ARCHIVES OF ACOUSTICS
20, 2, 115–138(1995)

LINEAR AND JUMP FREQUENCY CHANGES OF A SIGNAL IN A ROOM

L. RUTKOWSKI and E. OZIMEK

Institute of Acoustics
Adam Mickiewicz University
(60–769 Poznań, ul. Matejki 48/49)

The paper discusses the deformation of the instantaneous frequency of signals with linear and jump frequency changes propagating in a room. The instantaneous frequency deformation in a room has been compared on the basis of theoretical and experimental data. It was found out that deformation of the instantaneous frequency for linear and jump frequency changes reached extreme value at the minima of the amplitude of the resultant signal. For linear frequency changes the deformation is proportional to the rate of frequency changes, and to the delay time of the reflected wave. In turn, for jump frequency changes, the deformation increase with an increase in the jump value. The instantaneous frequency reaches final value after a time equal to the reverbation time of a room.

1. Introduction

An acoustic signal propagating in a room is deformed both in the amplitude and frequency domains. Sound deformations in a room in the amplitude domain has been discussed in the literature [2, 3, 4, 6]. Results of the investigations led to the development of an objective method of speech intelligibility in a room, called the RASTI method [4]. This method is based on the concept of the Modulation Transfer Function (MTF) adopted to the room acoustics [3]. The (MTF) represents the modulation depth reduction as a function of modulation frequency. So far much less attention has been devoted to signal distortion by the acoustical parameters of a room in the frequency domain. The problem is important with reference to the propagation in a room of real sounds such as speech and music which are characterized by a considerable variability in the frequency domain. Our first approach to the problem [8, 9, 10, 12, 14] indicated the existence of a number of interesing effects. The basic issue when evaluating effects connected with sound deformation in a room is to get quantitative relations between the transmitted sound and the sound received in a certain points of a room. A preliminary analysis of the problem has been discussed in paper [7]. In the theoretical part of the paper general dependencies between the transmitted and received sound in the aspect of a spectral-correlational analysis were given. In the experimental part, changes in the spectral structure of complex sounds, propagating in selected rooms (models), with different spatial configuration and different reverberation times were determined. It has been found out that the value of changes is different in growth, steady state and decay process of a signal and depends on the location of the measurement point and the type of analysed sounds.

Sound deformation in a room was also discussed in the aspect of the multi-dimensional space theory [8, 9]. Assuming that the space of acoustic states of a room affects the signal space, producing as a result its deformation, relations between elements of these spaces were analyzed. We were also considering the possibilities of determining acoustic states of a room on the basis of the classification of sound deformation states.

Another interesting aspect of the frequency sound structure deformation in a room is the problem of changes in the so-called sound instantaneous frequency in the process of the growth and decay of signal [10, 14]. Generally, the resultant acoustic pressure in the sound growth or decay in a room can be treated as the signal of an amplitude and phase changeable time, which approximately can be expressed as follows:

$$p(t)=p_0(t)\cos\varphi(t), \tag{1.1}$$

where: $p_0(t)$ — acoustic pressure amplitude, $\varphi(t)$ — instantaneous phase of acoustic pressure.

The instantaneous phase $\varphi(t)$ of the resultant signal can be expressed as:

$$\varphi(t)=\omega_0 t+f(t), \tag{1.2}$$

where: ω_0 — frequency of the signal transmitted into the room, $f(t)$ — the function „modulating" the phase of the signal transmitted into the room.

Function $f(t)$ represents jump changes of the phase of the resultant signal, resulting from the summation of the direct sound and successive reflections with different phase shifts. These jump phase changes cause a change in the time interval between successive zero crossings of the resultant signal.

On setting the instantaneous phase derivative in relation to time we get a value which characterizes the rate of changes of that phase, this being called instantaneous frequency:

$$\omega(t)=\frac{d\varphi(t)}{dt}=\frac{d}{dt}[\omega_0 t+f(t)]=\omega_0+\frac{df(t)}{dt}, \tag{1.3}$$

or otherwise

$$f(t)=\frac{1}{2\pi}\frac{d\varphi(t)}{dt}.$$

More details on the instantaneous frequency and its measurability are given in papers [1, 10]. It is interesting to note that in the literature [13] one may also find another definition of instantaneous frequency, based on the analysis of the number of zero crossings of the real signal investigated. In this case instantaneous frequency is defined as the ratio of the number of zero crossings of this signal, determined over some time interval $\Delta\tau$, and the value of this interval. This ratio corresponds to the mean density of zeros of the signal over this interval and is sometimes called Rice frequency (f_R):

$$f_R = \lim_{T\to\infty} \frac{N}{\Delta\tau},$$

where N is the number of „positive" or „negative" zero crossings of the signal and $\Delta\tau$ is the averaging time interval.

According to (1.3), the sound instantaneous frequency, measured in the growth or decay process, is not equal to the frequency generated into the room but varies (fluctuates) around that value in agreement with the derivative of $df(t)/dt$. Quantity $\omega(t)$ as defined by expression (1.3) is thus a theoretical one, as it determines the value of the instantaneous frequency at a given time t, which cannot be implementend in experimental conditions. In these conditions, in expression (1.3) the differential quantities were replaced by the difference ones, i.e.

$$\omega(\Delta t) = \frac{\Delta\varphi}{\Delta t}. \tag{1.4}$$

In keeping with expression (1.4), the measure of the instantaneous frequency of the signal is the ratio of its phase change $\Delta\varphi$, occurring in the time interval Δt, over the duration of this interval. It has been generally stated that observed changes in the instantaneous frequency in a room have a random character and are within the range of several Hz. In a few special cases they can reach much greater values [10, 14].

2. Signal with linearly changing frequency

Let us consider a case when a sinusoidal signal, whose frequency is increasing linearly, is transmitted into the room, i.e.

$$\omega(t) = \omega_0 + \alpha t, \tag{2.5}$$

where: ω_0 — initial frequency, α — rate of frequency changes.

Let us assume that at a measuring point of the room there is a superposition of the direct wave and the first reflected wave which will reach the measuring point with a certain delay Δt (Fig.1).

