THE ERROR DUE TO MASKING IN THE MEASUREMENT OF DIFFERENCE TONES BY THE METHOD OF BEST BEATS

by

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FOREWORD

The author wishes to express his deepest appreciation to Dr. James P. Egan for

(1) his sage advice and encouragement

(2) his right ear which did half of the listening in this study

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INTRODUCTION

When two or more pure tones of medium or high intensity stimulate the ear, it responds nonlinearly. As a consequence of this nonlinear response, harmonics and combination tones are heard in addition to the primary tones. Direct measurement of the intensities of distortion tones in human ears is not feasible at the present time; instead, indirect methods of measurement must be resorted to. The principle method used, that known as the "method of best beats," employs a listener to match the known intensity of an exploring or probe tone to the intensity of the distortion tone being measured. The frequency of the exploring tone is chosen such that it differs from the frequency of the distortion tone by two or three cycles per second. The listener then adjusts the intensity of the exploring tone until the beats he hears are most prominent (best beats). At this point of maximum loudness change it is assumed that the listener has set the intensity of the exploring tone so that its displacement in the cochlea is equal to that of the distortion tone. It has been shown that if the tone whose intensity is being measured is well above threshold and is not being masked, a listener can accurately match intensities using the method of best beats (1, 2, 3, 4). However, if the tone whose intensity is being estimated by the method of best beats is near absolute threshold or is being masked, the listener overestimates the intensity of the tone being measured (5). Under conditions of masking, the conventional method of best beats is not an accurate method for measuring the intensity of a distortion tone.

Egan and Klumpp (5) developed a procedure to correct for the overestimation of the intensities of masked tones measured by the method of best beats, and applied it to the measurement of the first aural harmonic (700 c.p.s.) which was partially masked by the 350 c.p.s. tone producing it. Other distortion products of the ear, such as sum and difference tones, suffer masking from the primary tones producing them, and presumably their intensities, as measured by the conventional method of best beats, also need correction for listener overestimation.

The present investigation is an attempt to determine the amount of overestimation in the method of best beats for three first-order difference tones ($f_2 - f_1$) under several conditions of masking. A more nearly correct estimate of the intensities of three difference tones, 200 c.p.s., 700 c.p.s., and 1000 c.p.s., is given.

EXPERIMENTAL PROCEDURE

Three pure tones were simultaneously presented to one ear of a listener by means of a dynamic earphone (Permoflux Corporation, type PDR-10) mounted in a small rubber cushion and held in a headband. The unstimulated ear was covered by an unconnected PDR-10 earphone also mounted in a small rubber cushion. The primaries, f_1 and f_2, and the exploring tone, f_e, were generated by beat-frequency oscillators (General Radio Company, type 1304-A and Hewlett Packard Company, type 200-B). Before mixing with the primary tones, the exploring tone was filtered by an adjustable band-pass filter. (United Transformer Corporation, type 4C).

The experimenter controlled the intensities of the primary tones with attenuators calibrated in one-decibel steps; the listener controlled the intensity of the exploring tone with an attenuator calibrated in two-decibel steps. The frequency of the exploring tone was maintained within one-half cycle of $(f_2 - f_1) + 2.5$ c.p.s. Table 1 lists the intensities and frequencies of the primaries, f_1 and f_2, presented to each of the two subjects.

Under all conditions, the frequency of f_1 was fixed at 1200 c.p.s. The frequencies of f_2 were selected so that the first-order difference tones (200 c.p.s., 700 c.p.s., and 1000 c.p.s.) would undergo different amounts of masking by the 1200 c.p.s. primary. For example, the data of Wegel and Lane (6) show that the amount of masking produced

TABLE 1

Condition 1 (1000 c.p.s. first-order difference tone)

$f_1 = f_2$ in intensity

Subject	S.P.L. of each primary (2200 c.p.s. and 1200 c.p.s.)
R.K.	80,85,90,100
J.E.	77,80,90,100

Condition 2 (700 c.p.s. first-order difference tone)

$f_1 = f_2$ in intensity

Subject	S.P.L. of each primary (1900 c.p.s. and 1200 c.p.s.)
R.K.	70,75,80,85,90,100,110
J.E.	62,65,70,80,90,100

Condition 3 (200 c.p.s. first-order difference tone)

$f_1 = f_2$ in intensity

Subject	S.P.L. of each primary (1400 c.p.s. and 1200 c.p.s.)
R.K.	77,80,85,90,100
J.E.	72,75,80,85,90,100

Condition 4 (700 c.p.s. first-order difference tone)

f_1 (1200 c.p.s.) fixed at 100 db

Subject	S.P.L. of f_2 (1900 c.p.s.)
R.K.	50,53,55,60,70,80,90,100
J.E.	48,50,60,70,80,90,100

---

by a 1200 c.p.s. tone at an intensity of approximately 85 db S.P.L. is about 35 db at 1000c.p.s., 10db at 700 c.p.s., and zero at 200 c.p.s. In conditions 1, 2, and 3, the equally intense primaries were varied in intensity from about 65 db to about 100 db S.P.L. In addition, data were obtained with the amount of masking of a difference tone of 700 c.p.s. at a constant value. This was accomplished by holding the 1200 c.p.s. primary at a fixed intensity of 100 db. The primary interest lay not in the masking per se, but in the growth of the 700 c.p.s. difference tone as the intensity of the 1900 c.p.s. primary was increased.

