ALLOWANCE PROBLEM IN ROTATIONAL SYNCHRONOUS DISTORTION AS A STUDY ON TIMBRE DISCRIMINATION BY INFINITESIMAL POSITION-SHIFT IN THE SO-CALLED TIMBRE-SPACE

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To determine precisely and pertinently in what extent the distortion RSD (Rotational Synchronous Distortion) is allowable for communication purpose is vitally demanded in the practical engineering field where disc- and tape-recording equipments are indispensably used. This allowance study, however, involves a most fascinating problem in a purely scientific interest, because of its suggestive rôle for inquiries into the mechanism of timbre-discrimination. We cannot find any clues for timbre study without aid of this distortion. In the previous report on this distortion we stated the nature of this distortion RSD; it brings about the "timbre" change, "pitch" change and further, "quantity" (*i.e.*, duration) change. Consequently it becomes important to decide to what quality the judgement in the so-called allowance-test in fact resorts. Under these circumstances we have to study the problem of timbre-discrimination taking an actual speech-sound as main object of our observations. Before entering into the study and discussion of timbre-discrimination of speech-phones of complex nature, we must arrange for some preliminary experiments. Because, it is convenient and even well-advised to make ready for some basic data either available to an utterly unfamiliar problem to which we feel pretty at a loss, or rather responsible for some peculiar phenomena at which we are often surprised in a very front of uncultivated field of science.

Preliminary Experiments

Pitch discrimination test

A pitch-discrimination test—in an ordinary sense, but in the two (both incremental and decremental) directions—is necessary as our preparatory course of study. The circuit used is shown in Fig. 1(a) and the signal-presentation for this test is given in Fig. 1(b). The method of test is the so-called OCM (Operator Control Method) with restricted time in measurement. Two pitches, *i.e.*, 130~ and 198~ are selected as found frequently in conversation of male subject: These test frequencies as signal B in pitch-discrimination are supplied by LC oscillator, and variable frequencies as signal A in pitch-discrimination test are fed by CR oscillator. Test was planned in such a scope: by one-cycle step of difference, in the pitch-difference range of ± 4 cycles. Instruction for subjective judgement was: conforming to a presentation of signals given in Fig. 1(b), that is, during only two repetitions of a pair of AB, you must select one judgement; whether A is higher than B, or A is lower than B, or A is equal to B. The listening subjects were three male students with normal hearing acuity and discernment. The number of

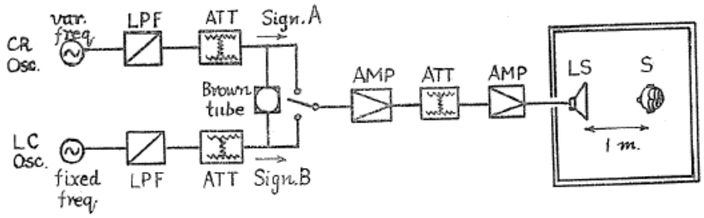

FIG. 1 (*a*). Block-diagram in pitch-discrimination test.

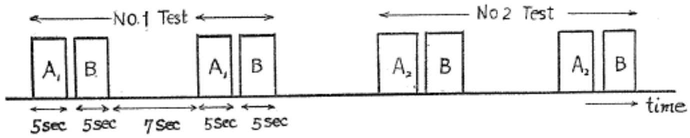

FIG. 1 (*b*). Signal presentation in pitch-discrimination test.

observations per listener is 30 for each step-condition. The total observations for all the three listeners are 90 per condition. The results are given in Fig. 2, where the abscissa gives the frequency deviation of two single-frequency tones in cps, and the ordinate means the percentage of voting at the rate of which the judgements of equality between signals A and B are made. As we shall show later, the shape of the figure, of course, depends on the practice effect of listening subject on one hand, and on the way of selection of step of cycle on the other hand. But we can read from this figure the tendency of symmetricity of the judgement. This is the general tendency of the pitch-discrimination of single-frequency tone. If we assume to take the deviation range at the point of voting that corresponds to 50% of maximum voting as an index of sharpness in pitch-discrimination, then we have the values given in Table 1.

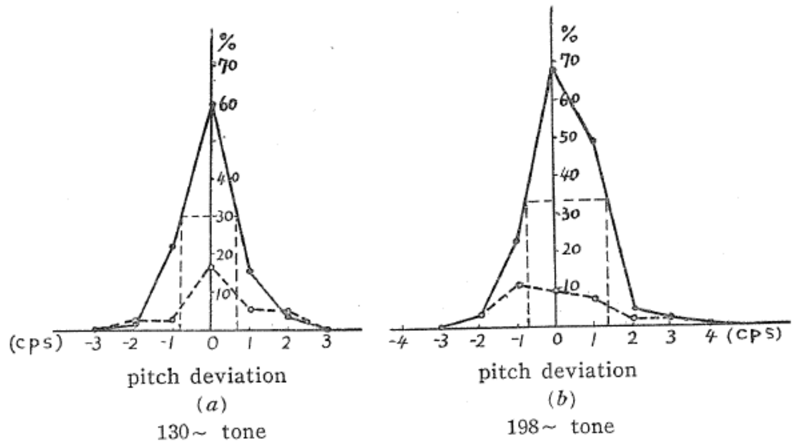

FIG. 2. Allowance characteristics of single frequency tone where were shown the characteristics: (*a*) for a pure tone of 130~ pitch; (*b*) for a pure tone of 198~ pitch.

