COMPLEX SIGNAL REFLECTION IN THE PERIPHERAL PART OF THE HEARING SYSTEM AND DESCRIPTION OF PHONETIC ELEMENTS

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ABSTRACT

Frequency structure of signal reflection in the peripheral part of the human hearing system is evaluated in terms of the combined cochlear potential observed at the ear-drum level. The reflection appears to include components missing in the signal spectrum. The explanation proposed implies the possible effect of a hearing feedback which, unlike the hearing reflex, provides for the appearance of signal envelopes propagating along the cochlear partition as separate waves.

The study of signal processing in the peripheral part of the hearing system (PPHS) is essential for getting an insight into the mechanism of human sound-information perception. Complex signal reflection in PPHS is of particular importance. Here signal reflection will be defined as a spatial distribution of exciting effects along auditory-nerve-fiber endings, formed as a result of the signal transformation by hearing mechanisms, allowing for feedback effects.

Until recently feedback mechanisms had been overlooked in simulating signal transformation processes in PPHS. The implications were that a result of signal processing in PPHS is a frequency-coordinate transformation similar to spectral analysis which is correlated with the excitations of auditory-nerve-fiber endings. A reflection of this type is also extensively used in phonetic studies in the form of dynamic spectrograms.

Recent electrophysiological experiments, however, have provided evidence for the propagation of vibrations, corresponding to complex-signal combination tones even at low stimulation levels, in the cochlear hydrodynamic system /7/. The fact that frequency components missing in the signal spectrum may appear in the signal reflection is incompatible with the idea of PPHS as a linear system which deals only with separating the signal into frequency components.

In the literature available combination frequency vibrations are often viewed as a product of signal distortion in its non-linear transformation in the cochlear vibration system. However, experiments with narcotized animals involve certain difficulties in determining the informational significance of the combination vibrations observed. To investigate the role of combination vibrations in signal reflection in PPHS it is necessary that the fact of their existence should be established and their level estimated. When using phonetically meaningful sounds as stimuli, the existence of a certain component in the reflection can be correlated with a certain characteristic of its perception. Of particular importance is to establish that vibrations with frequencies missing in the signal spectrum do exist in human PPHS, and to lay down a model of the mechanism causing their occurrence.

In this study the method of electrocochleography involving analog and digital accumulation was used in combination with fast Fourier transform /4, 8, 3/ to obtain combined cochlear potentials (CCP) and to analyze the frequency structure of vibrations in the human cochlea.

Assuming that receptor structures of organ of Corti interact in an electromechanical way with the cochlear hydrodynamic system, a variable component of combined cochlear potentials is considered to reflect the motion of cochlear mechanical structures under the effect of the stimulus or vice versa /6/.

The experiment was intended to identify, in the signal reflection in PPHS, the components missing in the sound stimulus spectrum by means of analyzing the CCP appearing at the human ear-drum under the effect of a complex sound stimulus.

Fig.1 shows two-tone stimulus spectrum (I) and typical CCP spectra successively for one subject, given two values of volume of sound.

Fig.2 shows the spectrum of vowel "a" (I) and the CCP spectrum (II) for the same subject. The comparison of the stimulus spectra with the CCP spectra reveals that the latter include components missing in the former. With a two-tone stimulus, a component of this kind is primarily the f_1-f_2 frequency component. The level of the newly appearing components has a value close to that of the level of response to spectral components present in the spectrum.

