38. PERCEIVED SOUND AND THE FREQUENCY RESPONSE CHARACTERISTICS OF THE HUMAN AUDITORY SYSTEM

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SUMMARY

A simple model of the human auditory system is presented from a dynamic response point of view - that is, input-output. The output of a human auditory system, which is defined as the perceived sound, is determined by multiplying the input acoustic stimulus by the square of the complex frequency response function of the auditory system. It is shown that, in terms of this model, the inverse equal noisiness (or equal loudness) contours are in effect the transfer function for the human auditory system. Perceived sound estimates obtained through the use of this model are presented and it is shown that these estimates agree with judgment test results as well as or better than the predictions obtained by presently accepted methods.

Arguments are presented which show that the results obtained through the use of this approach for input sound pressure level values in excess of 60 dB (re: 0.00002 N/m^2) can be considered valid. The further implication is that for input sound pressure levels above this value, the human auditory system can be considered to function as a linear system.

The so-called critical bandwidth phenomenon is also interpreted within the framework of the proposed model; however, the resulting critical bandwidths are greater than the presently accepted values. In the frequency region near the peak in the response curve, this model clearly predicts that the perceived sound level will decrease instead of increase for bandwidths greater than the critical band.

INTRODUCTION

When an auditory system is exposed to an acoustical stimulus, the resultant quantity is normally referred to as the "perceived noise." In the past, the magnitude of this perceived noise has been specified in several different ways. The approach by Stevens in references 1 and 2 provides a measure of this magnitude or loudness in terms of units of loudness called sones or its logarithmic equivalent is the loudness level in phons. Zwicker and Feldtkeller (ref. 3) and Zwicker (ref. 4) also present a measure of this loudness in phons. Kryter (ref. 5) and Kryter and Pearsons (ref. 6) present a similar approach in which they choose to describe the magnitude of the perceived noise as noisiness, where the unit of noisiness is called noys, and its logarithmic equivalent is the perceived noise level in PNdB.

The concepts presented in this paper provide yet another approach to the elusive problem of estimating the magnitude of the perceived noise. The ideas contained herein are being presented with the hope that these concepts will provide a simpler interpretation of the phenomena of perceived noise. In the author's opinion, it is necessary to introduce additional descriptive terms, in order to adequately discuss the magnitude of perceived noise associated with these new concepts. Instead of the output of an auditory system being referred to as perceived noise, it will be hereafter referred to as "perceived sound." The unit of perceived sound is called "perceived pressure" and its logarithmic equivalent is the "perceived sound level" in dB(J). These terms are defined in the text.

Perceived sound can be qualitatively described in many different ways. It can be described by the characteristics of loudness, noisiness, annoyance, distraction, discomfort, or any other desired quality. These so-called qualities of perceived sound are very subjective in nature and, consequently, are very difficult to determine. When a person is asked to judge the perceived sound in terms of one of its desired qualities, the reaction or, more specifically, the response of that individual is dependent upon that quality which he is being asked to judge. This is to be expected and is in fact borne out by the results of tests concerning perceived sounds of equal loudness and equal noisiness. These studies have revealed that subjects responded differently when asked to judge sounds of equal loudness, as compared with sounds of equal noisiness. Persons, therefore, seemed to respond differently to the various qualities which can be ascribed to the perceived sound. This difference may be due to the fact that the individuals are not sure just what it is they are trying to judge, or the differences may, in fact, be real. At any rate, loudness (or noisiness, etc.) is then a psychological term which is used to describe the magnitude of an auditory sensation.

The concepts introduced in this discussion can be applied to any desired quality of perceived sound, but in order to compare predictions with measured results, the subsequent equations are developed with the quality of noisiness in mind. If the response characteristics for a different quality are desired, mentally substitute that desired quality for noisiness.

SYMBOLS

BSPL	band sound pressure level
f	frequency
Af	frequency bandwidth
f_L	lower limit of band

f_U	upper limit of band
f_c	geometric mean center frequency of band
f_p	peak frequency
$\|H(f)\|^2$	frequency response function
$\|\mathcal{H}(f_c)\|^2$	relative auditory frequency response function
$\overline{J^2}(f)/Hz$	mean squared perceived pressure per unit bandwidth
$\overline{J^2_{\Delta f}}(f_c)$	perceived mean squared pressure in band
K, k_p	perceived constants
N,i	integers
OASPL	overall sound pressure level
OBPSL	octave band perceived sound level, dB(J)
OBSPL	octave band sound pressure level of input, dB
P_o	standard acoustic reference pressure, 0.00002 N/m^2
$\overline{P^2}(f)/Hz$	mean squared pressure per unit bandwidth
$\overline{P^2_{\Delta f}}(f_c)$	mean squared pressure in the band
PSL	perceived sound level
$S_I(f)$	power spectral density of input acoustic stimulus, $\overline{P^2}(f)/Hz$
$S_p(f)$	perceived spectral density of output, $\overline{J^2}(f)/Hz$
SPL_i	sound pressure level of input stimulus
s_p	perceived sound (mean squared value of perceived pressure)

STATE OF THE ART

When an attempt is made to determine the state of the art with regard to the definition, measurement, and calculation of perceived sound, the complexity and seemingly orderly progression of events is immediately evident. No doubt, one of the more recent studies to be examined would be that of Kryter (ref. 7), and then works of both Pearsons and Kryter (refs. 5, 6, 8, 9, and 10), Stevens (refs. 1 and 2), Mintz and Tyzzer (ref. 11), Beranek, Marshall, Cudworth, and Peterson (ref. 12), Churcher and King (ref. 13), and Fletcher and Munson (ref. 14). These studies do not represent the total effort of all workers in this area, but they have a more direct bearing on the topic of this paper. From these few basic studies, the total scope of this problem area is immediately apparent.

It is not the intent here to elaborate to any extent on what has been done in the past; those associated with this field are well aware of these facts. However, because the major discussion herein is concerned with the calculation of perceived sound, it may be well to mention the progression of events which have led to the presently accepted calculation schemes.

Those who have been faced with the necessity of computing the perceived sound of a given noise spectrum are well aware of the tedious and extremely time-consuming methods which have been devised. These techniques owe their origin, in reality, to the early pioneering work of Fletcher and Munson (ref. 14). One of the first attempts to calculate perceived sound (referred to as loudness at that time) was made by Gates (Discussion, ref. 13), who proposed that the total loudness of a complex sound could be found by a direct summation of the loudness units representing the spectrum of a complex sound. This technique was later elaboarated upon by Beranek, Marshall, Cudworth, and Peterson (ref. 12) and Mintz and Tyzzer (ref. 11). Stevens (refs. 1 and 2), however, found later that, if the total loudness was obtained through a summation of loudness units, this indicated loudness would exceed the actual loudness of the total noise by a factor of more than 2. Consequently, Stevens devised a summation procedure that was empirically derived from a series of tests which tended to weight the total loudness of a complex noise spectrum to the maximum loudness unit of that noise spectrum. This technique, which seemed to be successful in predicting the results of judgment tests, is in the form of a numerical calculation scheme. The unit of loudness used by Stevens is called sones, and its logarithmic equivalent is the loudness level in phons. Zwicker and Feldtkeller (ref. 3) and Zwicker (ref. 4) devised a procedure which is similar to that used by Stevens but is handicapped somewhat because it is in the form of a graphical calculation scheme.

Kryter (ref. 5) and then Kryter and Pearsons (ref. 6) devised a procedure almost exactly paralleling that of Stevens; the only exception is that this technique is derived for noisiness and Stevens' technique is intended to be used for loudness evaluation. Kryter's procedure is a numerical calculation scheme; that is, the scheme is based on experimental data presented in tabular form and the computations are performed with the aid of an empirical weighting equation. The unit of noisiness is called noys and its logarithmic equivalent is perceived noise level in PNdB.

All these calculation schemes are somewhat awkward to use and difficult to relate to a valid physical interpretation of the perceived quality of sound. It is also difficult, though not impossible (ref. 15), to build an instrument so that a direct measure of the perceived sound can be made.

The intent of this discussion is to put forth several ideas in order to simplify the calculation procedure for estimating the magnitude of perceived sound and present a simple model for describing the human auditory system. Doing so will place the calculation scheme on a firm physical basis. As a result of this simplified approach, it is shown that an instrument can easily be built so that a direct on-line measure of the magnitude of the perceived sound can be made. There is no need to discuss the obviously far-reaching benefit of an instrument of this nature.

In this paper, an attempt is made to show that this simplified procedure provides estimates which agree with the results of judgment tests as well as or better than the presently accepted methods. Additionally, it is not limited by complex sounds containing strong pure tone components or high level narrow-band energy. Furthermore, it is shown that this approach provides a better insight into the physical aspects of the human auditory system.

PERCEIVED SOUND MODEL

The basic intent of this discussion is to depart somewhat from present ideas and procedures. .Some may consider this departure as radical or reverting to concepts that have long since been abandoned, but it is believed that this departure is warranted in view of the simplicity and physical insight which can be achieved by the use of this very basic and simple method.

The proposal here is to consider the human auditory system from a dynamic response point of view - that is, input-output; this is illustrated in figure 1 as an input altered by the appropriate response function and the output.

The input implies any type of acoustic stimulus – that is, broad-band noise, narrow-band noise, pure tones, multiple tones, and so forth. By the use of certain assumptions concerning the statistical characteristics between tones in a multitone configuration or between tones and bands of noise, this input can be made to apply to any combination of tones and/or bands of noise. For the purpose of this analysis, it is assumed that tones in a multitone configuration and tones in bands of noise are statistically unrelated; therefore, the mean squared pressures will be added directly.

