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# Decibels and octaves, who needs them?[☆]

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## Abstract

Decibels and octaves have been in use for almost a century and appear to have become deeply entrenched. However, with the advent of digital signal processing, routine methods of measuring sound intensity (sound power flow per unit area) and the widespread use of pascal units for pressure, their usefulness is open to question. This short communication examines the origins of decibels and octaves and why they appear to have become a blind alley for acoustics.

## 1. Decibels

In the United States, logarithms to the base10 were used in the early 1900s to measure the relative power loss in electrical transmission lines. Initially they were called transmission units, TU. In 1923 scientists at Bell Labs renamed the TU the bel. Since the bel was too large they divided it by 10 and used the term decibel (dB) instead. The use of decibels for voice transmission over the telephone was an extension of electrical transmission. In Europe, a unit based on natural logarithms was employed, called the neper, after Napier the Scottish Mathematician who developed logarithms. From the time of Napier to the early 1900s, scientific and engineering computations were performed using logarithms.

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In the early 1900s, Bell Labs held a pre-eminent place in acoustics, having developed vacuum tube amplifiers (1912), condenser microphones (1916), loudspeakers (1918), the first public address system (1921) and the use of modulated light to record sound on moving photographic film (1923). This started the era of mass communication and for the first time gave acousticians the tools to quantify sound. In turn this brought with it the use of decibels which acousticians felt should be related to human hearing, based on

- The wide dynamic range of the human ear.
- Perception of loudness as roughly logarithmic (The Weber–Fechner Law).
- Making 0 dB the nominal threshold of hearing.

Since the decibel represents a power ratio, the far-field approximation, valid for plane and spherical progressive waves in a free field, was used to relate sound-power flow (intensity) to sound pressure, the only routinely measurable quantity, thus creating the sound-pressure level

$$\mathrm{SPL} = 20\log_{10}(p/p_0)\,\mathrm{dB},$$

where $p$ is sound pressure. In air, the reference pressure $p_0$ is the nominal threshold of hearing, 20 μPa, and in water it is 1 μPa. The pascal (Pa) is the SI unit of pressure in $\mathrm{kg\,m^{-1}\,s^{-2}}$. Relative to atmospheric pressure, it is small (1 Pa = 0.01 millibar), but it is ideally suited to measuring sound pressure, as can be seen from the following table, which ranges from the nominal threshold of hearing to pressures that can rupture the eardrum [1].

Table 1
Comparison between sound-pressure level and corresponding sound pressure in pascals

| SPL (dB) | Pascals |
|---|---|
| 0 | 20 μPa |
| 20 | 0.2 mPa |
| 40 | 2 mPa |
| 60 | 0.02 Pa |
| 80 | 0.2 Pa |
| 100 | 2 Pa |
| 120 | 20 Pa |
| 140 | 200 Pa |
| 160 | 2 kPa |
| 180 | 200 kPa |

From Table 1 it can be seen that

- The overall range in pascals covers a range equivalent to that of the meter, which is a quantity in everyday use not requiring a logarithmic scale.
- Noise control is concerned roughly with sound in the range from 40 to 90 dB or about 2 mPa to 1 Pa, a range that certainly does not need logarithms.

Drawbacks with the use of logarithms for sound pressure are:

- Elementary operations of addition and subtraction are needlessly complicated.
- Inaccuracy is obscured. It is generally assumed that an error within 1 dB is acceptable. However, in linear units this is about 12% for sound pressure and 24% for sound power.
- The reference pressure can cause confusion. Several years ago there was a major controversy with the US Navy because environmentalists thought that sea mammals were being exposed to sound pressures that were 26 dB higher than they actually were. To avoid such confusion it was proposed to add the reference pressure after the decibel quantity. But of course this increases the complication involved in the use of decibels. It would have been simpler just to use the linear quantity.
- Use of the far-field approximation to derive the sound-pressure level is deceptive, because it seems to imply that it is the only way to determine intensity (sound-power flow) from sound-pressure.

## 2. Octaves and the partitioning of the frequency scale

To find the frequency content of sound it is necessary to partition the frequency scale. It was probably familiarity with scales such as the piano keyboard that led to partitioning into octaves, which is a 2 to 1 frequency ratio. This created intervals that were generally too large to provide information about frequency content, which then brought about the use of $\frac{1}{3}$ octave and $\frac{1}{12}$ octave intervals. However, even these are too large for many applications. The human ear can distinguish much smaller differences in frequency [2].

The advent of electronic computers and digital signal processing in the 1950s–1960s changed the nature of frequency partitioning. For the first time frequency intervals could be small and evenly distributed. It then became possible to determine frequency content in much greater detail.

## 3. Sound-intensity measurement

Perhaps the biggest impact on the use of decibels has been the development of routine methods of measuring sound intensity. Acoustics is characterized by four quantities: sound pressure, sound velocity, sound-power flow per unit area (intensity) and sound power. Velocity and sound-power flow are vectors. Intensity is a non-descriptive term, having an association with the far-field approximation that can obscure its vector nature. Nevertheless the term is widely used and will be used here. The history of sound-intensity measurement has been given by Fahy [3]. A major breakthrough came with the discovery of the cross-spectral relation [4] and its application to the noise of motor vehicles and locomotives at General Motors [5]. Mathematically it is not possible to determine the instantaneous value of the sound-intensity vector using the pressure gradient in the momentum equation of acoustics. Instead Parseval's Theorem is used to derive the time average of sound intensity in the form of the cross-spectral relation [6], using measurements at two closely spaced microphones, as shown in Fig. 1.