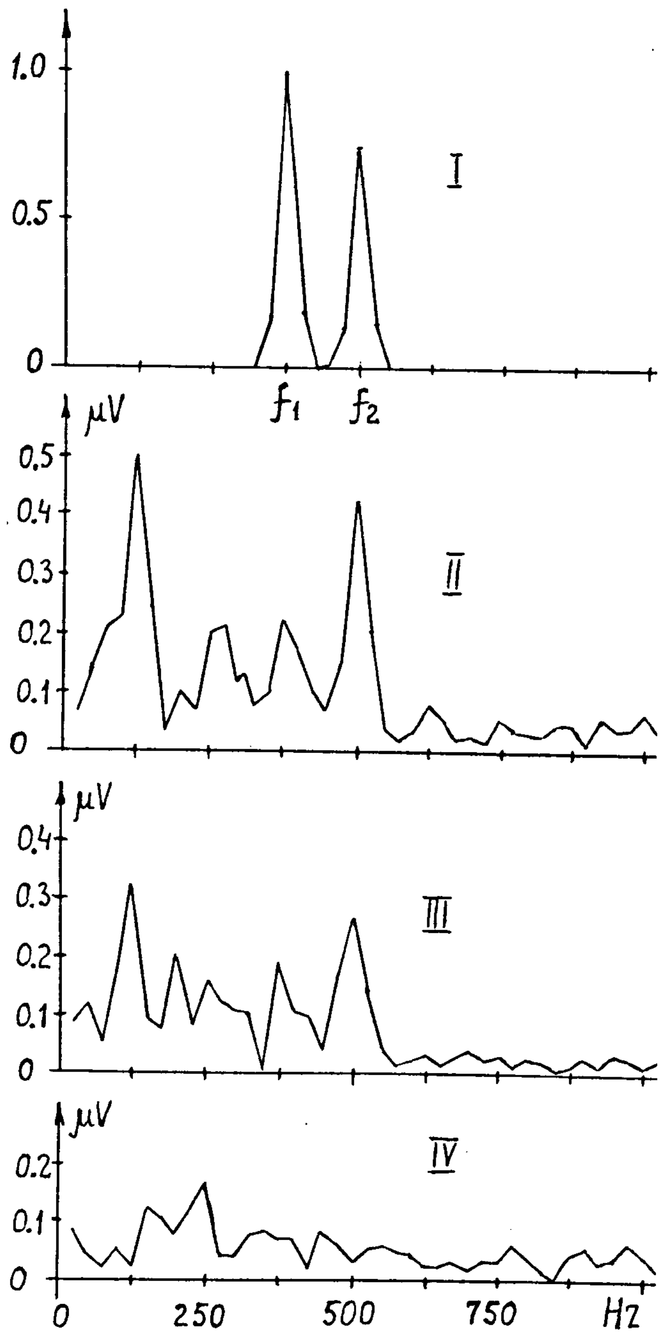

Fig.1. Two-tone stimulus reflection in the spectrum of CCP measured at the human ear-drum.
I - two-tone stimulus spectrum; II - CCP spectrum at the 100 db SPL stimulus level; III - CCP spectrum at the 85 db SPL stimulus level; IV - spectrum of noises measured at the human ear-drum level in an analogous accumulation mode. The pattern of the stimulus spectrum is shown in relative normalized counts in Y-axis. Quantization range - 156.4 mcsec.; number of counts in a sampling - 256; number of accumulated samplings - 1024.

