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## Calculation and Measurement of the Loudness of Sounds

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An equivalent-tone method for calculating the loudness of sounds is described. With this method the spectrum of the sound is divided into frequency bands which are treated as pure tones in determining their loudness. The individual values of loudness are added to obtain the total loudness of the sound. Calculations for bands of white noise and for complex tones are compared with subjectively obtained data of Pollack and Fletcher and Munson. The agreement between calculated and experimental values is good. It is felt that improvement of the method must await further psychoacoustic data.

**D**URING the past two decades several methods have appeared in the literature for calculating the loudness of sounds directly from their sound-pressure spectra or masking audiograms. In their classical work on loudness, Fletcher and Munson developed a method of calculation suitable for determining the loudness of complex tones from the frequency spectrum.<sup>1</sup> The loudness of a continuous spectrum noise may be calculated by a procedure developed by Fletcher and Munson which requires a subjectively determined masking audiogram as starting data.<sup>2</sup> Each of these methods is suitable only for the particular kind of noise for which it was developed, and each is somewhat cumbersome to use. Fletcher and Munson also outlined a procedure for calculating the masking audiogram of a continuous spectrum noise given its frequency spectrum.<sup>2</sup> They correctly restricted their method by

the condition that, "the intensity,  $I$ , does not change abruptly from one frequency region to another." When one attempts to use their method beyond this restriction, large discrepancies between calculated and subjectively determined loudness values can occur. For example, attempts to apply the Fletcher-Munson procedure to the calculation of the loudness of narrow bands of noise located at low frequencies leads to loudness levels which are lower than those subjectively determined by up to 25 phons.

In engineering applications a simple objective procedure for determining the loudness of any type of noise with reasonable accuracy is of great value. Several years ago, an attempt in this direction was made by two of the authors,<sup>3</sup> based on the early work of Fletcher and Munson and on suggestions contained in a paper by Churcher and King.<sup>4</sup> It will be shown in this paper that an extension of our method gives results that,

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<sup>1</sup> H. Fletcher and W. A. Munson, J. Acoust. Soc. Am. **5**, 82-108 (1933).

<sup>2</sup> H. Fletcher and W. A. Munson, J. Acoust. Soc. Am. **9**, 1-10 (1937).

<sup>3</sup> L. L. Beranek and A. P. G. Peterson, J. Acoust. Soc. Am. **20**, 592(A) (1948).

<sup>4</sup> B. G. Churcher and A. J. King, J. Inst. Elec. Engr. (London) **81**, 57-90 (1937).

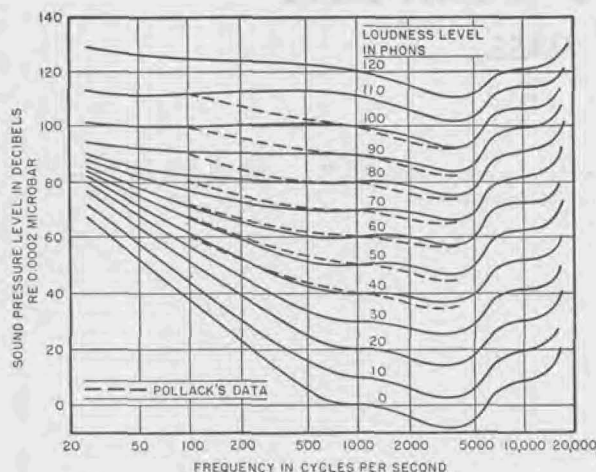


FIG. 1. Equal-loudness contours for pure tones by Fletcher-Munson (F-M) and for a 250-mel band of noise by Pollack.

from an engineering standpoint, agree well with subjective data of Pollack,<sup>5</sup> and Fletcher and Munson.<sup>2</sup> In addition to being simple, the operations inherent in this method may be performed electronically, thereby providing the basis for a loudness meter.

## I. LOUDNESS DETERMINATION FOR NOISE

### A. The Equivalent-Tone Method

Pollack's experiments suggest that a band of noise whose width does not exceed about 600 mels sounds as loud as a pure tone of the same intensity located at the mean frequency of the band. Thus, it appears that equal-loudness curves for bands of noise should closely resemble those for pure tones. Verification of this is seen from Fig. 1, which shows Pollack's data for 250-mel bands of noise plotted on the same sheet as the Fletcher-Munson equal-loudness contours. Even better agreement is obtained if the Churcher-King<sup>4</sup> curves are used (see Fig. 2). In making these comparisons, Pollack's curves were shifted downward 4

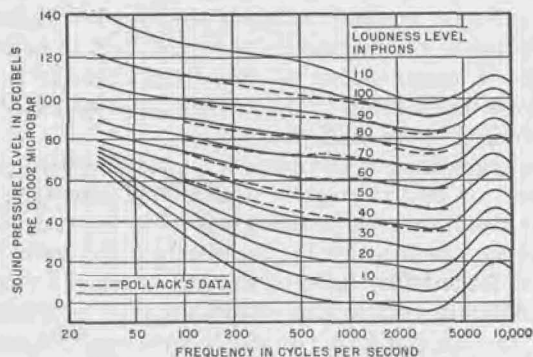


FIG. 2. Equal-loudness contours for pure tones by Churcher-King (C-K) and for a 250-mel band of noise by Pollack.