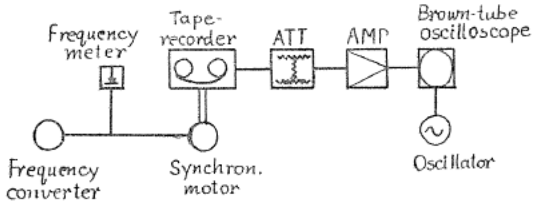

FIG. 3. Circuit diagram for measurement of the pitch-change of the pure tone caused by synchronous deviation.

TABLE 1. Allowance for Pitch Discrimination of the Pure Tones

Frequency of pure tone	Discrimination threshold in deviation (+) domain	Discrimination threshold in deviation (−) domain	Discrimination range (b)	Discrimination width ($\Delta f = b/2$)	Pitch sensitivity ($\Delta f/f$)
130～	+0.85～	−0.9～	1.75～	0.87～	0.0068
198～	+1.15～	−0.9～	2.05～	1.02～	0.0052

Pitch change of single-frequency tape-recorded tone by the deviation of source-frequency for synchronous motor

For changing the revolving speed of reproducing system in allowance test, we could not adopt the capstan-method by which the speed change is gross and discontinuous, and accordingly we adopted the converter-method which gives rise to the change of source-frequency for synchronous motor as driver of tape-recorder. We have studied here how the pitch of the recorded pure-tone changes according as the source-frequency deviates. In Fig. 4 we show it. We see there the pure-tone of 390 cycles recorded at the normal state of source-frequency (60～) varies conforming to a straight line as expected in advance. Accordingly we can calculate the rate of pitch change due to one-cycle change of source-frequency such as 6.65/390 =0.017. And we can further compute the pitch fluctuation (Δf) of the pure-tone of f cycles recorded at the normal source-frequency of F_0 cycles when the source-frequency comes to deviate from F_0 cycles to F cycles by the following formula

$$\Delta f = 0.017\,|F - F_0|\,f.$$

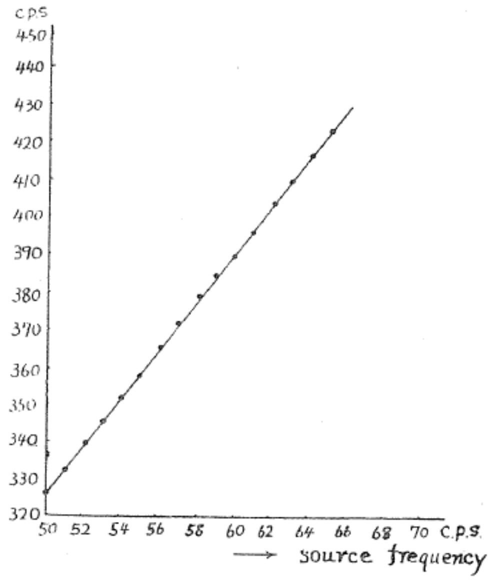

FIG. 4. Pitch change of the recorded pure tone caused by source-frequency deviation of the reproducing system.

Pitch-change test of the recorded complex sound due to the source-frequency deviation

Now we must proceed to make a similar test on complex sounds. As pitched timbre we make use of vowel "A" pronounced by a male subject at the pitch of

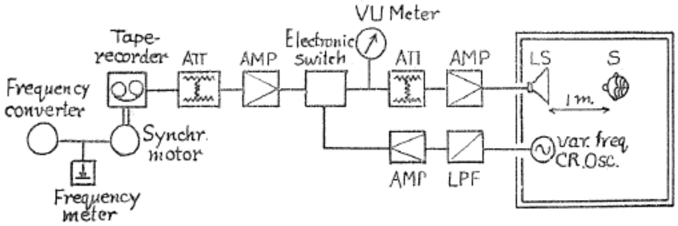

FIG. 5. Block-diagram of the circuit for pitch measurement of the complex sound applied to the distortion RSD.

130∼ and recorded in the tape-recorder at the source frequency of 58∼. We tested the measurements of pitch change by two male listeners in the range of source frequency from 54 cycles to 64 cycles. We show the circuit used in Fig. 5, and the result obtained in Fig. 6, where the standard deviation in measured values is added for reference. We can make clear one point that in spite of the deviation in the subjective measurement of pitch between listeners which used to occur in the pitch determination of complex speech-phones, the general tendency of the linearity of characteristics with the source-frequency change holds good nearly always. By aid of these two experiments in pitch change for pure-tone and for complex-sound, we will be in a position to compute the degree of distortion (given here always by the deviation or fluctuation of source-frequency from normal state) in terms of pitch-change observable in tested sound itself.

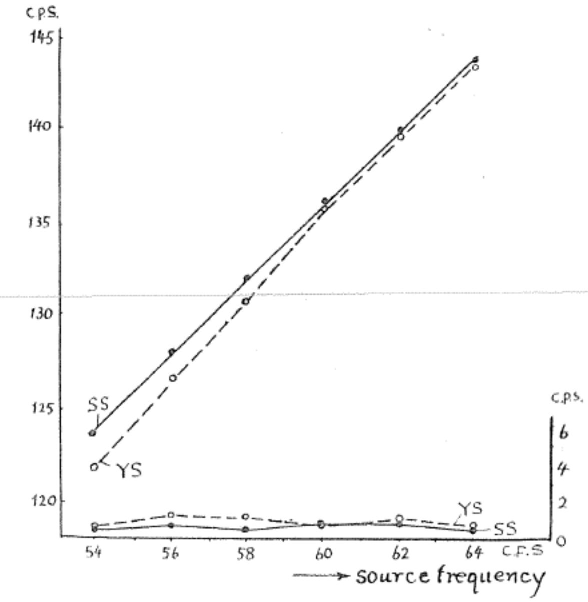

FIG. 6. Pitch change of the recorded complex sound (vowel "*A*") due to the deviation of source-frequency.

