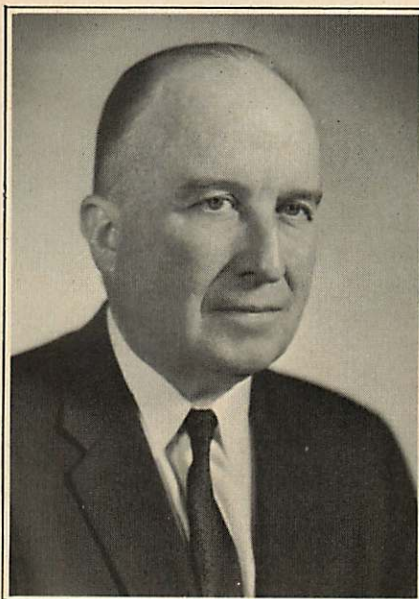# The Measurement of Loudness

Harry F. Olson*

THE ULTIMATE significant subjective destination of original or reproduced sound and noise is the human ear. Therefore, the varied responses of the auditory system are particularly important factors in the reproduction of sound. One of the response functions of the human hearing mechanism is loudness. The purpose of this paper is to describe a loudness meter based upon the fundamental principles of the loudness response of the human hearing mechanism.

When a sound or noise of any quality or structure impinges upon the human ear, the magnitude of the resultant sensation is termed the loudness. It is the intensive attribute of an auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud. Loudness depends primarily upon sound pressure but it also depends upon frequency and waveform of the stimulus. The units on the scale of loudness should agree with common experience estimates about the magnitude of the sensation. The measurement of loudness is a significant part of the audio art because the loudness of a sound or noise plays an important role in the reproduction of sound.

Loudness is functionally related to sound pressure level, frequency, and waveform. Turning this around, the sound pressure level as measured by a sound level meter does not indicate the loudness of a sound. However, a conversion can be made in the readings of a sound level meter employing octave band pass filters to obtain the loudness. This is indeed a long and tedious process, as the exposition in this paper will show. What is required is a loudness meter that indicates the loudness of a sound in real time. Furthermore, the loudness indication should agree with the loudness as perceived by the listener.

There are many uses for a loudness meter. For example, the loudness meter can be used to monitor the loudness of an audio program so that the peak permissible levels of all manner of audio program material will provide the same loudness to the listener. In the production of contemporary recorded music one of the objectives is to obtain the maximum loudness. For a certain maximum amplitude level of the signal, which is determined by the constraints of the record, a loudness meter can be employed to obtain the maximum program loudness by modifications of the frequency balance and timbre present in the signal. There are many other uses for the loudness meter in the measurement of sounds and noises.

Loudness Scale

The establishment of a loudness scale is a very complicated matter. A large number of investigators in many countries have carried out research on the loudness of a complex sound. A detailed description of the work is beyond the scope of this paper. Therefore, only the basic data on loudness required for the development of a loudness meter will be presented.

The unit of loudness is the *sone*. A sone is defined as the loudness heard by typical listeners when confronted with a 1000 Hz tone at a sound pressure level of 40 phons.

The loudness level of a sound is given by

$$P = 20 \log_{10} \frac{p}{p_0}$$

where p = loudness level, in phons,
P = measured sound pressure, in microbars, and
p_0 = a sound pressure of 0.0002 microbars

