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PERCEPTIBILITY OF PITCH CHANGES IN A TONAL SIGNAL EMITTED BY A MOVING SOURCE

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The starting point for the experimental research described here was a psychoacoustic analysis of the Doppler effect. The investigations were performed under laboratory conditions using an electronic model of a moving source. Data were obtained on the relationship between the sensations of pitch and loudness of a tonal signal under dynamic conditions.

1. Introduction

The starting point for the experimental research was a psychoacoustic analysis of the Doppler effect in the case of a tonal signal. The experimental investigations consisted in the considerations of the perceptibility by a static observer of a signal emitted by a moving source. This signal was characterized by a simultaneous change in its two physical parameters: frequency and intensity. Both quantities were also variable in time.

Analysis of the Doppler effect can, therefore, be reduced to the investigation of the perceptibility of pitch changes in a signal under the conditions of a simultaneous change in its loudness.

It can be assumed that the frequency f_0 of a tone emitted by a static source with respect to the observer is 1000 Hz. It can also be assumed in terms of the characteristic of motion of the source that it moves at the constant velocity v on a rectilinear trajectory distant by d from the static observer. Moreover, it can be assumed arbitrarily that the source passes the observer at the time $T = 0$. (Hence, the negative time half-axis corresponds to the source approaching the observer, the positive to the source moving away from the observer.)

The instantaneous values of the frequency $f(t)$ of the signal and the corresponding changes in the intensity level $L(t)$ of the same signal can be represented analytically by the following relations (cf. [5]):

$$f(t) = f_0\left(1 - \frac{v^2 t}{c\sqrt{(vt)^2 + d^2}}\right), \tag{1}$$

$$L(t) = L(d) + 10\log\left\{\frac{d^2}{(vt)^2+d^2}\left(1 - \frac{4v^2t}{c\sqrt{(vt)^2+d^2}}\right)\right\}, \tag{2}$$

where t – the time of the passage of the source with respect to the observer, $L(d)$ – the intensity level of the signal at the moment of the source passing the observer, and c – the propagation velocity of the tonal signal in the medium; with both relations valid under the assumption that $v \ll c$.

Fig. 1 shows, according to relations (1) and (2), the changes in the intensity level $L(t)$ of the signal and the corresponding changes in its frequency $f(t)$ over a 10-second motion of the source in the case when $v = 10$ m/s, $d = 10$ m ($c = 340$ m/s, $L(d) = 90$ dB).

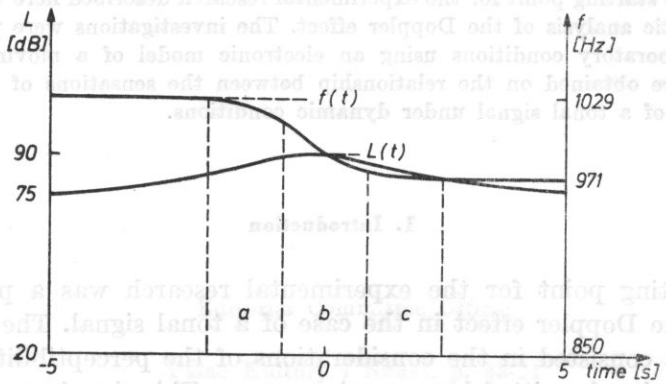

Fig. 1. Changes in the intensity level $L(t)$ of a signal and the corresponding changes in its frequency $f(t)$ over a 10-second motion of the source with respect to the observer ($v = 10$ m/s, $d = 10$ m)

a – the environment of the passage zone caused by the source approaching the observer, b – the passage zone, c – the environment of the passage zone caused by the source moving away from the observer

It follows from Fig. 1 that at both ends of the time interval the frequency changes in the signal are relatively slow compared to the frequency changes in the central part of the time interval under consideration. In the case of the source approaching the observer these changes occur against the background of increasing intensity level, while the source is moving away from the observer – against the background of decreasing intensity level.

Because of the motion characteristic of the source with respect to the observer this two-part area consisting of parts a and c, in which relatively slight frequency changes occur in the tonal signal, was called the environment of the passage zone. (The central part of the interval (b) was called the passage zone.) The experimental investigations described in this part of the paper concerned the environment of the passage zone.