The human auditory system consists of the ear and its associated physical hearing mechanisms, the nerve system, the brain, and any other elements, both psychological and physical, which would have any possible effect upon the total hearing process. This auditory system can be represented by a transfer function which will in turn operate in a systematic manner upon the input in order to transform it into the perceived sound. The auditory system is, by its very nature, a dynamic system and, because of this, it will have definite frequency response characteristics. These response characteristics will also vary from individual to individual; therefore, if the perceived sound that is representative of an average or typical listener is to be predicted, the response characteristics of the typical or average human auditory system will have to be used.

The output is the perceived sound, and the unit of perceived sound is called a perceived pressure. It is emphasized that this unit of perceived sound is not the same as the unit of noisiness (noy) and the unit of loudness (sone) which have been used in the past. The perceived pressure is directly related to the input sound pressure. By defining it in this fashion, a direct relationship can be established to relate noisiness to a physical quantity. The logarithmic equivalent of the perceived pressure is the perceived sound level in dB(J). The dB(J) is written in this manner to indicate that the output was obtained with a J weighting function. This is analogous to the notation used when presenting results obtained with the A, B, or C weighting scales presently in use. The perceived sound level in dB(J) is defined as follows:

$$PSL \equiv 20 \log_{10}\left\{\sqrt{S_p}/P_o\right\} \tag{1}$$

The perceived sound level can, therefore, be directly related to the input sound pressure level.

Another obvious benefit of defining perceived sound in this fashion is that it is now possible to discuss such things as a perceived spectrum or a spectral distribution of the perceived sound. Equation (1) can be extremely useful in determining what portion of the spectrum is having the most influence on the total perceived sound. Furthermore, the perceived spectrum can be presented as an octave band, a one-third octave band, a spectral density, or in any other desired form. These quantities are defined as follows:

$$\text{Band perceived sound level} \equiv 20 \log_{10} \left\{ \frac{\sqrt{\overline{J^2_{\Delta f}}(f_c)}}{P_o} \right\} \tag{2}$$

If Δf is equal to an octave band, equation (2) would become the octave band perceived sound level, and so forth.

The perceived spectral density of output is

$$S_p(f) \equiv \overline{J^2}(f)/\text{Hz} \tag{3}$$

This definition is analogous to the power spectral density of the input acoustic stimulus.

The overall perceived sound or, more specifically, the perceived sound can then be defined as follows:

$$s_p \equiv \int_0^\infty S_p(f)\, df = \int_0^\infty \overline{J^2}(f)/\text{Hz}\, df \tag{4}$$

These definitions are consistent with presently accepted terminology except they are now being related to the unit of perceived sound.

If the human auditory system is considered a constant parameter linear system, then the input and output (fig. **1)** can be related as follows (ref. **16):**

$$|H(f)|^2\, S_I(f) = S_p(f) \qquad (0 \leqq f < \infty) \tag{5}$$

It might be argued that the auditory system cannot be considered as a linear system, and in view of the present interpretation of perceived sound which normally expresses loudness in sones or noisiness in noys, this seems to be true. However, in light of the concepts which are being presented in this discussion, it can and will be shown that, within given amplitude ranges of the input stimulus, the auditory system can indeed be represented by a linear system.

Accepting the concept of a linear system for the present time, the characteristics of $|H(f)|^2$ will now be defined. If $S_I(f)$ and $S_p(f)$ are known, the characteristic definition would be complete. Upon close examination, it is easily seen that this is indeed the case. The quantity $S_I(f)$ can readily be measured, but although this cannot be done with $S_p(f)$, an individual can be asked to judge (perceive) with reasonable accuracy a constant noisiness function. The perceived values of constant noisiness are the equal noisiness (or equal loudness) contours which presently exist. From these equal noisiness curves, $|H(f)|^2$ can be determined.

First assume that the equal noisiness curves were obtained by judging the noisiness of bands of noise. (See **ref.** 6.) Equation (5) can then be written as

$$\int_{f_L}^{f_U} |H(f)|^2 S_I(f)\, df = \int_{f_L}^{f_U} S_p(f)\, df \qquad (6)$$

where f_U and f_L are the upper and lower limits of any arbitrary band. These upper and lower limits could also be made to apply to any desired band of interest – that is, octave band, one-third octave band, and so forth.

If $|H(f)|^2$ is assumed constant over the frequency band of interest, equation (6) can be written as

$$|H(f)|^2 \int_{f_L}^{f_U} S_I(f)\, df = \int_{f_L}^{f_U} S_p(f)\, df \qquad (7)$$

If a person is judging a constant noisiness, then $\int_{f_L}^{f_U} S_p(f)\, df$ is constant; also, the integral in the left-hand side of the equation is actually the mean squared pressure in the band. From this, then, equation (7) becomes

$$\overline{P^2_{\Delta f}}(f_c) \left|H(f_c)\right|^2 = k_p \qquad (8)$$

Converting equation (8) to the band sound pressure level in dB yields

$$\mathrm{BSPL}(f_c) + 10 \log_{10} \left\{ \left|H(f_c)\right|^2 \right\} = K \qquad (9)$$

Equation (9) states that as one proceeds from one band to the next throughout the whole audio range, the sound pressure level in each band must change in such a fashion that K remains a constant; this is by definition the concept of the equal noisiness curves. The only restriction is that the response function is assumed to be constant over the band of interest.

It is desirable to define a relative frequency response function. Therefore, this function will be defined such that $\left|H(f_c)\right|^2$ is unity when the sound pressure level of a band of noise or a pure tone centered at 1000 Hz equals K. From this definition, equation (9) becomes

$$10 \log_{10} \left\{ \left|H(f_c)\right|^2 \right\} = \mathrm{BSPL}(f_c = 1000\ \mathrm{Hz}) - \mathrm{BSPL}(f_c) \qquad (10)$$

where $\left|H(f_c)\right|^2$ is the relative auditory frequency response function and

$$10 \log_{10}\left\{\left|H(f_c)\right|^2\right\}$$

is the relative response in dB.

Equation (10) is the relationship that was used to obtain the relative auditory response function for a typical or average human auditory system. It can be seen from the derivation of the relationship that the term $BSPL(f_c)$ is, in reality, the equal noisiness curves and $BSPL(f_c{=}1000\text{ Hz})$ is the equal noisiness value at the center band frequency of 1000 Hz.

HUMAN AUDITORY RESPONSE FUNCTION

The method of Kryter and Pearsons (refs. 6 and 17) seems to give results which appear to be in better agreement with the results of judgment tests than any of the other existing techniques; therefore, the concept of PNdB seems to have gained general acceptance. For this reason, the relative auditory response function is determined from the data of Kryter and Pearsons.

If the input stimulus is restricted to levels which are greater than 60 dB (re: 0.00002 N/m^2), then, with the aid of the equal noisiness values presented in reference 17 and equation (10), the relative response functions can be determined. The results of this operation are presented in figure 2. The scatter band represented by the shaded region in figure 2 is the total scatter in the response function for this extreme range in sound pressure level. In view of the extreme variability which normally occurs in judgment tests which are used to arrive at the equal noisiness curves, this scatter band can be considered negligible. The average of this scatter is presented in figure 3, and it is this response function which has been used to obtain most of the results presented in this paper.

Examination of figure 2 indicates that the relative response function is independent of the amplitude of the input stimulus. From this, it can be concluded that the auditory system functions as a linear system for input sound pressure levels in excess of approximately 60 dB. This conclusion can also be drawn from the existing procedure for calculating perceived noise without resorting to the concepts presented herein and is clearly illustrated in figure 4. The perceived noise level in PNdB has been computed (ref. 17) for nine different spectrum shapes (fig. 4(b)) for various input levels of each spectrum. If attention is restricted to levels in excess of approximately 60 dB for the input stimulus, it is seen that, for a 10-dB increase in input (for a given spectrum), the perceived noise level increased by 10 PNdB. This in itself implies some sort of linear or one-to-one correspondence. Clearly, for levels below 60 dB and for low frequency energy spectra, the relationship is no longer linear. Furthermore, the family of curves presented in figure 4(b) merely reflects the influence of the frequency response characteristics of the human auditory system on these various input spectra.

APPLICATION OF THE PERCEIVED SOUND LEVEL

Now that the frequency response function of the auditory system has been determined, it is possible to compute the perceived sound level. This computation is easily done with the aid of equation (1) and the frequency response function of figure 3.

This proposed method is not restricted in the sense that it has to be applied to a given type of input format – that is, octave band form, one-third octave band form, and so forth – but works equally well with any type of input format since the response function is independent of bandwidth.

Inasmuch as the relative response function was defined such that the input stimulus was equal to the perceived level at a frequency of 1000 Hz, equation (1) can now be written in terms of this relative response function as

$$\mathrm{OBPSL}\left(f_c\right) = \mathrm{OBSPL}\left(f_c\right) + 10 \log_{10}\left\{\left|H\left(f_c\right)\right|^2\right\} \tag{11}$$

in units of dB(J). The only restriction on equation (11) is that the relative frequency response function is assumed to be constant within the octave band.

The point that should be emphasized now is the ease and simplicity by which the perceived sound level is determined. There is no need to have a weighting function which is related to the amplitude of the input stimulus as is presently in use with the noy or sone scales; this simplifies immensely the calculation procedure. The application of the proposed method is analogous to the procedure that would be used to correct acoustic test data because of the nonuniform frequency response characteristics used to acquire the data.