The listener was required to make three judgments at each of the tabulated intensities of the primaries. These judgments were: (1) "lower threshold for waver," the least intensity of the exploring tone which produces an audible waver; (2) "best beats," that intensity of the exploring tone which produces the maximum change in loudness; and (3) "upper threshold for waver," the greatest intensity of the exploring tone which still produces an audible waver of the difference tone. After the primaries were fixed at a given intensity, the three judgments were made in the sequence: lower waver, best beat, and upper waver. Before each judgment the experimenter set an arbitrary amount of attenuation in a pad which was in tandem with the listener's pad so that the listener could not use his previous settings as a clue in making his judgment. Judgments were made by the method of average error, that is, the subject bracketed his final setting by successively reducing his swings of the dial of the attenuator until he had reached his final setting. The length of time necessary for a single judgment averaged about 1.5 minutes.

The total amount of time spent on a single session varied, depending upon the number of intensities of the primaries necessary to trace out the difference tone. No session lasted longer than 50 minutes, and rest pauses were frequently given to guard against fatigue. On a typical session, for example, subject J.E. would make a total of 16 judgments in about 40 minutes. J.E. served in 16 sessions, four under each of the conditions listed in table 1. R.K. served in 24 sessions, six under each of the conditions listed in table 1.

Within a session, the order in which the intensities of the primaries were presented was varied randomly. The four conditions were presented from session to session in the following order:

J.E.: 1-1, 2-2, 3-3, 3-3, 2-2, 1-1, 4-4-4-4
R.K.: 1-2-3, 1-3-2, 2-1-3, 2-3-1, 3-2-1, 3-1-2, 4-4-4-4-4-4

Each of the two subjects used in this experiment had made several thousands of judgments of this type before the experiment began. No systematic practice effects were observed. The subjects had normal hearing, and all sessions were held in a quiet, sound-treated room.

Because it was more convenient, R.K. served as his own subject. In this case, the attenuator in tandem with the subject's attenuator, normally set to an arbitrary value by the experimenter, was given a twirl before each judgment. The judgment was then made by manipulating the subject's attenuator without knowing to what value the experimenter's attenuator had been set. Pad settings were recorded after the judgment, but no summations or conversions to sound pressure levels were made while the experiment was in progress. At no time did R.K. gain any clues as to what the setting of the subject's attenuator should have been. It is felt that there was no loss of objectivity in using this procedure.

Voltages sufficient to produce acoustic outputs of 100 db S.P.L. of each of the two primaries and of the exploring tone were applied to the earphone and the resulting sound complex was analyzed with a wave analyzer (General Radio Company, type 736-A). It was found that combination tones and harmonics produced by the earphone were at least 45 db down from the primaries. At acoustic outputs due to the combination of the three tones, f_1, f_2, and f_e with each at 110 db S.P.L., the distortion products generated by the earphone were at least 40 db down.

RESULTS

Figure 1 shows for subject R.K. the region of audible beats for a difference tone of 1000 c.p.s. The intensity of the exploring tone of 1002.5 c.p.s. required for best beats, upper threshold for waver, and lower threshold for waver is plotted as a function of the sound pressure level of the two equally intense primaries, 1200 c.p.s. and 2200 c.p.s. Each solid dot is the median of six judgments; the horizontal lines above and below each solid dot are the Q_1 and Q_3 points respectively. The dashed line represents the corrected level of the first-order difference tone of 1000 c.p.s. The dashed line was obtained as follows: At any given intensity of the primary tones, the difference between the intensity of the exploring tone required for upper threshold for waver and for lower threshold for waver is computed. For example, with both primaries at 90 db, the range of audible beats, is 64 - 29 = 35 db. In Table 2 is found the amount of overestimation corresponding to each computed range of audible beats. For subject J.E., the table values were read directly from the curve given in Figure 7 (5). For subject R.K., the curve given in Figure 7 was a compromise between data obtained in the quiet and data obtained in noise. Since the conditions of the present experiment most resembled the conditions of noise, a curve was drawn through the data points obtained in noise, and the values of Table 2 were read directly from this new curve. Again, using the same example, for R.K. the amount of overestimation corresponding to a range of 35 db is 7 db. This error of

TABLE 2

Giving the amount of overestimation in decibels as a function of the range of audible beats.*

R.K. (based on noise data)

Range of Audible Beats in Decibels	Amount of Overestimation in Decibels
5	16
10	14.5
15	13
20	12
25	10
30	8
35	7
40	6
45	5
50	5
55	3
60	2
65	1

J.E. (based on noise and quiet data)

Range of Audible Beats in Decibels	Amount of Overestimation in Decibels
5	16
10	13
15	11
20	9
25	7
30	5
35	4
40	2
45	1

* Derived from Figure 7 (5).

Figure 1

overestimation in db is then subtracted from the value for best beats. Thus, with primaries of 90 db, 7 db is subtracted from the value required for best beats, giving a point at 42 db for the ordinate. A straight line was then visually fitted to the corrected points. Errors of overestimation were computed at every intensity of the primaries at which data were taken. The correction at 100 db was calculated by extrapolating the curve for upper threshold for waver and then computing the range of audible beats. It may be noted that this subject (R.K.) overestimates the intensity of the difference tone of 1000 c.p.s. at all intensities of the primaries presented, but that the amount of error increases markedly once the range of audible beats begins to decrease. The region of audible beats, that area bounded by the curves for upper and lower thresholds for waver, is closed at an intensity of the primaries of 78 db, because several observations indicated that, at this intensity, the listener hears a beat or waver only occasionally. At intensities lower than 78 db of the primaries, no intensity of the exploring tone produced a beat or waver. The regions of audible beats in Figures 2, 3, 4, 5, 6, 11, and 12 are closed on this same basis.

