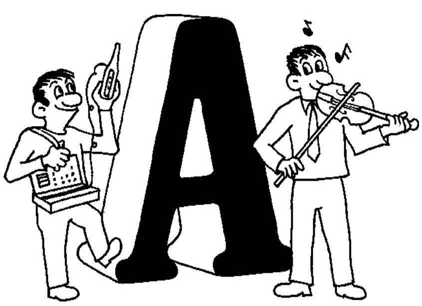
Acoustics from A to Z

Eric E. Ungar

During the March 1999 joint meeting of the Acoustical Society of America with the European Acoustics Association, held at the Technical University of Berlin, I had the opportunity to visit the Institute of Technical Acoustics of that university. Prominently posted on a bulletin board in a corridor, I found an eleven-page 1958 article which was coauthored by Lothar Cremer, the late former director of the institute.

This unusual publication, whose title may be translated as "The ABC of the Acoustics of Buildings," consists of brief verses. There is one verse for each letter of the alphabet; each deals lightheartedly with some aspect of acoustics, each is illustrated by a cartoon structured around the letter, and each is followed by a brief summary of related facts. I was so intrigued with this article's approach that I resolved to translate it and asked the director of the Institute, Professor Michael Möser, to send me a copy. Soon, after he kindly complied with my request, it became clear that translating the article without losing its basic spirit was beyond me. So, I decided to give up and start from scratch, developing my own verses and discussions, but maintaining the spirit. Here's the result.

ACOUSTICS deals with sound and noise;
One may be pleasant, one annoys.
How sound's produced and propagated,
And put to use, attenuated,
And how perception plays its part –
It is part science and part art.



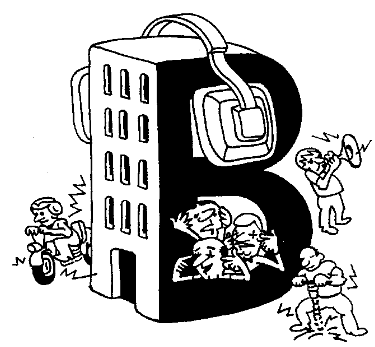
The story is told about George Washington Carver, the famous African-American scientist who studied peanuts and developed many uses for them, that as a young man he prayed that God reveal to him the secrets of the universe. Because God replied that "the peanut is more your size," Dr. Carver focused on a more limited field.

Many of us who work in acoustics also had ambitions to know all about acoustics, but we soon learned that the field is much too diverse. Acoustics, as Ira Dyer of MIT has said, deals with "anything that moves and many things that don't." That statement may be a little far-fetched, but it does convey the breadth of this art and science. To get an idea of this breadth one merely needs to look at the *Journal of the Acoustical Society of America*, for example. The topics covered there range from physics and engineering – aeroacoustics, underwater sound, ultrasonics, transduction, vibration, signal processing – through physiological and psychological acoustics – including speech production and perception, as well as human and animal bioacoustics – to noise effects and noise control, architectural acoustics, music and musical instruments. Many other fields are closely tied to acoustics – sound systems, audiology, acoustic oceanography and ultrasonic instrumentation to name a few. You can undoubtedly think of many others.

Clearly, the science of acoustics is well developed, and research is progressing on many fronts. The news lately has been rife with talk about such things as acoustic microscopy, acoustical refrigerators with no moving mechanical parts, and cochlear implants that enable people that have severely damaged hearing to hear again. Often, however, more than science is needed. In cases involving the noise exposure of communities or work areas, human relations and politics also play major roles. And, the artful application of judgment is usually needed to solve practical problems. Typically, they involve tradeoffs between conflicting requirements.

. . . .

In BUILDINGS where we have employment,
Or want to sleep or have enjoyment,
We need to stop intruding noise
From streets, TVs, and neighbors' toys,
From footfall impacts, other shocks,
Most anything that squeaks or knocks.



One person's music is another person's noise. It all depends on what we want to hear. Achievement of the desired acoustical environment in a room involves providing envelope structures that block noise intrusion from adjacent areas and adding acoustical absorption to avoid the build-up of noise that gets through the envelope.

In addition to dealing with audible "air-borne" noise in adjacent areas, one also needs to address "structure-borne noise" – that is, noise that results from mechanical vibrations of the envelope structures. The walls, floor and ceiling of a room tend to act somewhat like loudspeaker membranes whose vibrations in the audio frequency range radiate sound. Structurally radiated noise in rooms may result from people walking or chairs scraping upstairs and from vibrating equipment (refrigerator compressors, unisolated plumbing or the legs of pianos, for example) in contact with walls or floors.

What can you do to deal with noise from the neighbors? Ask them to avoid annoying activities at times when you don't want to hear them. Get them to install thick rugs or, better yet, a floating floor. Get vibrating equipment isolated. Build an isolated ceiling and secondary walls, so that you in effect have an isolated room within a room. Start living with permanent earplugs. Or, move elsewhere.

. . . .

CRITERIA for floor vibration
Or sound (that is, air oscillation)
Depend on what is really needed;
Intended usage must be heeded.
If set too tight, there's undue cost;
If set too loose, there's function lost.

In the index of any book on acoustics or on noise and vibration control you will find a profusion of listings under criteria. You will find criteria for environmental noise from aircraft and surface vehicles, for the prevention of hearing damage in industrial settings, for acceptable conditions in dwellings and offices, for efficient speech communication, for good listening conditions in class rooms and auditoriums. Also for acceptable vibration environments in buildings, surface vehicles and ships (sea-sickness effects are considered in standards being developed), for vibrations exerted on workers' hands and arms by machine tools, and for evaluation of the quality of rotating machinery. I apologize if I have omitted your favorite among the many other criteria that are available.

Many criteria that have been developed on the basis of extensive studies have gained broad acceptance, have been set forth in international and national standards, have been the basis of ordinances and regulations, and have been cited in cases involving litigation. But how firm are these criteria and standards? Standards are meant to represent the consensus of experts, and they do – to the extent that the experts participating in development of the standards can agree. Unfortunately, the number of specialists involved in this development process typically is small, some may have limited ranges of interest and concern, and some may have certain prejudices. Therefore, standards tend to reflect only the small amount of information on which the participants in the development process can agree. And even then, the consensus is not always one hundred percent. Some standards only address how measurements should be made, leaving criteria – the (usually controversial) magnitudes against which to judge the measured values – to appendixes that are not official parts of the standard.

Some criteria, for example those limiting the exposures of sensitive equipment, are set forth by the equipment suppliers. These criteria often are more stringent than necessary, perhaps because the sensitivity of the equipment is not well known or – as a suspicious person may feel – to give the supplier the opportunity to blame the noise and vibration environment for the occasional less than optimal performance of his equipment.

Equipment criteria often are written by non-specialists in acoustics and vibrations. This has led to problems with inappropriately specified noise spectrum weightings, with confusion between vibratory displacements and acceleration, and with omission of measurement duration and bandwidth requirements, among others. I have spent much time explaining to suppliers of optical equipment that relative displacements of the optical components are important, and not the absolute vibratory displacements of the equipment's support points. And I have often tried to convince clients that one cannot limit the displacement amplitudes of buildings to very small values in a range of frequencies that extends down to zero, relying on the argument that the moon induces tidal motions in the earth much as it does in the oceans and we as yet don't have the technology to hold the moon still.

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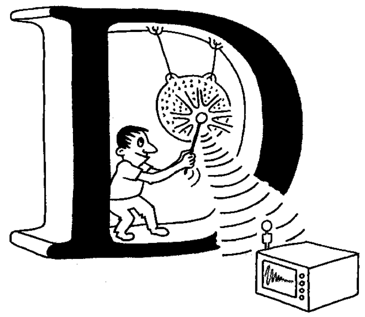
DAMPING's poorly understood.
It doesn't always do much good.
Although it may speed wave decay,
It makes few problems go away.
Damping does mean dissipation,
But may not yield attenuation.



According to my dictionary, the verb "to damp" means "to make damp; moisten" or "to check or retard the energy of" or "to stifle or suffocate, extinguish." Similarly, the verb "to dampen" is defined as "to make damp, moisten" or "to dull or depress." In acoustics and vibrations, however, 'damping' has nothing to do with moisture. Although 'damping' sometimes is used to mean attenuation, in precise technical language its usage preferably should be confined to processes involving energy dissipation.

I have long advocated that 'dampening' not be used instead of 'damping,' because 'dampening' primarily means 'moistening.' Nevertheless, the writers who produced my former employer's annual report a few years ago proudly proclaimed that "we dampen submarines." I found it difficult to explain how we can ask to be paid for that.

Most vibration textbooks deal only with viscous damping – that is, with damping due to a force that opposes the motion and is proportional to velocity. The primary reason for focusing on this type of damping is not that viscous damping necessarily represents the real world (although it fortunately is a reasonable approximation in many cases), but that the assumption of this sort of damping gives us linear differential equations with constant coefficients, which we know how to solve comparatively easily. So, in fact, we act much like the proverbial drunk who lost a silver dollar in the middle of the block, but looks for it near the corner because the street lamp's light is better there – that is, we solve an easier problem rather than the real one.

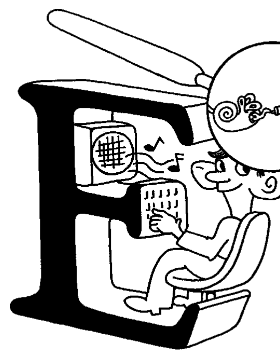
Of course, much can be learned from the textbook problems, and generally the answers we get from viscous damping analysis are reasonable as long as the damping is not too large. But, watch out! Most texts and handbooks, as well as much sales literature for vibration isolators, show equations and curves that indicate that the isolation that a spring-damper combination provides above a system's natural frequency is severely compromised by large damping. This result, derived for viscous damping, tends to overstate markedly this detrimental effect of damping for metal or rubber isolators, in which the damping is not of the viscous type.

Contrary to some misguided commercial claims, damping is not a cure-all. Basically, damping has a significant effect only on motions that are controlled primarily by energy dissipation. These motions include steady responses at and near resonance, freely decaying vibrations, and freely propagating waves; they do not include vibrations due to steady excitation at frequencies that are not near a system's natural frequency. Space limitations and my desire not to bore those of you who are not particularly interested in this topic keep me from further preaching here. Those of you who are curious to learn more may find my "Structural Damping" chapter[1] useful, though less entertaining than this brief discussion.

1. Chapter 12 of *Noise and Vibration Control Engineering*, edited by Leo Beranek and Istvan Ver, John Wiley & Sons, NY, 1997.

. . . .

The membrane of the human EAR
Responds to sound so we can hear.
Its motion vibrates tiny bones,
Wiggling small hair cells that sense tones.
Their nerve cells connect to the brain
From which we information gain.