Allowance Test

Meaning and method of allowance test

As we have already discussed in the preceding, our allowance study was made with a view to give some practically available data to the sound-recording engineering and further, if possible, to make some contribution to a green field of younger science such as timbre theory. In order to make service to practical engineering we must pay attention to the actual circumstances of practical field where the allowance problem really comes to light. Those who listen to the program of broadcasting, for example, naturally become conscious of some strange disorder when synchronous deviation in reproducing equipment becomes greater exceeding some extent of margins. To determine the threshold of consciousness of synchronous disorder is the present question. Ordinary listeners have not on hand any reference program without distortions which stands in comparison with the program with distortions. They are situated in such conditions that their judgements on the allowable limit of distortion are to be established *without direct comparison between undistorted and distorted programs*, of which the condition, if we want, may be expressed in other terms: in indirect comparison of the distorted program brought actually to their sensations with the undistorted program image stored in their minds as a sort of mental figure. From these considerations we can devise an *indirect comparison method* which faithfully conforms to the actual circumstance of judgement. But, on the other hand, we can lead also a *direct comparison method*, which does not imitate the practical boundary in actual program-listening but reflects some ideal form of timbre-discrimination in the severest sense. As for the selection of signals as representative of program, there may be also two ways: one, continuous speech, imitating real program; the other, discrete speech-phones (such as vowels), most adequate for strict detection of allowance in a problem of timbre-discrimination. Always guided by these two basic considerations in our research plan for allowance test—applicability to practical field and faithfulness to scientific inquiry—we tried to twist every two methods of judgement with every two selections of signal. And finally, we added some experiments on musical sound for the comparative study with speech-phone.

Experimental procedure

The circuit used for this experiment is shown in Fig. 7. For direct comparison of distorted program with undistorted one, *viz.*, for realizing the scheme of regularly alternating signal-presentation—each undistorted program-train coming after each distorted one—we made a device of switching between two sources (one, fixed source of 60∼; the other, variable-frequency source ranging from 50∼ to 70∼ composed of frequency-conveater fed by dc 12 V) for synchronous motor of the tape-recorder of which the tape was to be recorded precisely with the source of normal frequency of 60 cycles. By this circuit we also attained the indirect comparison, of which the signal-presentation is given in Fig. 8. Principally the undistorted program in this method must be resorted to the memory itself, and therefore the result of judgement must be subject to the inevitable deviation based upon the degree of retentiveness of individual listener. For avoiding the predominant effect

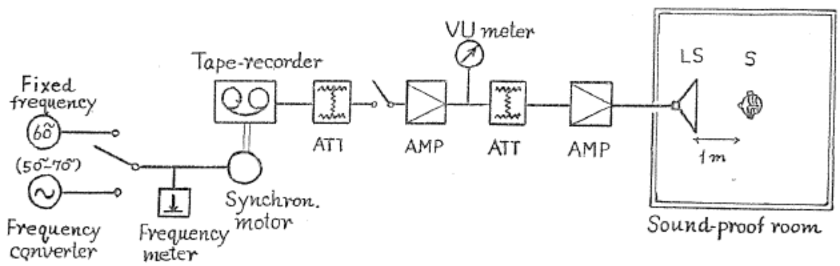

FIG. 7. Circuit diagram for allowance test in general.

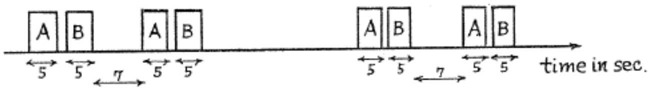

FIG. 8. Signal presentation in direct comparison method.

of subjective inequality in memory, and further positively for fixing the undistorted program-image more firmly in mind, we devised semi-indirect method where some series of distorted program-trains of short interval are followed by a series of undistorted program-train of considerably long interval as shown in Fig. 9. Instruction for judgement in this test is as follows. When the listener feels that the pitch of A is higher than that of B, mark the sign "*f*" on his test sheet; when he feels that the pitch of A is lower than that of B, mark the sign "*s*"; and when he feels that the two pitches of A and B are equal, mark the sign "*o*". These signs given by three male listeners of normal hearing were collected and calculated, resulting in so many data and characteristics. We counted for much, however, the data of "*o*" sign, indicating that the voting is based on the judgement of "non-difference" between two signals as to the pitches. Measurements were completed by a total of 90 observations for the three observers per condition. To check the deviations in the values measured, we obtain the deviation between testing-individuals and further some times the deviation between testing-periods.

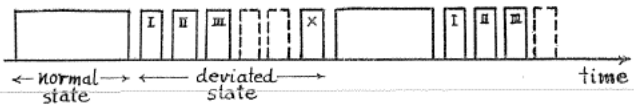

FIG. 9. Signal presentation of continuous speech or music in semi-indirect comparison method.