<sup>5</sup> I. Pollack, "Studies in the loudness of complex sounds," doctoral thesis, Department of Psychology, Harvard University, Cambridge, Massachusetts (1949).

decibels, which is about the usual difference between free field and earphone loudness determinations.<sup>6</sup> With this as a starting point, the procedure for calculating the loudness of continuous spectrum noise becomes identical to that used for pure tones, and will be called the *equivalent-tone method*. The procedure is as follows:

1. Divide the noise spectrum into bands of frequencies, each at least greater in width than a critical bandwidth for hearing,<sup>7</sup> but not greater in width than about 600 mels. As we shall show later, bands between 300 and 600 mels in width seem best.
2. Determine the sound-pressure level in decibels for each band.
3. By means of the equal-loudness contours for pure tones, find the loudness level in phons for each band corresponding to the sound-pressure level of step (2) and the mean frequency of the band.
4. Using the relation between loudness and loudness level (Fig. 3), determine the loudness in sones contributed by each band.
5. Add the individual values of loudness to obtain the total loudness in sones.

### B. Validity of Adding Loudnesses

The validity of step (5), which requires adding loudnesses for the total loudness, has been questioned by some experimenters.<sup>8,9</sup> Fletcher and Munson have shown that when tones are very close together loudnesses do not add directly.<sup>1</sup> They have also found consistent results when adding loudnesses, provided the tones are far apart.

Howes<sup>9</sup> has recently conducted experiments to test the validity of adding individual loudness values for multicomponent tones. He concludes that at levels above 80 db, the observed loudness of multicomponent tones is considerably less than the sum of the individual values of loudness, even when the tones are separated by as much as 500 mels. However, there is good reason to doubt that conclusion. A more strict interpretation of his results is that the judged loudness of multicomponent tones does not appear to be additive when one uses the relation between loudness and loudness level specified by Howes. The particular relation used by Howes is based only on loudness ratio determinations and monaural-binaural measurements for a tone in the vicinity of 1000 cps, with the intent to avoid initial assumptions of additivity involved in the Fletcher-Munson curve. In contrast with the relation of Fig. 3, the Howes curve levels off considerably at high levels. But his relation seems to be based on very little data

<sup>6</sup> L. L. Beranek, *Acoustic Measurements* (John Wiley and Sons, Inc., New York, 1949), pp. 730-731.

<sup>7</sup> H. Fletcher, *Revs. Modern Phys.* **12**, 47-65 (1940); Schafer, Gales, Shewmaker, and Thompson, *J. Acoust. Soc. Am.* **22**, 490-496 (1950). Between 100 and 1000 cps, a critical bandwidth is about 40 cps; and above that, it increases to at least 250 cps at 8000 cps.

<sup>8</sup> B. G. Churcher, *J. Acoust. Soc. Am.* **6**, 216-226 (1935).

<sup>9</sup> D. H. Howes, *Am. J. Psychol.* **63**, 1 (1950).

at high levels, and it also seems to have been influenced by an attempt to find a simple mathematical formula relating loudness and loudness level over much of the loudness range.<sup>8</sup> The recent data of Pollack<sup>5</sup> include loudness ratio determinations for a 1000-cps tone which indicate that in the range from 70 db to over 100 db, the curve of Fig. 3 should be tipped up instead of flattened. Similar results based on masking data were presented recently by Munson and Gardner.<sup>10</sup> If the curve of Pollack is used, the measurements of Howes no longer show the marked deviation from the hypothesis of additivity. It seems reasonable to assume, however, that at some level loudnesses will no longer be additive. These results serve to point up the need for further loudness ratio measurements at high levels for pure tones. Until such results are available, the Fletcher-Munson relation between loudness and loudness level, illustrated by Fig. 3, seems the most reliable, and the level at which widely separated tones no longer add in loudness is yet to be determined.

### C. Effects of Bandwidth

The equivalent-tone method is intended to be satisfactory for pure tones as well as for more complex signals, so that in performing step (4) for any noise, we must use the relation between loudness and loudness level that applies to pure tones or one that closely approximates it. When this function is specified, we cannot arbitrarily use any bandwidth for step (4) even though it fulfills the conditions of step (1). That the bandwidth has an optimum value is shown by the following considerations.

At levels above 40 db, the relation between loudness (in sones) and the loudness level  $L$  (in phons) for pure tones can be expressed very closely by the equation

$$S = 10^{(L-b)/a} \quad \text{or} \quad \log_{10} S = (L-b)/a,$$

where  $a=30$ , and  $b=40$  (see Fig. 3). Assume we analyze a uniform-spectrum broad-band noise of over-all sound-pressure level  $B$  into  $n$  bands, which we shall assume initially are of equal width in cycles. Then, if the level in each band is high enough so that no appreciable weighting by step (3) is necessary, we can compute the loudness  $S_c$ , by the equivalent-tone method, to be

$$S_c \approx n \cdot 10^{[B-10 \log_{10}(n)-b]/a} = 10^{[B+(a-10) \log_{10}(n)-b]/a}.$$

The subscript "c" means "computed."

This equation shows that the number of bands  $n$  makes no difference in the slope of the curve relating the logarithm of the loudness and the sound-pressure level. However, it can affect the position of the curve. For the particular value of  $a=10$ , the value of  $n$  has no effect on the result. This independence of  $n$  is approximately true at levels below 40 db.