Let us notice that as soon as the reflected wave reaches the measuring point, at any time t (e.g. 500 or 800 ms cf. Fig.1) there is a constant frequency difference between the direct and reflected waves, equal $\Delta f = 10$ Hz. In this case an effect similar to beating will occur. However, the effect is more complex because that frequency

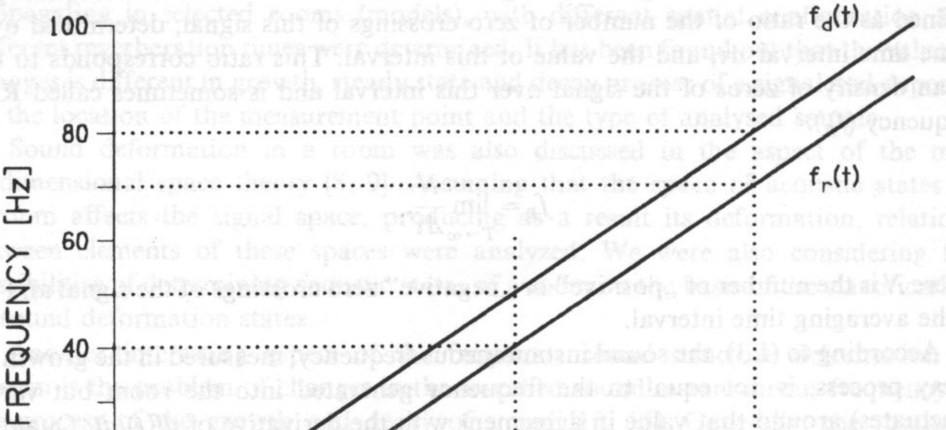

Fig. 1. Changes in instantaneous frequency in time for a direct wave $f_d(t)$ and reflected wave $f_r(t)$ (for clarity, time delay of the reflected wave equals $\Delta t = 100$ ms).

variations in time are continuous. For the assumed character of frequency changes the signal can be written as follows:

$$x(t) = x_0 \sin(\omega_0 t + \varphi_0 + \frac{\alpha t^2}{2}). \tag{2.6}$$

In the case of the direct wave and the reflected wave, the linear frequency change can be expressed as follows:

- direct wave: $\omega_d(t) = \omega_0 + \alpha t$,
- reflected wave: $\omega_r(t) = \omega_0 + \alpha(t - \Delta t)$.

The resultant signal at the measuring point in the room is equal:

$$x_{res}(t) = x_{0d} \sin(\varphi_d(t)) + x_{0r} \sin(\varphi_r(t)),$$

where: x_{0d}, x_{0r} — amplitudes of the direct and reflected waves, $\varphi_d(t), \varphi_r(t)$ — phases of the direct and reflected waves.

Phases of the direct and reflected waves, given that the initial phase $\varphi_0 = 0$, can be expressed as follows:

$$\varphi_d(t) = \omega_0 t + \frac{\alpha t^2}{2}, \tag{2.7}$$

$$\varphi_r(t)=\omega_0 t+\frac{\alpha t^2}{2}-\alpha \Delta t\ t. \tag{2.8}$$

The output signal resulting from the superposition of the direct and reflected waves can be written in the following form:

$$x_{\text{res}}(t)=A(t)\sin(\omega_0 t-\Phi(t)), \tag{2.9}$$

where: $\omega_0 t-\Phi(t)=\Phi_{\text{res}}(t)$ — phase of the resultant signal.

Considering the amplitudes and phases for the direct and reflected waves, following trigonometric transformations, we find formulae describing temporal changes of the instantaneous frequency and amplitude envelope. Changes in the frequency of the resultant signal:

$$\omega_{\text{res}}(t)=\frac{d\Phi_{\text{res}}(t)}{dt}=\omega_0+\alpha t-\frac{\alpha\Delta t(\delta^2+\delta\cos(\alpha\Delta tt))}{1+\delta^2+2\delta\cos(\alpha\Delta tt)}. \tag{2.10}$$

Changes in the amplitude envelope:

$$A(t)=x_{0d}\sqrt{1+\delta^2+2\delta\cos(\alpha\Delta tt)}, \tag{2.11}$$

where δ — the ratio of amplitudes of the reflected and the direct waves.

It can be seen in expression (2.10) that changes in the instantaneous frequency of the resultant signal occuring as a result of the superposition of two signals with linearly growing frequency have a more complex character than in the case with the elementary effect of beating. The amplitude envelope variation of the resultant signal is like the beating of two sinusoidal signals with a constant frequency difference.

3. Signal with jump changes of frequency

Let ut consider a case of a sinusiodal signal propagation in a room for which at a certain time a frequency jump appears. Such a change can be obtained by means of frequency modulation of the signal by a rectangular wave. The modulated signal $x(t)$ has the form:

$$x(t)=x_0\sin\left[\int_{-T/2}^{T/2}(\omega_1+\Delta\omega 1(t))dt\right]=x_0\sin\left[\int_{-T/2}^{T/2}\omega(t)dt\right], \tag{3.1}$$

where:

$$\omega(t)=\omega_1+\Delta\omega 1(t),$$

$$1(t)=\begin{cases}1 & \text{for } -T/2<t<0\\ 0 & \text{for } 0<t<T/2\end{cases},$$

$$\Delta\omega=\omega_2-\omega_1,$$

$$T=\frac{1}{f_m},$$

and ω_1 — the initial frequency value (i.e. before the jump), ω_2 — the final frequency value (after the jump), f_m — frequency of the rectangular modulation wave, $\Delta\omega/2$ — frequency deviation.
The conventional value of the carrier frequency of FM signal will be equal to:

$$\omega_0 = \omega_1 + \frac{\Delta\omega}{2}.$$

For relatively low frequency values of the rectangular signal ($f_m \to 0$) in the spectrum of the frequency modulated signal only two components with frequencies $\omega_1 + \Delta\omega/2$ and $\omega_2 - \Delta\omega/2$ can be distinguished. If a sinusoidal signal with a constant amplitude A and phase φ is transmitted into the room, then this signal, in a steady state, for frequency ω_1 can be represented in the following form:

$$x(t) = A \mid H(j\omega_1) \mid \sin(\omega_1 t), \tag{3.2}$$

Similary for frequency ω_2 one can write:

$$y(t) = A \mid H(j\omega_2) \mid \sin(\omega_2 t), \tag{3.3}$$

where: $\mid H(j\omega) \mid$ — the value of amplitude frequency response for frequency ω.
Let us further assume that at time $t=0$ a signal frequency jump from value ω_1 to value ω_2 occurs. After the frequency jump, given the assumption of an exponential sound decay, signal amplitude, for frequency ω_1 will decrease in accordance with function:

$$x(t) = A \mid H(j\omega_1) \mid \exp(-kt)\sin(\omega_1 t). \tag{3.4}$$

In turn, signal amplitude, for frequency ω_2 will increase according to the form:

$$y(t) = A \mid H(j\omega_2) \mid [1 - \exp(-kt)]\sin(\omega_2 t), \tag{3.5}$$

where $k = 13.8/T_{60}$, T_{60} — room reverberation time for 60 dB decay. Let us assume that in the frequency range in question, in which the jump occurs, the dependence of the reverberation time on frequency is a slow-changing function.