Allowance for Continuous Speech

We have carried allowance-measurements for continuous speech, *viz.*, continuously varying speech as in natural conversation, both on male voice and female one, by either direct or indirect (strictly semi-indirect) comparison method. We shall show the results of such tests. In Fig. 10 we give the allowance characteristics for male voice, where are placed in parallel two kinds of result by direct and indirect methods. And the similars for female voice are shown in Fig. 11. In these figures the ordinates give the percentage of votings for the judgement of "non-difference" between signals A and B, and the abscissas indicate the deviations in source-frequency, *viz.*, the deviation from synchronous state. In full line are given the allowance characteristics on which the arrow sign shows the "unbiased standard deviation" between listeners as to the frequency deviation discriminable at the points of 50% of each maximum voting; By dotted curve we show the unbiased deviation between individuals as to the percentage of voting. As outstanding features by such a representation are pointed out:

(1) Generally speaking, the shape of the characteristics of allowance obtained by the direct method is found more sharp than that by the indirect method. As for the deviation, the characteristic in direct measurement is smaller in general than that in indirect measurement.

(2) So long as the indirect method is concerned, the difference in characteristics of allowance due to the difference between male and female voices does not

come into question. The figure of Fig. 10 (b) is, for example, quite similar to that of Fig. 11 (b), respecting not only the height of the characteristic but also its skewedness.

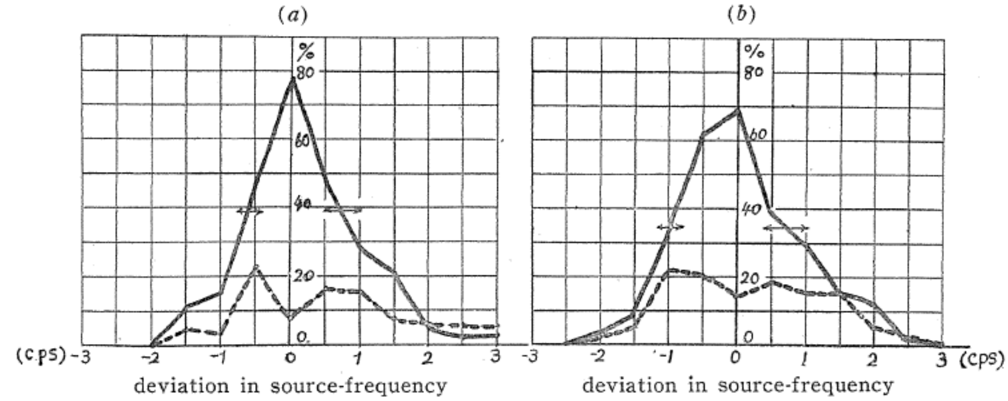

FIG. 10. Allowance characteristics for male continuous speech, (a): the result in direct comparison method, (b): that in indirect comparison method.

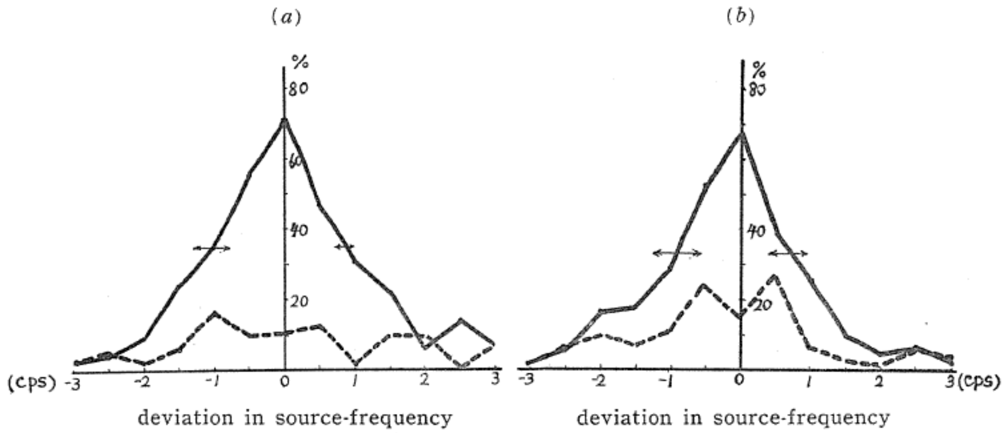

FIG. 11. Allowance characteristics for female continuous speech, giving by (a) the result in direct comparison method, and by (b) that in indirect comparison method.

(3) Judged from the result of direct comparison, however, the characteristic for male voice differs from that for female voice: First, the former is a little superior in sharpness to the latter (it means that the speech of male voice is slightly more susceptible to the influence of transitional distortion than female speech). Secondly, the former differs slightly from the latter in respect to the skewedness of characteristic. This difference is really small but seems to be important. For male voice the characteristic is slightly skewed in the negative-shift region (*viz.*, in D-domain in the previous expression). But, on the contrary, the characteristic for female voice is rather skewed in the positive-shift region (*viz.*, in U-domain in the previous expression.)

(4) As the margin of tolerance we tried to resort to the deviation range at the half voting point in the same manner as we have already done for pitch-discrimination. It seems reasonable: because the point of 50% of maximum voting almost

always corresponds to the maximum point of standard deviation, thus giving the point of threshold in judgement. For reference, we have also tested for violin tone, the results of which are shown in Fig. 12. The discrimination range for violin music is wider than that for speech, reflecting in some measure the fact that the listeners used are all amateurs in music, especially in violin music. The concrete data obtained in this experiment are summarized in Table 2.