For levels above 40 db, when  $a=30$ , the result of

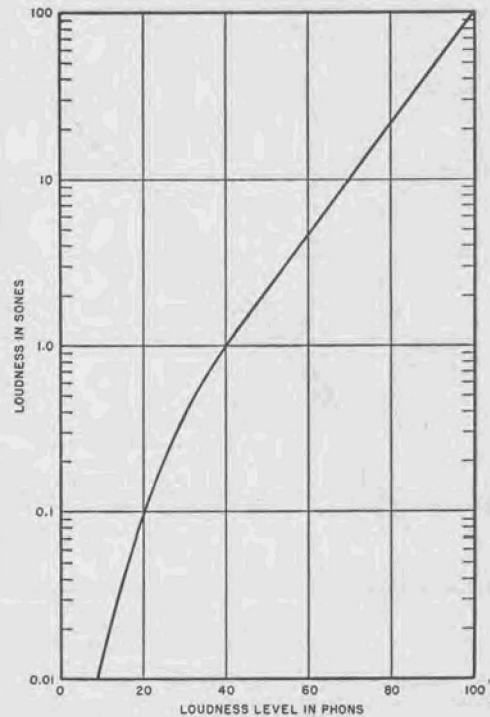


FIG. 3. Curve of loudness level vs loudness as determined by F-M.

using different numbers of bands is to shift the computed loudness to larger values as the number is made larger. The effect is not very marked, since a 2 to 1 change in the number of bands is equivalent to a 6-db change in the pressure level. But, obviously, there is an optimum value. In order to determine this optimum value, we need to know the subjectively determined relation between loudness and sound-pressure level for a broad band of noise.

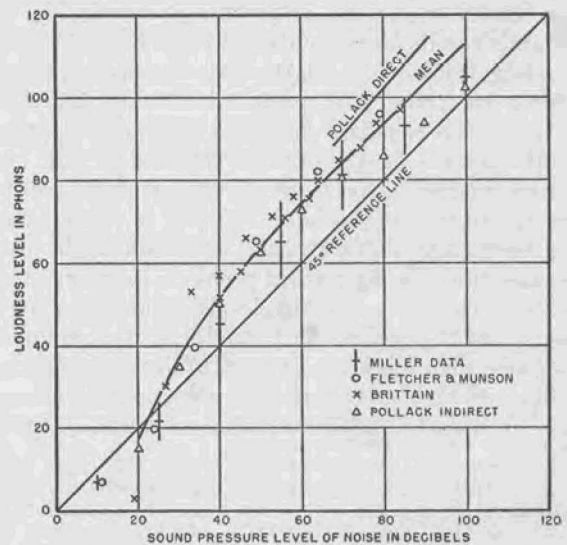


FIG. 4. Experimental data of Pollack, Fletcher and Munson, Brittain, and Miller for loudness judgments equating wide band noise to a 1000-cps tone.

<sup>10</sup> W. A. Munson and M. B. Gardner, J. Acoust. Soc. Am. 22, 185, (1950), Fig. 19.



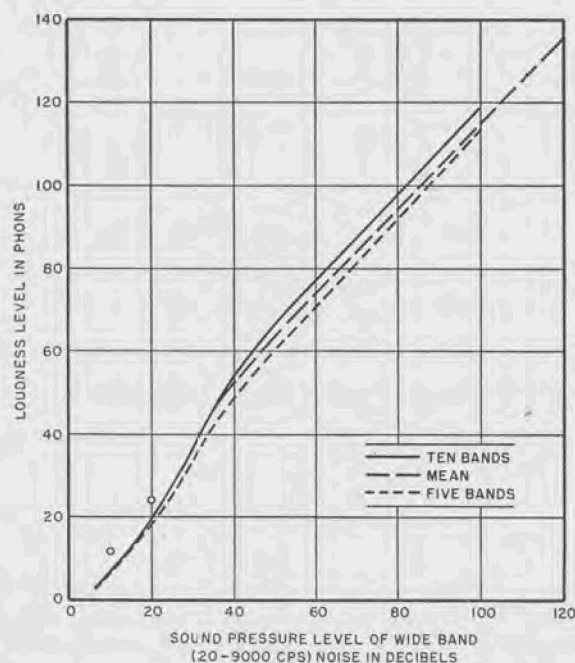


FIG. 5. Loudness level of (20-9000 cps) band of white noise. Mean curve is from Fig. 4. Curves are equivalent-tone calculations using bands of Tables I and II and C-K equal-loudness contours. Two points at low levels are for calculations using F-M equal-loudness contours. At higher levels the results using the F-M contours are essentially the same as those using the C-K contours.

#### D. Loudness of a Broad Band of Noise

The relation between loudness and sound-pressure level for a broad band of noise has been subjectively determined by a number of experimenters. Brittain,<sup>11</sup> Fletcher and Munson,<sup>2</sup> Miller,<sup>12</sup> and Pollack<sup>5</sup> have determined the loudness level by balancing the loudness of a broad band noise with that of a 1000-cps tone, and their results are shown as plotted points in Fig. 4. Brittain's results were obtained with a band of noise extending from 50 to 10,000 cps, with a reasonably uniform spectrum level produced at the observer's position by an equalized loudspeaker system. Fletcher and Munson's data apply to a broad band of noise but with the frequency spectrum adjusted at each level to give approximately uniform masking of pure tones over the range to 10,000 cps, and their data can be used only as a guide for the present problem. However, they show very clearly that at high levels, a sound of a given sound-pressure level is much louder if it is a broad band noise than if it is a pure tone. Miller's results were obtained with a band of noise with a reasonably uniform spectrum from 150 to 8000 cps and monaural covered-

ear listening. Pollack's noise extended only to 5800 cps, and he also used monaural covered-ear listening.