Considerable masking of the 1000 c.p.s. difference tone by the 1200 c.p.s. primary is indicated by the fact that the corrected level of the difference tone is traced down to an intensity of 25 db. There is reason to believe that by use

Figure 2

of the correction technique it is possible to trace out the growth of a distortion tone from the absolute threshold (10 db S.P.L. for R.K.) providing the distortion tone is not undergoing more than approximately 16 db of masking.

Figure 2 shows for the other subject (J.E.) the same relations as those shown in Figure 1. As before, the solid lines are visually fitted to the data, and the dashed line represents the corrected difference tone. Each solid dot is the median of four judgments. Variability of judgments about each solid dot are not shown since upper and lower quartiles based on four judgments have little meaning. However, for the most part, the variability of J.E. is less than the variability of R.K. for similar judgments. A comparison of Figure 2 with Figure 1 indicates close similarity in the shape of the regions of audible beats and the slope and intercepts of the corrected difference tones of 1000 c.p.s. Unlike subject R.K., J.E. accurately matches the intensity of the exploring tone to the difference tone at high intensities of the primaries. However, he shows the same marked overestimation of the intensity of the difference tone at lower intensities of the primaries.

Figure 3 shows for R.K. the intensity of the 702.5 c.p.s. exploring tone required for best beats, upper threshold for waver, and lower threshold for waver as a function of the sound pressure lever of the two equally intense primaries, 1200 c.p.s. and 1900 c.p.s. Each solid dot is the median of six judgments, and the horizontal

Figure 3

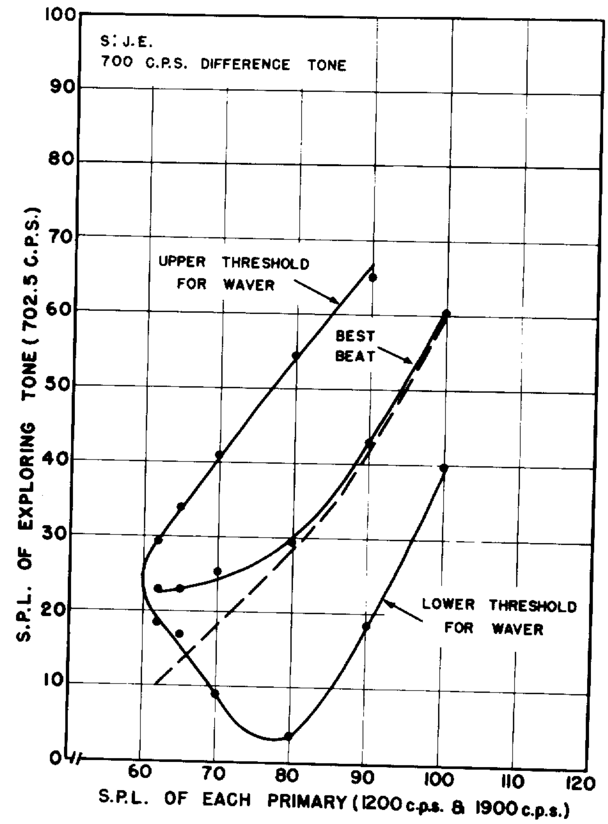
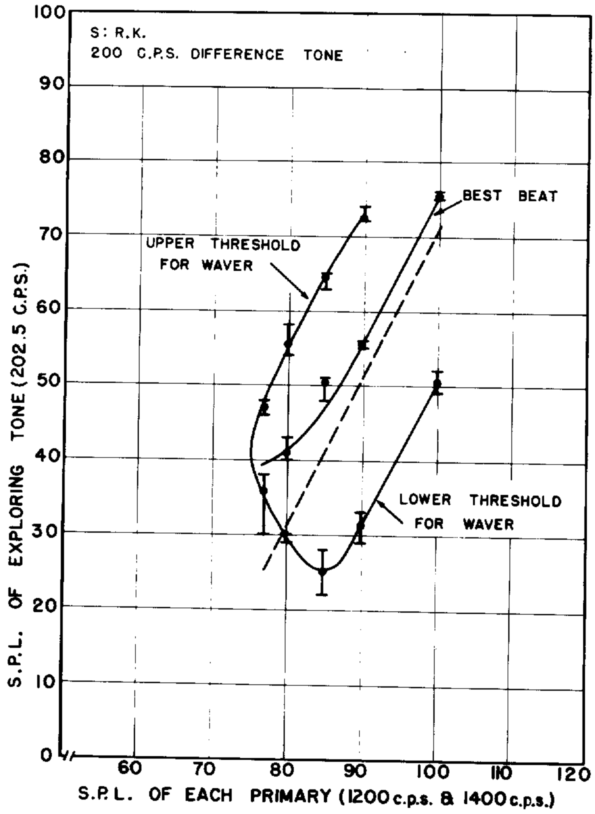

S: J.E.
700 C.P.S. DIFFERENCE TONE
UPPER THRESHOLD FOR WAVER
BEST BEAT
LOWER THRESHOLD FOR WAVER
S.P.L. OF EXPLORING TONE (702.5 C.P.S.)
S.P.L. OF EACH PRIMARY (1200 c.p.s. & 1900 c.p.s.)
0
10
20
30
40
50
60
70
80
90
100
60
70
80
90
100
110
120

Figure 4

lines about each dot include the middle 50% of the judgments. Four of the six judgments lie on or within the horizontal bars. The solid lines are visually fitted to the data. The corrected level of the 700 c.p.s. difference tone, is represented by the dashed line, which is visually fitted to the points obtained by subtracting from the curve for best beats the amount of overestimation, based on a consideration of the range of audible beats. The intensity of each of the two primaries was increased to 110 db for this condition only, in an effort to determine whether the slope of the difference tone changes as the primaries become quite intense. As can be seen, the slope of the difference tone remains essentially constant.