The loudness level [1] of a sound or noise is expressed as n phons, when it is judged by normal listeners to be equally loud compared to a pure tone of frequency 1000 Hz consisting of a plane progressive sound wave radiating to the observer, the sound pressure of which is n (decibels) above the standard ref-
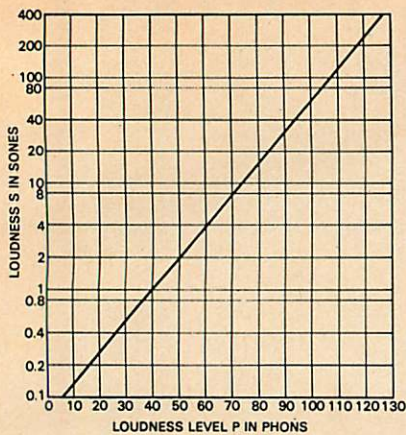
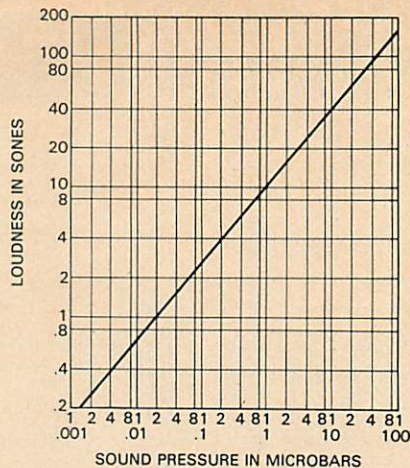**Fig. 1**—The relation between the loudness in sones and the loudness level in phons.

Fig. 2—The relation between loudness in sones and the sound pressure in microbars.

erence sound pressure of 0.0002 micro-bars.

The relation[1] between loudness in sones and loudness level in phons is given by

$$S = 2^{(P-40)/10}$$

where S = loudness, in sones and
P = sound pressure level, in phons, given by equation 1.

The relation between the loudness in sones and the loudness level in phons is shown by the graph of Fig. 1.

The relation between loudness in sones and sound pressure in microbars, shown by the graph of Fig. 2, indicates that there is a nonlinear relationship between the loudness in sones and sound pressure in microbars.

Measurement Of Loudness

In order to provide a measure of the loudness for the complex sounds of speech, music, and noise, there must be a means to separate the complex sounds into manageable segments. In particular, to establish the loudness of a complex sound, at least three specifications must be available as follows:

1. A scale of subjective loudness. This is termed the *sone scale* described in the preceding section.

2. The equal loudness contours for discrete frequency bands of the complex sound.

3. The rule by which loudness adds as the discrete frequency bands of the complex sound are added.

If specifications 1, 2 and 3 can be established, then the loudness of the
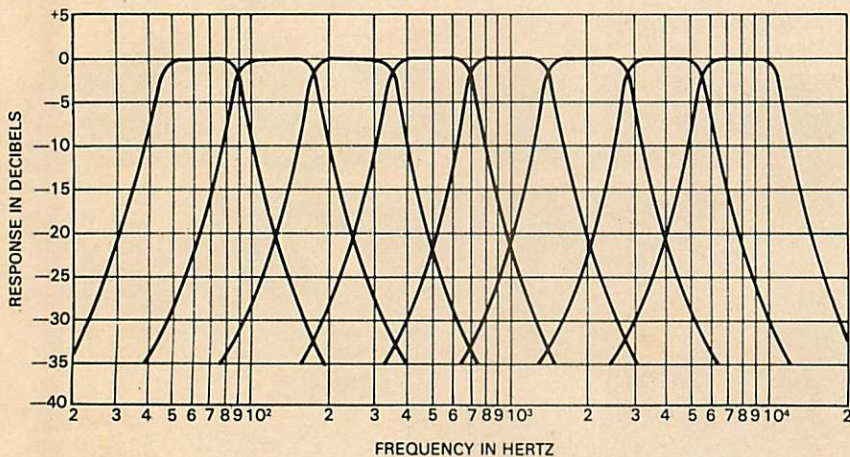

