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LOUDNESS DETERMINED BY POWER SUMMATION

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1971

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-2300		

4. Title and Subtitle	5. Report Date
LOUDNESS DETERMINED BY POWER SUMMATION	May 1971
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Walton L. Howes	E-6020
	10. Work Unit No.
9. Performing Organization Name and Address	129-01
Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))		18. Distribution Statement
Acoustics	Noise	Unclassified - unlimited
Loudness	Auditory system	
Psychoacoustics	Annoyance	
Sound	Aircraft noise	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	14	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

The predicted overall loudness of steady, broad-band noise is usually computed by summing weighted loudnesses of subbands of the noise intensity (mean-square pressure) spectrum. It is proposed, instead, that the overall loudness should be computed by summing weighted intensities of subbands ("critical bands") of noise and then obtaining the loudness of the sum. The proposed computation method seems to yield better agreement with published loudness judgment data than does the usual method. It appears that the proposed method should also yield better agreement with annoyance judgments than does the "perceived noise" method of Kryter.

INTRODUCTION

The magnitude of the auditory sensation produced by a sound stimulus defines its loudness. If the attention of an individual is consciously directed toward perceiving the sound, then the individual is capable of establishing quantitative relations among the subjectively judged loudnesses of different sounds. The remaining problem is to relate these subjective judgments to the physical attributes of the sounds so that the loudness of any sound can be predicted.

REVIEW

For pure tone stimuli (specifically 1 kHz) Knauss proposed (ref. 1) on the basis of test data at suprathreshold levels that loudness $\mathscr{L}$ is proportional to the 1/3 power of the acoustic intensity. S. S. Stevens recognized (ref. 2) that the word intensity should refer to mean-square pressure, which is really the quantity more closely related to sound measurements. Even more specifically, in practice the squared sound pressure p^2 is averaged over a finite time which should correspond to the auditory integration time ($\approx$0.2 s). Hence, test data indicate that for a pure tone

$$\mathscr{L} = k\left(\widetilde{p^2}\right)^s \tag{1}$$

where $s \approx 1/3$, and the tilde denotes an average over the auditory integration time. The proportionality constant k implicity accounts for the physical power transmitted to the auditory cortex. This transmittance is a function of frequency and, over some frequency ranges, is a function of the mean-square sound pressure as well (ref. 3). The transmittance is a maximum in the general neighborhood of 1 kilohertz, that is, within the frequency interval in which the auditory system is most sensitive.

The loudness of sounds which include a broad spectral range of frequencies can also be evaluated quantitatively by subjective methods. However, the establishment of a correct relation between loudness and physical characteristics has proved more elusive for broad-band sounds than for pure tones. Although the unweighted, or the A or B weighted, sound-pressure level of a broad-band sound is sometimes a good measure of its loudness level, this is not generally true. (In acoustics, "level" implies that the magnitude is expressed in decibels.)

Historically, the first serious attempt to predict the loudness of sounds appears to have been by Steinberg (ref. 4). Steinberg's empirical loudness formula - based on the erroneous Fechner law, rather than equation (1) - was so general that it incorporated implicitly the presently recognized constituents, namely, physical power, transmittance function, power summation, and critical bands, required for a satisfactory loudness prediction formula. Unfortunately, the experimental data available to Steinberg were unsatisfactory. Consequently, when Fletcher and Munson (ref. 5) published much improved loudness judgment data and their own loudness calculation procedure based on loudness summation, Steinberg's formula was thenceforth disregarded. The acceptance of loudness summation by subsequent investigators has persisted for nearly 40 years, and "loudness summation" has become a common term in psychoacoustics. In the present context loudness summation implies that the overall loudness of a broad-band noise is determined by summing the loudnesses of its individual components in the form of pure tones or subbands of the overall spectrum. Loudness summation has no theoretical basis and has never been claimed to have one (ref. 6).