As in the case of the 1000 c.p.s. difference tone, the intensity of the 700 c.p.s. difference tone is considerably overestimated by the conventional method of best beats at lower intensities of the primaries.

Figure 4 shows for J.E. the same relation as shown for R.K. in Figure 3. Each solid dot is the median of four judgments and all curves are visually fitted to the data. As before, the dashed line represents the corrected 700 c.p.s. first-order difference tone. The region of audible beats of Figure 4 is similar to the region of audible beats for Figure 3. The slope and intercepts of the 700 c.p.s. difference tones for the two subjects do not show the marked similarity that exists in the case of



S: R.K.
200 C.P.S. DIFFERENCE TONE
BEST BEAT
UPPER THRESHOLD FOR WAVER
LOWER THRESHOLD FOR WAVER
S.P.L. OF EXPLORING TONE (202.5 C.P.S.)
S.P.L. OF EACH PRIMARY (1200 c.p.s. & 1400 c.p.s.)

Figure 5

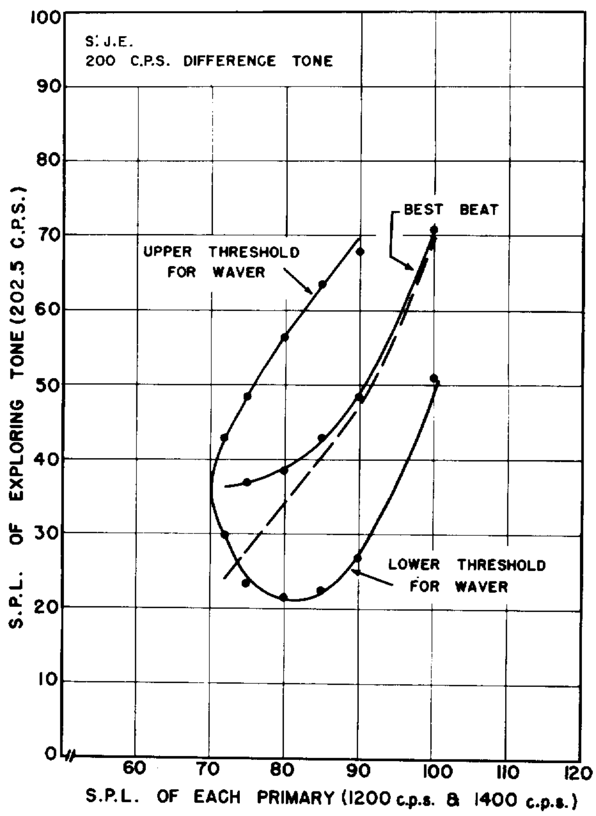
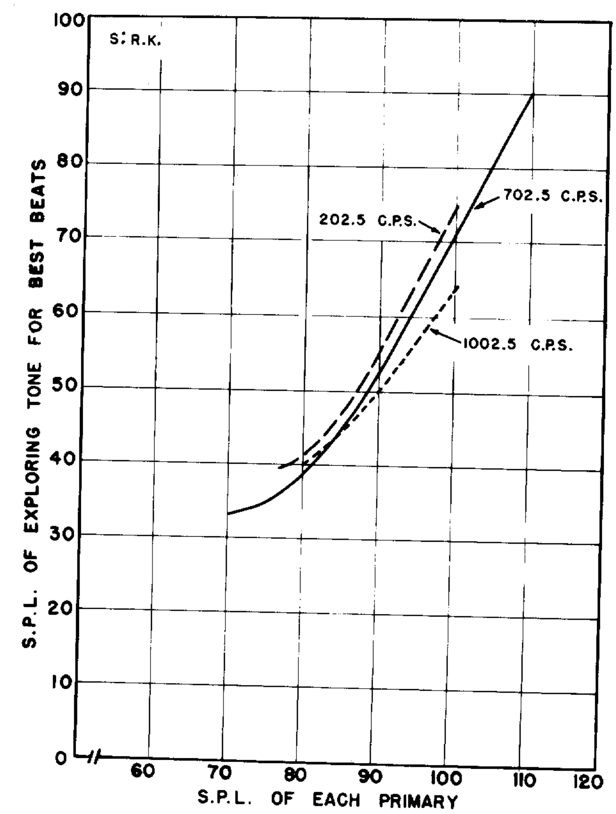

S: J.E.
200 C.P.S. DIFFERENCE TONE
UPPER THRESHOLD FOR WAVER
BEST BEAT
LOWER THRESHOLD FOR WAVER
S.P.L. OF EXPLORING TONE (202.5 C.P.S.)
S.P.L. OF EACH PRIMARY (1200 c.p.s. & 1400 c.p.s.)
0
10
20
30
40
50
60
70
80
90
100
60
70
80
90
100
110
120

Figure 6

the 1000 c.p.s. difference tones. However, the same listener error of overestimation of the intensity of the 700 c.p.s. difference tone appears at low intensities of the primaries. As shown in Figures 3 and 4, the correction applied makes it possible to trace the difference tone to the subject's absolute threshold at 700 c.p.s.