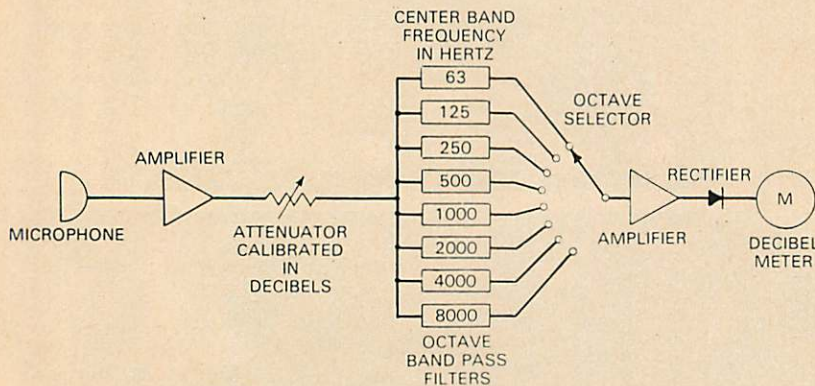**Fig. 3**—The frequency response characteristics of the octave band pass filters.

Fig. 4—Schematic diagram of a sound level meter for measuring the sound level in an octave.
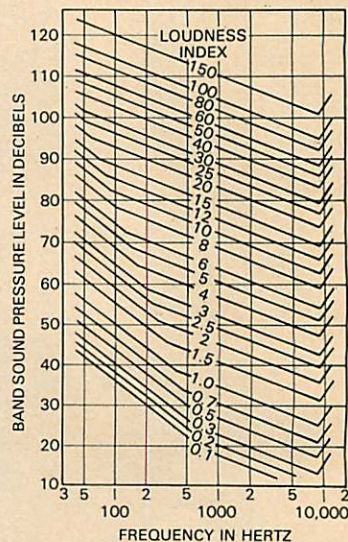

Fig. 5—Contours of equal loudness index for octave bands in the audio frequency range.

complex sounds of speech, music, or noise can be determined. The objective and subjective information[2,3,4] relating to the specifications of items 1, 2 and 3 have been established by investigators concerned with the subject of loudness. Furthermore, these investigators have shown that the loudness of a complex sound can be determined from the physical data on the complex sound in conjunction with the specifications of items 1, 2 and 3.

The specific method for determining the loudness of a complex sound is to split the audio frequency range into frequency bands. This is a complex procedure in which the complexity increases with the number of frequency bands. From a practical standpoint there should be as few frequency bands as possible without sacrificing frequency selectivity. A suitable frequency band appears to be the octave. The frequency response characteristics of the octave band pass filters employed in this development project are shown in Fig. 3.

The system for determining the sound pressure level in the eight different octave bands in the audio frequency range is shown in Fig. 4.

When the sound pressure level in each octave band has been measured, the next step is the proper summation of these data to provide the total or overall loudness of the complex sound. In this investigation and development, the procedure selected for calculating the loudness of a complex sound is the one developed by S.S. Stevens.[2] This is also the standardized procedure[5] as given in ISO-R532 Method A. In accordance with this Standard, the relation between the total loudness and the loudness index in each octave band is given by

$$S_T = 0.7\,S_M + 0.3\,\Sigma\,S$$

where S_T = total loudness of the complex sound, in sones,

S = loudness index in each octave band, and

S_M = greatest of the loudness indices.

The loudness index is obtained from the graph of Fig. 5. The sound pressure level in each octave band is determined by means of the system of Fig. 4. Employing the geometric mean frequency for each octave band, the loudness index for each octave band is determined from Fig. 5. Then the total loudness of the complex sound in sones is computed by means of equation 3.
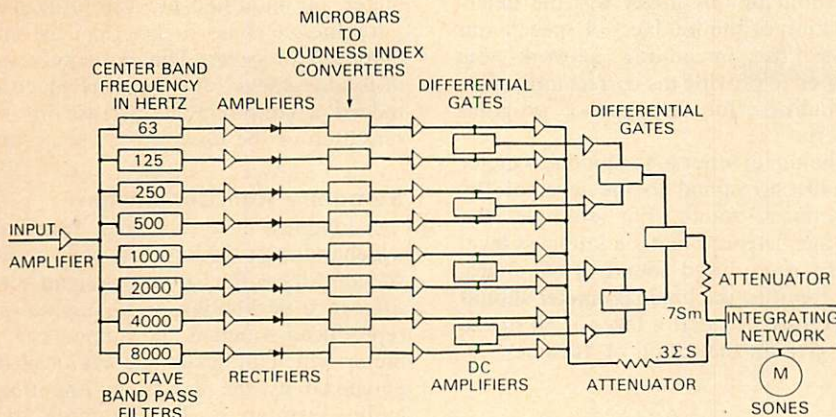