It is a simple matter to construct an electronic instrument to measure directly the perceived sound level. This is analogous to the A, B, or C weighting scales presently in use. It will be shown that predicted subjective responses obtained with the aid of the response curve in figure 3 agree with judged responses as well as or better than estimates obtained by using any of the presently accepted loudness or noisiness prediction methods. Furthermore, it will be shown that, by slight modification of the response curve in figure 3, even better agreements between predicted and judged results can be obtained.

Before the comparison of results is introduced, it is important to discuss the relative significance of the absolute magnitude of the perceived sound level predicted by the proposed method in comparison with that predicted by other methods. It is almost meaningless to compare the absolute values resulting from these methods because of the way in which the reference for the loudness level and perceived noise level was arbitrarily defined and also because of the difference in the weighting characteristics between the proposed method and these other methods - that is, the methods of Kryter, Stevens, and Zwicker. It might be argued that the reference of the proposed method is just as arbitrary. Indeed, this may be true but, because of the manner in which this reference was defined, it is believed that more physical meaning can be placed on these results. In any event, in order to avoid this problem, the absolute magnitudes are not compared directly, but instead each is compared with its own standard (difference from the standard); then these differences are compared. This is the conventional procedure.

In order to provide an indication of the difference between the values obtained by the proposed method and those obtained by other methods (Kryter's in particular), the spectra of figure 4(a) were recomputed with the aid of the proposed method. These results are presented in figure **5.** In comparing the results of figures 4 and **5,** as well as other comparisons presented later in this paper, it is seen that the perceived sound level (PSL) estimates (numerical values) are always less than the perceived noise level (PNL) estimates (numerical values). The amount they differ depends upon the breadth of the energy of a given input sound spectrum as well as the location, in frequency, of the predominant energy. In general, it seems that the broader the energy distribution and the lower the peak frequency of this energy, the greater the difference between the PSL and the PNL. For the type III spectra of figure 4(a), this difference is about **6.5.** For spectra narrower than type I (spectra **1** to 4 of fig. **6),** this difference is about **3.**

EVALUATION OF THE PROPOSED METHOD

Now that the frequency response function has been developed, the ability of the response function of figure **3** to predict the results of judgment tests will be determined. Insofar as this response function has been developed from a noisiness point of view, comparison is restricted to those judgment tests in which the subjects were asked to judge noisiness. In doing so, only the results of tests performed by Kryter (ref. 5), Kryter and Pearsons (ref. **6),** and Little (ref. 18) will be used.

Comparison With Bands of Noise Without Tones

Kryter and Pearsons (ref. **6)** performed a very comprehensive test series in which subjects were asked to adjust the level of the comparison stimulus of nine widely different spectra (fig. **6)** until each was just as acceptable (noisy) to them as the standard spectrum.

The levels of these spectra have been adjusted so that they correspond to the average result of the judgment tests for which each of the comparison stimuli was as acceptable as the standard stimulus. Table 1 compares the predictions of various assessment methods, both electronic and other prediction methods. Table 1 shows that the proposed method and the method of Kryter seem to have better agreement with the results of the judgment tests when comparing the average differences from the standard. For an ideal method, these differences should be zero - in fact, the method should predict the same value for each of the judged spectra - this can be used as a gage to determine the superiority of one method over another.

A more detailed account, delineating the difference from the standard for each of the individual comparison spectra, is presented in table 2. Another equally valid gage is the ability of a prediction method to "rank," in the order of noisiness or loudness whichever the case may be, any given input spectra.

Hereafter, to simplify the discussion of the results, only comparisons between the proposed method and that of Kryter are made. In reality, the techniques of Kryter, Stevens, and Zwicker are essentially from the same mold; therefore, conclusions drawn concerning the method of Kryter can, in general, be applied to those of Stevens and Zwicker.

The other means of determining the adequacy of a given prediction method, as mentioned previously, is its ability to rank any given input spectra. The input spectra cannot be ranked according to the predicted magnitude of noisiness presented in table 1 because obviously they should all be the same value. The variations which are presented merely indicate the inadequacies of the methods and provide some measure of the prediction accuracy. The rank therefore has to be determined by different means.

One means of determining the rank is to readjust all the results of the judgment tests (i.e., the spectra presented in fig. 6) to a constant overall sound pressure level value. By doing this, the spectrum which had to be increased the most to obtain the selected overall value would be judged the "noisiest" and the spectrum which was changed by the smallest amount would be judged the "least noisy." This then provides valid results based on judgment tests from which the predictions, determined from the readjusted values, can be compared.

The judgment tests of Kryter and Pearsons (ref. 6) were determined in this fashion, and the results are presented in table 3. From this table, both techniques are seen to rank the input spectra about equally as well; however, both techniques seem to rank spectrum 6 noiser than it should be. In light of this present approach and after examining the input spectra in figure 6, a slight change in the high frequency portion (approximately 5000 Hz) of the frequency response function (fig. 3) could easily shift spectrum 6 into its proper order without affecting the ranking of the other spectra.

From an earlier study by Kryter (ref. 5), an additional comparison between predicted and judgment results can be made. In this study the subjects were asked to judge, by the method of paired comparison, the noisiness of six different types of aircraft spectra. The results of this comparison are presented in tables 4, 5, and 6. The PNdB values were determined by using the noy curves of reference 17. These tables show that both methods, again, are equally as effective in predicting the results of judgment tests. The predictions in the order of noisiness are better for these judged results than they were in the previous comparison.

It seems appropriate at this time to question the methods which various investigators have used in the past to obtain the "average results" of their judgment tests. Stevens (ref. 19), in discussing this problem, is of a similar opinion that too little attention is paid to the method used in averaging the data. Because of the large variations in the results, which seem to be inherent in most judgment tests, different averaging methods could introduce a rather significant bias. The subjective bias which is already present in the data is bad enough, but this problem is being compounded because of this so-called "averaging bias."

The common method of averaging the results is to obtain the arithmetic average of the decibels. When viewed from an energy standpoint, this operation is actually obtaining the geometric mean value of the mean squared sound pressures of the input stimulus. In other words,

$$\sum_{i=1}^{N} \frac{SPL_i}{N} = 10 \log_{10}\left\{\frac{1}{P_o^2}\left(\overline{P_1^2}\,\overline{P_2^2}\,.\,.\,.\,\overline{P_N^2}\right)^{1/N}\right\}$$

The proposed method for estimating noisiness returns the calculation procedure to an energy basis; consequently, it implies that the judgment results should be averaged by using the mean squared pressures of the input stimulus. This operation, therefore, results in the arithmetic mean of the mean squared pressures; that is,

$$\overline{P^2} = \sum_{i=1}^{N} \frac{\overline{P_i^2}}{N}$$

If the arithmetic mean of the mean squared pressures is compared with the geometric mean, it can be shown that

$$\sum_{i=1}^{N} \frac{\overline{P_i^2}}{N} \geqq \left(\overline{P_1^2}\,\overline{P_2^2}\,.\,.\,.\,\overline{P_N^2}\right)^{1/N}$$

Because of the extreme variability which is present in most judgment test data, the decibel values obtained from the arithmetic means are, in general, usually greater than the numerical average of the decibels (geometric mean). The amount by which one exceeds the other is a function of the range of values to be averaged, as well as the distribution of the values within this range.

Another method commonly used (ref. 19) is as follows: The decibel values to be averaged are first converted to their equivalent sone values, then the arithmetic mean of these sones is computed, and finally this averaged value is converted back to its equivalent decibel value. This is the analogous procedure that would be followed for obtaining the average based upon the mean squared pressures. But because the weighting of the amplitude of the input stimulus by sones in comparison with that by mean squared pressures is drastically different, the resulting average will not be the same. Averaging by the use of sones will, in general, result in a value which will fall between the values obtained by the first two methods cited.

Take a typical judgment test result and determine the average with the aid of these three different methods. Assume that the values to be averaged are those given by judged results of spectrum 4 of figure 16 in reference 6. The corresponding averages are

Average of the decibels	80.0 dB
Average of the mean squared pressures	83.3 dB
Average of the sones	81.2 dB

These differences may not seem to be significant at first glance, but it must be emphasized that this is introducing an artificial bias into the subjective response; furthermore, it makes valid comparisons of the results of different investigators exceedingly difficult if not impossible. This "error" is comparable in magnitude to the time error which has been observed; that is, the error in judging the second sound in a given pair as being noisier than the first, even though they are both the same amplitude.

There is yet another means of determining the average results of judgment tests. This average is obtained by plotting a curve of the percentage of people judging the comparison stimulus to be potentially noisier than the standard against the amplitude of the comparison stimulus. The point at which the 50-percent line crosses this curve is then the sound pressure level that is required for that comparison stimulus to be perceived as noisy as the standard. The question being raised here is, "How is this average related to the three other methods previously discussed?"

Having touched briefly on the fact that the weighting of the amplitude of the input stimulus by sones (or noys) and the weighting of the amplitude of the input stimulus by mean squared pressures are drastically different from each other, the consequences are examined. First of all, it is well known that, if the input sound pressure level changes by a factor of 10 dB, the mean squared pressure changes by a factor of 10, but the noy (or sone) value would change by a factor of only 2. It can be seen from this that the noy (or sone) scales put a great amount of emphasis upon the lower sound pressure levels of a given spectrum. If these noisiness units (or loudness units) are summed to arrive at a total noisiness (or loudness) value, the result would be proportionately greater than the sum of the mean squared pressures; this is believed to be the reason why it has been proven that the total noisiness (or loudness) cannot be obtained through a direct summation. Stevens (ref. 1) first recognized this fact and subsequently derived an empirical relationship for summing these noisiness (or loudness) units. The results of this study indicate that this summing procedure, even though "seemingly correct" values are achieved through its use, still merely reflects the improper weighting characteristics of the input stimulus and, furthermore, that the so-called "bandwidth effect" – that is, the variation of coefficients for different types of data analysis – is also a manifestation of the same improper weighting. This bandwidth effect implies that the noisiness (or loudness) is dependent upon how the data are reduced, but this implication is not realistic. This study concludes that, if the proper weighting is used – that is, that which is proportional to the mean squared pressure – the total perceived level can be obtained through a direct summation.