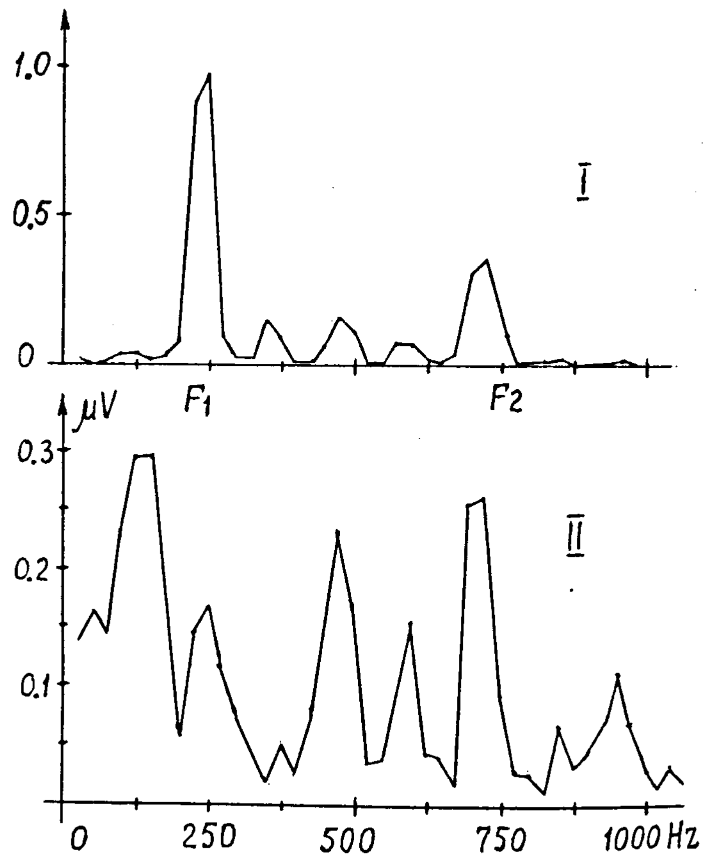

Fig.2. Vowel spectrum reflection in the spectrum of CCP measured at the human ear-drum.
I - spectrum of vowel "a"; II - CCP spectrum at the 95 db SPL level of volume of sound. The measuring conditions are identical to those listed in the caption of fig.1.

Fig.2 demonstrates that the general pattern of the spectrum of response to a vowel is significantly different from that of the spectrum of the vowel presented at the input of the human hearing system.

The most convenient way of discussing the results obtained is to make use of the model of signal transformation in PPHS. The functional structure of such a model was described in /10, 11/. Compared to the earlier models of signal transformation in PPHS /3/, the model under discussion includes a mechanism realizing the feedback which significantly affects signal reflection in PPHS.

Consider the possible properties of the mechanism in question.

The possibility that in addition to the feedback circuit ensuring hearing reflex there exists in PPHS a feedback effected along the signal envelope was first suggested in /10/. The mechanism realizing the latter feedback was termed "hearing feedback". It was also shown that the action of this mechanism may account for the effects such as residual tones and inhibition of the first harmonic of microphonic potential /12/.

It is obvious that the inhibition of the first harmonic of microphonic potential /12/ can be accounted for by the existence of the hearing feedback, provided the value of a difference-frequency component stipulated by its effect is comparable to that of the response to the first harmonic of the stimulus. The experimental results shown in fig.1 indicate that the amplitude of the f_2-f_1 frequency component of CCP spectrum and that of the f_1 frequency component of CCP spectrum are values of the same order of magnitude.

Thus, experimental evidence has been obtained for the assumption that the inhibiting effect may be accounted for by the effect of the difference-frequency component of CCP spectrum. Again, the value of this component being great, it is possible to assume that its informational significance is by no means less than that of the CCP spectrum components caused by the effect of those components which are present in the stimulus spectrum. Accordingly, a similar explanation of residual tone perception is available.

The fact that the relative amplitude of the CCP spectrum component resulting from the effect of the stimulus whose spectrum does not include such component is not dependent on the stimulus level indicates that the component in question is caused by the action of a specialized parametric mechanism dealing with separation of the signal informational characteristics rather than by non-linear distortions in transforming the signal in PPHS.

A problem to be solved concerned experimental identification of the paths taken by the signal envelope to get back to the analyzer part of PPHS, i.e. to the cochlea, upon being formed. One possibility suggested in /10, 11/ was the "cochlea - receptor cells - auditory nerve - facial nerve - stapes - cochlea" circuit. The newly obtained experimental data make it possible to consider the "cochlea - receptor cells (acting as envelope extractors) - cochlea" circuit as well.

Upon getting to the inner ear by either way, the envelopes are propagated along the basilar membrane and form the maximum deflection at a corresponding point, thus producing a new channel where a new envelope can be extracted whose variable component will again pass along the feedback circuit and will be summed up with other envelopes etc. until a dynamic equilibrium reflection of the stimulus is obtained. Thus, the hearing feedback model appears to be an integral part of the model of PPHS analyzer part and the whole system should be viewed as a parametric non-linear signal analyzer, with its characteristics depending, alongside with other factors, on the type of signals being analyzed. Realization of the hearing feedback model requires concrete definition of the envelope, formulation of the rules of its formation and introduction of PPHS in the analyzer part of the model.