The first book of Caesar opens with *Gallia omnes in partes tres divisa est* – all of Gaul is divided into three parts – as I remember (surprisingly) from my high school Latin. Anatomists similarly consider the human ear in terms of three parts: the outer, inner and middle ear. I suspect that both of these somewhat artificial divisions into three parts were made for the same reason: to divide a complex entity into smaller parts that can be discussed more easily.

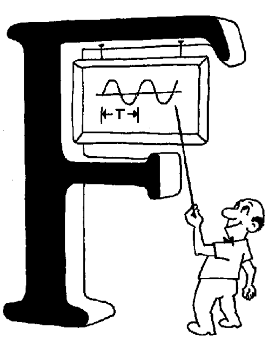
The outer ear consists of the fleshy appendage attached to the head, called the pinna. This Latin word means 'sail' and undoubtedly was chosen by someone with large protruding ears who lived near a windy beach. The pinna and the ear canal with which it communicates channel sound waves to the canal's termination, the eardrum or "tympanic membrane."

The middle ear works somewhat like Thomas Edison's phonograph: a membrane, set into motion by sound waves, is connected to a mechanical amplification system that communicates the amplified motions to the next stage. In the ear the mechanical amplification is achieved by a set of tiny bones or 'ossicles,' which connect to the so-called oval window. The ossicles make this window move in and out much like a piston and these motions are transmitted via the inner ear's essentially incompressible fluid to the basilar membrane and the organ of Corti. This organ is not a musical instrument; rather, it is essentially a membrane that supports a forest of about 20,000 hair cells of different types and lengths, which respond differently to sounds at different frequencies. These hair cells are connected to nerve cells that communicate with the brain, which does most of the difficult data processing.

Hearing loss may result from damage to any of the conductive mechanisms or from damage to the neurological elements. My wife's hearing loss was reduced by surgical freeing of the ossicles that had become locked together and could not transmit the sound-induced vibrations well. Noise-induced hearing loss most often results from damage to the hair cell structures, which deteriorate, break off and are not regenerated. 'Presbycusis' – the hearing loss we experience as we get older – begins with loss of the hair cells responsible for hearing the higher frequencies. In more ways than one, the hairless hear less.

. . . .

The FREQUENCY of oscillations
Tells us how many fluctuations
Up and down from mean are reckoned
Per unit time (minute or second).
The unit 'Hertz' is now preferred;
Cycles-per-second's been interred.



Although I have the utmost respect for the German physicist Heinrich Hertz (1857-1894) after whom the unit of frequency is named that used to be called "cycles per second," I wish the world would have stayed with the old designation. I have never had to explain what "cycles per second" means or how many cycles per minute correspond to a given number of cycles per second, but the uninitiated often need to be told what 'Hertz' (Hz) means.

According to such eminent references as Cyril Harris' *Handbook of Acoustical Measurements and Noise Control*, the frequency of a periodic phenomenon is defined as (a) the number of times the phenomenon repeats itself in one second or (b) the reciprocal of the period, where the period is the time it takes for the phenomenon to repeat itself. These definitions, however, are not entirely precise. Visualize a simple sinusoidal trace that goes through one cycle each second. It clearly repeats itself once per second, but it also repeats itself once every two seconds, once every three seconds and so on to infinity. So, its frequency would be not only 1 Hz, but also 1/2 Hz, 1/3 Hz, etc. Thus, at least for simple stationary signals it may be more precise to define the frequency as equal to the reciprocal of the *shortest time* it takes for any portion of the signal to repeat itself.

And what about a signal that never repeats itself – as is the case for most signals in the real world? The usual spectrum analysis is done by sampling a signal over a selected time interval and assuming that the sample repeats itself forever. So, if we apply the foregoing definition to this repeated sample signal, we find that its frequency corresponds to the arbitrary length of the sample we took – implying that the signal's frequency is arbitrary. If the signal indeed is random, so that it never repeats itself, then its period would be infinite and its frequency would be zero.

Spectrum analyzers fortunately are not bothered by these definitional dilemmas. They typically process data sampled over specified intervals on the basis of the assumption that the samples are repeated indefinitely, fit the sum of a series of (infinitely extended) sinusoids to the data, and report the magnitudes of these sinusoids as a function of their frequencies. (The frequency of the sinusoids is defined as suggested at the end of the first paragraph above.) This so-called Fourier transform process allows one to represent a time-varying signal sample in terms of a series of frequency-dependent values.

It has been told that the French mathematician Fourier,[2] who invented the transform, used to take quite a long time to work out the necessary integrals, while his younger brother took about half as long. Consequently, the older brother came to be known as Slow Fourier and the younger sibling came to be known as Fast Fourier. In recent years the latter achieved fame posthumously by lending his name to the Fast Fourier Transform (FFT) algorithm that is implemented in modern digital spectrum analyzers.

2. Fred Schloss of Wilcoxon Research sent me the following interesting footnote to history: "Jean Baptiste Joseph Fourier was orphaned at a young age and later debarred from the Army on account of his lowness of birth and poverty. However, he went into the 'State of de Nile' with Bonaparte, 1798, and became governor of half of Egypt. He took an important part in preparation of the famous 'Description de l'Egypte.' His mathematical discoveries were the result of his interest in the conduction of heat."

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G's refer acceleration
To our earth's own gravitation.
Displacements may be very small
For g's that aren't small at all.
And so, in many situations,
Velocity's used to mark vibrations.

Nowadays it is not much of a trick to measure accelerations of 1 milli-g (mg) at 1 kHz. The corresponding displacement amplitude turns out to be of the order of a mere 10^{-8} inches, which is equal to about 0.0002 micrometers or 2 Ångström units. Compare this to the 40 micrometer typical diameter of a human hair and to the wavelength of visible light, which is in the 4000 to 8000 Ångström range!

It is interesting to explore what happens if I drop an accelerometer onto a floor from a height of 10 cm, for example. If the floor were to cause the accelerometer to decelerate uniformly, making it come to rest within 10^{-3} cm, then the accelerometer would experience a mere 10,000 g and probably would be damaged. That's one reason for being careful with accelerometers.

In many vibration situations one observes relatively small accelerations and relatively large displacements at low frequencies. At high frequencies, the situation tends to be reversed. That is why displacement sensors are better at low frequencies and accelerometers are better for measurements at high frequencies. Velocity is often used to characterize or specify vibrations, because it tends to exhibit mid-range magnitudes over larger ranges of frequency. Among the criteria that are stated primarily in terms of velocity are those for judging the quality of rotating machines, for determining the perceptibility of vibrations and for assessing the suitability of a floor for various types of sensitive equipment.

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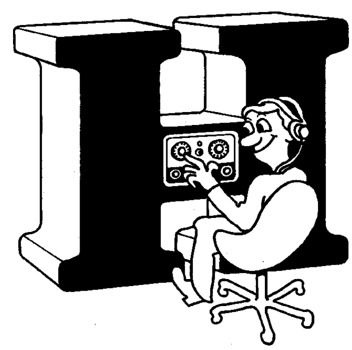

The HEARING threshold, it is known,
Is six dB for a pure tone
Precisely at one thousand Hertz,
Agreed upon by most experts.
The smallest pressure we can hear?
A billionth of an atmosphere.

To be precise, according to the American National Standards Institute's specification for audiometers, the threshold of perception (measured at the ear) of a pure tone at 1 kHz is 6.5 dB relative to the standard 2×10^{-5} Pa. This sound pressure level corresponds to an acoustic pressure of 4.3×10^{-10} atmospheres. The threshold generally is greater at frequencies that deviate from 1 kHz. For example, at 20 Hz the threshold is about 90 dB higher and at 20 kHz it is about 50 dB higher than that at 1 kHz. Although the frequency range of human hearing is generally stated as extending from 20 Hz to 20 kHz, the human ear actually is sensitive to a wider range.[3]

The standard threshold of perception applies to "young persons with no otological irregularities." As we get older, our hearing sensitivity at frequencies above a few kHz decreases, causing older people to have increasing difficulty distinguishing 't' from 'p' and 's' from 'f' sounds, for example. Unfortunately, much information content of spoken sounds lies in this range. To quote Bies and Hansen,[4] "Old folks may not laugh as readily at jokes, not because of a jaded sense of humor, but rather because they missed the punchline" – I assume they meant due to a hearing loss.

The threshold of pain due to sound in the audio frequency range is about 145 dB, corresponding to a sound pressure of the order of 0.004 atmospheres. In the *infrasound* range, below 20 Hz, the pain threshold is higher. As discussed by von Gierke and Nixon[5] intense infrasound typically is more felt than heard. It may cause dizziness, coughing, breathing problems and localized pain, but generally has no effect on hearing. Intense ultrasound (above about 17 kHz) can cause headaches, tinnitus (a spontaneous ringing sensation in the ears) and malaise, but its detrimental effect on hearing has not been generally demonstrated. These adverse effects on ultrasound occur only in people who can hear these high-frequency sounds; those of us who are older are safe.

3. Peter Narins, Professor of Physiological Science at UCLA, took me to task – and rightfully so – regarding the statement I made to the effect that the threshold of hearing corresponds to 6.5 dB. He pointed out that the hearing of about 1.5 million visitors was tested at a Bell Telephone exhibit at the 1938 New York World's Fair and it was determined that at 1.0 kHz the average sound pressure to evoke a threshold sensation was 0.0002 dynes per square centimeter. This value has since been used as the standard reference sound pressure, in reference to which the hearing threshold corresponds to 0 dB. This is correct, of course. The 6.5 dB I cited corresponds to the threshold sound pressure measured at the eardrum. The external ear provides amplification, enabling us to perceive at the eardrum a pressure that corresponds to an external sound pressure of 0 dB. (For more details see Chapter 123, "Hearing Thresholds" by W. A. Yost and M. C. Killion, in the *Encyclopedia of Acoustics*, edited by M. J. Crocker, John Wiley & Sons, Inc., 1997.)
4. *Engineering Noise Control*, D. Bies and C. H. Hansen, Unwin Hyman Ltd., 1988.
5. "Damage Risk Criteria for Hearing and Human Body Vibration," H. E. von Gierke and C. W. Nixon, Chapter 16 of *Noise and Vibration Control Engineering*, L. L. Beranek and I. L. Ver, Eds., John Wiley & Sons, Inc. 1992.

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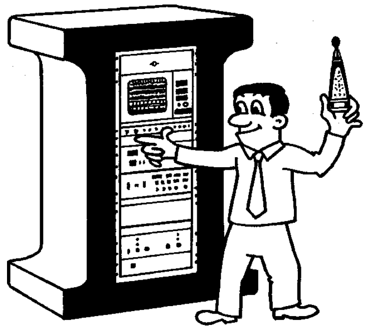
INSTRUMENTS for measuring sound
For many years have been around.
Recent years have seen improvement
In sensing sound, and also movement.
Some systems are so fast and small
They almost aren't there at all.