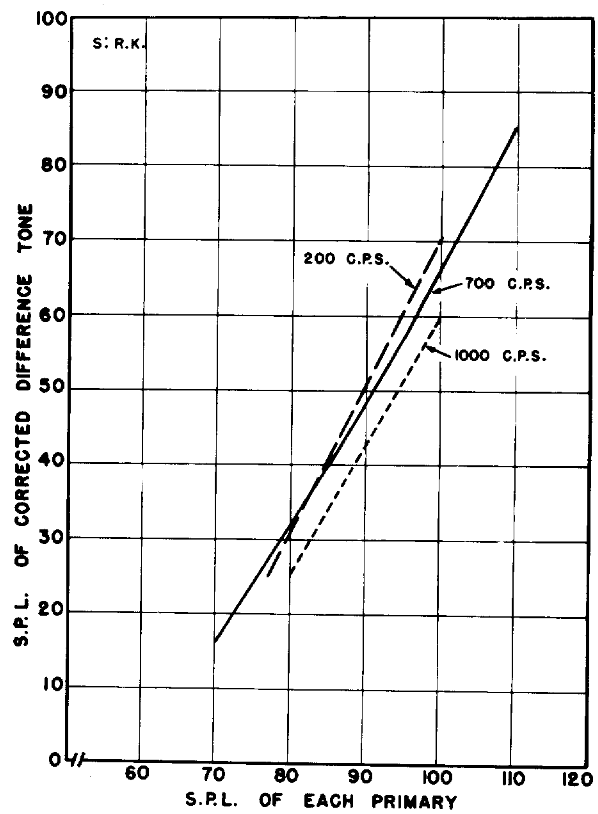
Figure 5 presents for subject R.K., the S.P.L. of an exploring tone of 202.5 c.p.s. as a function of the S.P.L. of two equally intense primaries of 1200 c.p.s. and 1400 c.p.s. for judgments of upper threshold for waver, best beats, and lower threshold for waver. Each solid dot is the median of six judgments and all curves are visually fitted. The horizontal lines about each solid dot mark off the Q_1 - Q_3 limits of the judgments. The dashed line represents the intensity of the corrected difference tone of 200 c.p.s. The same overestimation occurs in the measurement of this difference tone, which is not being masked by the 1200 c.p.s. primary to any appreciable degree. In a sense, the 200 c.p.s. difference tone is being masked by the subject's absolute threshold. With the application of the correction procedure, the 200 c.p.s. difference tone is traced down to the subject's absolute threshold at 200 c.p.s.

Figure 6 presents the same relationships for subject J.E. as are presented in Figure 5 for subject R.K. All solid dots are the medians of four judgments and all curves are visually fitted. The dashed line represents the corrected



S: R.K.
S.P.L. OF EXPLORING TONE FOR BEST BEATS
100
90
80
70
60
50
40
30
20
10
0
60
70
80
90
100
110
120
S.P.L. OF EACH PRIMARY
202.5 C.P.S.
702.5 C.P.S.
1002.5 C.P.S.

Figure 7



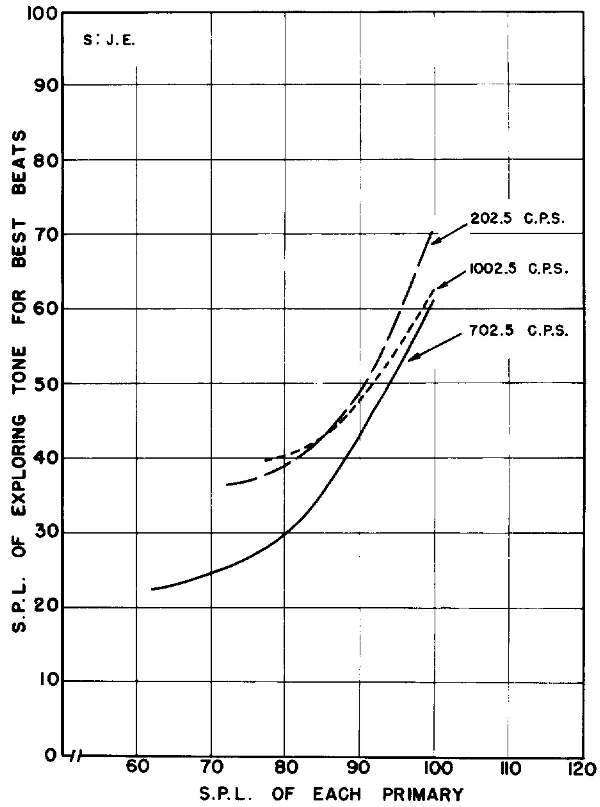
S: R.K.
200 C.P.S.
700 C.P.S.
1000 C.P.S.
S.P.L. OF CORRECTED DIFFERENCE TONE
S.P.L. OF EACH PRIMARY
0
10
20
30
40
50
60
70
80
90
100
60
70
80
90
100
110
120

Figure 8

200 c.p.s. difference tone. The shape of the region of audible beats of a 200 c.p.s. difference tone for the two subjects is similar, and the corrected difference tones have approximately the same intercepts. As in the case of the 700 c.p.s. difference tone, the corrected difference tone of 200 c.p.s. starts at J.E.'s absolute threshold at 200 c.p.s.