2. Methodology of the experimental investigations

In the environment of the passage zone the point of interest was a determination of the dynamic, and at the same time generalized, frequency discrimination thresholds. (Such a definition of the thresholds can be justified by that when the source is moving the signal it emits changes simultaneously its frequency and intensity, and, therefore, the change perceived in the pitch of the signal is a function of two variables. Both physical parameters of the signal are also variable in time, and, therefore, pitch changes are also dynamic (cf. [1]).)

Tests for the psychoacoustic investigations were prepared in the following stages:

1. Tabulation by means of a computer of the instantaneous values of the frequency $f(t)$ and the intensity level $L(t)$ of the signal, according to relations (1) and (2), which occurred at every 10^{-1} s in the case of different velocities v of the motion of the source and different distances d of the motion trajectory from the observer, with the velocity v taking the values 10; 20; 30 m/s, and the distance d being 1; 5; 10 m.

2. Application in the experimental investigations of a purposebuilt electronic model of a moving source (cf. [2]). The results obtained correspond, therefore, only approximately to the real conditions of the Doppler effect perception, since the following factors were not represented in the model of the acoustic field constructed: the spatiality of sound radiation and detection and the damping of the acoustic wave by the medium. The results correspond, therefore, to an explanation of some general phenomena in a simultaneous perception of frequency and intensity changes in simple sounds rather than to detailed investigations of a specific physical effect.

3. Recording on punched tape of the parameters of acoustic signals, i.e. of the instantaneous values of frequency and intensity level, emitted by the source in both parts of the environment of the passage zone. The acoustic signals obtained from the electronic model of the source were turned into tests; the latter, in turn, were recorded on magnetic tape.

4. Presentation of tests by earphones to both ears of a listener.

The component signals of the tests consisted of increasingly longer time intervals when the source approached the observer (A_n) and increasingly shorter ones when the source moved away ($A_{n'}$). In both cases the intervals covered the whole area of the environment of the passage zone (cf. Fig. 2).

The durations of the particular component signals fell in the interval 4-7s, while the number of signals in a test varied between 5 and 17. (The number of signals in a test depended on the width of the environment of the zone passage, and, accordingly, on the distance d of the motion trajectory from the observer.) The order in which the particular components, (A_n or $A_{n'}$), occurred in a test was established by dependent random selection, i.e. each component signal was selected only once for a test.

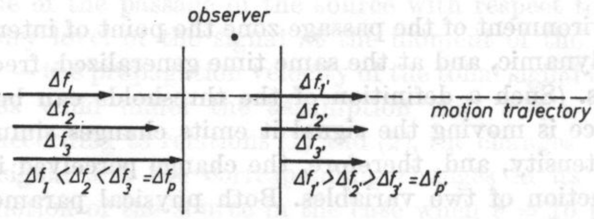

Fig. 2. A diagram for making the relevent test signals in the case of the source approaching the observer — A_n, and moving away from the observer — $A_{n'}$; → the signal emitted by the source, Δf_i — the frequency difference occurring in the signal

The pause between the particular component signals was 8s and was devoted to a listener's answer. Each test was begun by the 8-second signal A_0 of constant frequency and amplitude, i.e. a tone of the frequency $f_0 = 1000$ Hz and the intensity level $L(d) = 90$ dB, which corresponded to a signal emitted by the source at the moment of its passing the observer (cf. Fig. 3).

The investigations were performed on four listeners: two women and two men aged 22-30 years (one of them a musician). Before the investigations these listeners were examined audiologically and underwent a series of preliminary training-type investigations.

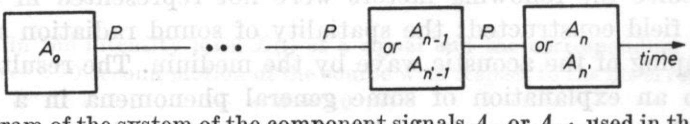

Fig. 3. The diagram of the system of the component signals A_n or $A_{n'}$, used in the experimental investigations; P — the pause

The listener's task was to answer the question as to whether in the course of a given signal (A_n or $A_{n'}$) a change in the frequency of this signal could be perceived, or not. There were two admissible answers: "yes" and "no". Each test was presented 20 times.

3. Analysis of the results

The results of the investigations were represented in the form of psychometric functions which gave the values of the dynamic generalized frequency discrimination thresholds Δf_p, obtained in the case of the source approaching the observer, and $\Delta f_{p'}$, obtained in the case of the source moving away from the observer. Figs. 4 and 5 show examples of the psychometric curve in both cases of the motion of the source with respect to the observer.