Ted Schultz, with whom I worked at BBN for many years, liked to tell the story of how he made measurements of airframe noise in one of the earlier Douglas transport aircraft. He used the only suitable filters available then, namely an analog system that permitted him to measure the noise level in one octave-band at a time. So, he had the pilot climb to a comfortable altitude and shut off the engines so that engine noise would not drown out the airframe noise, and then he measured the noise in one octave-band during a gliding descent. Then the pilot would restart the engines and repeat the process until Ted got data in all eleven octave-bands.

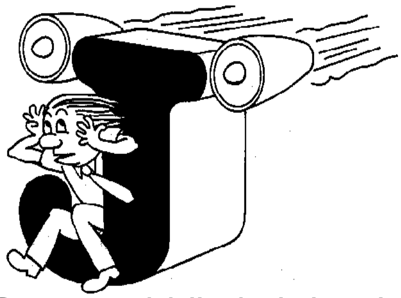
With today's instrumentation, one short glide would have sufficed to acquire all the data, analyze it in octave, one-third-octave, or narrow bands, display it and even print it out. And, today's equipment would weigh at most only a kilogram or two, where Ted's 'portable' system was portable by perhaps two people or a mule.

Modern microelectronics and digital technology have made possible all sorts of compact and energy-efficient signal processors and recorders, with features too numerous to mention. Similar technology also has led to accelerometers with built-in processing chips that condition (e.g., amplify, filter, limit, integrate) the acceleration signal. It also has given rise to accelerometers that weigh only a few carats, where a carat (equal to 0.2 grams) is the unit in terms of which the weight of precious stones is usually stated.

Modern technology also has led to laser systems that allow one to measure the vibrations of objects without attaching anything to them. These systems enable one to measure the motions of a given point on a vibrating object over a wide range of frequencies. Some such systems can even scan the surface of an object and generate a plot of its amplitude distribution. These systems have at least one drawback, in addition to their cost – they only work if the gross motion of the test object relative to the laser is small.

. . . .

JETS make noise from mixing flow
Of their exhausts with air that's slow.
Their turbines may act siren-like
To generate a spectrum spike.
Bypass fans give quiet thrust,
For modern aircraft they're a must.



Sir James Lighthill, who died in July 1998 at age 74, is credited with development of the theory of jet noise. (You may have read that he succumbed while attempting a nine-mile swim around one of the islands in the English Channel – a swim that he had done earlier at least a dozen times.) One of his students, John E. Ffowcs Williams, tried to explain this theory to some of my colleagues and me while we worked together at Bolt Beranek and Newman some time ago. He showed us the basic equation, which covered an entire blackboard which wrapped around the room, and he discussed the meaning and implication of each term. Although he was unsuccessful in making me understand everything, he later went on to high academic positions at prestigious British establishments and was responsible for much work related to control of noise of the Concorde supersonic transport.

According to Lighthill's eighth-power law, the sound power produced by a jet mixing with the ambient air varies as the eighth power of the jet velocity. So, a slower jet should be a lot quieter. This is precisely what is behind the relative quiet of fan-jet engines, which in essence produce a wider, slower air jet than do pure jet engines, yet provide the same thrust. In the newer large-diameter high-bypass-ratio turbofan engines, jet mixing noise usually is not the dominant component; so-called core noise generated within the engines (due to combustion and density inhomogeneities) and the siren-like noise from fans, compressors and turbines take on more prominent roles.

Powell and Preisser[6] reviewed the advances in aircraft noise reduction: "When normalized to total engine thrust, today's new transports are about 20 dB quieter than those introduced in the 1950s . . . This reduction resulted from major engine cycle changes that improved fuel efficiency and incremental efforts that required careful optimization to preserve thrust and efficiency. Low-bypass-ratio turbofan engines introduced in the 1960s provided greater propulsive efficiency and lower noise . . . But with jet exhaust no longer the primary noise source, further improvements in total engine noise required reductions in fan-generated noise. These resulted mainly from elimination of inlet guide vanes, a decrease in the number and rotational speed of fan blades and improved blade aerodynamic design. A major breakthrough was the fan blade passage frequency 'cutoff' design concept . . . in which the BPF tone does not propagate outside the engine nacelle. In addition, advances . . . allowed acoustic treatments to be designed or tuned for enhanced absorption of the fan tones."

Active noise cancellation is also in the works but hasn't quite been reduced to practical installations, as far as I know. Eventually, only noise due to flow over the airframe itself will be left. This airframe noise should be relatively benign in general; in tests some years ago researchers at Wright Field were unable to measure noise from aircraft in unpowered flight past a microphone array at times when crickets were active.

6. "Research for quieter skies," C. A. Powell and J. S. Preisser, *Aerospace America*, August 1999.

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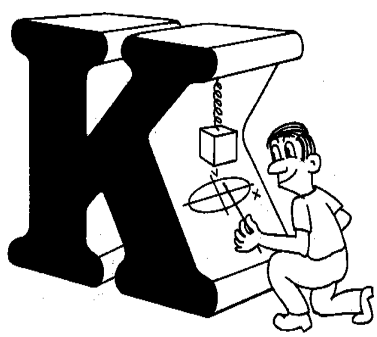
KINETIC is the energy
That always works in synergy
With energy that is potential.
Both of them are quintessential
For unforced periodic motion.
We sometimes fail to grasp this notion.



I have often expressed amazement about how much one can understand about vibrations from studying the simplest of all the conceptual vibrating systems – namely, a mass connected to a spring, possibly with an added damping element. Of course, some of the utility of the mass-spring model stems from the fact that the behavior of any mode of a dynamic system corresponds to that of an equivalent mass-spring system. But why is a simple mass-spring assemblage an appropriate representation of anything that can vibrate?

The answer is that such an assemblage incorporates an element that can store kinetic energy and one that can store potential energy – and an interchange between potential and kinetic energy is at the core of any vibration. Let's consider the simplest situation of free (unforced) vibration of a spring-mass system. If the mass is deflected from equilibrium and released with zero velocity, then it initially has no kinetic energy, but there is potential energy stored in the spring. The spring accelerates the mass, giving it kinetic energy, but losing some of its potential energy in the process. This goes on until the mass reaches the equilibrium position, where the spring's potential energy storage is zero and all of the energy of the system is kinetic. As the mass moves further, it deflects the spring, causing energy to be stored in it, but giving up a corresponding amount of kinetic energy. And so on.

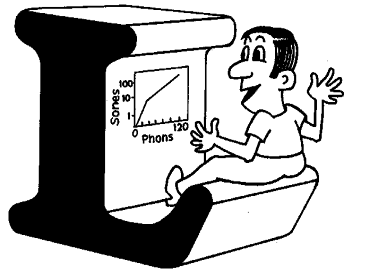
A few years ago *Sound and Vibration* and I offered a prize to that reader who would give me the best physical explanation (that is, without the use of mathematics) of why a simple undamped mass-spring system has a definite natural frequency. Although *S&V* gave away the prize, I was not entirely satisfied with the explanation. So, here is mine. Can you challenge or improve upon it?

A system has a natural frequency if, as it vibrates in absence of external forces, it takes the same time to complete each cycle. Because the total energy (the sum of the kinetic and the potential energy) in an undamped freely vibrating system is constant, the instantaneous magnitude of the potential energy determines the corresponding instantaneous magnitude of the kinetic energy. This now implies that whenever the mass passes a given location (measured in terms of displacement from equilibrium) it does so with the same velocity. This velocity establishes the time interval it takes for the mass to move from one point to the neighboring one. Therefore, the mass always takes the same time to move from one point to any other point and it always takes the time for the entire round-trip it makes in a cycle. In other words, all cycles have the same period and thus the same frequency.

The foregoing argument, incidentally, is not limited to linear springs, but also applies to springs with nonlinearites. For nonlinear springs, the natural frequency depends on the amplitude, as determined by the initial displacement and velocity. Why is the natural frequency of an undamped mass-spring system with a linear spring (a spring whose deflection is proportional to the applied force) independent of the amplitude? Borrowing from the language of textbooks: this is left as an exercise for the reader.

. . . .

The LOUDNESS of a sound we hear
Tells how intense it may appear.
For simple or for complex tones,
One measures it in phons or sones.
But how we do perceive a sound
Depends on what else is around.



Loudness refers to the subjective evaluation of a sound. A 3 dB change in sound pressure level (which corresponds to a doubling or halving of the sound power) results in a barely perceptible change in the perceived loudness. A 10 dB increase in the sound pressure level (which corresponds to a tenfold increase in the sound power) is judged as doubling the loudness. According to Bies and Hansen,[7] if one started with 100 trombone players behind a screen, all doing their best, and if 99 of them leave, the audience would perceive a loudness reduction by a factor of four. Advertisements that claim a 99% noise reduction for similar scenarios "are written by the uninformed for the ignorant."

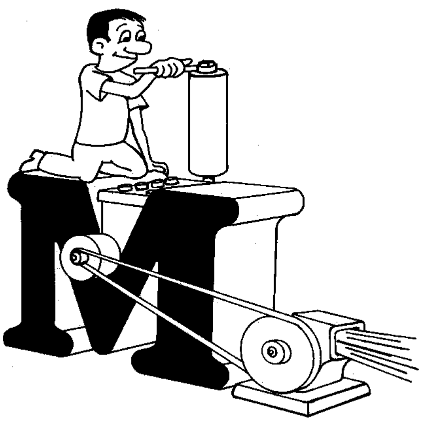
One 'sone' is defined as the loudness of a 1-kHz tone at a sound pressure level of 40 dB. A 1-kHz tone at *n* sones is *n* times as loud as this 40-dB tone. A 10 dB increase in the sound pressure level results in doubling of the loudness in sones. Plots of the frequency-variations of the sound pressure levels that correspond to a given loudness are called "equal-loudness contours," which are labeled by 'phon' numbers. All points on such a contour correspond to the same perceived loudness; thus, a 40 phon tone at 60 Hz sounds just as loud as a 40 phon tone at 8000 Hz, even though the related sound pressures may be quite different. For pure tones, the sone and phon measures are simply related, but for more complex sounds the situation becomes more *phon*ey.[8] Methods for estimating the loudness of sounds that are not pure tones are discussed by Small and Gales,[9] for example.

'Masking' – interference in the perception of one sound by the presence of another sound – may make communication difficult. And, it may constitute a critical safety issue, for example, where construction noise may mask an alarm signal or where a pedestrian's earphones may mask the sound of an oncoming car. Sound masking may also have beneficial effects, some of which are realized by the installation of sound masking systems in open-plan offices in order to eliminate the distractions caused by neighboring conversations. Unfortunately, the masking needed to cover up the rock music from a neighboring apartment would have to be so loud that it would lead to more insanity than the music itself.