ARGUMENT FOR POWER SUMMATION

Herein, it will be shown that the overall loudness of broad-band noise is not determined by loudness summation, but rather by power (more specifically, average power) summation over bandwidths equal to the so-called "critical" frequency bands defined and specified by Zwicker, Flottorp, and Stevens (refs. 7 and 8). Subjective loudness judgment tests (ref. 8) have shown that, surrounding every audible frequency, there exists a so-called critical frequency band. All sounds which possess the same sound pressure and do not exceed the local critical bandwidth are equally loud. If the bandwidth of a sound is widened beyond the limits of the local critical bandwidth while the sound pressure is held constant, then the loudness of the sound increases. In fact, these conditions define the critical band.

As a basis for the claim that power summation should supersede loudness summation, note that the phenomena which occur in the auditory system are certainly physical phenomena (not psychological phenomena) involving the transmission of information to the brain. The transmission of information requires the transmission of physical power. The psychoacoustic quantity called loudness is an intensive quantity which for a pure tone is proportional to a numerical power of the relative transmitted physical power Π averaged over the auditory integration time, that is,

$$\mathscr{L} = \kappa \tilde{\Pi}^{s} \tag{2}$$

where κ is a proportionality constant. This is so because of equation (1) and the fact that, for sound waves, average physical power is proportional to mean-square pressure. Hence, it is to be expected that power transmitted to the higher nervous system constitutes the physical embodiment of loudness. All physical operations within the brain, including summations, must involve physical power. Hence, it is expected as an extension of equation (1) and the existence of critical bands that power summation (as opposed to loudness summation) determines the overall loudness. (The critical band phenomenon implies that eq. (1) is valid, not only for pure tones, but also for complex sounds not exceeding the critical bandwidth. This corresponds to power summation over the bandwidth. Hence, loudness summation is certainly invalid within critical bands.)

The failure of loudness summation is best illustrated by Stevens' empirical formula (ref. 6) for the overall loudness $\mathscr{L}$ of broad-band noise. This formula was also adopted by Kryter (ref. 9) and many others for calculating the annoyance of noise. Stevens' formula is

$$\mathscr{L} = \mathscr{L}_m + F\left(\sum_{n}^{N} \mathscr{L}_n - \mathscr{L}_m\right) \tag{3a}$$

$$= \sum_{n}^{N} F_n \mathscr{L}_n \tag{3b}$$

$$= \kappa \sum_{n}^{N} F_n \tilde{\Pi}_n^s \qquad (3c)$$

where $\mathscr{L}_m$ is the loudness of the loudest of N frequency bands of noise enclosing the audible noise spectrum, $F < 1$ is an empirical function of the sound pressure (ref. 10), $F_n = 1$ for $n = m$, and $F_n = F$ for $n \neq m$. Equation (3a) is the formula as presented by Stevens. When rewritten as equation (3b) it is clear that equation (3a) involves a weighted loudness summation. The third form, equation (3c), will permit ready comparison with the power summation formula for loudness. Because $F < 1$, it follows that $\mathscr{L} < \sum_{n}^{N} \mathscr{L}_n$, that is, the observed overall loudness is less than the sum of the loudnesses in the subbands. Therefore, if equation (3) is correct, then unweighted loudness summation fails. Equation (3) appears to possess an important fault. Specifically, the function F must be determined from the overall loudness. This means that, in order to compute the loudness of a sound, the loudness of that sound must already be known. For a given sound the function F can be computed from subjective loudness judgments, but it cannot be proved that the same function F will be the correct one for any other sound. In fact, examples will be presented in which equation (3) apparently fails.

If loudness summation is replaced by power summation, the preceding difficulties do not arise. The loudness appears to be correctly determined by transmitted power summation, and the formulation does not involve functions, such as F, which may differ for each noise under study.