Now the perceived noise level and the perceived sound level are computed for the judgment test results of Kryter and Pearsons (ref. 6), but, instead of using the average of the decibels as before, the average computed by the arithmetic mean of the mean squared pressures is used. These results, presented in the same manner as before, are given in tables 7, 8, and 9, and the average difference from the standard is considerably less than before. The order of the predicted rank remains the same, but the ranking from the judgment test results have changed. This also indicates the necessity of averaging the results properly (by mean squared values). Averaging the results in this manner has improved the agreement between methods.

Comparison of Bands of Noise With Tones

Figure 7 presents the results of a study of a pure tone immersed in a band of noise performed by Kryter and Pearsons (ref. 6). The indicated tone-band combination of each comparison stimulus was judged by the method of paired comparison to be as noisy as the standard band of noise without a pure tone. The band of noise was from 3680 to 7500 Hz and the center of frequency was computed to be 5280 Hz. Tables 10 and 11 compare these judged results with the predicted results of the proposed method and the method of Kryter with the pure tone correction applied (ref. 9). It can be seen from these results that the proposed method is satisfactory. Generally it is not considered important where the pure tone is situated in a given band of noise. This study, however, reveals that the perceived level is critically dependent upon the location of the pure tone in the band of noise; this is particularly true in those frequency regions where the frequency response function is changing rapidly with frequency. (See fig, **3.)** If the frequency response function is flat within the band of noise, the location of the pure tone within the band of noise is not important.

In **1961** Little (ref. **18)** made a study in which **65** subjects were asked to judge the relative annoyance of two different types of present-day jet-engine sound spectra. One of these spectra had several high-amplitude narrow-band spikes. (See fig. **4** of ref. **18.)** The proposed method was applied to these judged spectra and the results compiled. ***(See*** fig. **8.)** Figure 8 presents the frequency distribution of energy that the average or typical human would perceive. These perceived spectra were judged to be equally noisy; therefore, the total energy associated with these spectra should be equal. It can be seen that the overall levels differ by approximately **1.5** dB(J). This again is considered to be a very good comparison especially for these types of spectra.

REVISED RELATIVE AUDITORY RESPONSE FUNCTION

The frequency response function presented in figure **3** was derived exclusively from existing data. This response function does a good job of predicting the results of judgment tests; however, it seems to be still lacking in certain respects. As mentioned previously, slight modifications in this response function can be made to achieve better agreement with judged results. Through "trial and error," a modified auditory response function was obtained. (See fig. 9.) This response function was applied to the judgment test of reference **6,** and the results tabulated in tables **12, 13,** and **14.**

Table **12** compares the absolute magnitudes of the predictions of the proposed method and the Kryter method. The spectra presented in table **12** were all judged to be equally noisy; therefore, an ideal assessment method should indicate the same value for each spectrum. As can be seen, the average difference is small – that is, -0.6 for the Kryter method and **-0.9** for the proposed method; for these types of spectra, such small values are considered to be very good.

Table **13** presents the individual differences from the standard. Table **14** presents the rank, in the order of noisiness, of each of the input spectra given in table **12.** The purpose of this exercise is to verify that the prediction technique is able to select the spectra that would be perceived to be the noisiest from a variety of input stimuli which all have the same total energy content; that is, the physical overall mean squared pressure is constant for all input spectra. The rank was determined in the same manner as before. It can be seen that the proposed method was successful in selecting the noisiest spectrum, whereas the Kryter approach ranked the noisiest spectrum (spectrum 3) fourth in the order of noisiness.

The other spectra, with the exception of 6, seem to be ranked in their approximate order.

INTERPRETATION OF THE CRITICAL BAND PHENOMENON

It is of interest to determine how much insight the proposed model can present in the interpretation of the "critical band phenomenon." These so-called "critical bands" can be determined very easily with the aid of the proposed model, and although the results do not agree with the presently accepted bandwidths (refs. 20 and 21), the similarities are amazing.

In light of the proposed method, the critical bandwidth can be explained in the following manner. Consider, for example, a pure tone acoustic stimulus (fig. 10) consisting of a two-tone complex with the two tones symmetrically centered about a center frequency f_c and separated in frequency by Δf. By using this as the input stimulus, the magnitude of perceived noisiness or loudness can be determined with the aid of the proposed method. In computing the perceived sound level, the center frequency was held constant and the bandwidth Δf was varied. By using the modified frequency response function in figure 9, the perceived sound level is computed with the given stimulus positioned at several center frequencies. These results are presented in figure 10, which shows that, for a given center frequency, as the bandwidth is initially increased, the perceived sound level remains constant until a "critical bandwidth" is reached. Beyond this critical bandwidth, the perceived level will change. Depending upon the center frequency, the perceived level will either increase or decrease. The change in the perceived sound is sometimes rather sudden (see f_c = 500 Hz and f_c = 10 000 Hz), and sometimes is very gradual (see f_c = 160 Hz). This effect is also a function of the center frequency of the input stimulus.

This critical band phenomenon can be interpreted as follows. As the bandwidth is increased, the upper frequency tone will be perceived to be noisier and the lower frequency tone will decrease in noisiness. These two effects tend to offset one another; thereby, approximately a constant total perceived noisiness is maintained until a critical bandwidth is reached where the upper frequency tone will become the controlling factor and the perceived sound level will increase. The upper frequency tone is the controlling one for center frequencies f_c below the peak frequency in the response function, that is, ≈3200 Hz; the lower frequency tone will control the perceived level for center frequencies above 3200 Hz. As expected from this model, with the center frequency at the peak in the response curve and with bandwidths greater than the critical band, the perceived level will decrease instead of increase. (See f_c = 2250 Hz and f_c = 3700 Hz in fig. 10.) It is not known whether this effect has been observed before. Also, for Δf much greater than the critical bandwidth, the perceived levels will also begin to decrease. (For example, see f_c = 10 000 Hz.)

The critical bandwidth is critically dependent upon the rate of change of the response function with frequency, that is, $d\left\{|H(f)|^2\right\}/df$. Slight variations in the response function will produce significantly different results. This fact could account for the difference between the results obtained from the proposed model and the presently accepted values of the critical band. To illustrate these differences, the critical bands determined theoretically by the proposed method, with the aid of the modified response function of figure 9, are compared (fig. 11) with those experimentally determined by Zwicker, Flottorp, and Stevens (ref. 20) and Zwicker (ref. 21).

The most prominent features in these theoretically computed critical bandwidths are the large mid frequency bulge (between 200 and 1000 Hz) and the sharp "apparent" discontinuity in the frequencyregion on either side of the peak in the frequency response function. The low frequency bulge is due to the "flattening out" of the response function in the 200 to 1000 Hz range and, consequently, a steeper slope in the response function would greatly affect the critical band values in this frequency range.

The apparent discontinuity is due, in part, to a relatively flat portion of the response function in the range from 2700 to 3500 Hz and also to the slope of the response function in the frequency region on either side of peak in the response curve. A more peaked function and/or a function with a greater slope would greatly affect the theoretically determined bandwidths in this region. It must be remembered that the frequency response function presented herein was obtained by applying a smooth function to only nine data points within the frequency range from 50 to 12 000 Hz, and, furthermore, the equal nosiness curves were obtained with relatively large bandwidth signals; this would cause the validity of the assumption that $|H(f)|^2$ is constant within the band to be questioned. The frequency resolution is therefore very poor for this type of analysis. The proposed model suggests that the equal noisiness function (or loudness, etc.) should be determined with smaller bandwidths of the input acoustic stimulus at more closely spaced center frequencies within the audio range of interest. This would allow the frequency response function of the human auditory system to be determined with greater frequency resolution and accuracy.

CONCLUDING REMARKS

A model of the human auditory system was proposed to function as a simple input-output system. For a system of this type, the output (defined as the perceived sound) can be determined by multiplying the input acoustic stimulus by the square of the complex frequency response function of the human auditory system. The results obtained through the use of this model are in agreement with results obtained in recent judgment tests. The small variability which is present in the predicted results (approximately 5 dB(J)) is considered to be insignificant in view of the extremely large variability which is inherent in most judgment test results (usually 10 to 20 dB).

The results of these studies suggest the following comments:

1. The human auditory system may be considered to function as a simple input-output linear system (at least for input sound pressure levels in excess of approximately 60 dB).

2. The results of the perceived sound which are obtained through the use of this model agree with judgment test results as well as or better than estimates obtained by the presently accepted methods.

3. A simple instrument may be built to obtain a direct on-line measure of the perceived sound as well as the spectral distribution of the perceived sound.