7. *Engineering Noise Control*, D. Bies and C. H. Hansen, Unwin Hyman Ltd., 1988.
8. David Towers of HMMH, an experienced punster, felt the need to top my "phon number" and "phoney" wordplay. His comment: "To each his sone!"
9. "Hearing Characteristics," A. M. Small, Jr., and R. S. Gales; Chapter 17 of *Handbook of Acoustical Measurements and Noise Control*, C. M. Harris, Ed.; Mc-Graw-Hill, Inc., 3rd Edition, 1991.

. . . .

MACHINERY of any kind
Brings two main types of noise to mind.
One's from surface radiation
Due to structural vibration.
The other comes from pressured air
As air is moved from here to there.



Intake and exhaust noise usually predominates in engines or compressors, because intakes and exhausts are acoustic monopole sources that radiate sound efficiently. What is left when intakes and exhausts are quieted often is called "casing noise" – that is, noise radiated from the machine's structural envelope as the result of its vibrations. In machinery whose internal components do not communicate directly with the ambient air, casing noise is all there is.[10]

Noise-radiating casing vibrations may result, for example, from internal pressure pulses, from hydraulic systems, from imbalance of rotating parts, from reciprocating elements, and from impacts and other interactions of mechanical components, such as those of bearings and gears. The latter have some particularly interesting aspects.

At a small lunchtime conference some time ago, one of my colleagues pulled a ball taken from a ball bearing from his pocket, rolled it across the table and asked why this shiny, smooth ball should make so much broadband noise as it rolls across a polished wood surface. Try it; you'll be surprised how noisy it is! When we later repeated the same experiment on a flat glass mirror, we again observed considerable noise. I don't know whether any research has been done on this problem, but I conjecture that the tiny asperities on the surfaces interact, possibly producing local surface deformations and causing the surfaces to vibrate and thus to radiate sound. We didn't try lubricated balls or balls with resilient covers, but I bet these would have produced a lot less noise.

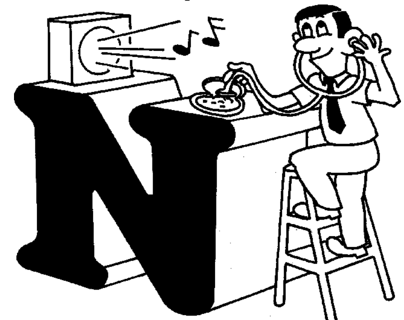
Combustion noise, which is responsible for the roar of furnaces and the "core noise" of jet engines, is due to nonuniform combustion, where there in effect occur local hot spots that behave as acoustic monopoles and thus radiate sound well. Temperature and density inhomogeneities behave as dipoles when accelerated in nonuniform flow.[11,12] Some flow-related acoustic phenomena involve feedback, such as those associated with edge tones and also some whistles.[13] There also may occur thermal-acoustic feedback phenomena exemplified by the Rijke tube, which first was reported in 1859. As Lord Rayleigh describes it:[14] "When a piece of fine metallic gauze, stretched across the lower part of a tube open at both ends and held vertically, is heated by a gas flame placed under it, a sound of considerable power and lasting for several seconds is observed almost immediately *after* removal of the flame." As he goes on to explain, the air column in the tube is driven at resonance by periodic transfer of heat from the gauze to the air, with appropriate phasing resulting from the combination of convection with the acoustic pressure oscillations. This phenomenon differs from that of "singing flames," in which acoustic pressures interact with the combustion process.

And, why do transformers make noise, where these have no intakes or exhausts, nor internal moving parts? The answer is magnetostriction – slight changes in the dimensions of iron or steel components resulting from changes in the magnetic fields acting on these components. Practical and economic constraints make it difficult to reduce the noise produced by large power transformers at the source. But I'm glad that power companies have not let this get in the way of providing our homes with electricity; otherwise, we would have to watch TV in the dark.

10. Frank Kushner of the Elliott Company has pointed out that a particular type of what I have called casing noise is left when intake and exhaust noises are removed and internal components of machinery do not communicate directly with the outside air. He indicated that piping noise tends to be an important component, for example in the centrifugal compressors with which he is concerned. As he stated, sound waves at frequencies above the cutoff frequencies of the attached pipes travel easily along the pipes, exciting cross-modes in the gas and structural modes of the pipes. These pipes usually are much thinner and more compliant than the machinery casings. When no dissipative silencers are used in the gas streams, external treatment of the pipes needs to be given priority.
11. "Noise of Gas Flows," M. S. Howe and H. D. Baumann, Chapter 14 of *Noise and Vibration Control Engineering*, L. L. Beranek and I. L. Ver, Eds. John Wiley & Sons, Inc., New York, 1992.
12. "Combustion and Core Noise," J. R. Mahan and A. Karchmer, Chapter 9 of *Aeroacoustics of Flight Vehicles: Theory and Practice*; Volume 1, Noise Sources, H. H. Hubbard, Ed., NASA Reference Publication 1258, 1991.
13. "On the Edgetone" A. Powell, *Journal of the Acoustical Society of America* 33, April 1961, pp. 395 - 409.
14. *The Theory of Sound*, J. W. S. Rayleigh, 1896. Republished by Dover Publications, New York, 1945. Volume II, Section 322i.

. . . .

A noisy NOISE annoys an oyster
And quiet noise annoys a cloister.
Annoyance from a sound, it's true
Depends on what one wants to do.
Shaped noise can be used to mask
A sound that complicates a task.



I must admit that I have no idea whether oysters can perceive any sound at all; I was just carried away by the cadence of the words. But I do remember hearing a paper concerned with sound perception by fleas that was presented at an Animal Bioacoustics session of the Acoustical Society of America a few years ago. At that time ultrasonic flea collars for dogs were being advertised aggressively and a study was carried out to determine their efficacy. This study, which was not sponsored by manufacturers of flea collars, found that: (1) fleas cannot perceive sound; (2) ultrasound emitted by the flea collar would be blocked and absorbed by the dog's fur so that little sound would reach any fleas; and (3) in a comparison investigation, dogs wearing ultrasonic flea collars harbored a somewhat greater number of fleas than dogs without such collars.[15] I don't recall whether anyone concluded that dogs might be driven to distraction by the ultrasound.

According to a paper presented by Douglas Barret of HMMH at the 1999 Summer Meeting of the Transportation Research Board, nuns objected to construction of a highway near their convent, insisting that quiet and serenity were essential to their work. They protested, even though the noise at the site was predicted to increase by a mere 10 dBA above the present 45 dBA. They may not have realized how valid their objections were. Highway noise levels typically are stated in terms of the energy-average levels observed during a day's loudest one-hour period – and changes in this noise level clearly do not account for the greater interruption of the evening quiet by short-duration loud noise intrusions from passing trucks.

Quite a different situation exists in the "Land of the Rising Decibels," as described in a recent newspaper article.[16] According to this article, the "Japanese are subjected to a variety of clatter that is perhaps unlike anywhere else in the world." Not only do their vending and ATM machines talk to customers with electronic voices and escalators tell them to watch your step, but there also are demonstrators with bullhorns everywhere. Even in rural towns one can hardly escape from the ubiquitous public address systems which spew forth messages at all hours of the day and night. Some public address proclamations quoted in the article include, "Children, go home, it's getting dark." "Don't use too much water, it hasn't rained in recent days." "Make sure the stove is off before you go to bed." On trains, passengers are instructed to turn off their cell phones, with announcements that are much louder and more annoying than the telephones themselves.

Although there is much quiet objection (pun intended) to this noise pollution, a citizens' group organized about a decade ago to fight this pollution reportedly has had little success, largely because some of their cultural attitudes prevent the Japanese from expressing their discontent publicly.

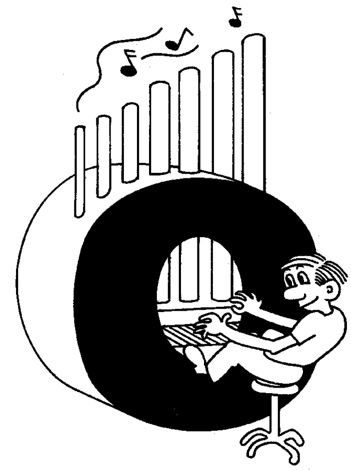
We've all heard that one person's music is another person's noise. But quiet may not be the optimum situation and what is noise to one person may be music to another. I've been in noisy offices of plant managers who were happy to hear the production machinery; they felt that they were making money as long as everything was running, and quiet was an indication of trouble. Some plant personnel could even identify problems from changes in the noise they heard in their offices and they objected strongly to any proposal to give them more quiet.

In a recent survey of workers in cubicles in open-plan offices, about 70% reported that noise was the number one distraction, with conversational noise and the lack of acoustical privacy as the leading cause of acoustical dissatisfaction and stress. The most practical solution here consists of making more noise – adding a 'masking' noise to reduce the information content of the total noise perceived by a listener. The installation of sound masking systems has become more prevalent in recent years and studies have shown that use of such systems has resulted in significant productivity improvements.

15. Dr. William Murphy of the National Institute for Occupational Health and Safety sent me the following e-mail: ". . . Dr. Glenis Long presented (this) work at the St. Louis ASA meeting in 1990. . . My favorite photograph from the study was the one in which more fleas were sitting on the ultrasonic transducer of the activated collar than on the inactive collar."
16. "Now, the Land of the Rising Decibel," S. Moshavi, *The Boston Sunday Globe*, 23 September 2000.

. . . .

An ORGAN pipe emits a tone
When air into one end is blown.
Its pitch is given by its length
And somewhat by the blowing strength.
In many instruments, indeed,
The tone's established by a reed.



Every introductory text on acoustics talks about organ pipes and how their lengths are related to the wavelengths and frequencies of the tones they produce. However, discussions of how steady blowing into a pipe produces oscillations generally are left to specialized texts. Clearly, if the injected airflow were entirely smooth, no oscillations would occur.