The specificity of the present investigations caused the psychometric curves obtained here to be different from the "classical" curves in two respects:

1. Changes in the frequency Δf of the signal are caused by motion of the source; and this fact determines the value of these changes, and, therefore, within successive signals A_n or $A_{n'}$ their frequency does not change by a constant value ($\Delta f \neq$ const).

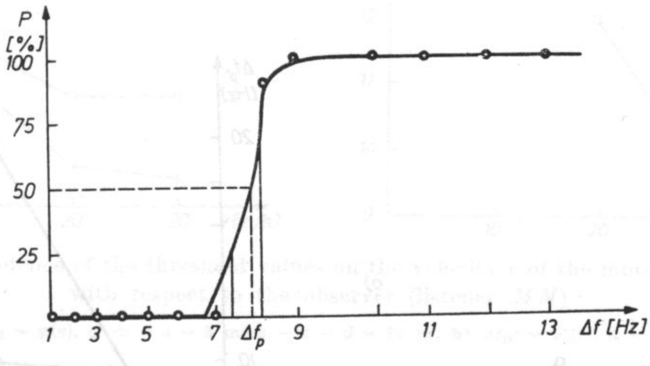

Fig. 4. The results of the experimental investigations in this part of the environment of the passage zone which corresponds to a source approaching the observer ($v = 10$ m/s, $d = 10$ m, $\Delta f_p = 8.30$ Hz, listener *MM*)

***1* – 1.05, *2* – 1.97, *3* – 2.81, *4* – 3.77, *5* – 4.65, *6* – 5.81, *7* – 7.36, *8* – 9.44, *9* – 10.75, *10* – 13.99, *11* – 15.97, *12* – 18.20, *13* – 20.67**

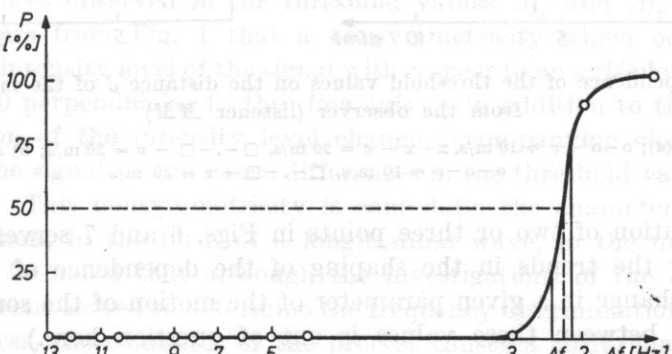

Fig. 5. The results of the experimental investigations in this part of the environment of the passage zone which corresponds to a source moving away from the observer ($v = 10$ m/s, $d = 10$ m, $f_p = 20.02$ Hz, listener *MM*)

***13* – 1.14, *12* – 2.06, *11* – 3.18, *10* – 3.86, *9* – 5.90, *8* – 6.62, *7* – 7.45, *6* – 8.41, *5* – 9.53, *4* – 10.84, *3* – 18.29, *2* – 20.76, *1* – 23.44**

2. The particular tests presented to listeners consisted of natural Doppler signals from a source in the area of interest, i.e. in both parts of the environment of the passage zone. In none of the signals, therefore, the frequency change Δf was equal to zero. (The signal A_0 emitted at the beginning of each test played the role of a kind of "a reference signal".) As a result of this, the point $\Delta f = 0$ is absent from the abscissa.

Fig. 6 a, b shows the dependence of the threshold values on the distance d of the motion trajectory from the observer. In turn, Fig. 7 a, b illustrates the dependence of the corresponding threshold values on the velocity v of the motion of the source with respect to the observer.