4. The proposed model provides an alternative interpretation of the critical bandwidth phenomenon.

5. The proposed model provides new insight into the operational aspects of the human auditory system.

6. The proposed model may eliminate the cumbersome and complicated procedures now used to compute the perceived sound.

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TABLE 1.– COMPARISON OF ASSESSMENT METHODS FOR NOISES JUDGED TO BE EQUALLY NOISY (ACCEPTABLE)

[An ideal assessment method should indicate same value for each indicated spectrum. (From Kryter and Pearsons, ref. 6)]

Spectrum / Assessment method	1	2	3	4	5	6	7	8	9	Range	Average differenc from standard
	Noise 150-30 Hz	Standard Noise 600-1200 Hz	Noise 400-4800 Hz	Noise 4800–10 000 Hz	Noise 150-4800 Hz "flat"	Noise 150–4800 Hz +6 dB/Oct slope	Noise 150–4800 Hz –12 dB/Oct slope	Diese engine	707-120B landing turbofan with hushkit		
Overall "flat", dB	92.0	90.0	80.5	80.0	80.5	83.0	84.5	81.0	80.0	12.0	-6.5
A scale, dB	82.0	90.0	19.0	14.5	19.5	81.0	80.5	79.0	80.0	15.5	-10.4
B scale, dB	90.5	90.0	18.5	15.0	19.5	81.0	83.0	84.5	80.0	15.5	-8.5
C scale, dB	92.0	90.0	19.5	16.5	80.0	81.5	84.5	81.0	80.0	15.5	–1.4
Stevens (average[a]), phons	89.7	93.5	87.3	90.5	91.5	92.3	88.0	88.8	90.0	6.2	–3.8
Zwicker[b] 1/3-octave band, phons	92.5	91.0	87.0	89.0	95.5	96.5	95.5	95.0	95.5	10.0	-3.7
Kryter (average[a]), PNdB	92.8	94.3	91.8	89.5	92.0	95.8	90.3	90.5	93.0	6.3	-2.3
Proposed, dB(J)	89.5	91.0	88.9	86.6	87.0	92.2	84.0	84.6	87.3	8.2	-3.4

[a]Average of octave and 1/3-octave band values.

[b]Calculated by E. Zwicker.

TABLE 2.– DIFFERENCE FROM STANDARD (COMPARISON MINUS STANDARD)

Spectra (from table 1)	Prediction method: Kryter, PNdB (a)	Prediction method: Proposed, dB(J) (a)
	b94.3	[b]91.0
1	-1.5	-1.5
2	0	0
3	–2.5	–2.1
4	–4.8	–4.4
5	–2.3	–4.0
6	+1.5	+1.2
7	–4.0	*-1.0*
8	–3.8	–6.4
9	–1.3	–3.1
Average difference from standard	–2.3	–3.4

[a] + indicates overestimation;
- indicates underestimation.

[b]Level of standard.

TABLE 3.- RANK (ORDER OF NOISINESS) OF PERCEIVED SPECTRA

[Input spectra readjusted to constant OASPL value]

Rank of perceived spectra	Prediction method: Kryter (a)	Prediction method: Proposed (a)	Rank from judgment test (a)
Noisiest	9	6	4,9
	6	3	---
	6	9	3,5
	5	4	---
to	3		
	4/7	2/5	6/7
	7	7	8
	2	8	2
Least noisy	8 1	1	1

[a]Numbers refer to spectra in table 1.

TABLE 4.- COMPARISON OF ASSESSMENT METHODS FOR NOISES TO BE JUDGED EQUALLY NOISY

[An ideal assessment method should indicate same value for each indicated spectrum. (From Kryter, ref. 5)]

Assessment method \ Indoor spectrum		B	C	D	E	F	Range	Average difference from standard
		Caravelle	Comet	707-09	707-15A	707-22		
Kryter (octave band[b]), PNdB	94.0	89.8	88.2	90.0	86.6	89.7	7.4	-5.1
Proposed, dB(J)	87.8	82.6	81.5	82.9	80.0	82.9	7.8	-5.8

[a]Super-Constellation.

[b]Computed by using revised noy curves from Kryter and Pearsons (ref. 17).

TABLE 5.- DIFFERENCE FROM STANDARD (COMPARISON MINUS STANDARD)

Spectra (from table 4)	Prediction method	
	Kryter, PNdB (a)	Proposed, dB(J) (a)
	[b]94.0	[b]87.8
A	0	0
B	-4.2	-5.2
C	-5.8	-6.3
D	-4.0	-4.9
E	-7.4	-7.8
F	-4.3	-4.9
Average difference from standard	-5.1	-5.8

a - indicates underestimation.

b Level of standard.

TABLE 6.- RANK (ORDER OF NOISINESS) OF PERCEIVED SPECTRA

[Input spectra readjusted to constant OASPL value]

Rank of perceived spectra	Prediction method		Rank from judgment test (a)
	Kryter (a)	Proposed (a)	
Noisiest	D,F	F	E,F
	---	D	---
to	E	E	D
	C	C	C
	B	B	B
Least noisy	A	A	A

TABLE 7.- COMPARISON OF ASSESSMENT METHODS FOR NOISES JUDGED TO BE EQUALLY NOISY (ACCEPTABLE)

[An ideal assessment method should indicate same value for each indicated spectrum. Average judged results obtained through average of mean squared pressures. (From Kryter and Pearsons, ref. 6)]

Spectrum / Assessment method	1	2	3	4	5	6	7	8	9	Range	Average difference from standard
	Noise 150-300 Hz	Standard Noise 600-1200 Hz	Noise 2400-4800 Hz	Noise 4800-10000 Hz	Noise 150-480 Hz "flat"	Noise 150-4800 Hz +6 dB/Oct slope	Noise 150-4800 Hz -12 dB/Oct slope	Diesel engine	707-120B landing turbofan with hushkit		
Kryter (average[a]), PNdB	94.3	94.3	92.7	92.8	93.3	97.2	91.3	92.7	95.7	4.5	-0.6
Proposed, dB(J)	91.0	91.0	89.8	89.9	88.3	93.6	85.0	86.8	90.0	6.0	-1.7

[a]Average of the octave and 1/3-octave band values.

TABLE 8.- DIFFERENCE FROM STANDARD (COMPARISON MINUS STANDARD)

Spectra from table 7)	Prediction method: Kryter, PNdB (a)	Prediction method: Proposed, dB(J) (a)
	[b]94.3	[b]91.0
1	0	0
2	0	0
3	-1.6	-1.2
4	-1.5	-1.1
5	-1.0	-2.7
6	+2.9	+2.6
7	-3.0	-6.0
8	-1.6	-4.2
9	+1.4	-1.0
Average difference from standard	-0.6	-1.7

[a] + indicates overestimation;
- indicates underestimation.

[b]Level of standard.

TABLE 9.- RANK (ORDER OF NOISINESS) OF PERCEIVED SPECTRA

[Input spectra readjusted to constant OASPL value]

Rank of perceived spectra	Prediction method: Kryter, (a)	Prediction method: Proposed, (a)	Rank from judgment test (a)
Noisiest	9	6	3
	6	3	5
	5	9	9
	3	4	4
to	4	5	6
	7	2	7
	2	7	8
	8	8	2
Least noisy	1	1	1

[a]Numbers refer to spectra in table 7.

TABLE 10.- COMPARISON OF ASSESSMENT METHODS FOR STIMULUS TO BE JUDGED EQUALLY NOISY

[Ideal method should indicate same value for each indicated stimulus. (From Kryter and Pearsons, fig. 8 of ref. 6)]

Stimulus	Prediction method	
	Kryter, PNdB	Proposed, dB(J)
S	90.5	89.5
C-1	92.5	90.5
C-2	88.0	88.7
C-3	84.0	87.5

TABLE 11.- DIFFERENCE FROM STANDARD (COMPARISON MINUS STANDARD)

Stimulus	Prediction method	
	Kryter, PNdB (a)	Proposed, dB(J) (a)
	[b]90.5	[b]89.5
S	0	0
C-1	+2.0	+1.0
C-2	-2.5	-0.8
c-3	-6.5	-2.0
Average difference from standard	-2.3	-0.6

TABLE 12.- COMPARISON OF ASSESSMENT METHODS FOR NOISES JUDGED TO BE EQUALLY NOISY (ACCEPTABLE)

[An ideal assessment method should indicate same value for each indicated spectrum. Average test values were obtained through the average of the mean squared pressures and by applying the response function of fig. 9. (From Kryter and Pearsons, ref. 6)]

Spectrum / Assessment method	1	2	3	4	5	6	7	8	9	Range	Average difference from standard
	Noise 150–300 Hz	Standard Noise 600–1200 Hz	Noise 2400–4800 Hz	Noise 4800–10 000 Hz	Noise 150-4800 Hz "flat"	Noise 150–4800 Hz +6 dB/Oct. slope	Noise 150-4800 Hz –12 dB/Oct. slope	Diesel engine	707–120B turbofan hushkit		
Kryter (average[a]), PNdB	94.3	94.3	92.7	92.8	93.3	97.2	91.3	92.7	95.7	4.5	–0.6
Proposed, dB(J)	91.0	90.1	89.5	87.7	88.9	93.5	85.0	87.0	91.3	8.5	–0.9

TABLE 13.- DIFFERENCE FROM STANDARD (COMPARISON MINUS STANDARD)

Spectra (from table 12)	Prediction method	
	Kryter, PNdB (a)	Proposed, dB(J) (a)
	[b]94.3	[b]90.1
1	0.0	+0.9
2	0.0	0.0
3	–1.6	–0.6
4	–1.5	–2.4
5	–1.0	–1.2
6	+2.9	+3.4
7	–3.0	–5.1
8	–1.6	–3.1
9	+1.4	+1.2
Average difference from standard	–0.6	–0.9

TABLE 14.– RANK (ORDER OF NOISINESS) OF PERCEIVED SPECTRA

[Input spectra adjusted to constant OASPL value]

Rank of perceived spectra	Prediction method		Rank from judgment test (a)
	Kryter (a)	Proposed (a)	
Noisiest	9	3	3
	6	6	5
	5	9	9
	3	5	4
to	4	4	6
	7	2	7
	2	7	8
	8	8	2
Least noisv	1	1	1

[a]Numbers refer to spectra in table 12.