At a certain time after the frequency jump, there will be a superposition of the decaying signal of frequency ω_1 and the growing signal of frequency ω_2. The resultant signal will be

$$z(t) = X_0 \exp(-kt)\sin(\omega_1 t) + Y_0[1 - \exp(-kt)]\sin(\omega_2 t). \tag{3.7}$$

where $X_0 = A \mid H(j\omega_1) \mid$, $Y_0 = A \mid H(j\omega_2) \mid$.
Next, we transform equation (3.7) to the following form:

$$z(t) = R(t)\sin(\varphi_r(t)),$$

where $R(t)$ — amplitude envelope of the resultant signal, $\varphi_r(t)$ — phase of the resultant signal.

After trigonometric transformations we get the following formula describing changes in instantaneous frequency after the frequency jump:

$$\omega(t)=\frac{d\varphi_r(t)}{dt}=\omega_1+\Big\{Y_0^2\Delta\omega(1-\exp(-kt))^2+X_0Y_0\exp(-kt) \\ \times[k\sin(\Delta\omega t)+\Delta\omega(1-\exp(-kt))\cos(\Delta\omega t)]\Big\}\cdot\frac{1}{R^2(t)} \tag{3.8}$$

where

$$R(t)=\sqrt{X_0^2\exp(-2kt)+Y_0^2(1-\exp(-kt))^2+2X_0Y_0\exp(-kt)(1-\exp(-kt))\cos(\Delta\omega t)}$$

— amplitude envelope after frequency jump.

On the basis of expression (3.8), calculations of changes of instantaneous frequency and the amplitude envelope of the signal after the frequency jump were made. The results of calculations allow to analyze these changes in detail with respect to such parameters as: the range of frequency jump Δf, room reverberation time T and quantity $\delta = |H(j\omega_2)| / |H(j\omega_1)|$.

4. Results of calculations and experiment for linear frequency changes

In order to check the machanism of the instantaneous frequency changes for linear FM, computer calculations were performed. For clarity of interpretation we took into account the superposition of direct and reflected waves. The aim of the calculations was to show how the rate of frequency changes, amplitude and time relations influence the resultant signal of instantaneous frequency changes.

Figures 2 and 3 show changes in frequency and the amplitude envelope for the ratio of amplitudes of the reflected wave to the direct wave $\delta=0.85$, delay of the reflected wave $\Delta t=20$ms and the rate of frequency changes α, respectively 250Hz/s and —250Hz/s.

Characteristic deflections of instantaneous frequency from the linear dependence, indicated in Fig.2 and 3 by a dotted line, can be observed. Minima of the amplitude envelope correspond to extreme frequency deflections, irrespective of their direction.

It was interesting to find out to what extent the instantaneous frequency changes depend on such parameters: α — rate of frequency changes, δ — the ratio of the amplitudes of the reflected wave to the direct wave, Δt — time delay of the reflected wave. For this purpose, computer calculations were made whose results are shown in Fig. 4–6. The results, for clarity of the drawings, only refer to the deformation introduced as a result of the superposition which in reality occurs at the background of the linear frequency (cf. Fig. 2–3).

Analyzing the data shown in Fig. 2, 3 and 8 one can generally say that the minima of the amplitude envelope correspond to considerable deflections of the signal instantaneous frequency. The value of the deflection (Fig. 4–8) depends on the rate

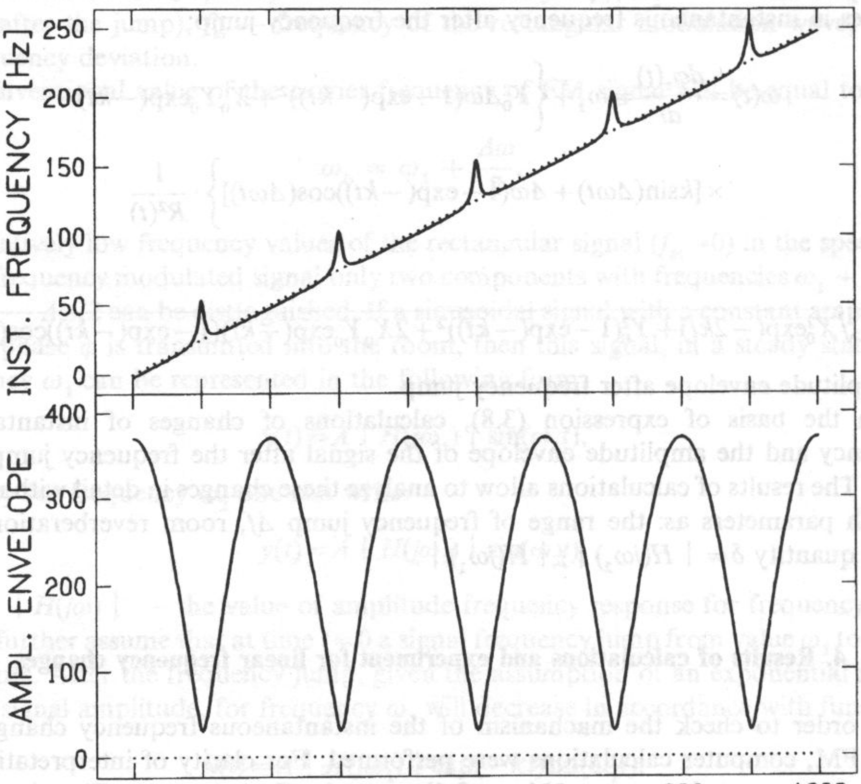

Fig. 2. Computer calculations of changes in instantaneous frequency and amplitude for a signal with a linearly growing frequency, for $\alpha = 250$ Hz/s, $\delta = 0.85$ and $\Delta t = 20$ ms.

of frequency changes, delay time of the reflected wave and the ratio of the amplitudes of the reflected wave to the directed wave. The frequency for which extreme deflection of frequency occurs depends linearly on the product of the rate of frequency changes α and time dealy Δt; this frequency corresponds to the frequency of changes in the amplitude envelope (Fig. 2–3). Furthermore, one can notice that with the increase in the amplitude ratio δ (Fig.5), deflections of instantaneous frequency lose their quasi-sinusoidal character and for large values of δ assume the form of short, one-sided deflections of high value. The direction of extreme frequency changes depends on the direction of frequency changes in the direct signal (sign at α) and whether coefficient δ is smaller or greater than 1. The time interval in which single frequency deflection occurs is inversely proportional to the rate of frequency changes, echo delay time, and the amplitude ratio δ.