The scatter of the available data is considerable, but some of this scatter is undoubtedly a result of differences in technique and differences in noise spectrum, as well as being the normal large deviations encountered in these subjective measurements. The results of Miller and Pollack show little difference in loudness of a 1000-cps tone and a broad band noise at a level of 100 db. This result does not seem to be the usual experience, and, in fact, Pollack gives other results which contradict this one. He determined a function relating loudness and sound-pressure level for a wide band of noise by asking subjects to double and halve the loudness by adjusting the sound-pressure level as well as by using a monaural-binaural comparison. He called the loudness curve obtained in this fashion a "direct" loudness curve. The high-level end of this curve has been converted by the relation of Fig. 3 to a loudness-level curve and is plotted in Fig. 4 as the line labeled "direct." This curve shows a slope greater than unity compared to the trend of less than unity which his points for the loudness balance method show. However, the data for this "direct" curve are not extensive enough to consider it more than supplementary information for an average curve. As we mentioned before, he also obtained a direct curve for a pure tone, and if this curve instead of Fig. 3 were used to convert the "direct" loudness curve to loudness level, the slope on Fig. 4 would be unity.

The obvious answer to the scatter of the data shown on Fig. 4 is that a more extensive subjective investigation of this relation between loudness level and sound-pressure level for a broad band noise should be made. Until the results of such an investigation are available, the curve drawn in Fig. 4 labeled "MEAN" seems a reasonable one to use as the desired relationship.

#### E. Optimum Bandwidth for Broad Band Noise

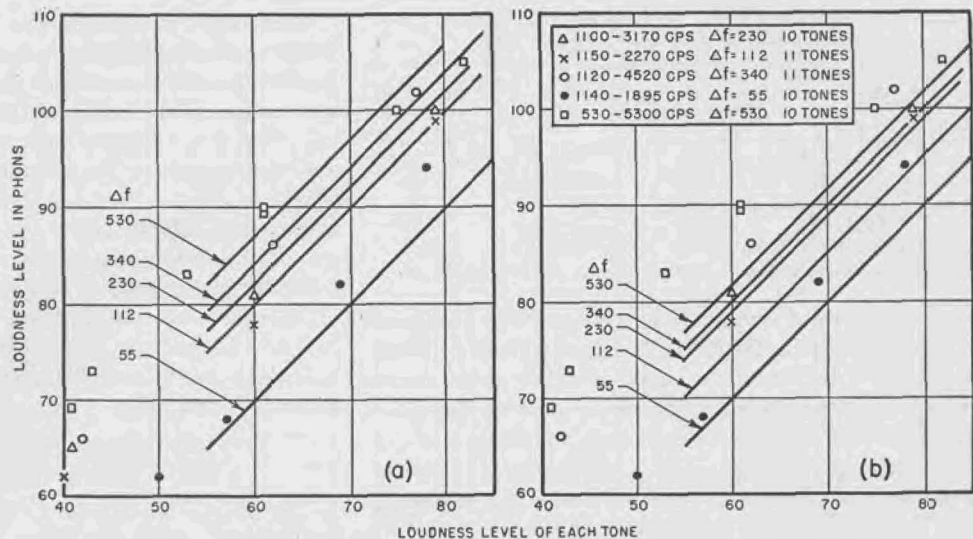
One can compute a value for the number of bands  $n$  to give the best fit to this "MEAN" curve, and the value is 5. However, this computation is on the basis of division of equal width in cycles. Because of the behavior of the ear, it seems more reasonable to divide the spectrum so that it has an equal number of critical bands in each of these larger bands or so that it has the same number of pitch units, mels, in each band. These are essentially equivalent,<sup>13</sup> and this division has been done. The resultant calculated loudness, using weighting by the Churcher-King curves, and with 300 and 600 mels per band, gives the curves shown in Fig. 5. These seem to be reasonable extremes in the size of bands to use for calculations to test the method, until more extensive data show more definitely the optimum size band.

<sup>11</sup> F. H. Brittain, *J. Acoust. Soc. Am.* **11**, 113-117 (1939).

<sup>12</sup> G. A. Miller, *J. Acoust. Soc. Am.* **19**, 609-619 (1947). His results are given in terms of sensation level. The sensation level of his broad band noise is converted to sound-pressure level by adding 10 db, and the sensation level of the equally loud 1000-cps tone is converted to sound-pressure level by adding 7 db. See J. E. Hawkins, Jr., and S. S. Stevens, *J. Acoust. Soc. Am.* **22**, 6-13 (1950).

<sup>13</sup> W. A. Munson and M. B. Gardner, *J. Acoust. Soc. Am.* **22**, 182 (1950), Fig. 12.

Fig. 6. Loudness levels of complex tones with components of equal-loudness. Points are subjectively determined data of F-M. Curves are equivalent-tone calculations using (a) Table II (300-mel) and (b) Table I (600-mel) bands.