OUTLINE OF POWER SUMMATION METHOD

Because the mechanical portion (within the ear) of the auditory system is linear (ref. 11) and the electrochemical portion (the nervous system) is nonlinear (ref. 12), in that the amplitude of the transmitted whole-nerve signal is proportional to a power-law function of the sound pressure amplitude, the mathematical theory of loudness reported in reference 13 can be derived. It follows from this theory that, for broad-band noise,

$$\mathscr{L} = \left(\sum_{n}^{N} \tilde{\Pi}_n \right)^s \qquad (4)$$

where $\tilde{\Pi}_n$ is the relative average power transmitted to the auditory cortex in each of N critical frequency bands throughout the auditory integration time. Note that loudness summation implies that the exponent s is applied before summing (eq. (3c)), whereas power summation (eq. (4)) implies that s is applied after summing.

The critical-band phenomenon suggests that the sound spectrum should be resolved into bandwidths equal to critical bandwidths. The critical bandwidth is an increasing function of the band mid-frequency. For frequencies less than 500 hertz the critical bandwidths are approximately 100 hertz, whereas for frequencies greater than 500 hertz the critical bands are roughly one-third octave in width (ref. 8).

The transmitted relative power in any given frequency band k is expressed in terms of measurable quantities according to

$$\Pi_k = T_k \tilde{p}_k^2 \tag{5}$$

where T_k is the average transmittance of the internal auditory system (starting at the eardrum) in the k^{th} band and $\tilde{p}_k^2$ is the relative, mean-square sound pressure in the k^{th} band measured at the eardrum over the auditory integration time. Values of the entire transmittance (external plus internal) are obtained by inverting and normalizing equal loudness curves for pure tone stimuli, as measured, for example, by Fletcher and Munson (refs. 5 and 14) for listening with earphones, or Robinson and Dadson (ref. 15) for direct listening to plane, progressive waves incident from the front. (One should be wary about applying published transmittance curves for listening with earphones because the external transmittance may be a sensitive function of the earphone geometry and frequency response, the geometry of the observer's head, and the tightness of fit.) It is convenient to let the T_n designate internal transmittance functions encompassing the auditory pathway from the eardrum to the auditory cortex because this function is independent of the source-observer geometry. For direct listening the Robinson-Dadson curves include both internal filtering plus external effects caused by diffraction of the sound by the head and transmission of the waves along the external auditory meatus to the eardrum. The external and internal effects can be separated by considering data obtained by Wiener and Ross (ref. 16) concerning the ratio of sound pressure in the free field to that at the eardrum. From these data the mean-square pressure at the eardrum can easily be calculated from knowledge of the mean-square pressure in the free field. If the sound field is diffuse, rather than made up of plane progressive waves, then the external filter function can be modified by using the data of Robinson, Whittle, and Bowsher (ref. 17), which relate the pure-tone transmittance functions for these two types of noise sources.

LOUDNESS PREDICTIONS AND JUDGMENTS COMPARED

The precision of loudness judgments is low in comparison with that of physical sound-pressure-level measurements simply because of deficiencies of the auditory system as an intensity measuring device. The standard deviation of repeated loudness judgments by one observer is of the order of 3 decibels, whereas the standard deviation for several observers, each making one observation, is of the order of 10 decibels.

A basic experiment in loudness determination essentially consists of subjectively equating the loudness of two sounds. Most experiments have been of this type. Equally important are experiments which require quantitative judgments of the relative loudness of two sounds of unequal loudness. Very few experiments of this type have been performed. When equal-loudness judgments are used to test any loudness prediction scheme, only the precision of the scheme is really tested. Equal-loudness tests, alone, provide no information on the accuracy of the method. The accuracy can only be determined by comparing predictions with unequal-loudness judgments. Fortunately, from the theoretical standpoint, most of the unequal-loudness tests consisted of comparisons of pure tones with the sound-pressure levels being noted (refs. 5 and 15). These tests have permitted the establishment of absolute relations between loudness and sound pressure for easily reproducible sounds, namely, pure tones. Then, the absolute loudnesses of other sounds can be determined by subjectively equating them to pure tones. Unfortunately, very few experimenters have chosen to do this. Rather, most experimenters have equated loudnesses of complex sounds, one of which they have called a standard, and thereby have been unable to establish the absolute loudness of any of the sounds tested. By this procedure only the precision (standard deviation) of predicted loudness levels of sounds judged equally loud can be computed, but the computed average loudness level has no absolute significance. Hence, the accuracy of the predictions cannot be determined.