The above results pertaining to instantaneous frequency changes refer to a relatively simple case of the superposition of a direct wave with one reflected wave.

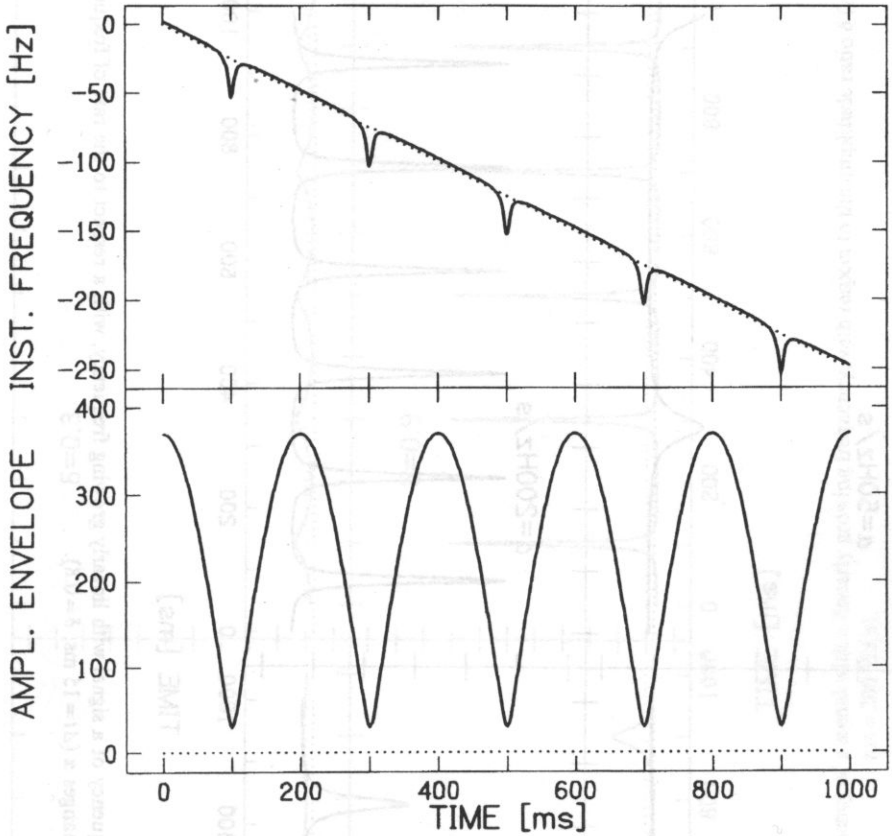

Fig. 3. Computer calculations of changes in instantaneous frequency and amplitude for a signal with a linearly growing frequency, for $\alpha=-250$ Hz/s, $\delta=0.85$ and $\Delta t=20$ ms.

Nevertheless, they permit an initial qualitative and quantitative analysis of deformation in the signal in the frequency domain. Computer analysis of frequency changes for a larger number of reflections is much more complex and does not permit a clear interpretation of these changes due to the growing number of signal parameters.

At the next stage of investigations, measurements of instantaneous frequency changes for a real room, i.e. under conditions in which a large number of reflections exist, were performed.

The measuring setup used in the investigations consisted of two sets — the transmitting set and the receiving set. The transmitting set consisted of computer (IBM PC486) which generated FM signals (linear or jump frequency changes) through 16 bit digital to analog converter, at sampling rate of 48.1 kHz and low pass filter at 8 kHz cut-off frequency. The signals were next supplied to the power amplifier and loudspeaker. The receiving set which consisted of two microphones with preamplifiers was connected to frequency demodulators and 16 bit analog to