Whether or not a division into bands of this order of magnitude might have any neurophysiological significance is not known. The division is based on determining an engineering solution to the practical measurement of loudness, and no justification for this division has yet been found beyond this practical problem.

Data taken with an analyzer having a larger number of bands can also be used for the present calculation of loudness. After step (3) of the method, the various narrow bands can be combined on an energy basis to yield the optimum number of bands for use in step (4).

When bands as broad as 600 mels are used, there is a serious problem of weighting at low frequencies and low levels. Weighting at the geometric mean frequency of the band is not satisfactory for pure tones at the ends of the band. In order to avoid serious errors from this mean-frequency weighting, it seems reasonable, when the sound-pressure level of the band is determined, to

use in step (2) an adjustable weighting characteristic similar to that now used in American Standard Sound-Level Meters. Then, the weighting can be set according to the band level, and large errors are avoided.

#### F. Optimum Bandwidth for Complex Tones

That there is an optimum value of bandwidth for calculating the loudness of complex tones by the equivalent-tone method is easily seen by considering the various possibilities. If the bands are so narrow that each component is in a separate band, then at high levels the calculated loudness level for ten tones of equal loudness is 30 phons higher than the loudness level of the individual tones. If the bands are so wide that all ten tones are included within one band, the calculated loudness level is about 10 phons higher than for one tone.

Fletcher and Munson have determined the loudness level of complex tones of many components with

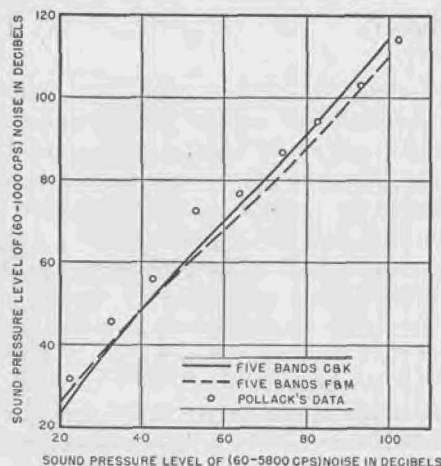


Fig. 7. Sound-pressure level (SPL) of flat wide band noise (60-5800 cps) vs SPL of equally loud (60-1000 cps) flat band of noise. Circles are subjectively determined data of Pollack. Curves are equivalent-tone calculations using F-M and C-K equal-loudness contours.

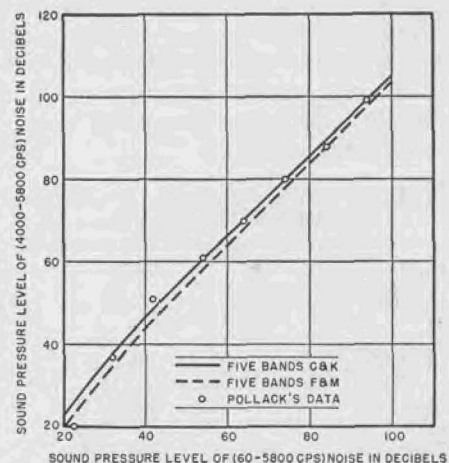


Fig. 8. SPL of flat wide band noise (60-5800 cps) vs SPL of equally loud (4000-5800 cps) flat band of noise. Circles are subjectively determined data of Pollack. Curves are equivalent-tone calculations using F-M and C-K equal-loudness contours.

TABLE I. Frequency limits of bands used in the equivalent-tone calculations. Approximately 600-mel bands.

Band	Frequency limits (cps)	Bandwidth (cps)	Pitch limits (mels)	Mean-pitch frequency (cps)
1	20-400	380	0-500	160
2	400-1200	800	500-1150	760
3	1200-2400	1200	1150-1750	1800
4	2400-4800	2400	1750-2450	3450
5	4800-9600	4800	2450-3050	6600

various values of frequency separation.<sup>2</sup> The pertinent subjective measurements are shown as plotted points in Fig. 6. These complex tones are made up of ten or eleven components, each adjusted to be of the same loudness. The five sets of data shown cover a range of frequency intervals from 55 to 530 cycles. The calculated loudness levels for 300-mel bands are shown in Fig. 6 (a), and those for 600-mel bands are shown in Fig. 6 (b).

The agreement between calculated and measured values is excellent for 300-mel bands and reasonably good for 600-mel bands. These results indicate that 300-mel or even slightly narrower bands are best suited for these complex tones. On the other hand, the optimum bandwidth for broad band noise seemed to be between 300 and 600 mels with the broader bands being slightly better than the narrower.

The differences in calculated results between using the 300-mel bands or the 600-mel bands are not so very great. For practical engineering work, it seems best to favor the optimum bandwidth for broad band noise, because that type of noise is encountered more often than are multicomponent equal-loudness tones.

### G. Comparison with Sound Level

It is interesting to consider the relations among the reading of a sound-level meter, the calculated loudness level by the equivalent-tone method, and the subjectively determined loudness level for various sounds. If the sound-level meter had continuous weighting according to frequency and level, both the sound-level meter and the equivalent-tone method would give the same result for pure tones. This result would be the loudness level for pure tones.

TABLE II. Frequency limits of bands used in the equivalent-tone calculations. 300-mel bands.