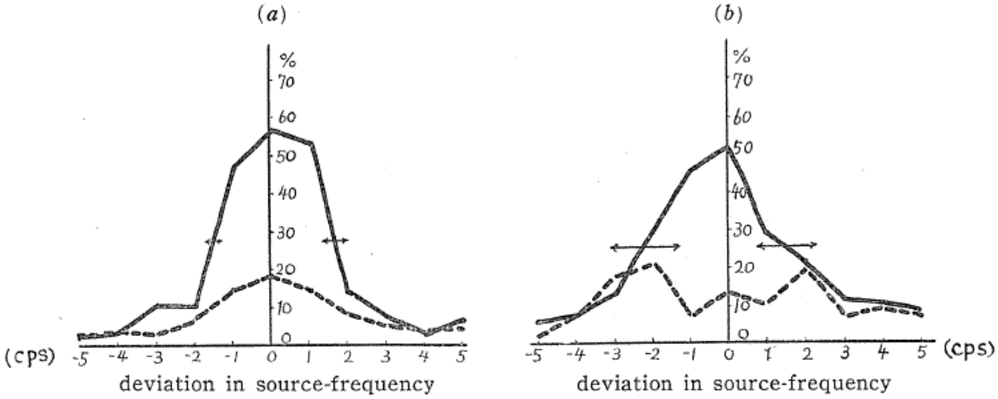

FIG. 12. Allowance characteristics for violin music, giving by (*a*) the result in direct comparison method and by (*b*) that in indirect comparison method.

TABLE 2. Allowance for Continuous Speech and Music

	Discrimination threshold in deviation				Discrimination width	
	DC Method		IC Method			
	(+) domain	(−) domain	(+) domain	(−) domain	DC Method	IC Methed
Male conversation	+0.7∼	−0.6∼	+0.7∼	−0.95∼	0.65∼	0.82∼
Female conversation	+0.85∼	−1.0∼	+0.7∼	−0.9∼	0.92∼	0.80∼
Violin music	+1.7∼	−1.5∼	+1.5∼	−2.2∼	1.60∼	1.80∼

Allowance for Sustained Vowels

Allowance test for stationarily sustained speech-phones was executed by the same circuit of Fig. 7 following the precept of signal-presentation given in Fig. 9. The sustained sounds were fed from the tape-recorder by endless processes. As this experiment belongs to a relatively exact measurement, so to say, we must investigate more closely the testing method at the beginning. We tried to check the influence of the selection of cycle-step upon the shape of allowance characteristics. We repeated for that purpose the quite same experiment, only changing the condition of cycle-step. The results are tabulated in Table 3, and are shown in Fig. 13 (*a*) and (*b*). The figure in Fig. 13 (*a*) corresponds to the case of one-cycle step condition and Fig. 13 (*b*) the case of half-cycle step condition. These figures tell us; when the cycle-step is large, the voting comes to concentrate in the middle, resulting in the sharpness of characteristic form; but the general tendency of the characteristics cannot be altered by changing the cycle-step number: for example, the discrimination-range given by these two cases are respectively 1.15∼ from (*a*) and 1.07∼ from (*b*), of which the difference is no more than 0.08∼.

However, we inclined to adopt in the present experiment the procedure of half-cycle step, *viz.*, a finely-scaled number-of-step method, in the expectation of the exactness and precision for the result of such allowance measurement.

TABLE 3. Detection of the Effect of the Selection of Cycle-Step Interval upon the Allowance Data

Selection of cycle-step	Discrimination threshold in deviation		Discrimination range	Discrimination width
	(+) domain	(−) domain		
One cycle step method	+0.50~	−0.65~	1.15~	0.57~
Half cycle step method	+0.25~	−0.82~	1.07~	0.53~

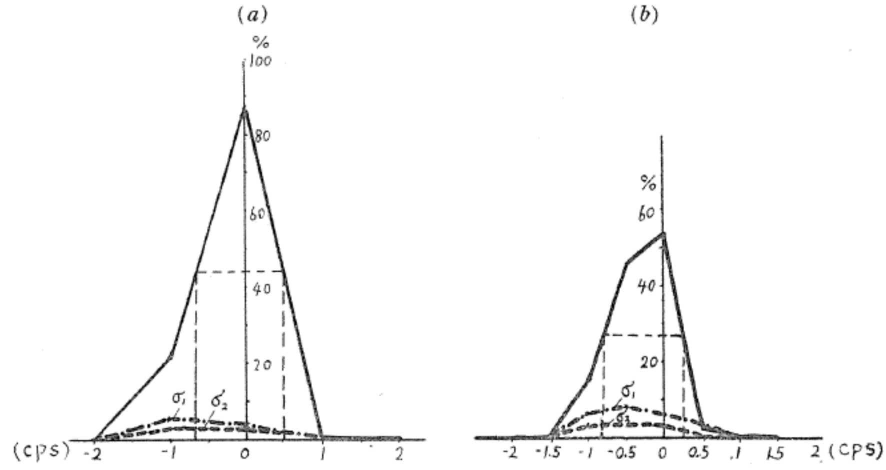

FIG. 13. Allowance characteristics for sustained vowel "*A*"; in (*a*) each one cycle step of deviation is selected, in (*b*) each 1/2 cycle step of deviation is selected. σ_1: unbiased deviation between periods, σ_2: unbiased deviation between listeners.