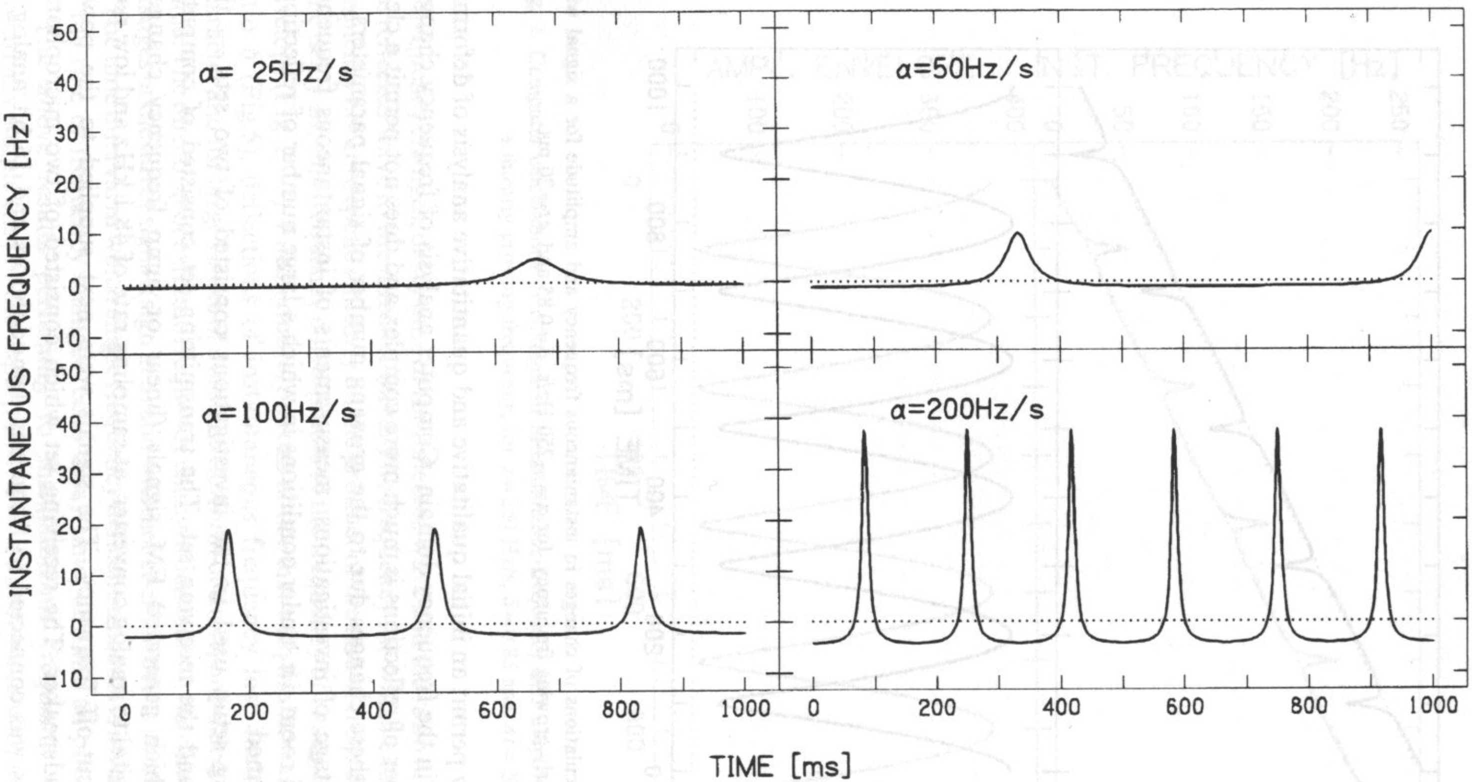

Fig. 4. Computer calculations of changes in instantaneous frequency of a signal with linearly growing frequency, with a respect to the rate of frequency changes α ($\Delta t = 15$ ms, $\delta = 0.8$).

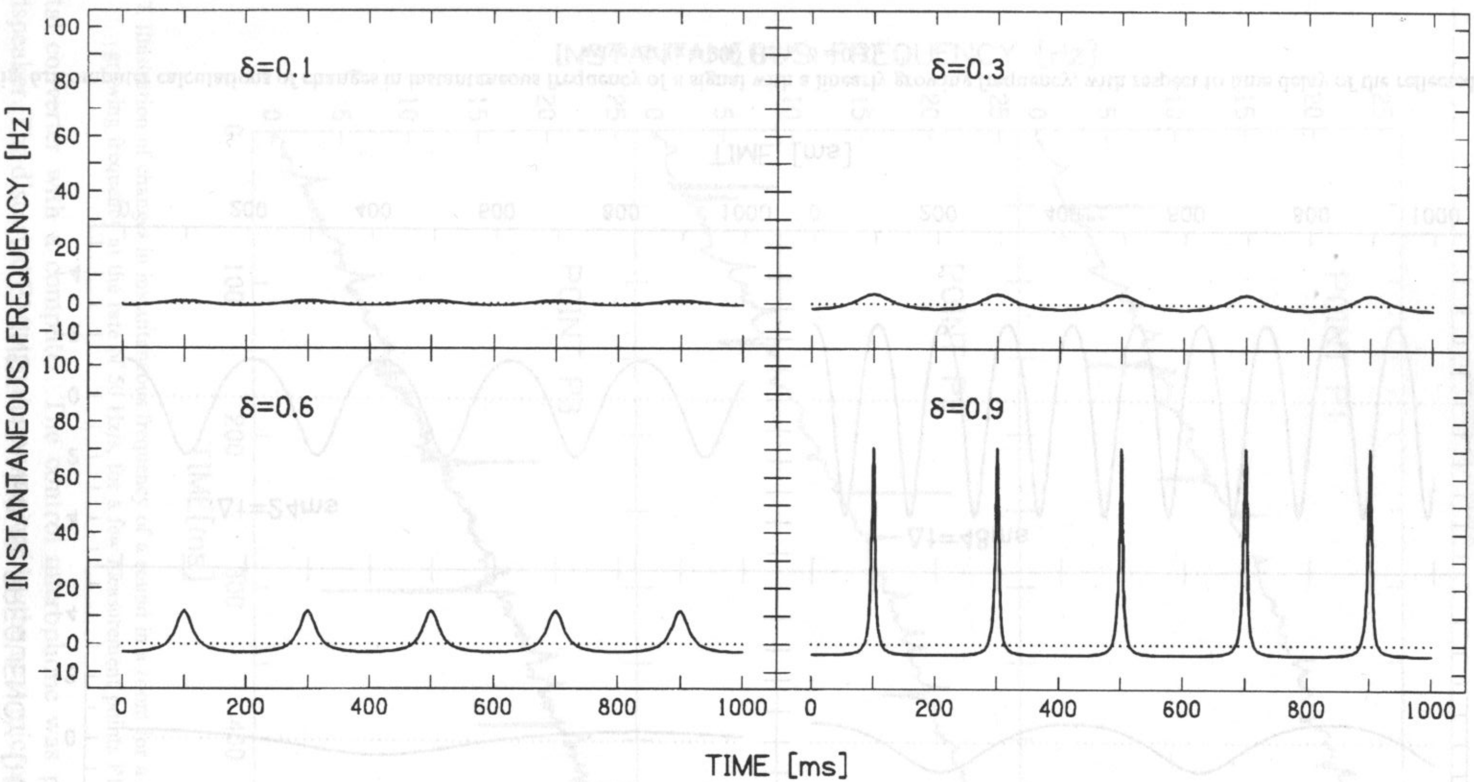

Fig. 5. Computer calculations of changes in instantaneous frequency of a signal with a linearly growing frequency, with respect to the amplitude ratio δ ($\Delta t = 25$ ms $= 200$ Hz/s).