In Figure 7 are replotted the uncorrected curves for best beat using subject R.K. for difference tones of 1000 c.p.s., 700 c.p.s., and 200 c.p.s. These curves are from Figures 1, 3, and 5, respectively. In Figure 8 are replotted the corrected levels of the 1000 c.p.s., 700 c.p.s., and 200 c.p.s. difference tones of subject R.K. These curves are the dashed lines of Figures 1, 3, and 5, respectively. If Figure 8 is compared with Figure 7, it can be seen that the correction applied to the best beat curves has two principle effects. The difference tones are mapped out from considerably lower sound pressure levels and the slopes of the difference tones become nearly constant.

In Figure 9 are replotted the curves for best beat for difference tones of 1000 c.p.s., 700 c.p.s., and 200 c.p.s. using subject J.E. These curves are from Figures 2, 4, and 6, respectively. Subject J.E. does not overestimate the intensity of the difference tone when the range of audible beats becomes larger than 40 db, hence the corrected difference tone of Figure 10 resulting from primaries of 90 and 100 db S.P.L. are quite similar to the uncorrected best



S: J.E.
S.P.L. OF EXPLORING TONE FOR BEST BEATS
100
90
80
70
60
50
40
30
20
10
0
60
70
80
90
100
110
120
S.P.L. OF EACH PRIMARY
202.5 C.P.S.
1002.5 C.P.S.
702.5 C.P.S.

Figure 9

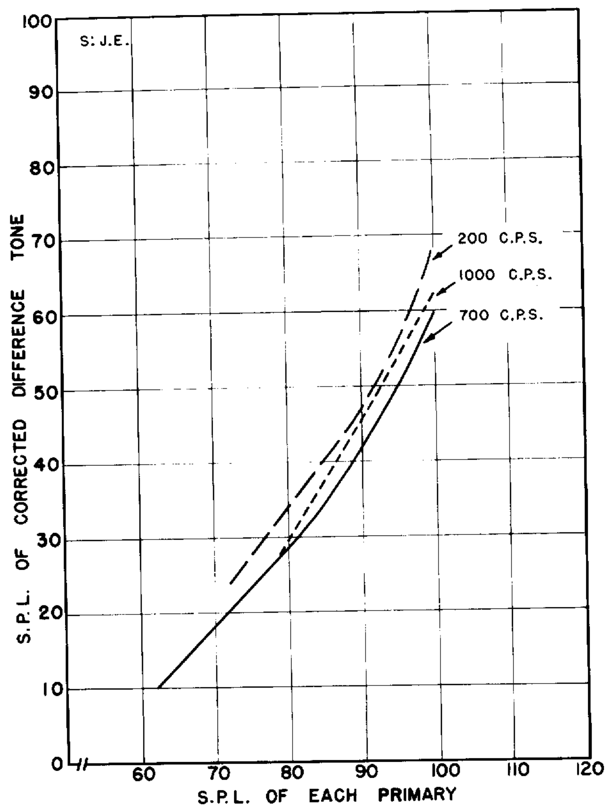

S: J.E.
S.P.L. OF CORRECTED DIFFERENCE TONE
S.P.L. OF EACH PRIMARY
200 C.P.S.
1000 C.P.S.
700 C.P.S.
100
90
80
70
60
50
40
30
20
10
0
60
70
80
90
100
110
120

Figure 10

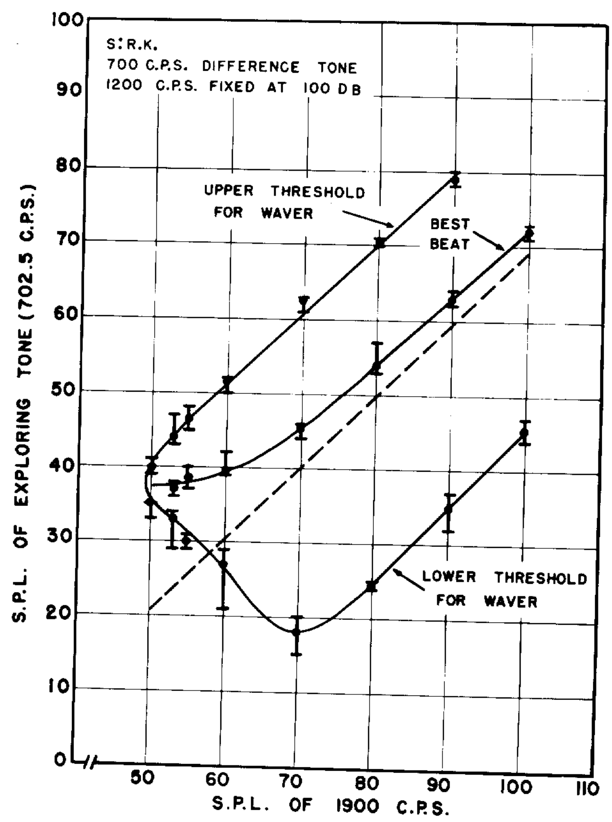

S: R.K.
700 C.P.S. DIFFERENCE TONE
1200 C.P.S. FIXED AT 100 DB
UPPER THRESHOLD FOR WAVER
BEST BEAT
LOWER THRESHOLD FOR WAVER
S.P.L. OF EXPLORING TONE (702.5 C.P.S.)
S.P.L. OF 1900 C.P.S.
0
10
20
30
40
50
60
70
80
90
100
110

Figure 11

beat curves of Figure 9. However, at S.P.L.'s of the primaries of less than 90 db, the corrected difference tones diverge sharply from the uncorrected curves for best beats. Applying the correction procedure has the effect of increasing the similarity of the curves for the three difference tones.