INPUT-OUTPUT CONCEPT OF HUMAN AUDITORY SYSTEM

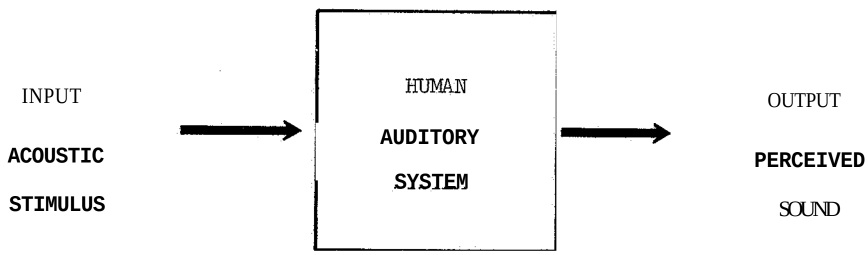


Figure 1

SCATTER BAND OF RELATIVE RESPONSE FUNCTION

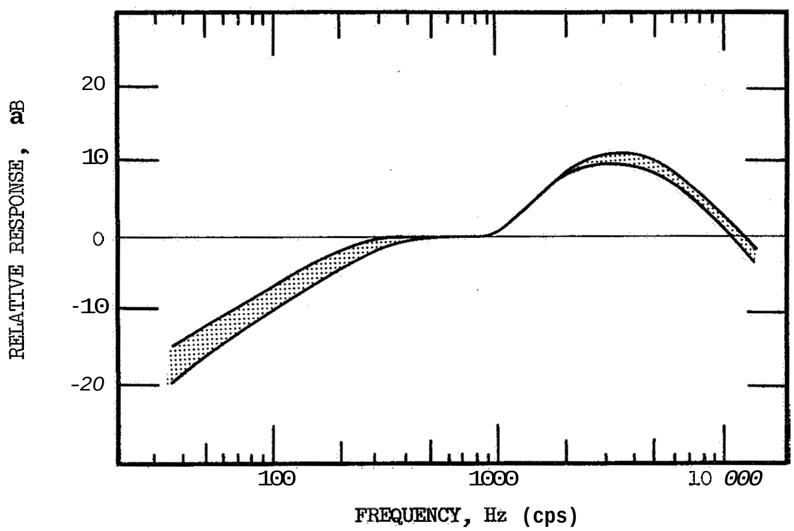


Figure 2

TYPICAL OR AVERAGE HUMAN AUDITORY RESPONSE FUNCTION (AVERAGE OF SCATTER BAND IN FIG. 2)