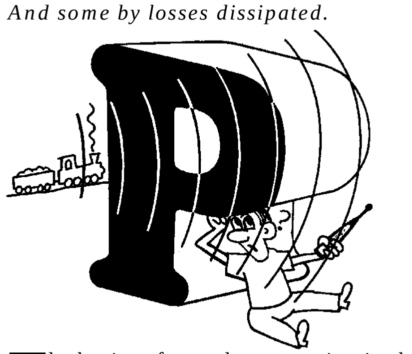
There are two basic types of organ pipes: flue pipes and reed pipes. In the former the incoming air stream passes through a narrow passage formed by a 'flue' and then impinges on the edge of a thin plate 'lip.' The resulting flow turbulence generates a rather broad band of frequencies in the pipe's air volume, which responds predominantly at its natural frequencies. The resulting oscillations then interact with the turbulent jet to stabilize both that jet and the acoustic oscillations. Reed pipes, as the name implies, use a vibrating brass reed to modulate the injected air, with the pipe and reed generally tuned to the same frequency. More details can be found in the excellent books by Rossing, Strong and Plitnik.[17,18]

The mechanism by which flutes produce sound is somewhat different: it is the same mechanism as that responsible for the whistle one hears as one blows across a bottle. A flute player essentially blows across a hole in the flute, resulting in some turbulence, which generates standing waves in the flute's volume and thus produces tones. A piccolo is a woodwind instrument that is about half the size of a standard flute. Its development has an interesting history. Professor Peter Schickele reports that a hungry Italian constructed the first piccolo by sautéing an ordinary flute in a frying pan until it had shrunk about fifty percent. This event later came to be known as the Mediterranean Flute Fry.[19]

17. *The Science of Sound*, T. D. Rossing, Addison-Wesley Publishing Co., New York, 2nd Edition, 1990.
18. *Music Speech Audio*, W. J. Strong and G. R. Plitnik, Soundprint, Provo, UT, 1992.
19. From "Bach to the Future," Diane Cyr, *U.S. Airways Attaché*, July 1999.

. . . .

In PROPAGATION through the air
Indoors, outdoors, everywhere,
Sound waves that spread out from a source
Take energy away, of course.
Pressure by spreading is abated
And some by losses dissipated.



The basics of sound propagation in the atmosphere have been understood ever since the wave nature of sound has been recognized. Sound pressure decreases with increasing distance from a source because the energy injected by the source is spread over larger and larger areas at locations further away from the source, and also because acoustic energy is dissipated as sound passes through the air. The attenuation due to dissipation is more pronounced at high frequencies and when the humidity is high. As Philip Morrison[20] puts it: "Energy loss in sound transport is the result of internal diffusion that wipes away the contrast between compressed crests and rarefied troughs as any pressure wave advances. The longer the wavelength of the sound, the farther it can go."

One can easily visualize that winds whose speeds increase with increasing altitude tend to refract sound propagating in the windward direction toward the ground, because here the sound travels faster (with respect to the ground) in areas of higher wind-speed. Because the speed of sound in air is proportional to the square-root of the absolute temperature, an atmospheric temperature profile marked by increasing temperature with increasing altitude has a similar effect. Thus, wind (and temperature) gradients can result in focusing of sound downwind from a source and the formation of quiet "shadow zones" upwind. In the 1960s, test firing of large rockets at NASA's Marshall Space Flight Center in Alabama was found occasionally to damage some buildings in downtown Huntsville several miles away as the result of atmospheric focusing of the rockets' intense low-frequency sound. NASA eventually instituted the use of meteorological balloons to measure the wind and temperature profiles before each planned

test firing and postponed the testing when calculations indicated a potential for focusing in built-up areas.[21]

Since sound that propagates from an atmospheric layer with a lower temperature to one with a higher temperature is refracted back toward the cooler layer, sound can be "trapped" in a "sound channel" formed by a cooler layer that is located between two warmer layers. Such trapped sound decreases with distance much less than freely propagating sound, sometimes enabling acoustic phenomena to be detected at very large distances. In the earth's atmosphere there exists a relatively permanent sound channel at high altitude, and it has been reported that the 1883 Krakatoa volcano eruption could be heard on the other side of the world. I have some doubts about that, because the audible components of the sound would have been attenuated over such long distances. However, the low-frequency components of the sound produced by the 1991 Mount Pinatubo eruption and by some nuclear explosions were detected by instruments thousands of miles away. Similarly, in the "Sofar Channel," a sound channel in the deep portions of the oceans, sound signals have been transmitted and received over great distances.[22]

As long as we are on the subject of atmospheric refraction, it is also interesting to consider wind blowing along the ground and across a noise barrier. The wind needs to accelerate to get over the barrier, resulting in a wind profile that may refract the sound toward the ground beyond the barrier – thus reducing its effectiveness.

20. "Wonders: Double Bass Redoubled," P. Morrison, *Scientific American*, May 1998.
21. Rudy Volin wrote: ". . .During a visit to the Marshall Space Flight Center (Huntsville, Alabama) in February 1967 my hosts asked me if I wanted to visit a static test firing of a Saturn second stage . . . I declined . . . Sure enough, the motel began to shake, followed by a brief low-frequency rumbling noise . . . I also heard, and I forget where, that occasionally focusing caused the noise from rocket firings at the Marshall Space Center to be transmitted to Birmingham, AL, which is a little over 100 miles southeast of Huntsville."
22. *Sound Waves and Light Waves*, W. E. Kock, Anchor Books, New York, 1965.

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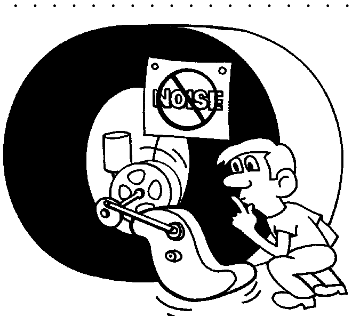


The quest for QUIET in the nation
Has led to useful regulation.
Some deals with the environment
To let us sleep and be content.
Some helps ensure that we can hear
When our retirement draws near.

According to some recent statistics, more than 20 million Americans are exposed to hazardous sound levels on a regular basis. There are approximately 28 million Americans who have some degree of hearing loss; about one third of these – more than 9 million – have been affected, at least in part, by exposure to excessive noise.[23]

Workers in some industries in the United States have routinely been receiving compensation for hearing loss at the time of their retirement. This situation changed with industry's compliance with the noise exposure limits promulgated by the Occupational Safety and Health Administration (OSHA). These limits in essence require a worker's daily eight-hour noise exposure not to exceed 90 dBA, with a 5 dBA increase in the permissible noise level for each halving of the daily exposure period, but with no exposure permitted above 115 dBA. For employees exposed to noise at different levels during a day, OSHA prescribed calculation of the ratios of the actual to the allowed exposure durations for the different noise levels and summing the resulting fractions – with the sum required not to exceed unity.

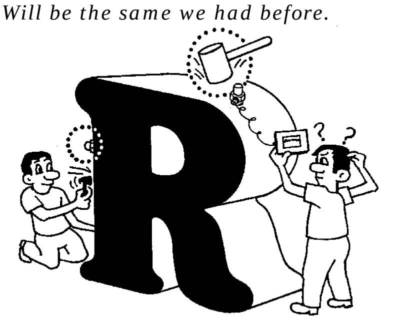
OSHA's regulations are based on the simplified distillation of the consensus of some experts. The fact that the formula adopted in these regulations is somewhat arbitrary, as evident from other agencies' adoption of other exposure limits, did not prevent me and my colleagues from developing a precise estimate of the number of overexposed miners in the United States. We relied on incomplete data on the noise levels to which personnel associated with various machines were exposed, assumed certain probability distributions of the exposure durations and noise levels and used only the available partial census of mine workers.[24] In spite of all this handwaving and smoke, our estimation approach was adopted by other agencies and other countries.

I was reminded of the tenuous basis of our estimate when I read a recent article that described how a group of psychologists developed a happiness factor ranging from 0 to 1 and evaluated the average happiness of the populations of various countries. They also multiplied the happiness factor by the average life expectancy and came up with the average number of equivalent happy years per person. In case you're wondering, the Netherlands had the highest happiness factor (0.797) and the second highest number (61.66) of happy years, with Iceland having the most happy years (62.04) and the second highest happiness factor (0.793). The United States came in tenth, with a happiness factor of 0.760 and 57.76 happy years, below the Scandinavian countries, Belgium, Switzerland, Australia, Ireland, and Canada. The worst? Bulgaria (0.443 and 31.57 years), followed by Nigeria, Belarus, and Russia (0.510 and 34.48 years).[25] Do these numbers suggest that we in the U. S. would do well to move to Iceland to collect an extra couple of happy years? And, given the choice, should one opt for living five miserable years with a happiness factor of perhaps 0.2 or for living one glorious year with a happiness factor near 1.0?

23. "Hearing Loss Statistics," Anon., *The Older American*, p.15, September 2000.
24. "The Noise Exposure of Operators of Mobile Machines Used in U.S. Surface Coal Mines," Bolt Beranek and Newman Inc., Report No. 3688, November 1977. The methodology is described in "Statistical estimation of percentage of overexposed workers," E. E. Ungar and C. B. Cruikshank. Jr., *Journal of the Acoustical Society of America*, 64(1), July 1978, pp. 331-332.
25. "Happy hunting," Gareth Cook, *The Boston Globe*, October 11, 2000, p. A1. Note the precision of the quoted numbers!

. . . .

RECIPROCITY, it's strange,
Says that if we interchange
The point at which acts excitation
With that of motion observation,
The force-to-motion rate once more
Will be the same we had before.



Good old Maxwell's theorem! If your memory works like mine, you may remember its content, even though you may have forgotten its name. I had to look it up when I wanted to revisit the idea of reciprocity. According to this theorem, if a force F_A acting on the beam at point A causes a deflection D_{AB} at point B, and if a force F_B acting at B causes a deflection D_{BA} at A, then $D_{AB}/F_A=D_{BA}/F_B$. In other words, the ratio of the deflection to the force remains unchanged if the force application point and the deflection observation point are interchanged. This theorem can be quite useful for checking expressions for the deflections of beams or of other structural elements and it also permits one often to substitute an easier analysis for a more complicated one.[26]

The reciprocity principle in essence is a generalization of Maxwell's theorem. This principle states that the ratio of the exciting force to the observed velocity remains the same if the excitation point and the velocity observation point are interchanged, provided that the direction in which the force acts in each case is the same as that in which the velocity is measured in the other case. Lord Rayleigh

(1842 – 1919), who developed the basis for almost all of the acoustical theory in use today, initially demonstrated that the reciprocity principle holds under certain limited circumstances.[27] More recently it has been shown that this principle applies for any system whose differential equation of motion is symmetric in the spatial variables. Fortunately, this requirement is satisfied in all of acoustics, as long as the associated processes are mathematically linear – in other words, the reciprocity principle is valid for virtually all practical acoustical problems – including those where both structures and fluid volumes are involved.[28]

Interchanging of the excitation and response observation points can lead to experimental simplifications if one of these points is more accessible than the other. An interesting example is provided by Professor Priede's work on casing noise of piston engines. When he wanted to determine the vibration of an engine sidewall due to a known force pulse acting on one of the engine's pistons, direct measurement would have required having a shaker act on the piston and observing the sidewall's motion with an accelerometer. It turned out to be much simpler to apply reciprocity to his reciprocating engine (I couldn't resist this juxtaposition), to shake the sidewall, and to measure the resulting vibrations of the piston.[29]

Application of reciprocity to structural vibration problems is straightforward, but for airborne sound one runs into experimental complexities. For airborne sound, interchanging of the excitation and observation points is valid only if the sound source and the receiver have the same directional characteristics – e.g., if both have spherical directivity.[30] Nevertheless, reciprocity permits one relatively simply to relate acoustic radiation from structures to the responses of these structures to acoustic fields.