The microphones can be either in the side-by-side or face-to-face arrangement with the direction of the sound-intensity vector indicated by the arrows. The measurement point is midway between the microphones. The magnitude of the intensity vector is given by the

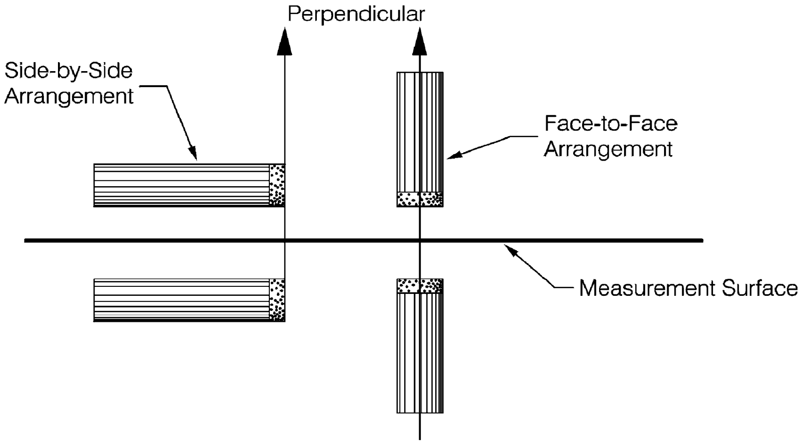

Fig. 1. Arrangements of the two microphones in a sound-intensity probe.

cross-spectral relation

$$I_n = -\mathrm{Im}[G(p_1, p_2)]/\rho ckd, \tag{1}$$

where Im is the imaginary part, $G$ is the cross-spectrum, $p_1$ and $p_2$ are the sound pressures at the two microphones, $\rho$ and $c$ are the density and speed of sound of the fluid medium, $k$ is the wavenumber, and $d$ is the microphone spacing. This relation is based on standard finite-difference approximations and is accurate if

$$kd \ll 1. \tag{2}$$

In addition to its mathematical derivation, there are experimental verifications of Eq. (1). Obviously the process of implementing the cross-spectral relation has to involve digital signal processing without the use of decibels

Possible sources of error with sound-intensity measurement are:

- Phase mismatch between the microphone channels. A practical solution to this problem using switching of microphones was developed at General Motors [4] but it does not appear to have been widely implemented by instrument makers.
- High levels of background sound pressure that can overwhelm the sound pressure involved with the intensity measurement.
- Poor understanding of finite-difference approximations.

It should be noted that there is a similarity between the two-microphone sound-intensity probe and the Pitot tube used in fluid dynamics to measure flow velocity. Both are based on pressure measurements.

## 4. Sound power

Perhaps the most important application of sound-intensity measurement is determining the sound power of a noise source by integrating the normal component of intensity over a surface enclosing the source. If the source is on a rigid base plane, such as a concrete floor, intensity can

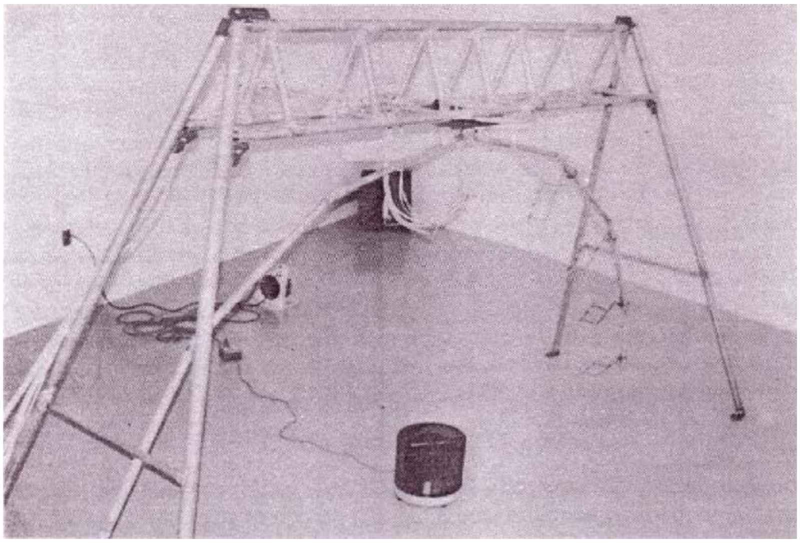

Fig. 2. Determining the sound power of a standard reference source in a reverberation room using sound-intensity measurement (reproduced with permission from Ref. [7]).

be assumed to be zero on this plane. Hence, the intensity measurements need only be made on the remainder of the surface enclosing the source. The integration has to be performed in linear units because it would be impractical to use decibels.

The sound power of a standard sound-power reference source has been determined in a number of different room environments [7], using a semicircular array of sound-intensity probes rotated over a hemispherical measurement surface enclosing the source on a concrete floor. Fig. 2 shows measurements being made in a reverberation room. In some of the reverberation-room tests an additional reference source was located outside the measurement hemisphere in the corner of the room, as shown in Fig. 2, in order to investigate the effect of increasing reverberation sound pressure in the room. Tests in different room environments with a concrete floor consistently showed an accuracy within a few percent of the manufacturers calibrated value of about 3.5 mW. In a practical application, the A-weighted sound power of a passenger car has been determined to range from about 1 to 10 mW depending on engine speed and load [8]. In these latter measurements, integration of sound intensity using the semicircular array was tested with a standard source.

ISO and ANSI standards [9,10] have been developed to determine sound power using sound-intensity measurement. However, these are deeply embedded in the decibel system with a complicated set of indicators that are probably difficult for technicians to understand. Also they do not make use of a reference source. These standards do not appear to have been widely used.

## 5. Conclusion

Strenuous efforts have been made to preserve the system of decibels and octaves. However, at this stage, acoustics would appear to be much better off without them. Like Roman numerals they could still be used to create an aura or other special effect.

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