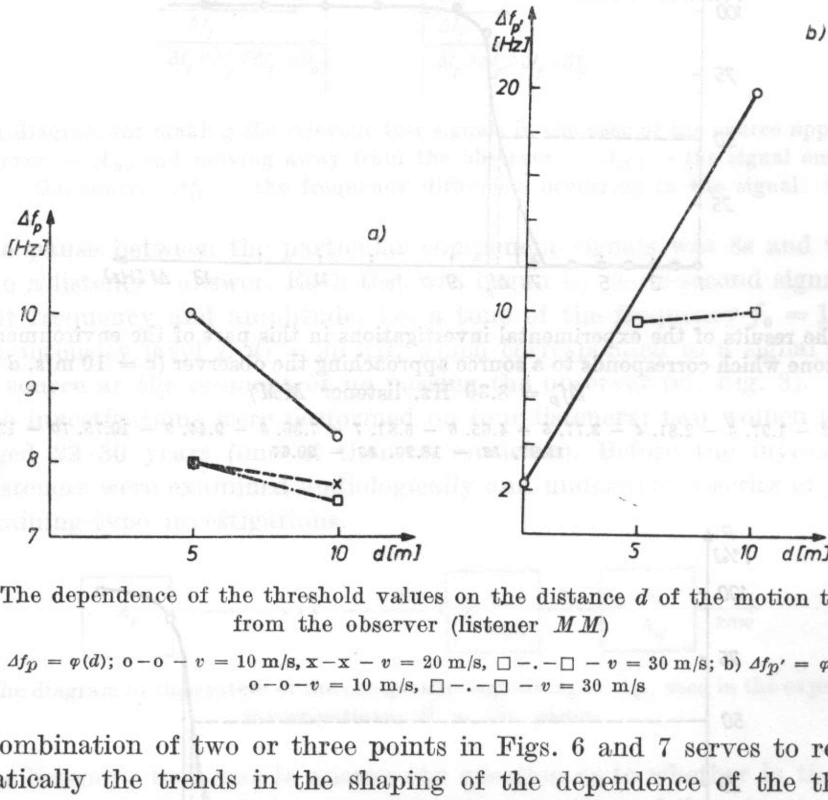

Fig. 6. The dependence of the threshold values on the distance d of the motion trajectory from the observer (listener MM)

a) $\Delta f_p = \varphi(d)$; o–o – $v = 10$ m/s, x–x – $v = 20$ m/s, □–.–□ – $v = 30$ m/s; b) $\Delta f_{p'} = \varphi(d)$; o–o–$v = 10$ m/s, □–.–□ – $v = 30$ m/s

(Combination of two or three points in Figs. 6 and 7 serves to represent schematically the trends in the shaping of the dependence of the threshold values on a change in a given parameter of the motion of the source; and any interpolation between these values is out of question here.)

It was found that the threshold values $\Delta f_{p'}$ are always greater than the corresponding values of Δf_p. This signifies that a change in the frequency of a signal which occurs against the background of decreasing intensity level is less perceptible (in the form of a change in the pitch of this signal) compared to the case when this change occurs against the background of increasing intensity level.

Explanation of the regularities observed should point out the following facts:

1. In signals from a source approaching the observer, i.e. in determination of Δf_p, a difference in the frequency of the signal, which can be perceived as a change in its pitch, occurs in the final time interval of this signal. In a signal from a source moving away from the observer, — i. e. in determination of $\Delta f_{p'}$ —however, this change occurs in the initial interval of the signal.

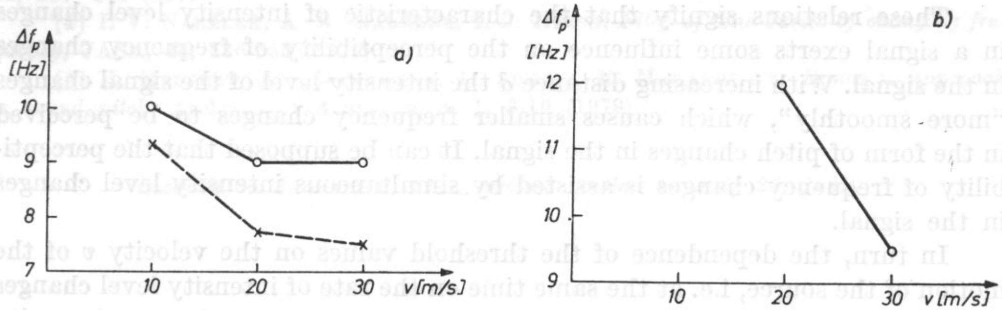

Fig. 7. The dependence of the threshold values on the velocity v of the motion of the source with respect to the observer (listener MM)
a) $\Delta f_p = \psi(v)$, o—o — $d = 5$ m, x — x — $d = 10$ m; b) $\Delta f_{p'} = \psi'(v)$, $d = 5$ m

According to NÁBĚLEK's suggestion [4], the listener estimates the pitch of a tonal pulse of varying frequency on the basis of an excitation model that is formed on the basic membrane at the moment when this pulse is ending. How the frequency of the signal changes in time is, therefore, significant for the process of the perception of the pitch of this signal. As a result, this may lead to differences observed in the threshold values Δf_p and $\Delta f_{p'}$.