To demonstrate the validity of power summation, loudness levels were computed for sounds judged equally loud, with one sound a pure tone. Data of this type have been reported by Corliss and Winzer (ref. 18) and by Pearsons, Horonjeff, and Bishop (ref. 19). Although in both studies the loudness levels were not varied much, nevertheless the accuracy of the power summation method can be demonstrated over a limited level range. (Assume that the test data are valid. Then, if Stevens' weighted-loudness-summation formula (eq. (3)) leads to accurate loudness predictions, this implies failure of unweighted loudness summation. If Stevens' formula fails, this logically indicates the failure of both the formula and the unweighted-loudness summation because the formula was originally developed from Stevens' own test data.)

Corliss and Winzer (ref. 18) presented loudness judgment data obtained using magnetic tape recordings of tapping machines and women's footsteps on various floor materials. These sounds were equated in loudness to a 1-kilohertz pure tone by nine observers individually in a reverberant laboratory room. The subjective loudness levels in phons, as well as the loudness levels computed assuming loudness summation (Stevens, ref. 6, Zwicker, ref. 20) and power summation (this report) are shown in table I. (Subjective loudness levels in decibels are often called phons.) In addition, the corresponding overall sound-pressure levels are shown, since Corliss and Winzer found that overall sound-pressure level was better correlated with subjective loudness judgments than with Stevens', and especially Zwicker's, prediction methods. It is evident from table I that power summation yields better agreement with the subjective matches than does overall sound-pressure level or loudness summation. The average absolute disagreement with subjective levels is 2.5 decibels for power summation, 3.5 decibels for overall sound-pressure level, 5.5 decibels for Stevens' loudness summation method, and 11 decibels for Zwicker's loudness summation method. The predictions by Stevens' method are not good, whereas those by Zwicker's method are certainly poor. In addition, when the data for the different sounds are assembled in order of decreasing loudness, it becomes apparent that power summation predicts better ordering, namely, 1, 2, 4, 5, 3, 6, than the other methods.

Pearsons, Horonjeff, and Bishop reported equal loudness judgments by twenty subjects individually estimating the louder of two sounds (paired comparison method) in an anechoic chamber. Some data, listed in table II, were for comparisons between pure tones and octave bands of noise centered at the tone frequency. Loudness levels computed according to the method of power summation are also tabulated. For pure tones the loudness level equals the sound-pressure level plus the loudness-transmittance level of the entire auditory system. For a progressive wave consisting of a 1-kilohertz pure tone the transmittance is set equal to unity, so that the loudness-transmittance level equals zero. Then the loudness level equals the sound-pressure level. This equality at 1 kilohertz is observed in table II. Otherwise, the computed loudness levels for the pure tones are greater than the sound-pressure levels, as they should be for progressive waves at the frequencies considered since the external auditory system is a sound amplifier at these frequencies (ref. 16). At the higher frequencies the external filtering induced by the head causes considerable amplification (12 db at 4 kHz) of the signal reaching the eardrum (ref. 16). Thus, the calculated loudness levels are quite accurate. The differences between the computed loudness levels of the sound pairs effectively judged equally loud are listed in the last column of table II, where perfect agreement between subjective judgments and computed values would correspond to a vanishing difference. The average absolute difference is 2.4 decibels.

Pearsons, Horonjeff, and Bishop also reported on equal loudness matches between the octave bands of noise and octave bands of noise containing pure tones, between simulated jet noise with and without a superposed pure tone, and between another broadband noise with and without a superposed pure tone. With the possible exception of the first case, only the difference between the computed loudness levels of the components of each pair are of interest because the absolute loudness levels cannot be established. For the entire set of tests the average absolute difference of the computed loudness levels of noises judged equally loud was 3 decibels when using the method of power summation.