The test of direct comparison method executed with the precaution mentioned above gives the allowance characteristics for five sustained Japanese vowels uttered by a male at the pitch of 130~ which are shown in Fig. 14, where is added for comparison further example of violin tone of "G" string. The data of discrimination-range and -width for each sound are shown in Table. 4. Discrimination width is narrowest for symmetrical "E" and wider for unsymmetrical vowels. Mean width of five vowels is 0.46~. Violin tone has narrower width. These are full of very interesting features, showing the existence of three types in their responses; First, symmetrical feature as shown in the vowel "E" just like the pure-tone response; Secondly, skewed type in up-domain such as given by the vowels "A", "O", "I"; Thirdly and lastly, skewed type in down-domain given by "U" vowel. Violin tone of "G" string (198~ tone) is somewhat like the vowel "E" in its response, *i.e.*, of some symmetrical character. It is not strange to us that the vowels "A" and "O" stand in the same side, setting apart the problem of their skewedness in up-domain. Very curious and strange to see the vowel "I" stands in an opposite side to the vowel "U". It is very interesting to consider why the vowel "I" belongs to the same group of "A" and "O". More fundamentally we cannot follow out the principle which

TABLE 4. Allowance Data for Sustained Vowels and Sustained "G" String Tone of Violin

	Discrimination threshold in deviation		Discrimination range	Discrimination width
	(+) domain	(−) domain		
Vowel "A", sustained	+0.27~	−0.8~	1.07~	0.53~
Vowel "I", sustained	+0.40~	−0.7~	1.10~	0.55~
Vowel "U", sustained	+0.60~	−0.3~	0.90~	0.45~
Vowel "O", sustained	+0.30~	−0.3~	0.60~	0.30~
Vowel "E", sustained	+0.25~	−0.7~	0.95~	0.47~
Vowel Mean, sustained	+0.56~	−0.36~	0.92~	0.46~
Violin "G"-string tone	+0.40~	−0.3~	0.70~	0.35~

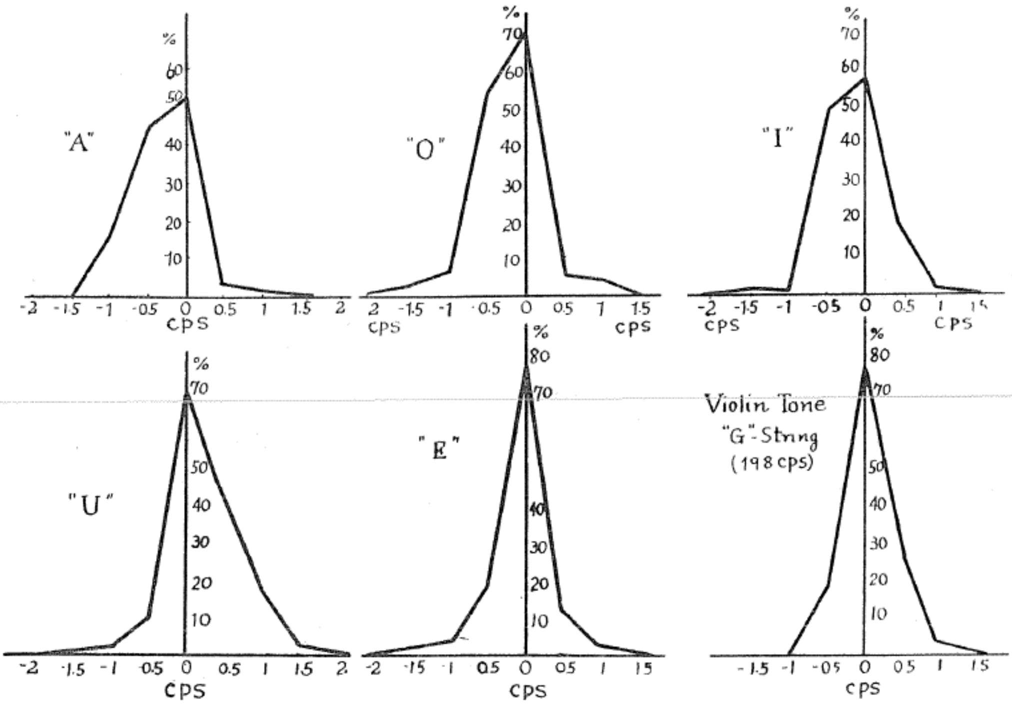

FIG. 14. Allowance characteristics for sustained oral vowels and "G"-string (198~) violin tone. Five oral vowels uttered by a male subject (SS) at the pitch of 130~, and observed by three male listeners. Every one point of the curves is a result of 90 observations per condition.

governs the relation between the skewedness of allowance-characteristics and the timbre-patterns of vowel. It is remained for future study. But it must be noticed here that the dissimilarity of the forms of allowance-characteristic does not come from either experimental failure or experimental deviation. In selection of the procedures in this experiment we were considerably prudent. We have proceeded to our study with carefully pre-arranged processes. But we tried to repeat the same test with every possible precaution. We did our best, for example, in tape-recording of voices, taking further precautions for fluctuations in pitch and level; we prepared further drilling for listening subjects for the purpose of obtaining more stable and more reliable characteristics. We studied this time only about the vowels "A" and "U". The result obtained with such a precaution is shown in Fig. 15. In comparison with the previous study, the allowance characteristics are found more sharply accounting for higher training of listener. But the skewedness of characteristic remains unaltered as shown in Table 5.

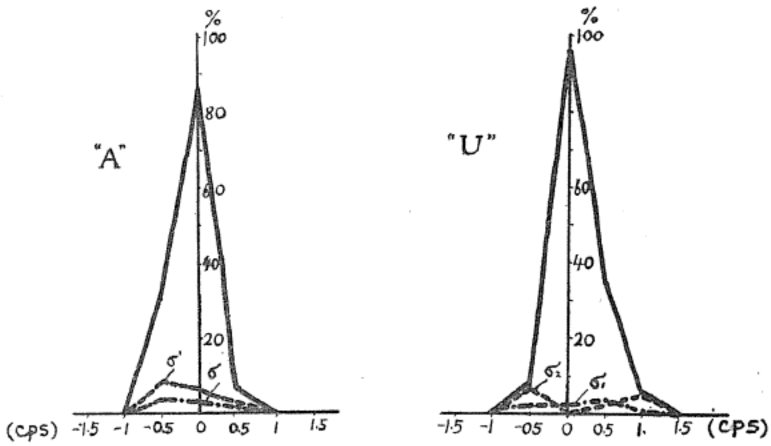

FIG. 15. Allowance test re-examined for the vowels "A" and "U" by male subject, uttered at 130~ pitch. Listeners are three. We denote by σ_1 unbiased deviation between periods, and by σ_2 unbiased deviation between listeners.