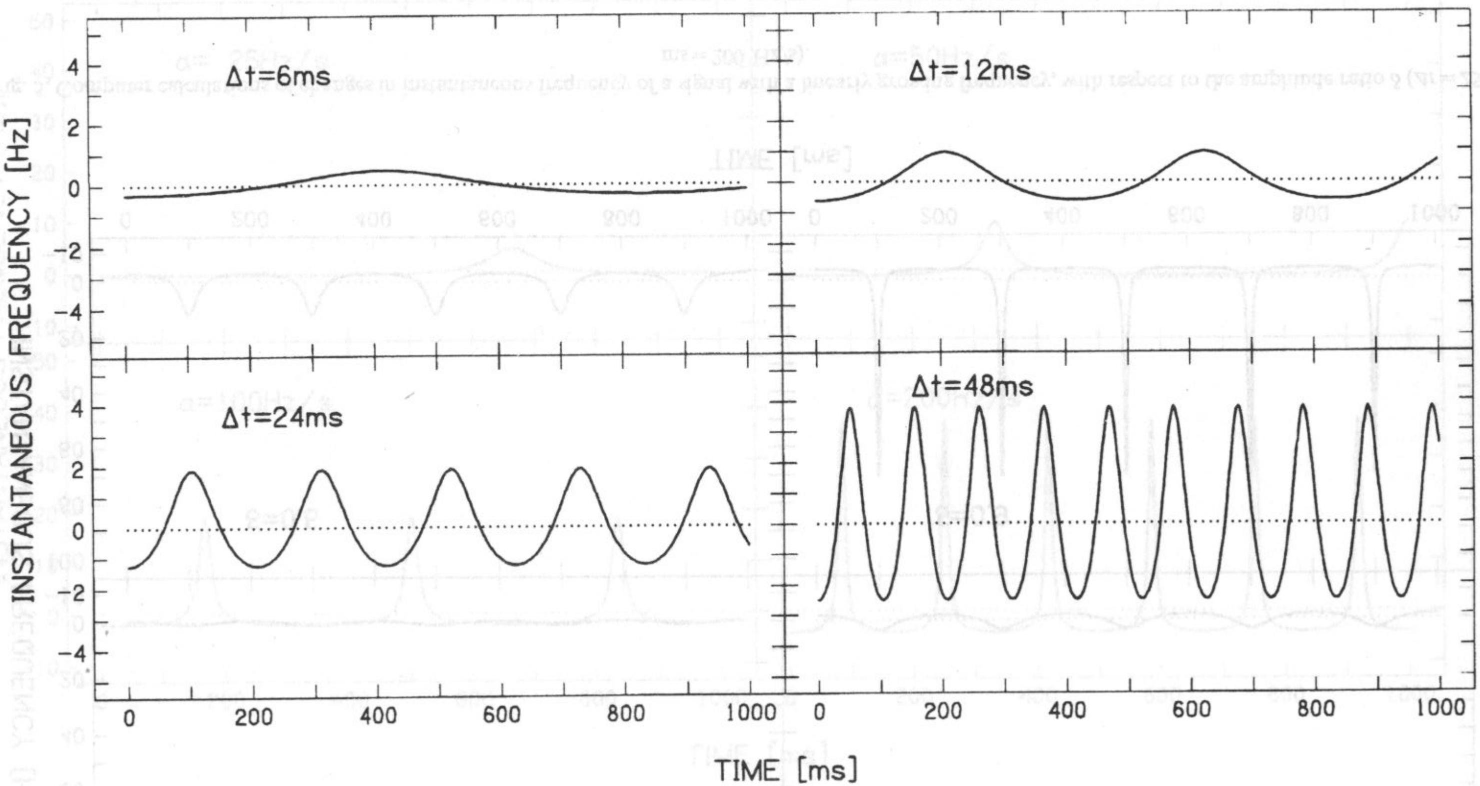

Fig. 6. Computer calculations of changes in instantaneous frequency of a signal with a linearly growing frequency, with respect to time delay of the reflected wave Δt ($\alpha = 200$ Hz/s, $\delta = 0.2$).

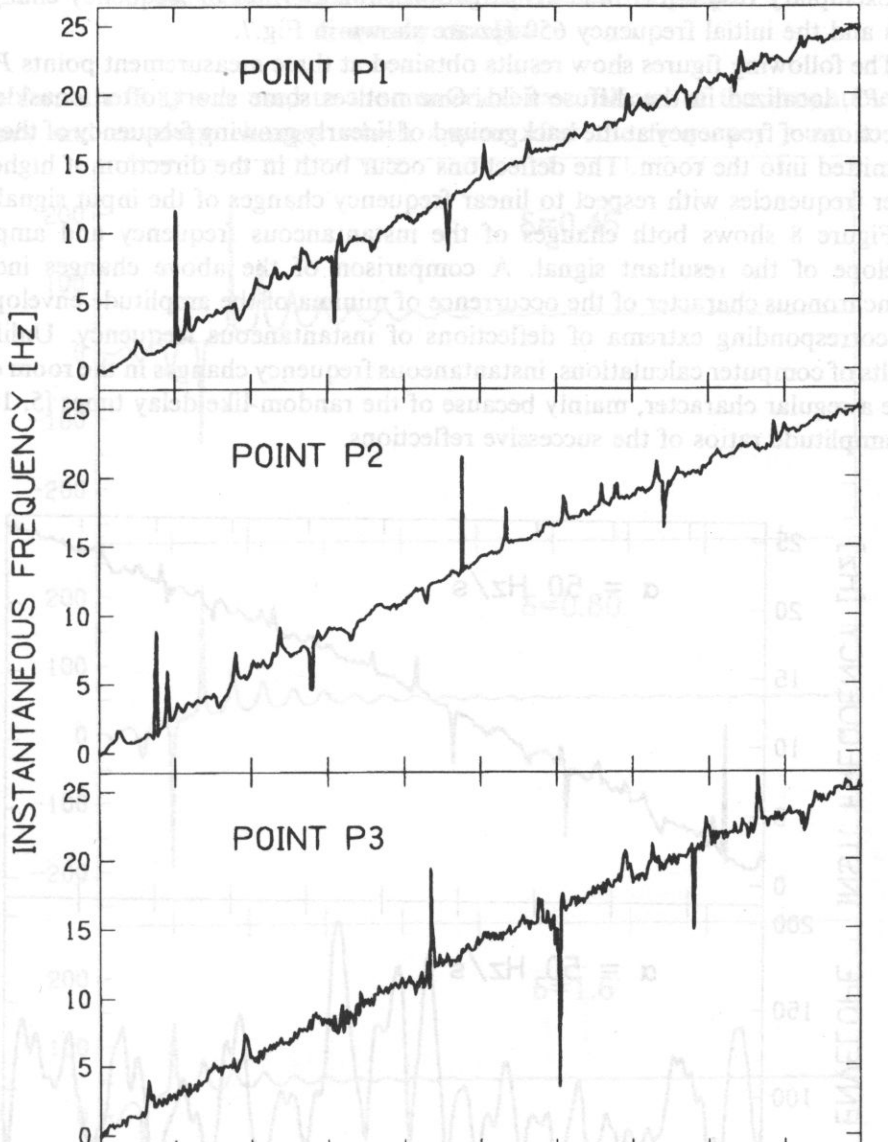

Fig. 7. Illustration of changes in instantaneous frequency of a sound in a room for a signal with linearly growing frequency at the rate of 50 Hz/s, for a few measurement points P1, P2, P3.

digital converter with a computer. The control microphone was placed near the loudspeaker. The distorted FM signal was received by the next microphone placed in the selected measurement point.