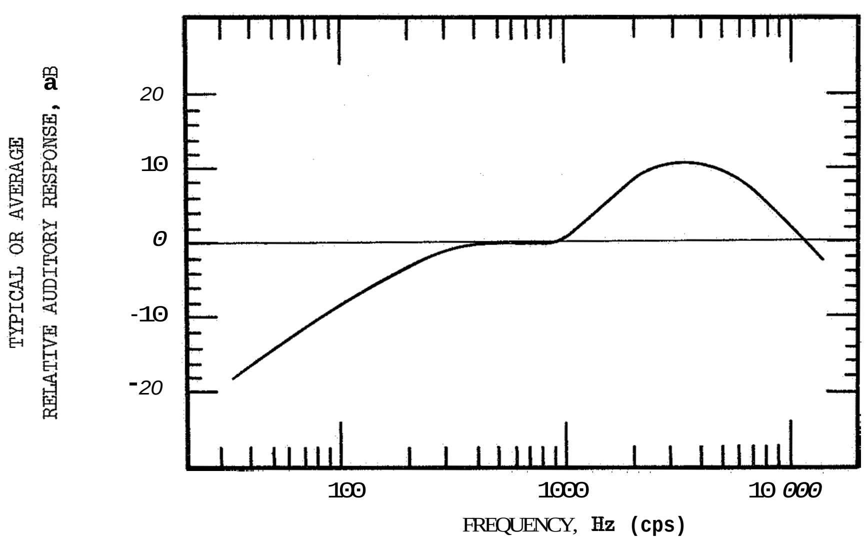


Figure 3

PERCEIVED NOISE LEVEL COMPUTED FOR VARIOUS ACOUSTIC STIMULI

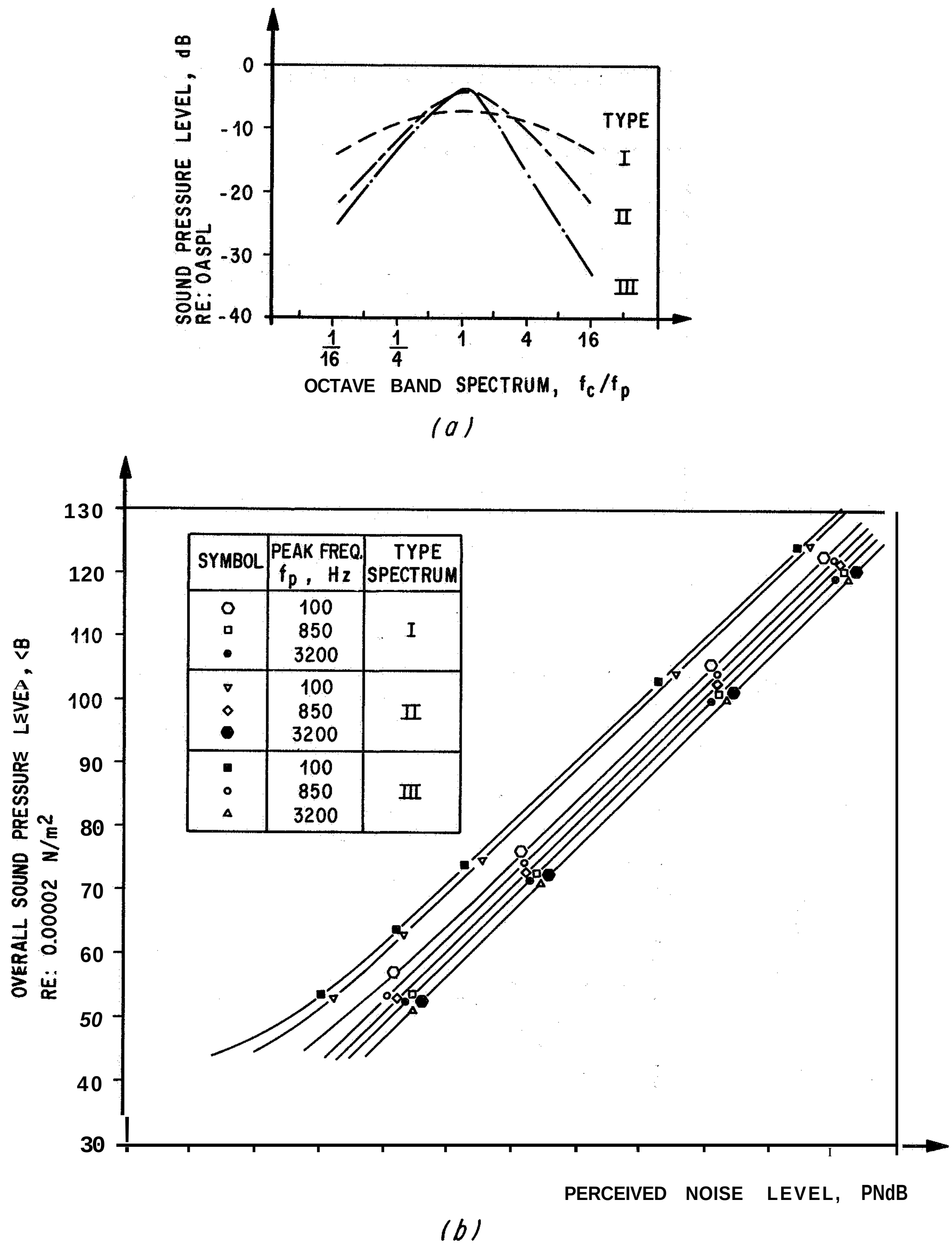


Figure 4

PERCEIVED SOUND LEVEL COMPUTED FOR VARIOUS ACOUSTIC STIMULI

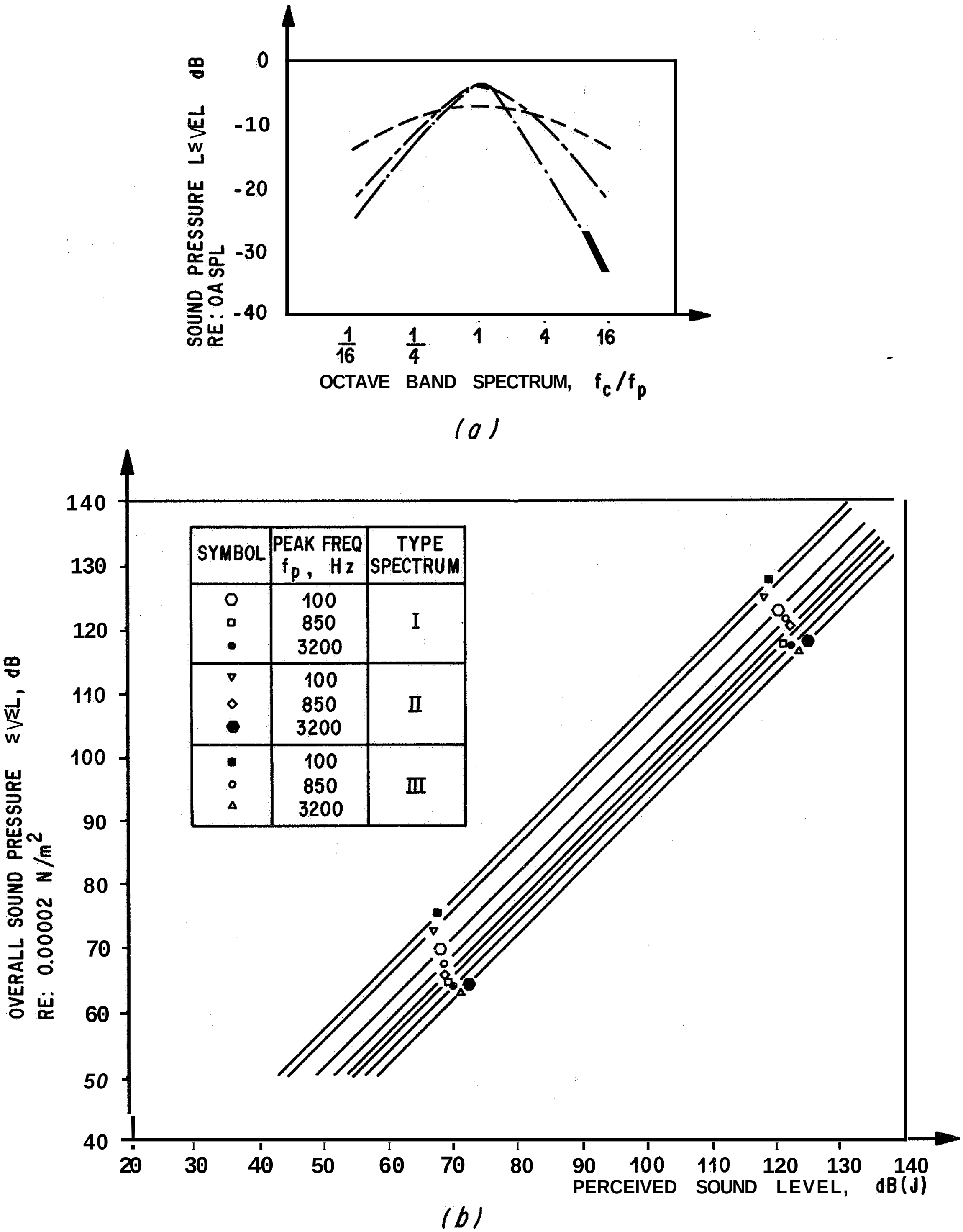
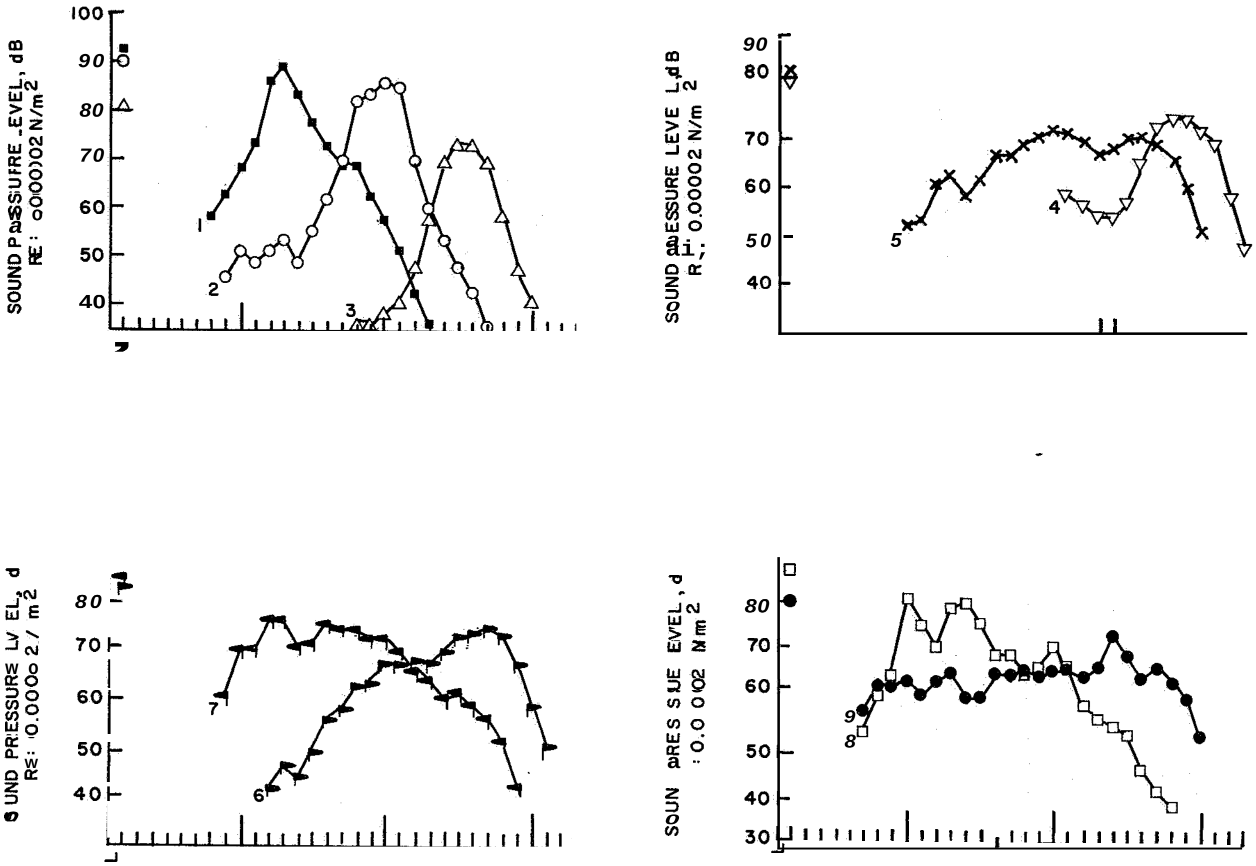


Figure 5

SPECTRA USED IN JUDGMENT TEST
(DATA FROM KRYTER AND PEARSONS, REF. 6)



RESULTS OF JUDGMENT TEST FOR COMBINATION OF PURE TONE IN BAND OF NOISE
(DATA FROM KRYTER AND PEARSONS, REF. 6)