Band	Frequency limits (cps)	Bandwidth (cps)	Pitch limits (mels)	Mean-pitch frequency (cps)
1	20-200	180	0-300	94
2	200-500	300	300-600	340
3	500-860	360	600-900	670
4	860-1330	470	900-1200	1080
5	1330-1900	570	1200-1500	1600
6	1900-2570	670	1500-1800	2230
7	2570-3450	880	1800-2100	2960
8	3450-4650	1200	2100-2400	4000
9	4650-6300	1650	2400-2700	5400
10	6300-9000	2700	2700-3000	7500

While the relations shown in Figs. 5 and 6 are given in terms of sound-pressure level, it is clear that at high levels, where the weighting is flat, the difference between a sound-level meter reading and the loudness level can be of the order of 15 phons for a broad band noise and of the order of 20 phons for a ten-component complex tone. As the previous analysis has shown, the corresponding differences for the equivalent-tone method are only a few decibels, being essentially within the accuracy of the present subjective data. The accuracy of the equivalent-tone method for determining loudness can be checked for still other types of sound whose loudnesses have been determined; this check is given in Secs. II and III.

### II. COMPARISON OF CALCULATED WITH SUBJECTIVE RESULTS FOR NOISE

The equivalent-tone method of calculation was applied to the continuous noise spectra used by Pollack.

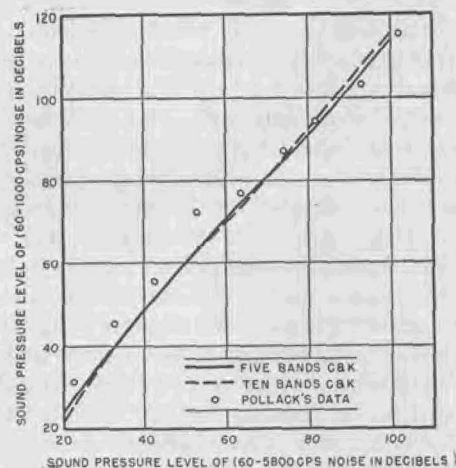


FIG. 9. SPL of flat wide band noise (60-5800 cps) vs (60-1000 cps) flat band of noise. Circles are subjectively determined data by Pollack. Curves are equivalent-tone calculations using bands of Tables I and II.

As we just stated, he has determined the loudness level in phons of a flat wide band (60-5800 cps) random noise as a function of the total sound-pressure level (Fig. 4). Results for narrower bands were also obtained and expressed in terms of the sound-pressure level of an equally loud wide band of noise.

Figures 7 and 8 show the sound-pressure levels of flat continuous spectrum noises of two bandwidths plotted against the sound-pressure level of a wide band of noise of equal loudness as calculated by the equivalent-tone method outlined above. The two sets of pure-tone equal-loudness curves of Figs. 1 and 2 and the 600-mel bands shown in Table I were used in obtaining the dashed and solid curves. The pure-tone equal-loudness curves, as well as the loudness vs loudness-level function used in the calculations, are based on the usual free field listening conditions. Although Pollack's data were obtained using a single earphone, the as-



sumption was made that the experimental relation between loudness and sound-pressure level would have the same form as for free field noise. The agreement between calculated and measured data is better when the Churcher-King equal-loudness contours are used.

Figure 9 shows a comparison of the calculations obtained from the five 600-mel bands of Table I and from the ten narrower bands of Table II. The Churcher-King equal-loudness contours were used.

Comparisons are also shown in Figs. 10 and 11 of the subjectively determined loudness levels obtained by Fletcher and Munson (and shown in Figs. 12 and 13 of reference 2) with the results obtained by the equivalent-tone method of this paper. The bands of Tables I and II were used in the calculations. The calculations for the narrower band of noise by the Fletcher-Munson method are also shown, and they are seen to be lower than the subjectively determined values by 12 to 25

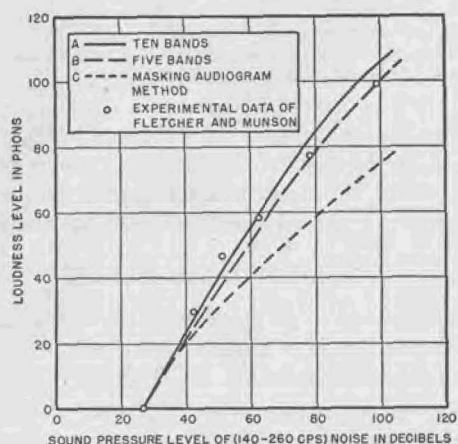


FIG. 10. Loudness of a (140-260 cps) flat band of noise. A. Equivalent-tone calculations, Table II bands; B. Equivalent-tone calculations, Table I bands; C. F-M masking audiogram method computed from the frequency spectrum. Fletcher and Munson limit their method to sounds with spectra that do not change abruptly.

phons at the higher levels, while those by the equivalent-tone method differ by much smaller amounts.

Pollack also showed data on loudness comparisons of bands of noise as a function of upper cut-off frequency, lower cut-off frequency, and broadening of bandwidth for a constant mean frequency. These results are shown in Figs. 12 to 14, along with results of equivalent-tone calculations. The agreement between calculated and measured data is satisfactory.