Another set of tests for which absolute loudness levels cannot be readily determined is that of Robinson and Bowsher (ref. 21). Their judgment data for only one loudness level were obtained by having 570 observers, 10 at a time, make paired comparisons of tape-recorded aircraft noises in a "moderately" reverberant room. The conditions for equal loudness, as well as the corresponding predictions, are shown in table III. Predicted annoyance levels are also included and are discussed in the next section. The standard deviations of these data in decibels relative to the average overall sound pressure, loudness, or annoyance are listed in table IV, wherein smaller numbers correspond to smaller standard deviations. For these data Zwicker's procedure exhibits the greatest precision, but power summation is a close second. When these data are compared with those of Corliss and Winzer, it again appears that the accuracy (as opposed to precision) obtained by assuming power summation is better than that obtained by assuming loudness summation.

To show in the case of the Robinson-Bowsher data that power summation is probably more accurate than loudness summation, it should be recalled that over the most sensitive range of the internal auditory system, say, from 200 to 1500 hertz at moderate to high sound-pressure levels, the loudness level of a pure tone approximately equals its sound-pressure level. Since the loudness of noise within a critical band equals the loudness of a pure tone possessing the same sound pressure at the band midfrequency, it also follows that the loudness level of a critical band of noise contained within the high auditory-sensitivity interval (200 to 1500 Hz) approximately equals its sound-pressure level. If the noise bandwidth exceeds the critical bandwidth, then the question of the appropriate summation, loudness or power, arises. The noise spectra used by Robinson and Bowsher are similar to those considered by Corliss and Winzer in that the energy tends to be concentrated in the high auditory-sensitivity interval. In the latter case, as already shown, power summation was the most accurate process by far, and the loudness levels predicted thereby agreed fairly well with the overall sound-pressure level (average absolute difference, 2.6 db). The values given by Stevens procedure were about 5 decibels too high and those given by Zwicker's procedure about 11 decibels too high. The fact that predictions according to Zwicker's procedure are high has also been noted elsewhere (ref. 22). All the same results and conclusions follow from the Robinson-Bowsher data. Hence, as before, power summation appears to yield a more accurate estimate of loudness than loudness summation.

ANNOYANCE

Finally, it is worthwhile to consider the method of power summation to predict annoyance, since annoyance and loudness are closely related. If the attention of an individual is consciously directed toward perceiving sounds, then the individual is capable of making quantitative judgments of the relative annoyance of different sounds, just as he is able to make relative loudness judgments. On this basis Kryter (ref. 9) devised an empirical annoyance prediction procedure paralleling Stevens' loudness prediction procedure. In order to differentiate his annoyance levels from Stevens' loudness levels, Kryter designated annoyance levels in perceived noise decibels (PNdb). The annoyance level in PNdb is equivalent to annoyance expressed in decibels. It appears that the accuracy of the annoyance prediction scheme has never been tested. The concensus of many tests is that annoyance levels judged over short time periods are equal to Stevens' loudness levels (refs. 23 and 24) unless the judged sound contains relatively intense pure tone components (ref. 19), that is, contains information as opposed to noise. Then, the annoyance level exceeds the loudness level. Because of its close relation to Stevens' loudness prediction method, Kryter's annoyance prediction method tends to yield similar numerical results in the absence of pure tones. An example is illustrated in table III. If Stevens' loudness predictions are doubtful, then Kryter's annoyance predictions must also be doubtful. The doubtfulness of prior annoyance predictions was apparently first suspected on theoretical grounds by Jones (ref. 24), who proposed power summation for computing annoyance based on a more elementary theory than in reference 13. More recently, Kryter (ref. 23) made the same proposal, but, in addition, noted that the sums must be over critical bands, whereas Jones rejected the significance of critical bands. The precision of the proposals was tested, but no attempts were made to test their accuracy. As it relates to these proposals, the loudness prediction procedure reported herein was independently derived from the theory in reference 13. The importance of the auditory integration time and the important effects of the noise source geometry and method of observation are included in the calculation procedure for the first time. Finally, the auditory transmittance function is based on tests using pure tones, rather than bands of noise. Pure tones can be accurately specified and reproduced. In general, this is not possible for noise.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 25, 1971,
129-01.