Exemplary results of these investigations, for the rate of frequency changes 50 Hz/s and the initial frequency 650 Hz are shown in Fig.7.

The following figures show results obtained at three measurement points *P*1, *P*2, and *P*3, localized in the diffuse field. One notices some short, often considerable, deflections of frequency at the background of linearly growing frequency of the signal trasmitted into the room. The deflections occur both in the direction of higher and lower frequencies with respect to linear frequency changes of the input signal.

Figure 8 shows both changes of the instantaneous frequency and amplitude envelope of the resultant signal. A comparison of the above changes indicates a synchronous character of the occurrence of minima of the amplitude envelope and the corresponding extrema of deflections of instantaneous frequency. Unlike the results of computer calculations, instantaneous frequency changes in the room do not have a regular character, mainly because of the random-like delay times [5, 15] and the amplitude ratios of the successive reflections.

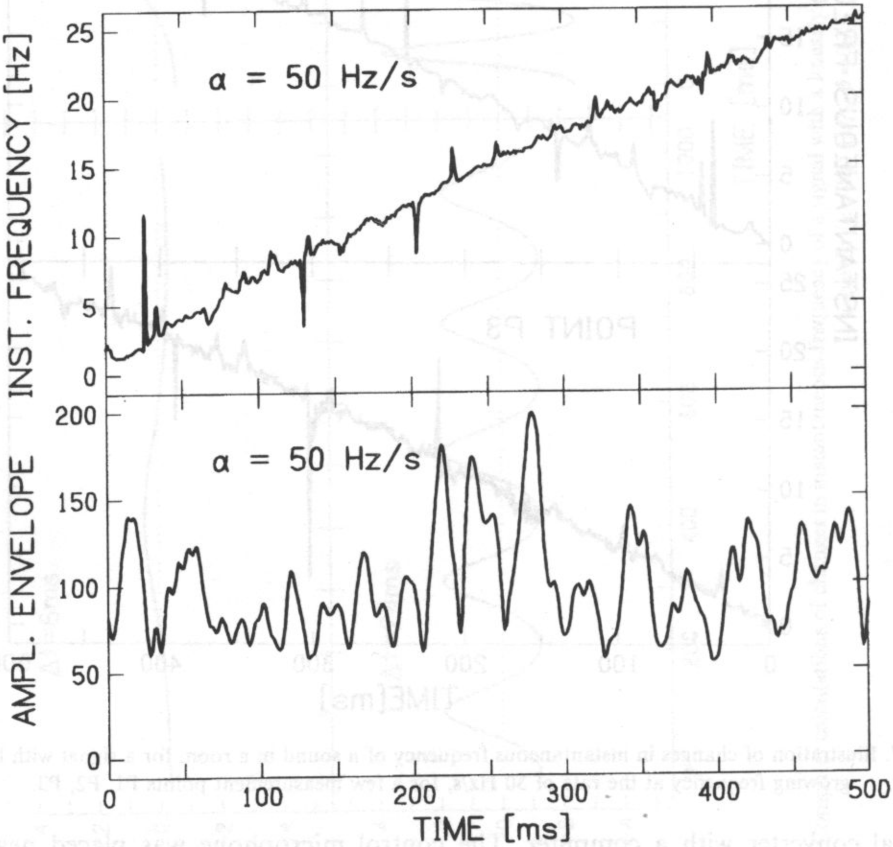

Fig. 8. Illustration of changes in instantaneous frequency and amplitude envelope recorded in a room for $\alpha = 50$ Hz/s.

5. Results of calculations and experiment for jump frequency changes

The formula (3.8) was used to the numerical calculations of the instantaneous frequency and envelope changes which appear after the frequency jump in the

