmaceutical and chemical manufacturing to electric power generation.

Putting sound to work

Lucas originally became interested in generating large-amplitude acoustic waves when he realized that such waves could drive acoustic compressors that, in turn, could be used in environmentally benign refrigerators and pumps. After founding Macrosonix to tackle the technical problems involved in generating and controlling high-amplitude sound waves, Lucas spent a year at Los Alamos National Laboratory, where he worked in the lab of acoustical physicist Greg Swift. Lucas and his collaborators at Macrosonix then worked for the next seven years to develop methods of modeling nonlinear phenomena associated with high-amplitude waves, find resonator geometries likely to achieve high amplitudes, create efficient mechanical drivers for their resonators and finally to harness a variety of high-energy acoustic effects to perform power hungry tasks such as gas compression, pulverization and electric power generation. By 1996, they had developed an acoustic compressor (see the figure on page 24) suitable for a commercially viable (and, yes, fairly quiet) acoustical refrigerator.

Developing viable acoustical technologies required a detailed understanding of the nonlinear phenomena associated with high-energy sound waves. Unfortunately most commercial software for acoustics implicitly assumes a small amplitude approximation. This forced the company to develop its own software for modeling the behavior of sound waves in cylindrically symmetric resonators. Beginning with conservation of mass and momentum (including viscous dissipation) and the state equation for an ideal gas, the team derived a set of coupled differential equations that could be solved numerically. As reported at the ASA conference,[1] Lucas, Yurii Ilinsky, Bart Lipkens, Thomas Van Doren and Evgenia Zabolotskaya used the resulting model to predict the behavior of sound waves in a variety of resonators, including the horn-cone and others shaped like a cylinder, a cone and a bulb. The model was crucial for predicting which resonators were likely to avoid shocks at high pressure amplitudes.

Shock waves tend to form when the relative phases of the wave's harmonics and fundamental frequency assume certain values. RMS uses resonator geometry to force the phases and amplitudes of harmonics to assume values



ACOUSTIC COMPRESSORS replace most of the mechanical parts in conventional compressors with standing sound waves. During one acoustic cycle, the pressure oscillates from high (red) to low (blue). In the first part of the cycle (upper image), low pressure in the narrow portion of the resonator closes the discharge (upper) valve and opens the intake (lower) valve, allowing low-pressure gas into the resonator. In the second part of the cycle (lower image), high pressure in the narrow portion of the resonator closes the intake valve and allows high-pressure gas to flow through the discharge valve. Because they use no oil and have few moving parts, acoustic compressors are expected to be clean and reliable. (Courtesy of Macrosonix Corp.)

other than those characteristic of shocks. For example, in consonant resonators, like a simple cylindrical cavity, the wave's harmonics coincide with the higher modes of the cavity, providing precisely the conditions needed to generate shocks. In dissonant resonators (such as a cone), modes are not equally spaced, and so harmonics are less likely to coincide with cavity modes. As a result, resonators that achieve high pressure amplitudes are most likely to be dissonant, although even many dissonant resonators produce severe shocks at low pressure amplitudes. Hence the importance of being able to accurately model the physical processes occurring within the resonator.

The Macrosonix team also determined that efficient generation of high-amplitude sound waves required a more effective method of driving the sound wave in the resonator. To effectively couple the mechanical motion of the driving force to the acoustic wave in the resonator, the team used a technique called entire-resonator drive, in which the resonator is shaken along its axis. In effect, this technique uses the entire inner surface of the resonator to drive the gas, rather than just a diaphragm or piston at one end, as was done in previous studies.[4] As a result, entire-resonator drive minimizes energy inefficiency. Even so, energy dissipation in the gas does raise its temperature and pressure, and therefore its sound speed and resonance frequency. Consequently, sensors in the cavity monitor the conditions in the gas and automatically adjust the drive frequency to remain on resonance.

According to Lucas, a major (so far unnamed) manufacturer of appliances has already licensed an RMS-based compressor design for use in a refrigerator, which is expected to be available commercially within two years. Lucas is confident that a range of other applications will mature in the near future. At present, however, researchers in acoustics are as interested in the characteristics of the high-amplitude acoustic waves as they are in their applications.

In the other paper presented by the company at the San Diego conference,[2] Lucas, Van Doren, Lipkens, Christopher Lawrenson and David Perkins described measurements of waveforms and their dependence on driving-force amplitude and frequency (near resonance), as well as the effects of different gases on the waveform for a variety of resonator geometries, including cylindrical, conical, horn-cone and bulb. In general, regardless of the resonator, as the driving force (and therefore pressure amplitude) increased, the sound waves first changed from smooth to distorted sine waves, then developed ripples and finally discontinuous shock waves. However, resonator geometry was crucial in determining the pressure at which those transitions occurred: Dissonant resonators achieved higher pressures than consonant resonators, and the horn-cone significantly outperformed the other dissonant resonators, as predicted by the Macrosonix model. The horn-cone was also more efficient at generating so-called DC pressure, a nonlinearly generated steady-state (nonoscillatory) pressure distribution that changes the local equilibrium pressure about which the sound waves oscillate. According to Lucas, such steady-state pressure distributions can generate pressure differentials within the resonator up to 3.3 atmospheres and can be used in valveless pumps and compressors, as well as to levitate heavy objects.

The researchers also observed interesting hysteresis in which nonlinear processes in the gases caused an upward or downward shift in the resonance frequency as resonance was approached from below relative to that measured when resonance was approached from above. Moreover, whether the shift was null, upward or downward was determined by the resonator geometry, rather than by the properties of the gas. Indeed, aside from small differences in the pressures attained that depended on how nonideal the gas was, the waveforms looked the same for the three different gases investigated—R-134 (1,1,1,2-tetrafluroethane, a refrigerant), propane and nitrogen. This finding suggests that the same resonators may be used with different gases.

A sound future

Although Macrosonix's nature as a startup high-tech firm has forced Lucas and his collaborators to maintain an applied, technical focus, Lucas is excited about the prospects for RMS in basic research as well as in technology. "RMS is a primary technology," he stresses. "This is the first technique capable of generating sound waves of such high amplitudes. I can't wait to see what other researchers will do with these techniques." If the reception given to the papers presented in San Diego is any indication, Lucas's fellow researchers are equally enthusiastic about potential applications of RMS in their own areas of research. As Steve Garrett of Pennsylvania State University put it, "If he ever puts these in commercial fridges, I'd buy one, throw away the fridge and just keep the pump to do science."

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