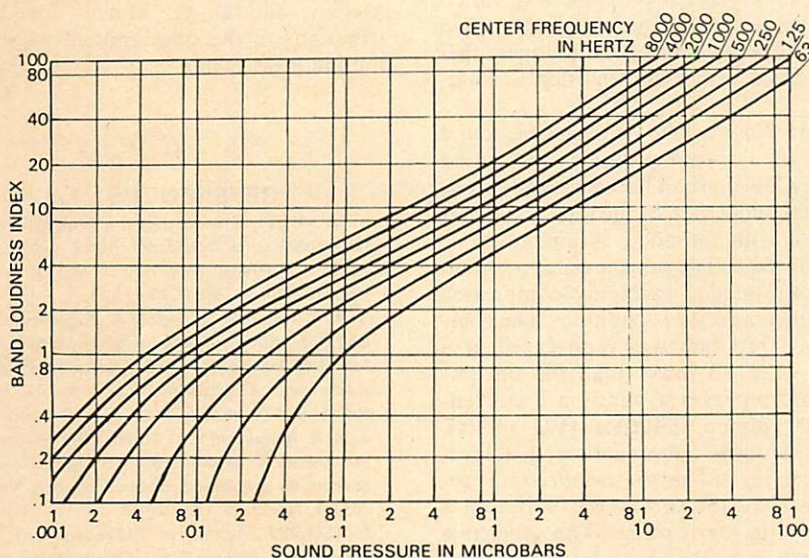Fig. 6—Schematic diagram of the elements of a loudness meter.

Loudness Meter

To provide a loudness meter requires an automated instrumentation of Fig. 4 incorporating the data of Fig. 5 and the procedures of the preceding section operating in real time. Specifically, equation 3 shows that the loudness meter must provide the following: the measurement of the loudness index in each channel, the summation of the loudness indices in all the channels, the selection of the channel with the greatest loudness index, the proper relation and summation of the sum of the loudness indices and the highest loudness index, and an indicating meter with the proper dynamics to depict the loudness of the complex sound in sones from the summation input.

A schematic diagram of the loudness meter[6] is shown in Fig. 6. The signal input is fed to eight octave band pass filters. The frequency response characteristics of the filters are shown in Fig. 3. The output of each band pass filter is followed by an amplifier coupled to a rectifier, which in turn is followed by

Fig. 7—The relation between the loudness index and the sound pressure in microbars for the octave bands of Fig. 3.

a microbar-to-loudness-index converter. The input-output characteristics of the eight microbar-to-loudness-index converters are shown in Fig. 7. These converters are in the form of nonlinear active elements as a part of operational amplifiers and their output is fed to a d.c. amplifier. The output of these amplifiers provides the loudness index for each octave channel, and the loudness index outputs from the eight channels are added by means of separate direct current amplifiers and fed to the attenuator coupled to integrating network and the sone meter. In order to determine the channel with the highest output, the eight microbar-to-loudness-index converters are fed to differential electronic gates in the form of a net-
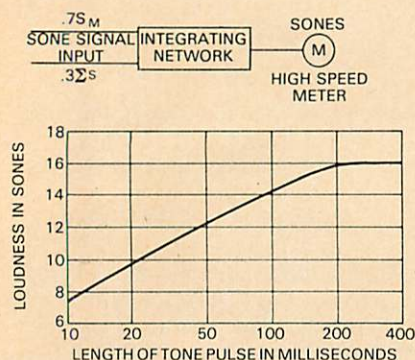

Fig. 8—The integrating network and high speed meter of the loudness meter. The graph depicts the relation between the loudness in sones and the length of the tone pulse in milliseconds.

work tree, the output of which is fed to an attenuator coupled to the integrating network and the sone meter. The two attenuators are adjusted to obtain the correct values of $0.7S_M$ and $0.3\Sigma S$. Under these conditions the sone meter will indicate the loudness in sones of an audio signal input to the loudness meter.