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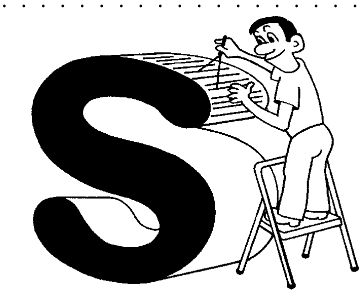


The greatest S*TRAIN within a plate*
Or beam or rod that may vibrate
Is very nearly equal to
A sort of Mach Number, times two,
In which velocity is found
As fraction of the speed of sound.

One clearly would expect the vibratory stress in a structural element to be proportional to the element's displacement and to its vibration velocity at a given frequency. However, it takes more than technical intuition to recognize that the maximum strain in a simple structural element is proportional to the ratio of the greatest vibration velocity in the element to the speed of sound (that is, the speed of longitudinal waves) in its material – and that the constant of proportionality generally is less than 2.0. This fact has been demonstrated for beams and plates vibrating in bending,[31] and it also applies to longitudinal vibrations of rods.

This "Mach number relation" is useful for estimating maximum vibratory strains and stresses. For example, consider a plate-like concrete floor on which one measures a maximum vibration velocity of 0.8 in./sec (2 cm/sec) – no matter at what frequency this occurs. Since the longitudinal wavespeed in concrete (given by $\sqrt{E/\rho}$, where E is the modulus of elasticity and ρ the density of concrete) is about 1.25×10^5 in./sec (3.2×10^5 cm/sec), we find that the greatest strain does not exceed $2(0.8)/1.25\times10^5 \approx 1.3\times10^{-5}$. If we multiply this by the modulus of elasticity of typical concrete, 3.4×10^6 psi (23,400 Mpa), we find that the maximum vibratory stress in this concrete floor does not exceed 45 psi (0.3 Mpa) – a value that generally is negligible from the standpoint of structural integrity. You'll have to agree that estimation of the maximum structural strain couldn't be done with less mental strain!

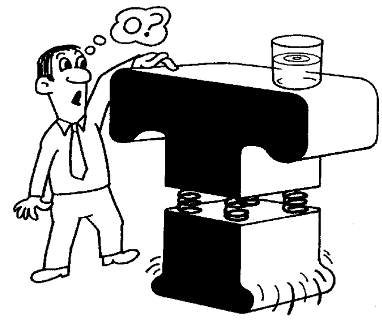
26. For instance, one can easily derive (or look up) the deflection y at any point x along a cantilever that carries a load F at its tip. If x is measured from the root (the built-in end) of the cantilever, then

$$y = \frac{Fx^2}{2EI}\left(L - \frac{x}{3}\right)$$

where L denotes the beam's length and EI its flexural rigidity, E represents Young's modulus and I the moment of inertia of the cross-section. The same formula also gives the deflection at the tip due to a force F applied at a distance x from the cantilever's root.
27. *The Theory of Sound*, Vol. I, §§ 104 - 110, Dover Publications, 1945.
28. A good discussion may be found in "Interaction of Sound Waves with Solid Structures" by I. L. Vér, Chapter 9 of *Noise and Vibration Control Engineering*, edited by L. L. Beranek and I. L. Vér, John Wiley & Sons, Inc., New York, 1992.
29. I couldn't find the exact reference, but much of Prof. Theo Priede's work is summarized in "Noise and Vibration Control of the Internal Combustion Reciprocating Engine," Chapt. 19 of *Noise and Vibration Control Engineering*, Ed. by L. L. Beranek and I. L. Vér, Wiley Interscience, New York, 1992.
30. For example, see *Structure-Borne Sound*, L. Cremer, M. Heckl, and E. E. Ungar, Spring-er-Verlag, Berlin, 1973, pp. 505 ff.
31. E. E. Ungar, "Maximum Stresses in Beams and Plates Vibrating at Resonance," *Transactions of ASME, Journal of Engineering for Industry*, 84, pp. 149-155, 1962. Also see Annex B to ISO Standard 4866:1990(E), "Mechanical vibration and shock – Vibration of buildings – Guidelines for the measurement of vibrations and evaluation of their effects on buildings." This annex, entitled "Estimation of peak stress from peak particle velocity," refers to a paper by Gasch, "Eignung der Schwingungsmessung zur Ermittlung der dynamischen Beanspruchung in Bauteilen (Utility of vibration measurements for determination of dynamic loads in structural elements)," *Berichte aus der Bauforschung*, 58, Wilhelm Ernst & Sohn, Berlin, 1968.

. . . .

Indeed, T*RANSMISSIBILITY*
Gives one the possibility
Of quantifying isolation –
But not in every situation.
It may not show the right amount
Of benefit due to a mount.



Everyone who has been concerned with vibrations has read about transmissibility in terms of a mass-spring-damper system that is constrained to move only along a line. The mass may be taken to correspond to a sensitive item that is to be protected from motion of a support to which it is attached; transmissibility then is defined as the ratio of the amplitude of the mass to the amplitude of the support. Or, the mass may be considered to represent a machine that generates an oscillatory force and the discussion focuses on the corresponding force that acts on the machine's rigid support. Here transmissibility is defined as the ratio of the amplitude of the force that acts on the support to the amplitude of the force that acts on the mass.

The two aforementioned transmissibilities are fundamentally different. In order to distinguish between them, I like to call the first one "motion transmissibility" and the second one "force transmissibility." It turns out that the mathematical expressions one obtains for these two different transmissibilities are identical, at least for the case of the simple mass-spring-damper system. Why? The textbooks I've seen don't say.

The reason can be traced to the reciprocity principle, which I've discussed under 'R.' The proof is rather simple and, in fact, leads to a more general conclusion. Consider a general linear system, such as one consisting of an arbitrary array of masses, springs and dampers. Apply a vibration to its support and observe the resulting motion of any selected point on the system to obtain the motion transmissibility from the support to that point. Now, hold the support rigid, apply a force at the selected point and observe the force that acts on the support to obtain the force transmissibility from that point to the rigid 'ground.' These two transmissibilities can be shown to be identical, at least if all points on the system are con-

strained to move only parallel to a given axis.[32,33]

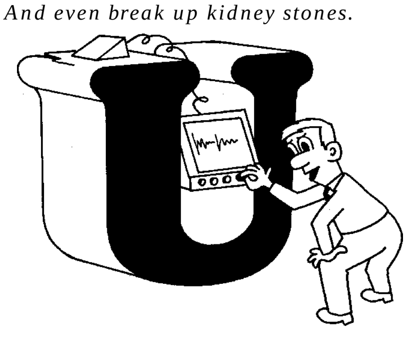
In many practical situations, transmissibility does not tell the whole story about the effect of isolation. For example, consider resilient rail fasteners – in effect, spring-like elements placed between the rails and the track bed in a railway system. The transmissibility does not tell us by how much replacing the usual rigid supports with resilient rail fasteners reduces the vibrations that are transmitted to the track bed. The problem here is that rail vibrations result from the interaction of irregularities on the contacting surfaces on the wheel and the rails, so that the rails tend to vibrate more if they are supported more resiliently. Thus, some of the isolation benefit implied by the reduced transmissibility is negated by the increased vibration input.

Transmissibility can tell the whole story by itself only if the excitation does not change as the isolation is changed. Otherwise, one needs to account for the characteristics of the excitation – that is, for the way the source responds to 'loading.' Thorough discussions of these and other aspects of transmissibility and isolation effectiveness may be found in Denys Mead's excellent book with the rather unpretentious title of *Passive Vibration Control*.[34]

32. See "Equality of Force and Motion Transmissibilities," E. E. Ungar, *Journal of the Acoustical Society of America*, 30 (1), p. 596, July 1991.
33. Dr. V. M. Ryaboy, now at the Newport Corporation, addressed this problem in the book *Elastic-Inertial Vibration Isolation Systems; Limiting Performance, Optimal Configurations* (M. D. Genkin and V. M. Ryaboy, Nauka Publishers, Moscow, 1988, in Russian) and indicated that this relation is valid also for more general conditions.
34. *Passive Vibration Control*, D. J. Mead, John Wiley & Sons, 1998.

. . . .

Ultrasound can cut or heal,
Inspect for flaws, or make a seal,
Or weld to make unsound things sound;
Its helpful benefits abound.
It's used to image cracks in bones
And even break up kidney stones.



Nowadays probably everyone is familiar with some of the many applications of ultrasound – sound at frequencies above the range of human hearing. Ultrasonic welding of plastic parts is widely used; ultrasonic inspection of critical components has become routine, and sophisticated ultrasonic monitoring methods have been developed for the purpose of detecting incipient structural failures. There exists a relatively mature technology for the detection of "acoustic emissions" – that is, of the high-frequency vibrations produced in structural components as cracks begin to form or grow. Recent patents describe an ultrasonic inspection system that can be used to predict the remaining fatigue life of the structural element being inspected and an acoustic microscope for the full-depth inspection of welds as these are being made.

Modern medicine uses ultrasound routinely for many purposes. The progress of embryos developing in the womb is almost always monitored with the aid of ultrasound and I would expect that most of us have seen some of the resulting pictures. I found out about many other fascinating medical applications of ultrasound when I listened to Larry Crum's talk on "Recent Developments in Medical Ultrasonics" at the December 2000 meeting of the Acoustical Society of America. He described various techniques for obtaining more detailed images and better contrast, enabling the localization of damaged tissue, of tumors and of blood flow. He also presented video clips showing how contrast agents, consisting of stabilized microbubbles that are injected into the bloodstream, can be used to determine the functioning of various parts of the heart. He discussed how such microbubbles that contain drugs may be burst by an ultrasound pulse when they are in the appropriate location to deliver the drugs to a selected site. Furthermore, he told of clinical trials in which high-intensity focused ultrasound was used to destroy tumors without invasive surgery and without harming adjacent tissues, and he described others in which sites of internal bleeding were imaged by ultrasound and sealed. As he put it, "image-guided, transcutaneous, bloodless surgery devices are now under development and 'Star Trek medicine' is just around the corner." I, for one, am grateful.[35]

35. I also am particularly grateful for the life-saving detection by ultrasound of cancer in one of my kidneys about ten years ago. Otherwise, the world would have been spared my rhymes.

. . . .