TABLE 5. Allowance Data for Vowels "A" and "U"

	Vowel "A"		Vowel "U"	
	Anterior test	Posterior test	Anterior test	Posterior test
Discrim. threshold in deviation (+)	+0.27~	+0.3~	+0.6~	+0.40~
Discrim. threshold in deviation (−)	−0.80~	−0.4~	−0.3~	−0.25~
Discrimination range	1.05~	0.7~	0.9~	0.65~
Degree of unsymmetricity	0.53~	0.1~	0.3~	0.15~

We must further investigate certain effects of individual listeners upon the forms of allowance-characteristic. Because, we had better be precautious against a possibility of some predominancy of some abnormal individual which happens to determine predominantly the average form of characteristics.

Lastly, we must make a final comment on the cause of these phenomena. But it is too difficult to be answered immediately. All that we can do at the present stage is only to suggest that the timbre discrimination must be differentiated from the pitch discrimination, and further to describe that the timbre discrimination looks actively to work in the determination of the allowance judgement for sustained vowels. By inspecting the figures in Fig. 16 the allowance characteristics of five vowels, compared with the allowance of pure tone (*i.e.*, the so-called pitch discrimination), we see clearly how the timbre discrimination is differentiated from the pitch discrimination. For the better understanding of that, to the abscissa of this figure we gave, for the first time, the pitch deviation of vowel due to RSD instead of the cycle deviation of source-frequency used exclusively before. As a

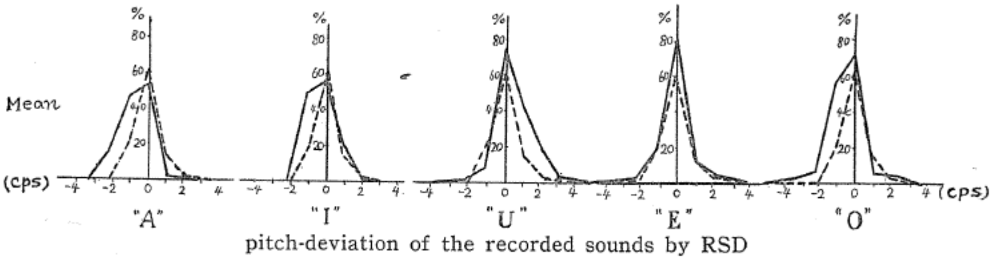

FIG. 16. Mean allowance characteristics of three listeners for five sustained vowels of 130~ pitch, showing the difference between timbre-discirimination (in full curves) and pitch-discrimination (in dotted curves), the abscissa being taken for the pitch deviations of vowels and pure tone.

measure of distortion RSD, the pitch deviation of taped voice is more direct than the deviation of source-frequency. The former representation is more suitable and serviceable in the essential study of timbre problem. The latter is fit only for practical purpose. In Fig. 17 we show the characteristics of the five vowels of male voice by the similar representation but viewed from individual listener's side, that is, the characteristics per vowel as well as per ear. By these figures we can understand:

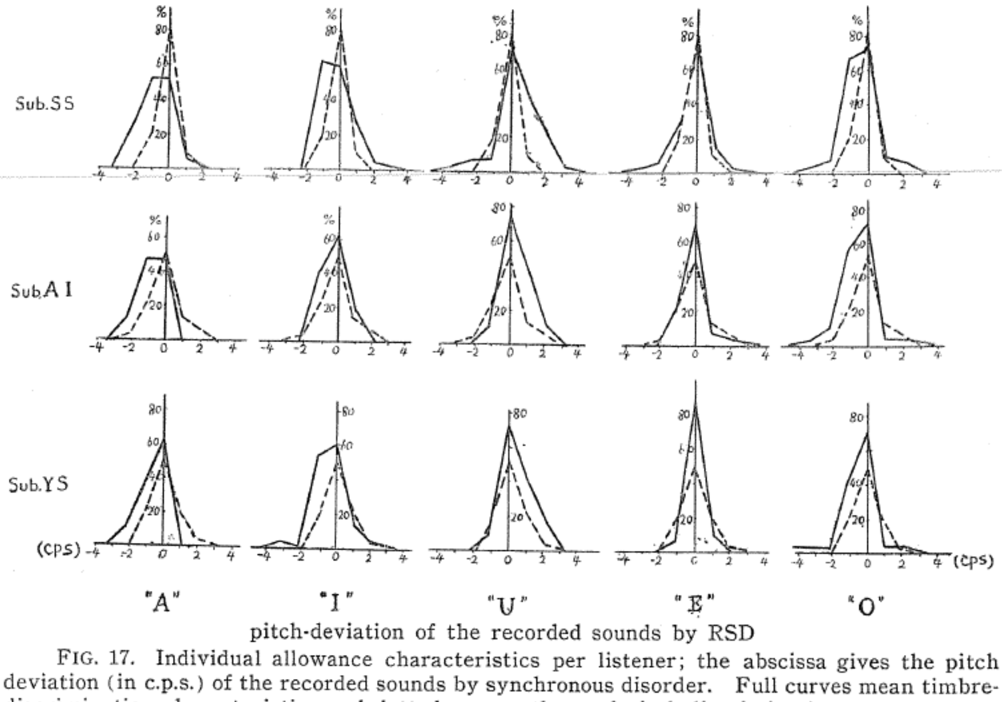

FIG. 17. Individual allowance characteristics per listener; the abscissa gives the pitch deviation (in c.p.s.) of the recorded sounds by synchronous disorder. Full curves mean timbre-discrimination characteristics and dotted curves those of pitch-discrimination.