### III. RESULTS FOR COMBINATIONS OF TONES

Calculations for combinations of tones have also been made by the equivalent-tone method for a wider range of levels than shown in Fig. 6. Weighting is assumed to be continuous in level and frequency, and to be determined by the weighted total level in the band. This calculation procedure was applied to the free field data of Fletcher and Munson<sup>1</sup> for combina-

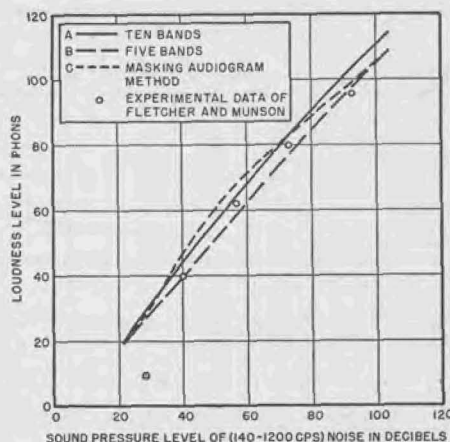


FIG. 11. Loudness of a (140-1200 cps) flat band of noise. A. Equivalent-tone calculations, Table II bands; B. Equivalent-tone calculations, Table I bands; C. F-M masking audiogram method computed from the frequency spectrum.

tions of ten pure tones. Figures 15 to 17 show the results of the calculations together with the original experimental data. Both ordinate and abscissa are expressed as loudness level in phons in conformance with the published data of Fletcher and Munson. The five-band and ten-band curves were calculated using the frequency division of Table I and Table II, respectively.

### IV. DISCUSSION

The agreement of the calculated curves with the experimental data of Figs. 7 to 17 is felt to be a satisfactory indication of the engineering usefulness of the method by which the calculations were made. Because of the variability inherent in experimental data based

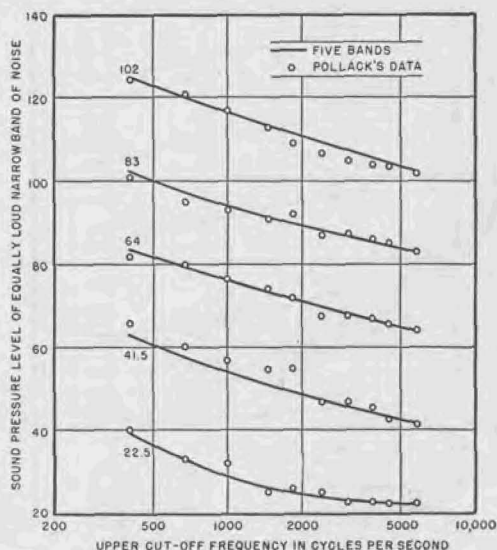


FIG. 12. Equal-loudness contours for bands of noise with a lower cut-off frequency of 60 cps and the indicated upper cut-off frequencies. Figures on curves are SPL of equally loud wide band noise (60-5800 cps). Circles are subjectively determined data of Pollack. Curves are equivalent-tone calculations using bands of Table I and C-K contours.

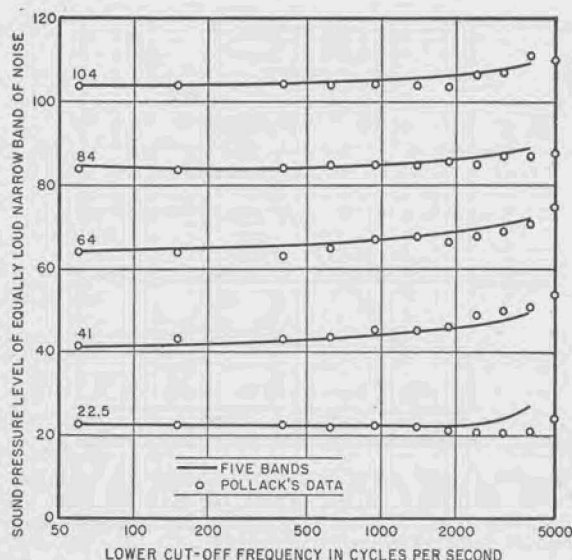


FIG. 13. Equal-loudness contours for bands of noise with an upper cut-off frequency of 5800 cps and the lower cut-off frequency as indicated. Figures on curves are SPL of wide band (60-5800 cps) noise. Circles are subjectively determined data of Pollack. Curves are equivalent-tone calculations using bands of Table I and C-K contours.

on subjective estimates, it is probably unwise to attempt to deduce from the data opinions as to which of the two sets of bands or which of the two sets of equal-loudness curves is more accurate. For the sake of simplicity in calculations, division of the spectrum into a small number of bands is, of course, desirable. For line spectra or for continuous spectra which slope steeply at low frequencies or are very irregular in

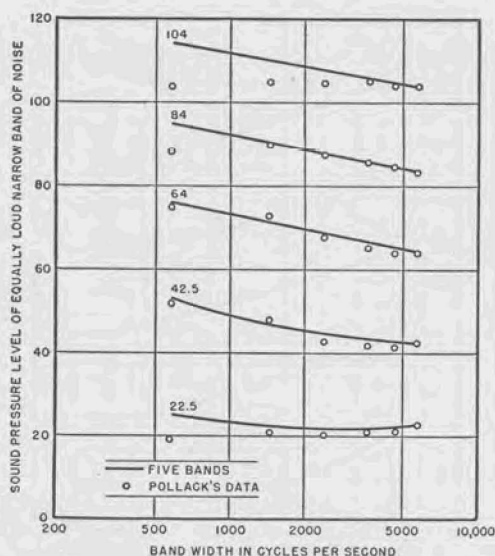


FIG. 14. Equal-loudness contours of bands of noise of the band-width indicated. Center frequency of bands is 1500 cps. Figures on curves are SPL of equally loud wide band noise (60-5800 cps). Circles are subjectively determined data of Pollack. Curves are equivalent-tone calculations using bands of Table I and C-K contours.