In Figure 11 are shown the upper threshold for waver, best beats, and the lower threshold for waver of a first-order difference tone of 700 c.p.s. The 1200 c.p.s. primary was fixed at 100 db while the 1900 c.p.s. primary was successively set at 50, 53, 55, 60, 70, 80, 90, and 100 db (Condition 4). As before, the dashed line represents the corrected level of the difference tone of 700 c.p.s., and is a straight line visually fitted to the points resulting from subtracting the correction provided by Table 2. The magnitude of the correction is based on the range of audible beats at each intensity of the 1900 c.p.s. primary listed above. Each solid dot is the median of six judgments and the horizontal lines about the solid points delineate the 25% and 75% points when the six judgments are rank-ordered on the basis of intensity. The slope of the 700 c.p.s. difference tone generated by raising the intensity of only one primary is less than that of the same difference tone generated by increasing two equally intense primaries as in Condition 2.

When the intensity of the primary of 1900 c.p.s. reaches 100 db, then of course the intensity of the two primaries are equal and there is a duplication of the intensities used in Condition 2. If the intensity of the 702.5 c.p.s. exploring tone required for best beats and lower threshold for waver in Condition 2 and Condition 4 are compared for subject R.K., it will be seen that there is close agreement between the medians of six judgments obtained at two different times.

1200 c.p.s. and 1900 c.p.s. at 100 db

Condition 2, Fig. 3,	lower waver	46.5 db	best beat	70.5 db
Condition 4, Fig. 11,	lower waver	45.5 db	best beat	72.0 db
	difference	-1.0 db	difference	1.5 db

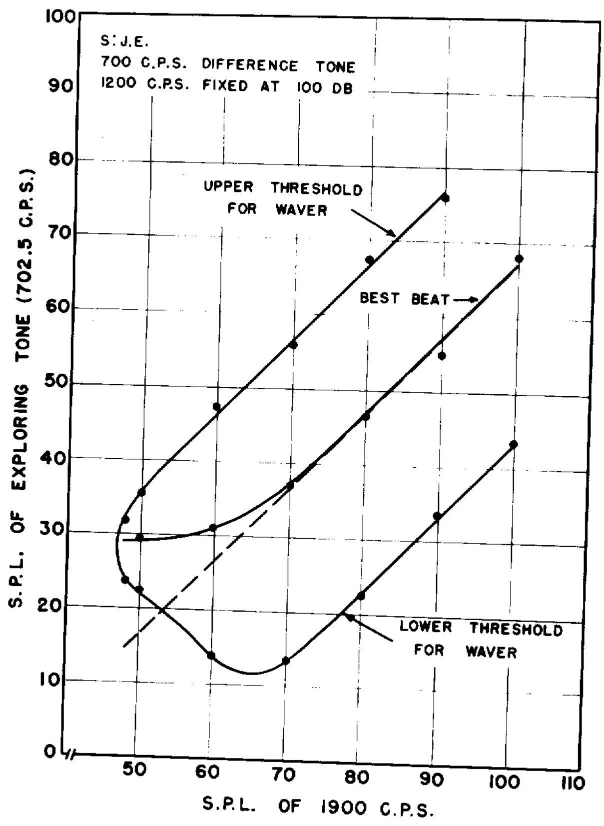
These differences are of a magnitude that might be expected from repetition of a measurement of this type.

For subject J.E., the same comparison does not yield such satisfactory results:

Condition 2, Fig. 4,	lower waver	40.0 db	best beat	60.5 db
Condition 4, Fig. 12,	lower waver	43.5 db	best beat	68.0 db
	difference	3.5 db	difference	7.5 db

It is difficult to explain why there should be discrepancies in J.E.'s data taken under identical conditions. The small variability of J.E.'s data for primary beats (3, 4, 5) would support the hypothesis that the amount of distortion actually may vary over an interval of several weeks. Not enough is known about the stability of the nonlinear characteristics of the ear to provide any basis for speculation.

It appears from casual inspection that the ranges of audible beats are larger in Figure 11 than the corresponding ranges in Figure 3. This apparent difference is an illusion,


S: J.E.
700 C.P.S. DIFFERENCE TONE
1200 C.P.S. FIXED AT 100 DB
UPPER THRESHOLD FOR WAVER
BEST BEAT
LOWER THRESHOLD FOR WAVER
S.P.L. OF EXPLORING TONE (702.5 C.P.S.)
S.P.L. OF 1900 C.P.S.
0
10
20
30
40
50
60
70
80
90
100
50
60
70
80
90
100
110

however, due to the difference in slope of the difference tones, for once the curves for upper and lower threshold for waver become parallel, the range of audible beats remains relatively constant at about 40 db in both Figure 11 and Figure 3.

Figure 12 shows for subject J.E. the same relations as shown in Figure 11 for R.K. Each solid dot is the median of four judgments. All curves are visually fitted, and the dashed line represents the corrected difference tone. If Figure 12 is compared to Figure 11, it may be seen that the two regions are quite similar. The usual overestimation of the intensity of the difference tone occurs at low intensities of the 1900 c.p.s. tone. Except for a vertical displacement of 3 or 4 decibels upward, the corrected difference tone of Figure 11 is nearly identical with the corrected difference tone of Figure 12. It is interesting that the difference tones are not traced to threshold under condition 4 (Figures 11 and 12).