(1) The speciality in skewedness of characteristic looks utterly based upon the speciality of vowel, not reflecting the special inclination of listener.

(2) The allowance in pitch-discrimination at the corresponding pitch (*viz.*, 130~) by three listeners is inscribed in the same figures, showing the considerable difference of acuities between timbre and pitch discriminations.

To give the idea of good comparison of speech-phones with musical instrument sounds, we added also here in Fig. 18 the mean and individual characteristics of the violin tone of 198~ pitch observed by the same three listeners.

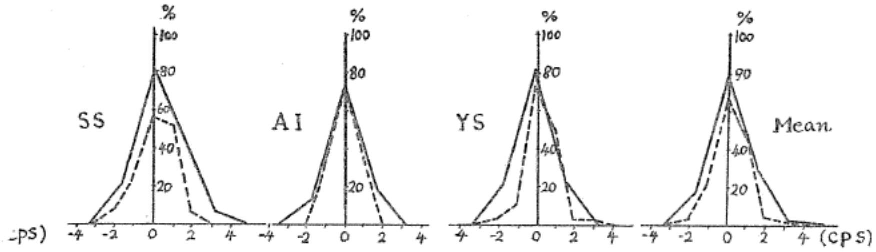

FIG. 18. Allowance characteristics for sustained violin "G" string tone, showing mean characteristic of three listeners and individual characteristics per listener. The abscissa gives the pitch deviation (in c.p.s.) of the recorded sound by synchronous disorder. Full curve means timbre discrimination and dotted curve pitch discrimination.

Conclusion

By summarizing the results of our experiment on allowance we can point out the following facts. It is to the practical field that the measurement by indirect comparison (IC) for continuous signals (CS) is most applicable. But we can recommend the measurement by direct comparison (DC) for discrete signals (DS) as the most suitable for the scientific study on timbre quality. In the selection of an index of synchronous disorder we used, for the same reason, the source-frequency deviation for practical application, and in scientific interest we used directly the pitch deviation of the recorded sounds. The tests in the combined cases of IC and DS, and DC and CS were followed out in wider interest. What we can say with some conviction from our experience is not so much. We shall state in the order of importance:

(1) The difference of voices between male and female can be detectable by DC for CS. But there is no difference perceptible between them by the method IC. The difference detectable by DC: male conversation is marked by the skewedness in D-domain and female conversation by the skewedness in U-domain. The number of examples was not large. And this difference was not much. But we think this inclination might hold good in general. We need, however, further examples for more solid verification.

(2) For exact measurement, sustained signal is preferable to variable signal. The difference of phoneme quality is detectable thereby. As for Japanese vowels,

TABLE 6. Discrimination Range and Width of Various Sounds

	Discrimination range	Discrimination width
Pure tone (130~)	1.75~	0.87~
Male voice (CS)	1.30~	0.65~
Vowel (mean value of male voices, 130~)	0.92~	0.46~
Pure tone (198~)	2.05~	1.02~
Female voice (CS)	1.85~	0.92~
Violin tone, sustained ("G" string, 198~)	0.70~	0.35~
Continuous violin music	3.20~	1.60~

"A", "O" and "I" seem to belong to one group, the vowel "U" to an opposite group, and the vowel "E" stands in an intermediate positoin, forming thereby symmetrical characteristic. The opposite nature of "A" and "U" was re-ascertained in repeated test by way of precaution. The validity of "I" and "O" vowels which stand in the same side of "A" vowel and further the symmetricity of the vowel "E" must be re-examined in further studies.

The numerical values of discrimination-width are given only for reference. Discrimination width defined as a measure of allowable deviation of source-frequency in the reproducing system and obtained by the direct comparison method is shown in Table 6. Smaller width means the keener (or higher) sensibility of the signal towards the distortion. Greater width means, on the contrary, duller (or lower) sensibility. The more complex the timbre construction becomes, the keener becomes its sensibility. It is our conclusion.

Discussion

The distortion RSD operates as a transitional distortion towards signals. For this reason the position study of timbre can be attained only by this distortion. We can make clear the physical construction of sounds by spectre analysis. But the problem of timbre quality cannot be solved unless we resort to subjective observation. Allowance test is very significant and even indispensable in timbre study. We have explained by giving the actual data of measurements. We can probably conclude that the complex sounds has smaller value in discrimination-width (*i.e.*, more keenly sensible to distortion) as they have more complicated timbre constructions. The problem of *symmetricity* or *unsymmetricity* of the allowance-characteristics in distortion RSD, and further, the problem of *skewedness* of the unsymmetrical shape (there arise two modes of skewedness, *i.e.*, the skewedness in U-domain and the skewedness in D-domain) will stimulate lively interest, and, moreover, they will be able to furnish the most significant and most precious informations when we pay some respect to the internal fine-structure of vocalic timbres. It will be very suggestive, in this case, to see how these delicate features are connected either with the so-called *phoneme quality* of vowelic voice or with its *vocal quality*. It is a question remained to be studied in near future.

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