Viscosity, it is a fact
On fluid flow has the effect
Of slowing down the speed near things
Like piping walls and airplane wings.
It causes turbulence decay
By making eddies go away.

According to Sir Isaac Newton,[36] "The resistance arising from the want of lubricity in the parts of a fluid is, all other things being equal, proportional to the velocity with which the parts of the fluid are separated from one another." Nowadays, we would be more inclined to say that in smooth flow with a simple geometry the shear stress in a fluid is proportional to the velocity gradient. The constant of proportionality, as we all learned in Physics 101, is known as the viscosity.

Since liquids are more viscous than gases (water at room temperature being about 50 times as viscous as air) and lend themselves to easier experimentation, it is no surprise that viscosity was first studied in liquids. Jean L. M. Poiseulle (1799-1869) enabled experimenters to avoid the grief associated with direct measurement of shear stress in a fluid by coming up with a simple expression that relates the volume rate of laminar flow through a tube to the pressure difference across it, to the tube geometry and to the viscosity. In gratitude for this "Poiseulle's Law" the unit of viscosity in the international system (SI), dyne-sec/cm^2, has been named 'poise.'

Not to be outdone by a Frenchman, the British mathematician and physicist, Sir George Stokes (1819-1903), showed that one can also determine the viscosity of a fluid by measuring the terminal velocity of droplets falling through the fluid. The 'stoke,' the SI unit of kinematic viscosity, is named after him. It is interesting that in 1913 Robert A. Millikan relied on Sir Stoke's equation for determining the charge of the electron from his famous oil drop experiment.

Just to obtain an idea of the wide range of viscosities that have been measured: the viscosity of hydrogen at 0° C is about 10^{-4} poise, that of water at 20° C is about 10^{-2} poise, that of typical engine oil is about 1 poise at operating temperatures, and that of glass changes from 10^{13} to 10^{7} as its temperature is changed from 400° C to 800° C.

The relative importance of viscous effects in a flow regime generally is judged by Reynolds' number, named after Osborne Reynolds (1842-1912). This number is equal to the ratio of the inertia force to the viscous force in the flow. At small Reynolds numbers, which typically correspond to low flow speeds, viscous forces predominate and tend to keep the flow laminar. At high Reynolds numbers, inertia effects overwhelm viscous effects and the flow becomes turbulent. But still, it is viscosity that causes the turbulent eddies to decay. Some researchers, in fact, consider laminar flow as a limiting case of turbulent flow: “Larger whorls have smaller whorls that feed on their velocity, and smaller whorls have lesser whorls . . . and so on, to viscosity.”[37]

36. F. Cajori, *Sir Isaac Newton’s Mathematical Principles of Natural Philosophy and His System of the World*, University of California Press, Berkeley, 1934.

37. According to David Rice of Tulane University, the English physicist, Lewis Fry Richardson (1881-1953), wrote the following, which appears in Richardson’s book *Weather Prediction by Numerical Process*, Cambridge University Press, 1922, p. 66, which book was reprinted in 1965 by Dover Publications:
Big whirls have little whirls,
That feed on their velocity;
And little whirls have lesser whirls,
And so on to viscosity.

As David and also Rudy Volin informed me further, this verse is a parody of one by Augustus de Morgan (1806-1871), which may be found in *A Budget of Paradoxes*, Longman, Green and Company, London 1872, p. 377:
Great fleas have little fleas upon
their backs to bite ‘em
And little fleas have lesser fleas, and
so ad infinitum.
And the great fleas themselves, in
turn, have greater fleas to go on;
While these again have greater still,
and greater still, and so on.

Going back yet further, the foregoing supposedly was inspired by Jonathan Swift (1667-1745), who had written
So, naturalists observe, a flea
Has smaller fleas that on him prey;
And these have smaller still to bite ‘em;
And so proceed ad infinitum.

Rudy Volin indicated that the foregoing may be found in *On Poetry in the Works of Jonathan Swift*, Volume XIV, Bickers & Son, London, 1883, Second Edition, p. 311. In addition to mentioning some of the foregoing information, Albert George of Cornell University referred to F. Gilford, Jr., “On the Origin of Richardson’s Rhyme,” Bulletin of the American Meteorological Society, Vol. 53, No. 6, June 1972, and recommended reading Sydney Chapman’s introduction to the Dover reprint to learn how very interesting a person Richardson was. Demonstrating that one can improve on a classic, Cliff O’Hearne of Polymer Dynamics Inc., suggested adding the following two lines to the original verse:
To a state of particles discrete,
In random motion known as heat.

David Rice pointed out that the classics refer to ‘whirls,’ not to ‘whorls,’ but I am comforted by David Towers’ observation that, “*It’s a small whorl after all.*”

. . . .

WAVES, like ripples in the sea,
Transmit power as they flee.
Though mass points near their home
base stay,
They transport energy away.
If waves spread as they propagate,
Their amplitudes attenuate.

We who work in the fields of sound and vibration have a pretty good idea of what a wave is. However, I have been unable to come up with a definition that is both simple and technically satisfactory. I felt a little better about this failure when I turned to Professor Tolstoy’s definitive book on Wave Propagation[38] and read in his first chapter that “various definitions . . . can be offered. A very simple definition can be given, once it is admitted that energy degradation effects (e.g., attenuation due to viscosity, heat conduction, . . ., etc.) are secondary and that waves are fundamentally conservative phenomena. Once this is agreed upon, one may define a wave as nature’s mechanism for transporting energy without degradation and without transporting matter. . . . this most illuminating and general definition . . . emphasizes the primary role of waves as a means of energy transport . . .”

After we’ve thrown a pebble into a pond, our eyes follow the spreading ripples that seem to tell us that the water is moving outward from the point of impact. But if we focus on a small leaf or a wood chip floating on the surface, we can observe that these rock back and forth without going anywhere. If we are very astute observers, we might note that the particles move along little circles in the vertical plane. It was only fairly recently that sound was understood to propagate in air without the air particles travelling from the source to where the sound is heard. Lord Rayleigh, the father of modern acoustics, pointed out that if sound propagation involved gross motion of the air, rather than wave propagation, then a cricket that is heard at a considerable distance would need to move a tremendous mass of air all at once. I can’t find the exact reference and don’t remember the details, but a simple calculation shows that a hemisphere of air with a 10-meter radius weighs roughly 2100 kg (or 4500 lb.) – quite a lot for a little cricket to push to be heard at 10 meters.

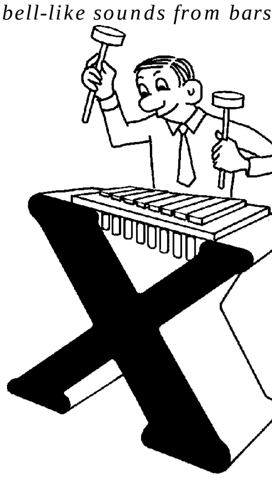
In sound waves in fluids and in compressional waves in solids, the particles oscillate in the direction of propagation. In shear waves and torsional waves, the particles move in directions that are perpendicular to the direction of propagation. Of the various types of elastic waves the so-called Rayleigh waves, which dominate the propagation of energy along the surfaces of solids, are of great interest. Such waves are typical of earthquake motions along the surface of the earth and also play significant roles in certain ultrasonic inspection applications. Rayleigh waves are characterized by ‘retrograde’ elliptical motion of the particles, where the planes of the ellipses are aligned with the direction of propagation and the vertical and where at its topmost position a particle moves in the direction opposite to the direction of propagation.

The foregoing are the simplest cases, which are best known in the acoustics community, but many other types of waves have been studied. These include not only nonacoustic waves, such as electromagnetic ones, which involve the complexity associated with polarization, but also waves that are not governed by relatively simple linear equations. In particular, surface waves in the ocean, which are affected by gravity and whose character depends on the depth and on the configuration of the bottom, are of great interest to oceanographers, ship designers and surfers. However, the latter are likely to have limited interest in the underlying science, so we’ll just wave goodbye to them unwaveringly.

38. Ivan Tolstoy, *Wave Propagation*, McGraw-Hill Book Co., New York, 1973.

. . . .

XYLOPHONES owe their crisp timbre
To bars and mallets made of timber.
The bars’ bright tones are amplified
By tuned tubes near their underside.
A cousin is the glockenspiel,
With bell-like sounds from bars of steel.



There aren’t many English words that begin with X, and I’m very happy that one of the few that does is related to acoustics, so that I can complete this alphabet. Although I have little firsthand knowledge of xylophones, I was able to glean some interesting information from one of Thomas Rossing’s books[39] and I have based some of the following discussion on this information.

Etymologically, the word *xylophone* comes from the Greek *xylon* meaning ‘wood,’ and *phone* meaning ‘sound.’ It seems to be unrelated to “knocking on wood,” which in olden times was done to alert the spirits thought to reside in wood. At any rate, xylophones, marimbas, vibraphones (or vibraharps) and xylomarimbas all consist of tuned bars that vibrate and produce sound at their natural frequencies when they are struck. The bars of xylophones and marimbas typically are made of rosewood or of synthetic materials, whereas the bars of vibraphones usually are made of aluminum. Soft mallets are used to play the marimbas, giving them a rich, mellow tone, whereas a xylophone is played with hard mallets and has a crisper sound.

All of the aforementioned instruments have tubular resonators mounted near the struck bars to amplify the bars' tones and the various resonances of these tubes also add to the character of the instrument's sound. Vibraphones have motor-driven discs at the top of their resonator tubes to open and close these, so as to produce the *vibrato* characteristics of these instruments. Because their aluminum bars ring for relatively long times, vibraphones also are provided with pedal-actuated dampers that permit the musician to suppress this ringing.

Xylophones and their cousins belong to the larger class of idiophones – defined as instruments that produce sound via their natural resonances when they are struck, rubbed, plucked or shaken. This class also includes gongs, bells, pianos, hollow logs and human skulls.

Idiophone also comes from the Greek. We already know what 'phone' means. The root of *idio* is the Greek *idios*, which means peculiar or separate and indicates individuality or isolation – akin to the German *eigen* as in 'eigen value' and 'eigen frequency,' referring to a characteristic value and characteristic (i.e., natural) frequency. Yes, the English designation *idiot* also comes from the Greek *idiotos*, meaning a private person or perhaps a loner – somewhat different from the meaning of the English word which I shall refrain from applying to some of the modern so-called musicians.

39. *The Science of Sound*, Thomas D. Rossing, Addison-Wesley Publishing Co., New York, 2nd Edition, 1990.

Young's modulus, let me explain,
Relates the axial stress to strain
For simple tension in a bar,
As long as it's not stretched too far.
If the bar's section can't contract,
Poisson's effect gets in the act.