A possible technical realization of the hearing feedback model is described in /1/. As follows from the fundamental scheme of the model/1/, the output signal reflection will include frequency components missing in the analyzed signal, their frequency values characterizing the mutual disposition of the signal spectral components. Occurrence of reflection components resulting from secondary interactions is also possible.

Correlating vowel spectra to the frequency structures of their reflections in PPHS shown in fig.2, it can be seen that the latter include spectral components missing in the stimulus when the frequencies of components in the stimulus spectrum are close enough. Thus, the CCP spectrum of vowel "a" includes F2-F1, F2+F1 frequency components.

The foregoing implies that envelope extraction in non-linear analyzer channels is significantly affected by a frequency-selectivity formation mechanism referred to in the literature as that of sharpening of cochlear gain-frequency characteristics (GFC). As stated above, the earlier studies /3/ make it possible, by using non-linear transformations, to lay down a model ensuring a sufficient degree of cochlear GFC sharpening to account for the difference between the shape of auditory-nerve frequency-threshold curves and GFC of cochlear hydrodynamic system.

Recent experiments /13/ have demonstrated, however, that at low signal levels the cochlear GFC themselves appear to have a shape close to that of auditory-nerve frequency-threshold curves.

The only seemingly possible way of accounting for the above effects is to assume the existence of an electromechanical interaction of receptor cells with cochlear vibration systems, presuming the interaction to form local feedbacks of quick-response leading to regeneration processes.

Alongside with the new experimental evidence, a model of the sharpening mechanism must also make allowance for the whole complex of properties recognised in the earlier studies of signal processing in PPHS disregarding feedback effects.

The basic principles of a model of cochlear GFC sharpening mechanism amount to the following.

1. At low vibration levels cochlear GFC are to be close to auditory-nerve frequency-threshold curves.
2. At high vibration levels cochlear GFC are to be close to those measured by von Békésy.
3. The structure of spatial-frequency signal reflection in PPHS is characterized by the location of auditory-nerve fibers with given characteristic frequencies in the low-frequency slope area of the amplitude-coordinate characteristic of the basilar membrane /6/.
4. The effect of one harmonic signal involves an increase of neuron pulsation frequency above the threshold value only in a relatively narrow range near the values of the signal frequency close to the characteristic frequency.
5. With the effect of two signals, one being tuned to the characteristic frequency of the neuron observed and the other being a test signal, neuron pulsation frequency at low test-signal intensities is considerably higher than the spontaneous one throughout the range of test signal retuning.
6. The increase in test signal intensity with certain kinds of detuning is accompanied by the formation of inhibition areas. The width and depth of the areas increase with an increase of test signal intensity.
7. The inhibition areas are asymmetrical in relation to the characteristic frequency, being deeper towards the high-frequency region.

The above requirements are met by the model of PPHS GFC formation which includes a frequency-coordinate transformer /5/ with a frequency-dependent voltage transformation device /2/. The degree of feedback can be controlled as described in /9 /. A calculation has revealed that the scheme allows sharpening of PPHS GFC by a factor of 20 to 24, while preserving a phase characteristic close to the linear one.

From the above considerations the following conclusions can be drawn. Signal reflection in PPHS appears to be a result of both a complex interaction of non-linear mechanisms of vibration processing in the inner ear and the effect of feedback circuits due to electromechanical interaction of receptor systems of organ of Corti with cochlear partition vibration system, as well as of the circuits realizing hearing feedback. Since the formation of signal reflection in PPHS involves the appearance of components missing in the spectrum of the stimulus signal and may be accompanied by secondary interaction of these components, one should expect the reflection to differ considerably from the stimulus spectrum, particularly with speech signals whose form is fairly complex.

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