Throughout this paper medians have been used as measures of central tendency instead of means because it was felt that the platykurtic distribution of the judgments makes a statement of variability in terms of means and standard deviations meaningless. For example, in Figure 11, if the range of judgments for lower threshold for waver at an intensity of 70 db of the 1900 c.p.s. primary is computed on the basis of three standard deviations on either side of the mean, the range would extend from 8.8 db to 26.8 db. The actual range of the six judgments at this lower threshold for waver is from 14 db to 22 db. Furthermore, regardless of whether the means or medians are used as measures of central tendency, the shapes of the regions of audible beats and of the best beat curve remain essentially the same. For subject R.K., all medians given on all the graphs lie within 1.0 db or less of the corresponding means. For subject J.E., whose data points are based on only four judgments, the medians lie within 1.0 db or less of the corresponding means at all data points but four. At these four points, the differences between the medians and the mean are 1.25, 1.25, -1.75, and 2.5 db.

Variability of the data was such that, on the average, a difference of 3.6 db or more between two means would occur by chance only once in 100 such differences. The differences of major concern in the present study are larger than 3.6 db.

No judgments of upper threshold for waver at S.P.L.s of 100 or 110 were required of either of the subjects. It was found that at these intensities of the primaries, there really was no intensity of the exploring tone which would give a clearly defined upper threshold for waver. As Trimmer and Firestone (7) have pointed out, the introduction of an intense exploring tone to an already overloaded transducing system, such as the ear, results in complex changes in quality and loudness. As the exploring tone is raised in intensity, the waver attached to the difference tone never seems to disappear; the primaries appear to waver; sometimes a disembodied low frequency tone may waver. It is possible in the case of 1200 c.p.s. vs. 2200 c.p.s., that the second aural harmonic (2400 c.p.s.) of the 1200 c.p.s. primary is reacting with the 2200 c.p.s. primary to produce a difference tone of 200 c.p.s. which appears to waver. In other conditions (1200 c.p.s. vs. 1900 c.p.s. and 1200 c.p.s. vs. 1400 c.p.s.), it is not clear just what is wavering. The same complex wavering occurs to a lesser degree during best beat judgments at primary intensities of 90 and 100 db and 110 db, but for best beat judgments, it appears that the listener can successfully ignore this interference and can make an accurate and consistent judgment (5).

DISCUSSION AND CONCLUSIONS

The primary interest in this paper is in the measurement of the intensity of a first-order difference tone at or near its threshold. It is clear that when the difference tone first becomes measureable, the range of audible beats is small and the measurement obtained by using the conventional method of best beats is in error. Regardless of whether the difference tone is being masked by the primaries (Condition 1, 1000 c.p.s. difference tone) or whether it is first detected at the subject's absolute threshold(Condition 3, 200 c.p.s. difference tone), the results obtained by the conventional method of best beats must be corrected by an amount which is related to the range of audible beats.

In 1942, Moe (2) used the method of best beats to measure the intensity of a first-order difference tone of 260 c.p.s. which was generated by equally intense primary tones of 950 c.p.s. and 690 c.p.s. His findings, based on three listeners, do not agree with the results of this paper. Moe's curve based on best beats, for a 260 c.p.s. first-order difference tone, lies about 20 db above the uncorrected best beat curves of both J.E. and R.K. at all intensities of the primaries. It is unlikely that individual differences would cause such a large discrepancy.

Fletcher (8) has proposed that the amount of distortion *generated in the ear is independent of frequency and is solely a function of the intensity of the impressed sound.* This assumption is reasonably well substantiated by the findings of the present paper. An examination of the corrected curves of either subject indicates that for the three frequencies investigated, this assumption holds to a first approximation for first-order difference tones. Subject R.K. shows some correlation between the frequency and intensity of the difference tone. At any given intensity of the primaries, the 200 c.p.s. difference tone is more intense than the 700 c.p.s. difference tone which in turn is more intense than the 1000 c.p.s. difference tone. Subject J.E. does not show this order. The discrepancies between the intensities of the difference tones of either subject substantiate Fletcher's hypothesis rather than disprove it.

Certain qualitative observations that were made during the regular sessions make possible a simple rule for the use of the correction procedure. The intensity of the primaries at which the difference tone first became audible was noted. Under all conditions and for both subjects, the intensity at which *the difference tone was first heard by itself,* with no exploring tone present, agrees remarkably well with the intensity at which the error of overestimation begins to become appreciable. For example, in Fig. 12, subject J.E. begins to overestimate the intensity of the 700 c.p.s. difference tone when the intensity of the 1900 c.p.s. primary is approximately 70 db. The 700 c.p.s. difference tone first becomes audible as a separate and distinct tone at this same intensity of the primary. This suggests that a quick test to determine whether or not the intensity of a difference tone, as measured by the method of best beats, needs to be corrected for overestimation, is to determine whether or not it is audible as a separate and distinct tone in the complex producing it. If it is audible by itself, then the intensity of the exploring tone for best beats may be taken to be equal to the intensity of the harmonic or combination tone being measured. If, with no exploring tone present, the tone being measured is not heard as a separate tone, then a correction based on a consideration of the range of audible beats is necessary.

SUMMARY

Intensities of first-order difference tones of 200 c.p.s., 700 c.p.s., and 1000 c.p.s. for two subjects were measured by the method of best beats. It was shown that the results obtained by the conventional method of best beats were in error near the threshold of the difference tones measured. The error of overestimation was shown to operate under several conditions of masking. Corrections, based on the width of the region of audible beats, were applied to the best beat curves obtained, and more nearly correct estimates of the intensities of the three difference tones were presented.

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