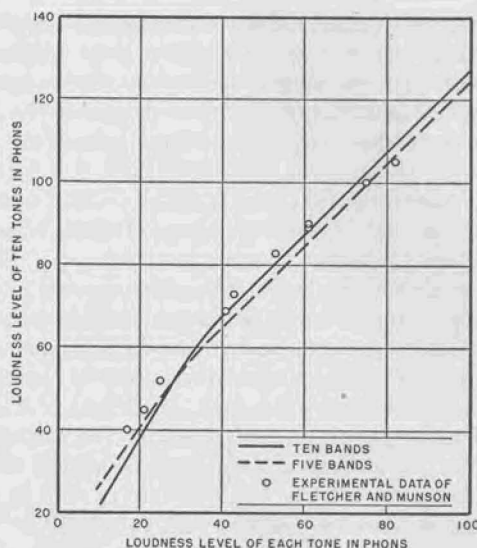


Fig. 15. Loudness of 10 equally loud tones from 530-5300 cps. Separation between tones is 530 cps. Circles are subjectively determined data of F-M. Curves are equivalent-tone calculations using the F-M equal-loudness contours.

shape, continuously adjustable frequency weighting is necessary. In the design and construction of a portable loudness meter, the choice of a smaller number of bands would provide practical and economic advantages.

## V. THE LOUDNESS METER

The *equivalent-tone* method provides the basis for a direct-reading loudness meter. Such a meter could be constructed as shown in Fig. 18. The electrical output of the microphone is passed through a set of band-pass filters which are manually switched into the circuit one at a time. The output of the filter is then amplified, and the resulting signal is attenuated with potentiometers having response characteristics approximating the free

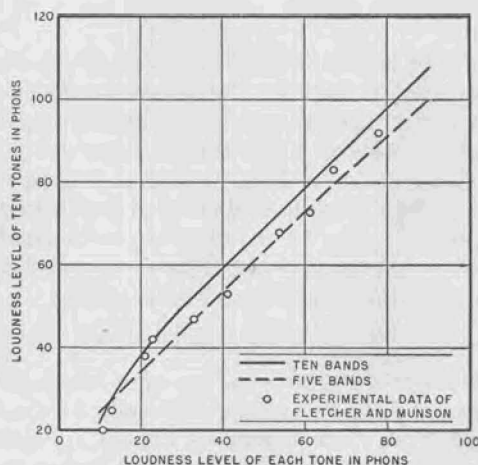


FIG. 16. Loudness of 10 equally loud tones from 50-500 cps. Separation between tones 50 cps. Circles are subjectively determined data of F-M. Curves are equivalent-tone calculations using the F-M equal-loudness contours.



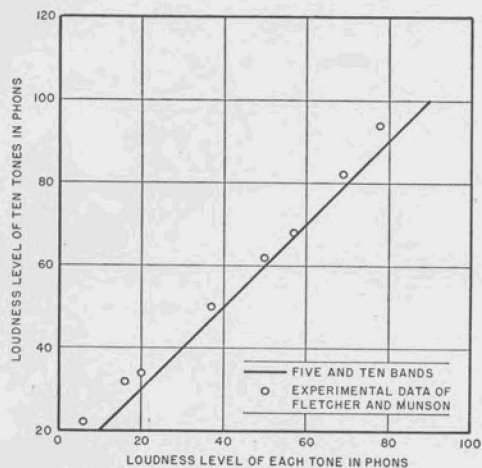


FIG. 17. Loudness of 10 equally loud tones from 1400–1895 cps. Separation between tones is 55 cps. Circles are subjectively determined data of F-M. The results of equivalent-tone calculations using the F-M equal-loudness contours are the same for five bands and ten bands, since all the energy is in one band. The curve is the result of the calculations.

field equal-loudness contours. For levels above 90 phons, the equal-loudness contours are assumed to have a

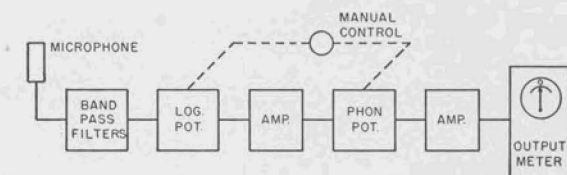


FIG. 18. Block diagram of a direct-reading loudness meter.

“flat” frequency response, and a logarithmic potentiometer is used for attenuation at these higher levels. Below 90 phons, a phon potentiometer having the desired response of the equal-loudness contours is used. The two potentiometers are mechanically connected so as to provide continuously weighted attenuation for levels of 30 to 150 phons. For each band, the attenuation is adjusted to give a mid-scale reading on the output meter, and the value of loudness is read from the calibration on the control. The values of loudness for the individual bands are then added to obtain the total loudness of the input sound. The use of the phon potentiometer makes it possible to make loudness measurements on pure tones, complex tones, and continuous spectrum noises.