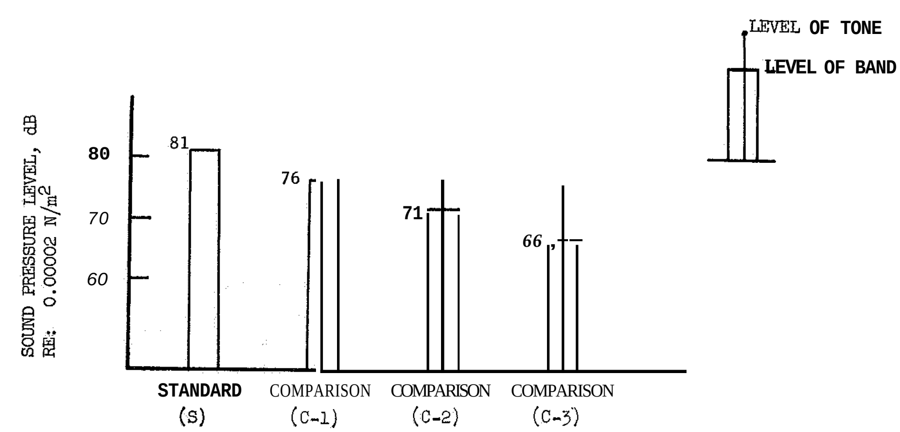


Figure 7

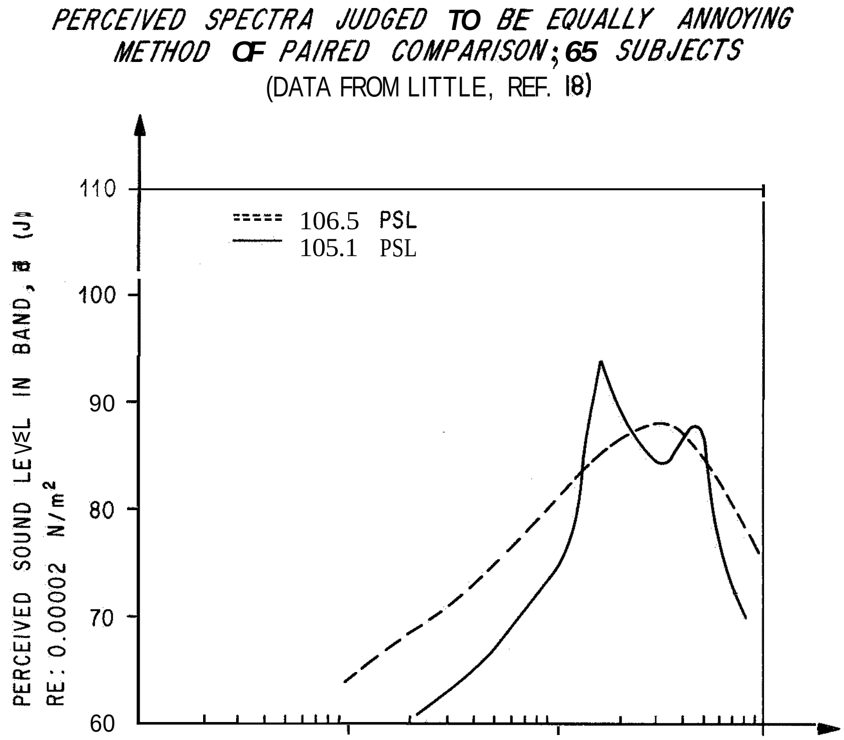


Figure 8

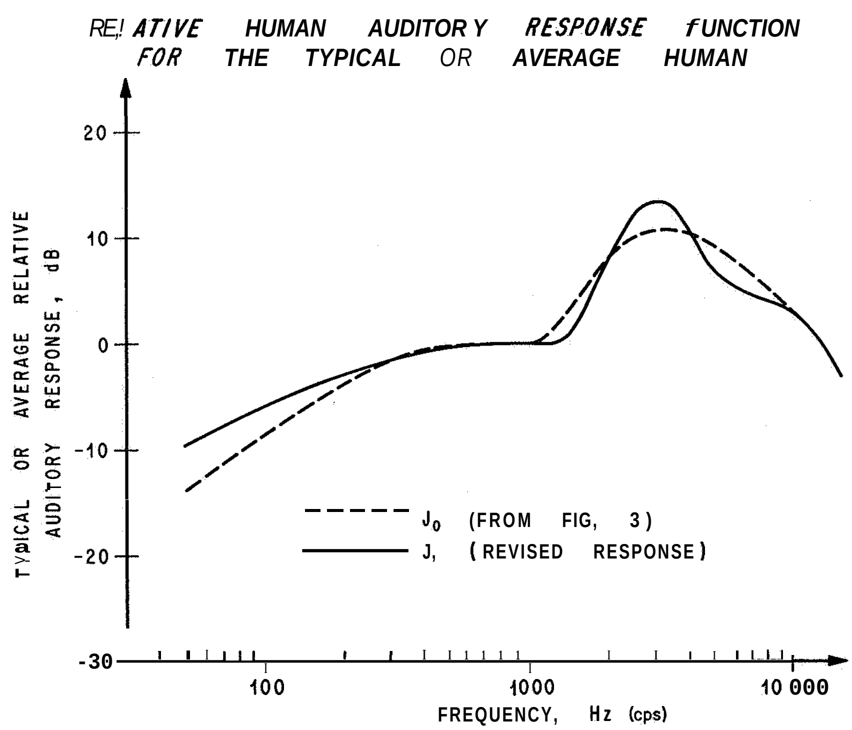


Figure 9

DEPENDENCE Of PERCEIVED SOUND ON THE SPACING Of TONES IN A TWO-TONE COMPLEX FOR VARIOUS CENTER FREQUENCIES

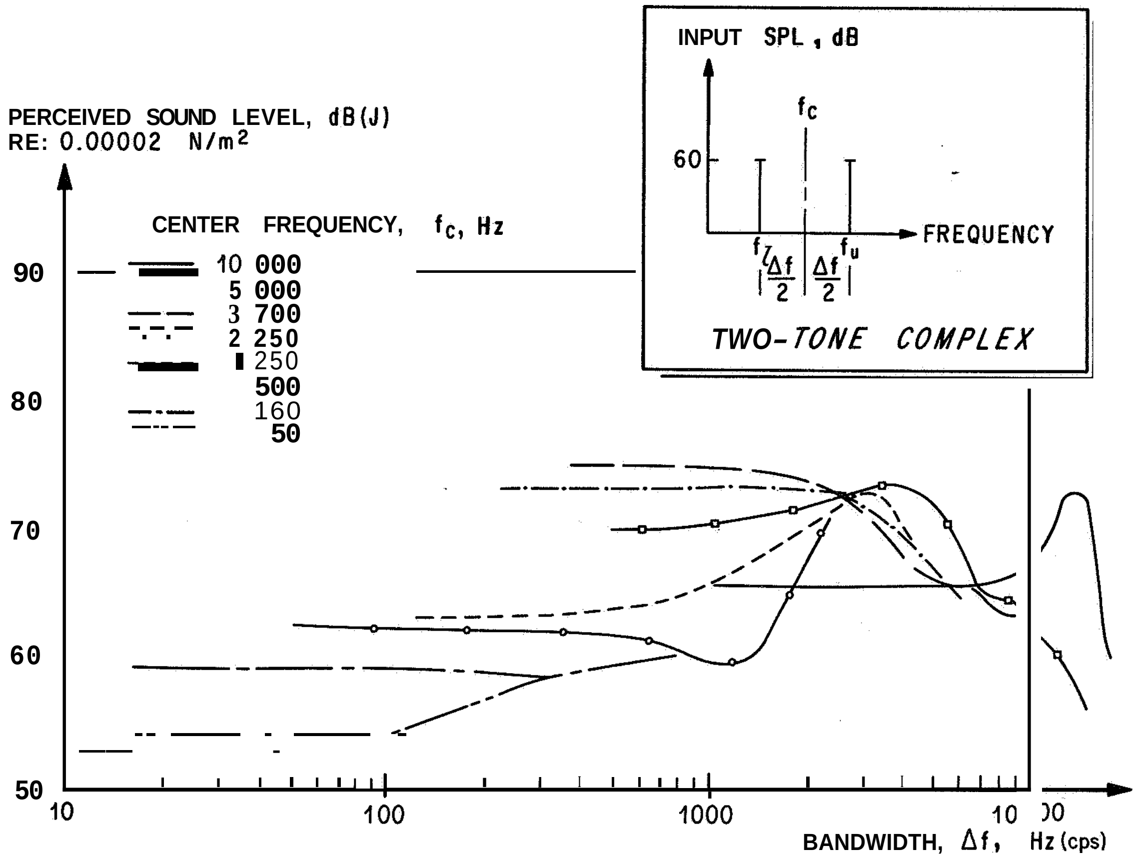


Figure 10

CRITICAL BANDWIDTH PRESENTED AS A FUNCTION OF CENTER FREQUENCY OF BAND

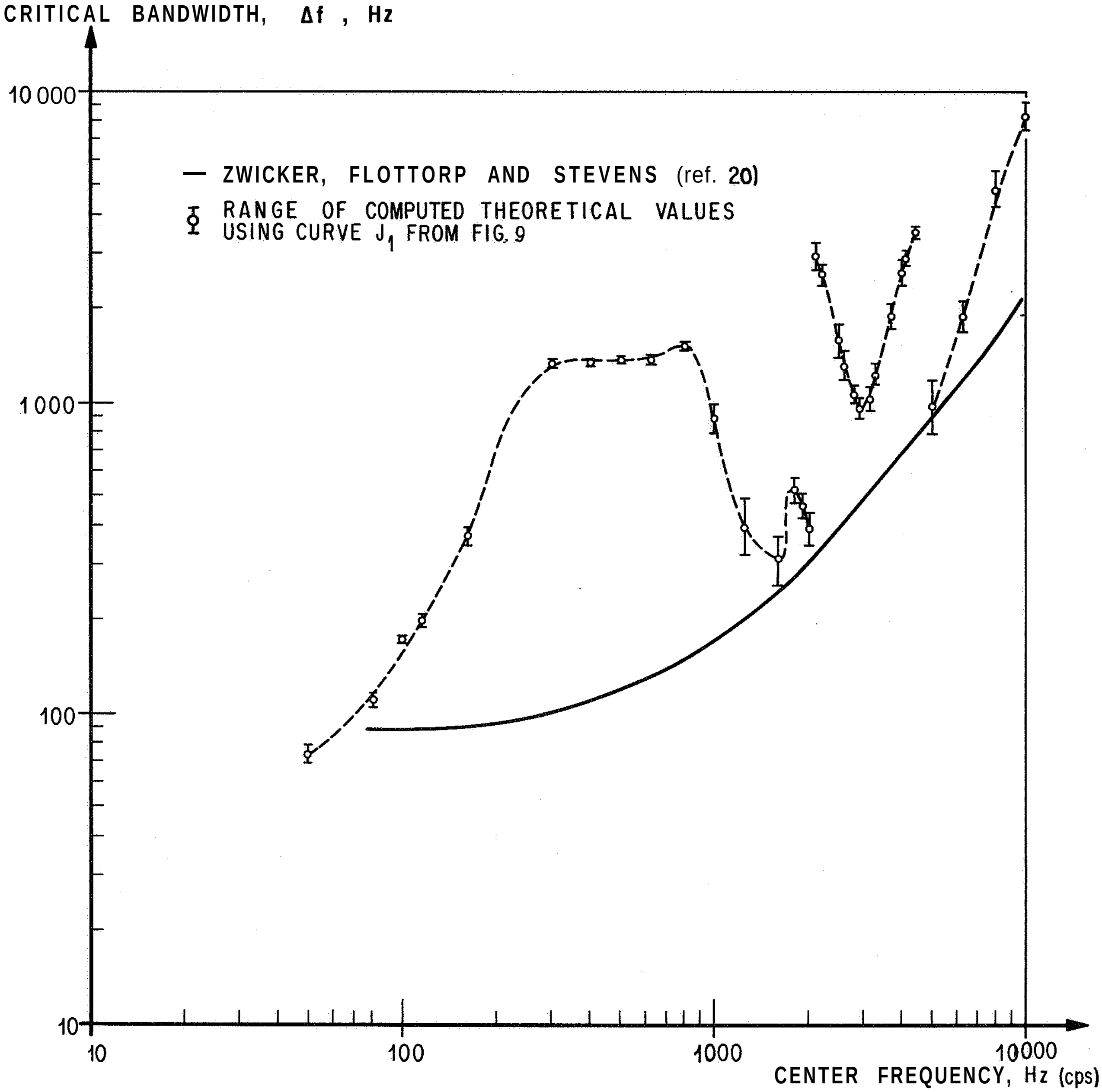


Figure 11