The remaining and very important subject is the dynamics of the amplitude characteristic of the indicating meter. The amplitude response of the indicating meter system should correspond to the ear response to individual, repetitive and overlapping short, medium, and long time pulses of sound and continuous sounds. Since most sounds of speech and individual musical instruments are of short duration, this then becomes a very important problem. The basic question is the loudness of a complex sound as a function of the time the sound persists. Obviously, a short pulse of sound of amplitude equal to a long pulse of sound will exhibit a lower loudness level. From published data and data obtained from this develop-

ment (loudness as a function of the time length of the sound pulse), the graph shown in Fig. 8 was drawn. As would be expected, the loudness of a relatively short time pulse of sound decreases with the duration of the time of the pulse. This data was used to develop an integrating network in conjunction with a high speed indicating meter. A block diagram of the integrating network and the high speed meter for indicating the output of the loudness meter in sones is shown in Fig. 8. The integrating network consists of active growth and decay networks applied to an operational amplifier. Since the main intended application for this meter was the determination of the loudness of speech and music, the integrating network was tailored to provide the correct indication of loudness for this type of program material.

The signal input to the loudness meter should correspond to the level of the reproduced sound. For example, the average listener prefers a loudness level of the reproduced sound of 80 phons. The input to the loudness meter should be adjusted so that a level of 80 phons will give an indication of 16 sones.

Performance Of The Loudness Meter

A large number of subjective tests have been carried out to determine the performance of the loudness meter employing reproduced speech and music. A few of the tests and results will be described.

Test No. 1. The reproduced sound level of a *musical* program was varied over wide limits. The observers agreed that the indication of the loudness meter agreed with their sensation of loudness.

Test No. 2. The reproduced sound level of a *speech* program was varied over wide limits. The observers agreed that the indication of the loudness meter agreed with sensation of loudness.

Test No. 3. The same musical program was reproduced in highly compressed and uncompressed conditions. The compressed program was reproduced at a level of 2 dB lower than the uncompressed program as read on a conventional volume indicator (VU meter). The loudness meter indicated a level 3 sones higher for the compressed program. Here the two meters indicated a reversal in the readings. The subjective evaluation by the observers agreed with the loudness meter. This shows the conventional volume indicator does not indicate loudness.

Test No. 4. Speech was recorded at a low speaking level and at an almost

shouting level. The two were reproduced at the same top level of 80 dB as indicated by a conventional volume indicator (VU meter). The shouting speech indicated a higher loudness on the loudness meter. Again the observers agreed with the loudness meter.

Test No. 5. Employing a contemporary musical program, the loudness meter was used to provide the maximum loudness for the same peak level as the unchanged program. The main operations were compression and changes in the frequency distribution. Employing a reproduction peak level of 85 dB as indicated on a peak reading level meter, the modified program indicated a loudness 6 sones higher than the unmodified program. This is an increase in loudness level of 6.7 phons which is indeed a considerable increase in the sensation of the loudness.

Summary And Conclusion

A loudness meter has been described which indicates the loudness of an audio signal. Since the ultimate significant subjective destination of all original or reproduced sound is the human ear, a meter which indicates the loudness as perceived by the ear is an important audio instrument. For example, the loudness meter will become a very useful tool for determining the loudness of any simple or complex sound or noise, for monitoring the maximum permissible level of all manner of audio programs, for obtaining the maximum loudness of an audio program for a certain maximum peak level, etc.

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