The incredibly talented Thomas Young (1773-1829), who also made numerous contributions in acoustics and optics,[40] is credited with discovering that the elastic stress in a metal rod is proportional to the strain; the modulus that bears his name is defined as the ratio of the stress to the strain. However, the basic discovery that the elongation of a rod is proportional to the force applied to it was made by Robert Hooke (1635-1703) before Young came into this world. The same Hooke, by the way, was first to suggest use of a rotating toothed wheel to produce a tone of a desired pitch.[41]

The proportionality of force to elongation or of stress to strain (or vice versa) is determined from experimental evidence and thus only is valid within the accuracy of the measurements. It is fortunate that this proportionality is a good approximation for metals, both in tension and compression, for strains normally encountered in practice. For analyses of metal structures, a constant Young's modulus (also called modulus of elasticity) is taken to apply for stresses up to the so-called proportional limit. Beyond that limit, stress and strain are no longer proportional to each other to an acceptable approximation. In polymers (plastics and elastomers – that is, rubbery materials), such as may be used for vibration isolation, loads and deflections are nearly proportional only for very small loads, and the stress-strain curves in tension and compression tend to be different, generally with greater effective moduli of elasticity applying in compression than in tension. This gives us the hint that conventional elastic analysis methods may not work too well for polymeric materials.

If one pulls on a metal rod along its axis, the rod not only elongates along this axis but its cross-section shrinks. Similarly, if one compresses a solid rubber pad, the pad thickness decreases and its sides bulge out. The ratio of the strain perpendicular to the loading axis to the strain along the axis is called Poisson's ratio, named after the French mathematician Siméon Denis Poisson (1781-1840). Poisson's ratio is between about 0.25 and 0.33 for most structural materials; for rubbery materials, it approaches 0.5.

One can easily visualize that it should take more force to achieve a given axial deformation if the cross-section is prevented from shrinking or expanding than it does for a rod or pad with no constraints on the cross-section. In fact, from elasticity theory[42] one can readily determine that constraining the cross section *changes the ratio of the axial stress* to the axial strain from E (Young's modulus) to $E(1-n)/((1+n)(1-2n))$, where n stands for Poisson's ratio. For a rubbery material with n near 0.5 this becomes a very large number indeed.

If a compressive load is applied to a rubber pad that is confined between two metal plates, where there is excellent lubrication between the rubber and metal, then the pad's edges can move outward without constraint, and the pad's effective stiffness is given essentially by E multiplied by the pad's area and divided by its thickness. If the edges of the pad are fully confined, then the compressive stiffness of the pad is much greater, given (at least for small strains) by the foregoing expression with all those n terms.

If the top and bottom surfaces of the pad are bonded to the metal plates or if there is considerable friction between the pad and the plates, then the parts of the pad edges near these surfaces cannot move outward, and the rest of the edges cannot move as freely as they could in the absence of any edge constraint. In this case, the compressive stiffness of the pad is between the two values we discussed, and it depends on the pad's geometry as well as on the value of Poisson's ratio. The geometry effect is usually represented in terms of the pad's "shape factor," defined as the ratio of the pad's loaded area to the area that is free to bulge. For example, the shape factor of a rectangular pad of length L, width w, and thickness h, is equal to $Lw/(2h(L+w))$. Note that little bulging can occur around a thin pad, for which the shape factor is large – thus, the effective pad stiffness increases with increasing shape factor.[43]

The foregoing discussion of pad stiffness pertains only to solid pads, not to pads of foam material. In foams, the material can bulge into the small interior open spaces, so that the shape factor plays no significant role and the stiffness of a pad of a given thickness depends essentially only on its loaded area – a distinct selection and design advantage. Suppliers of isolation pads offer pads cleverly achieving the same advantage by providing the pads with ribs, dimples, knobs, and the like, so as to obtain the same free-to-bulge area per unit surface area for any (large enough) pad.

Even knowing the shape factor, we're still not in good enough shape. A pad's dynamic stiffness typically depends on the static load and the amplitude of the vibration the pad experiences, and also on the temperature. After all, elastomers are viscoelastic materials whose stiffness and damping properties vary with frequency and temperature. As such, they also are subject to creeping – that is, to deflecting continually under a given static load.[44] Much theoretical information about such materials is available, but so many factors affect any practical application that theory can only serve as a guide and development generally requires a great deal of empirical testing.

40. According to Robert Beyer (see next footnote), "Young was a master of many languages, both contemporary and ancient, a practicing physician and a student of Egyptology. (He pioneered in translation

work on the hieroglyphics of the famous Rosetta stone before Champollion.) He was also a first class physicist in optics and elasticity. He was elected a fellow of the Royal Society of London at the age of 21, primarily for his work on the eye . . .”

41. *Sounds of our Times*, Robert T. Beyer, Springer-Verlag, New York, 1999.
42. For example, *Applied Elasticity*, C.-T. Wang, McGraw-Hill Book Co., Inc., New York, 1953. This old text, left over from my graduate school days, still is one of the best I’ve seen.
43. For example, see “Rubber Springs,” William A. Frye, Chapt. 35 of *Shock and Vibration Handbook*, Ed. by Cyril M. Harris and Charles E. Crede, McGraw-Hill Book Co., New York, 2nd Edition, 1976.
44. *The Handbook of Viscoelastic Damping*, D. I. G. Jones, John Wiley & Sons, Ltd., Chichester, England, 2001, contains a great deal of useful information about the behavior of viscoelastic materials – and not just about damping.

. . . .

The number Zero is unique
And carries with it much mystique.
It can mean there is no amount
Or just: “Begin here to count.”
If you divide by it you find
An answer that is undefined.

Ask the proverbial man in the street about zero, and he’ll tell you that zero means “nothing” or that to him zero means nothing. We probably also can confound him with the following more-or-less well-known syllogism:[45] “Nothing is better than fresh bread. But stale bread is better than nothing. Therefore, stale bread is better than fresh bread.”

Zero certainly does not always indicate the absence of something. If we are at zero latitude, that does not mean we are nowhere. It merely means that we are on the equator. A temperature of zero degrees does not imply that there is no temperature and a sound pressure level of 0 dB does not mean that there is no sound. Zero is often taken to represent an arbitrary datum from which deviations are measured, and the datum has no meaning other than that given it by its definition.

It is interesting to observe that the early number systems, including that of the Romans, represented numbers without using zeros. For example, a Roman might have written that in just VII years from the year MMIII, we’ll be in the year MMX – in contrast to our using zeros and “positional notation” to write that in just 7 years from the year 2003, we’ll be in the year 2010. Recall that in our decimal system we use positional notation proceeding from right to left, going from $10^0 = 1$ to higher powers of 10, so that the number 2003 means $(3\times10^0) + (0\times10^1) + (0\times10^2) + (2\times10^3)$. Note that in positional notation zero is not really a number, but merely a “place holder” indicating the absence of an entry corresponding to a particular power of 10.

However, mathematicians wanted to treat zero like a number, and that necessitated making up some special rules for zero, so as not to spoil the system of mathematical operations. Because multiplication of any finite number by zero is defined as resulting in zero, one finds for example that $7\times0 = 3\times0 = 0$. Thus, if zero were to behave like an ordinary number, we could divide through by zero and conclude that $7 = 3 = 1$. In order to avoid destruction of the structure of arithmetic, division by zero is not permitted – or, in other words, the result of division by zero is undefined.

And, what does 6^0 mean, for example? We know that $6^2 = 6\times6$, that $6^3 = 6\times6\times6$, and that 6^n represents the result we get by multiplying 6 by itself n times. In order to preserve the usual rule that $a^{b+c} = a^b\times a^c$, which follows directly from the definition of a^n, with n representing any integer, one needs to require that $a^b\times a^0 = a^b$ because $b+0 = b$. This requirement can only be satisfied if $a^0 = 1$ for all numbers a, resulting in the counter-intuitive statement that multiplication of any number by itself 0 times (or, of multiplication of a number by itself not at all?) results in 1.

As we know, if we multiply any finite number by 0 we get 0. Clearly, $0\times0 = 0$, and $0^n = 0$ for all integers n. Now, here is any interesting question: if $a^0 = 1$ for all a and $0^n = 0$ for all n, is 0^0 equal to 1 or to zero? If you want to pursue this question and learn more about the structure and philosophy of mathematics, as well as about the origin and myths that surround development of the idea of zero and the symbol 0, I recommend that you peruse the very erudite little book entitled *The Nothing That Is; a Natural History of Zero*.[46] I have based much of the foregoing discussion on what I read in that book and I close with its intriguing introduction: “If you look at zero you see nothing; but look through it and you will see the world. For zero brings into focus the great, organic sprawl of mathematics, and mathematics in turn the complex nature of things . . .”

Now, at long last, this series of alphabetical excursions into acoustics-related topics and word play is finished. And we have arrived at nothing.

45. A syllogism, as you may recall, is a logical construct like: “If A is greater than B and B is greater than C, then A is greater than C.”
46. By Robert Kaplan, Oxford University Press, 1999.

Acknowledgment

As I have mentioned, the idea for this alphabetical series came from one published in 1958 by the late Professor Lothar Cremer of the Technical University of Berlin. I am greatly indebted to Jack Mowry, the editor and publisher of *Sound and Vibration*, for his encouragement and enthusiastic support of my ABC editorials, which are collected here. I also am grateful to Jack for his involving his Art Director, Jerry Garfield, in this project and to Jerry for his cartoons, which managed to capture just the right nuances of my essays.

I have particularly enjoyed all the comments and inputs I have received from so many of the readers of *Sound and Vibration* and from my colleagues at Acentech Incorporated. I have had great fun writing this series and am a bit sorry that there aren’t more letters in the English alphabet.

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Misuse of ‘Accuracy’ and ‘Data’

The proper usage and meaning of words is of vital importance in the technological world. We have an ingrained habit of misusing the word accuracy. We say that a measurement or a value has an accuracy of ±1%. What does this mean to you? I hope you say that it is terribly inaccurate. In that case, why boast about it? In the engineering world, if ±1% accuracy is good, ±1/2% accuracy is even better! Of course, we mean *inaccuracy* or *uncertainty*. I prefer the latter. How did this misuse ever begin? It is utter nonsense, but it is very difficult to overcome. Please help.

Now let me point out a common grammatical error. The term ‘data’ pops up often in technical literature. Many people treat the word ‘data’ as a singular noun. But it is plural. It is a Latin word: *datum* is singular and *data* is plural. We are so used to seeing, “The data is good” that “The data are good” sounds improper. That is unfortunate. But we have made more strides in overcoming this error than we have with the misuse of the word accuracy.

One more thing, please do not buy into the popular argument that grammatical errors and misuse of words are not important because the only thing that matters is that people understand what you mean. That is ridiculous. If you don’t believe it, ask a lawyer.

Anthony J. Schneider, *The Little Brown Book*