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TABLE I. - COMPARISON OF MEASURED OVERALL SOUND-PRESSURE LEVEL[a] AND COMPUTED LOUDNESS LEVELS WITH SUBJECTIVE LOUDNESS-LEVEL JUDGMENTS FOR VARIOUS NOISES

[Data from Corliss and Winzer, ref. 18.]

Noise source	Subjective loudness level, phons	Overall sound-pressure level, db	Loudness level, phons		
			Stevens (ref. 6)	Zwicker (ref. 20)	Howes (this report)
Tapping machine on -					
1. Concrete	81	81.5	86	91	83.6
2. Vinyl tile over concrete	80	81	85.5	92	82.6
3. Oak blocks over concrete	74.5	78.5	80.4	86	77.7
Footsteps on -					
4. Concrete	77.8	83	86	88	81.5
5. Vinyl tile over concrete	75.8	81	82.5	86	78.0
6. Oak blocks over concrete	74.5	80.5	77	86	74.0

[a]Referenced to 2×10^{-5} $N\cdot m^{-2}$.

TABLE II. - COMPARISON OF MEASURED OVERALL SOUND-PRESSURE LEVELS[a] AND COMPUTED LOUDNESS LEVELS FOR JUDGED LOUDNESS EQUALITY OF PURE TONES AND OCTAVE BANDS OF NOISE CENTERED AT THE TONE FREQUENCY

[Data from Pearsons, Horonjeff, and Bishop, ref. 19.]

Tone frequency, Hz	Octave band		Pure tone		Loudness-level difference, phons
	Overall sound-pressure level, db	Loudness level, phons	Overall sound-pressure level, db	Loudness level, phons	
250	98.0	98.4	97.0	97.9	0.5
500	94.0	95.4	88.5	90.4	5.0
1000	95.5	97.4	94.5	94.5	2.9
2000	96.5	102.4	97.5	101.3	1.1
4000	95.5	106.3	98.0	108.8	-2.5

[a]Referenced to 2×10^{-5} $N\cdot m^{-2}$.

TABLE III. - COMPARISON OF MEASUREMENTS AND COMPUTED LOUDNESS AND ANNOYANCE LEVELS FOR VARIOUS AIRCRAFT SOUNDS JUDGED EQUALLY LOUD

[Data from Robinson and Bowsher, ref. 21.]

Sound	Overall sound-pressure level, db	Sound level A, db	Loudness level, phons			Annoyance level, PNdb
			Stevens	Zwicker	Howes	
Bristol helicopter hovering	93.7	87.6	100.8	104.7	92.4	101.0
Westland helicopter taking off	96.8	91.2	102.8	105.7	94.2	103.4
Fairey Rotodyne taking off	89.0	85.9	98.0	103.8	90.3	100.7
Fairey Rotodyne flying past	96.3	89.4	101.9	106.0	91.8	102.2
Boeing 707/120 climbing	91.0	88.8	98.2	105.1	91.3	100.1

TABLE IV. - STANDARD DEVIATION LEVELS[a] OF DATA IN TABLE III

Measurement or calculation	Standard deviation level, db
Overall sound-pressure level	-1.8
Sound level A	-3.5
Loudness level from Stevens	-3.3
Loudness level from Zwicker	-7.2
Loudness level from Howes	-4.5
Annoyance level	-4.9

[a]Referenced to average values of sound pressure, loudness, or annoyance.

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