2. It follows from Fig. 1 that a nonsymmetricity which occurs in the changes of the intensity level of the signal with respect to an axis plotted through the point $t = 0$ perpendicular to the time axis — in addition to the difference in the direction of the intensity level change accompanying changes in the frequency of the signal — can cause differences in the threshold values Δf_p and $\Delta f_{p'}$ obtained. (This nonsymmetricity is caused by the character of acoustic wave propagation, in the form of a longitudinal wave, in the medium.)

It should be noted that although the investigations of the environment of the passage zone served to determine the frequency discrimination thresholds, but, nevertheless, the character of the process causes a corresponding change in the intensity level of a signal, and also in its duration, to be "ascribed" to each threshold value in the frequency difference Δf_p or $\Delta f_{p'}$ since these values (frequency, intensity level, and duration of the signal) are closely interrelated. An exact analysis of the influence of changes in the intensity level and duration of the signal on threshold values obtained needs further investigations.

It follows from Figs. 6 and 7 that

1. In the case of the threshold values Δf_p:

(a) these values decrease with decreasing distance d, which means that smaller differences in the frequency of a signal are perceived as changes in its pitch;

(b) these values also decrease with increasing velocity v; although the change in the threshold values is different for the velocity change from 10 to 20 m/s than for that from 20 to 30 m/s (for the latter velocity change the threshold values change only very slightly).

These relations signify that the characteristic of intensity level changes in a signal exerts some influence on the perceptibility of frequency changes in the signal. With increasing distance d the intensity level of the signal changes "more smoothly", which causes smaller frequency changes to be perceived in the form of pitch changes in the signal. It can be supposed that the perceptibility of frequency changes is assisted by simultaneous intensity level changes in the signal.

In turn, the dependence of the threshold values on the velocity v of the motion of the source, i.e. at the same time on the rate of intensity level changes in the signal, can be explained preliminarily by that with such great intensity level changes the listener can find it difficult to identify the particular psychoacoustic parameters. He can thus take intensity level changes (which in classical approach correspond to pitch changes) for pitch changes in a signal (cf. under static conditions [1]).

2. In the case of the threshold values $\Delta f_{p'}$:

(a) their dependence on the velocity v of the motion of the source shows the same tendency as in the case of Δf_p;

(b) their dependence on the distance d of the motion trajectory from the observer is, however, contrary to that in the case of the threshold values Δf_p. This partly results from the fact that a full set of these values was not obtained in the case of the determination of the threshold values $\Delta f_{p'}$ (including those for the musician). The perceptibility of frequency changes in a signal under the conditions of a source moving away from the observer was rather difficult for the listeners.

4. Conclusions

On the basis of a psychoacoustic analysis of the Doppler effect data were obtained on relations between the sensations of loudness and pitch under dynamic conditions. It was found that intensity changes can in some cases make it easier, or more difficult in other cases, to perceive frequency changes in a signal. If follows in addition from experimental data that a frequency change in a signal against the background of decreasing intensity level is less perceptible than that against the background of increasing intensity level.

References

[1] A. Czajkowska, *Psychoacoustic analysis of perception and evaluation of simultaneous intensity and frequency variations in tonal signals* (in Polish), doct. diss., Adam Mickiewicz University, Poznań.

[2] U. Jorasz, A. Kamasa, J. Koludo, *Electronic model of a moving source* (in Polish), Archiwum Akustyki, **16**, 4 (1981).

[3] R. Makarewicz, *Intensity of sound field generated by a moving source*, Acustica, **41**, 267, 271 (1979).

[4] I. V. Nábělek, A. K. Nábělek, I. J. Hirsh, *Pitch of tone bursts of changing frequency*, JASA, **48**, 536-553 (1970).

[5] H. Ryffert, A. Czajkowska, U. Jorasz, R. Makarewicz, *Dynamic approach to sound pitch*, Archives of Acoustics, **4**, 1, 3-10 (1979).

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