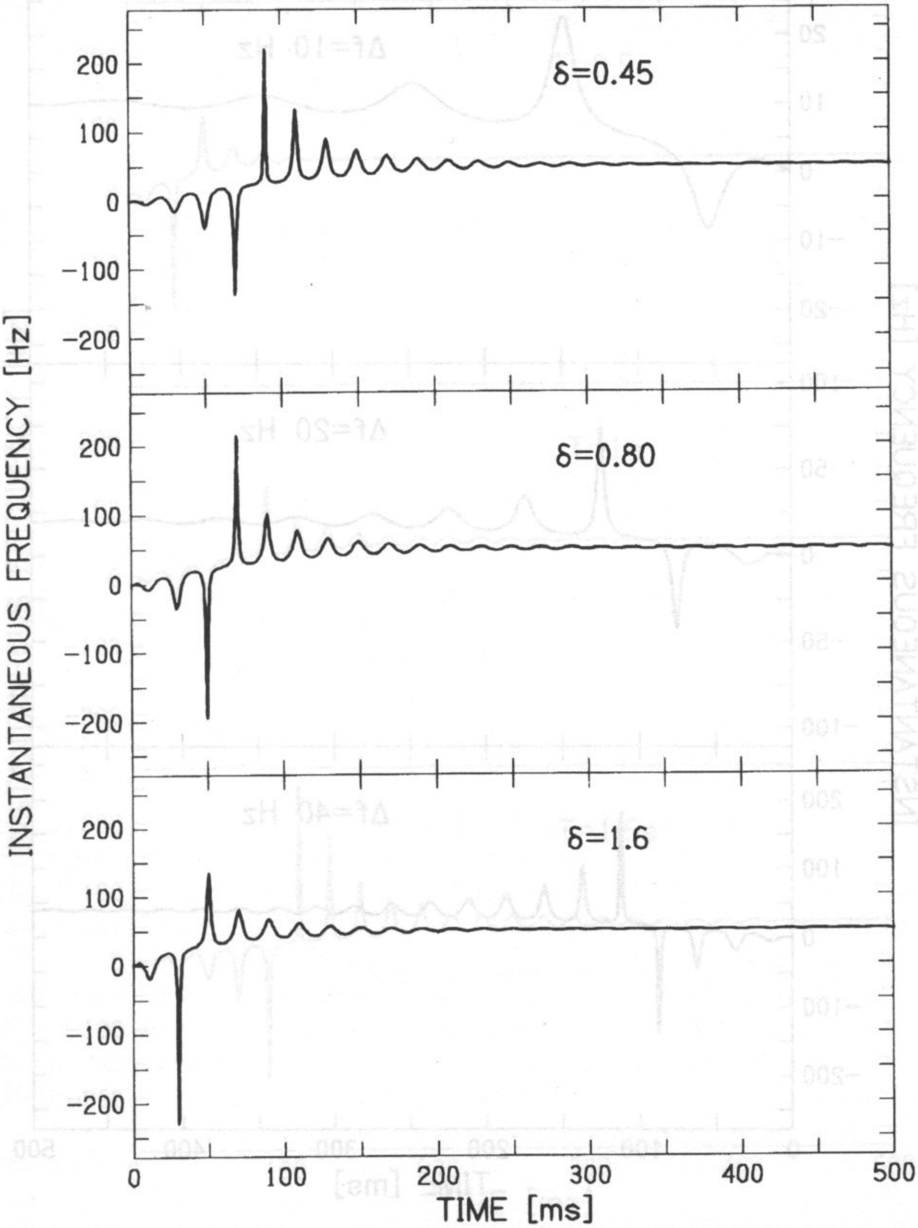

Fig. 9. Computer calculations of changes in instantaneous frequency of a signal, due to a frequency jump, for selected values of coefficient δ.($\Delta f = 50$ Hz; $T = 1$s).

room. The only difference between presented calculations and results for the real room is an assumption that the room decay process is an exponential one. Calculations were performed for selected signal parameters (range and direction of frequency jump) and room dependent parameters (amplitude ratio and reverberation time).

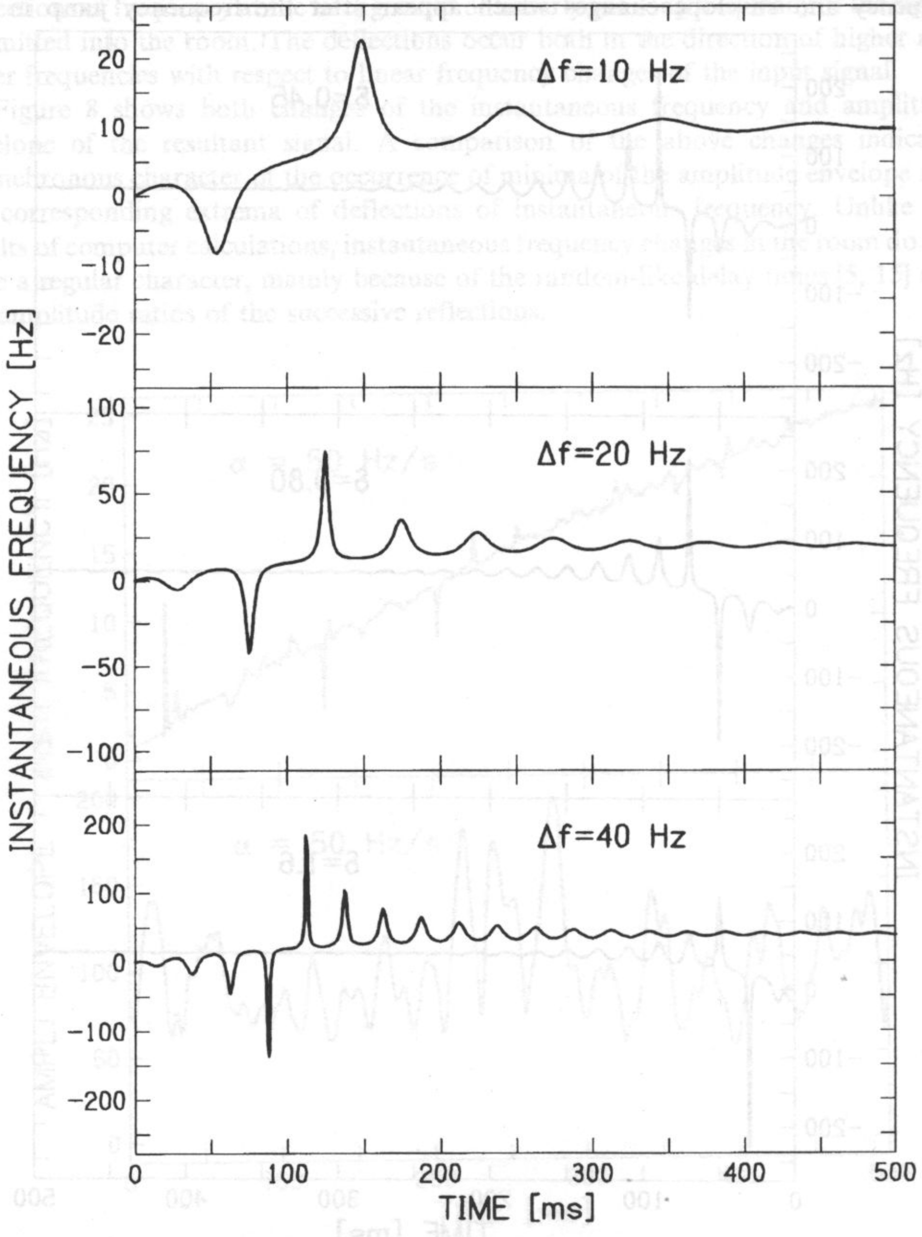

Fig. 10. Computer calculations of changes in instantaneous frequency of a signal, due to a frequency jump, for selected values of frequency jump $\Delta f.(\delta=0.1;\ T=2\text{s})$.

Exemplary results of the calculations are shown in Figs. 9–12.

The moment at which signal frequency jump occurs corresponds to the zero value on the time axis. At successive time moments we observe characteristic fluctuations of instantaneous frequency nad then a fixed frequency value which corresponds to the

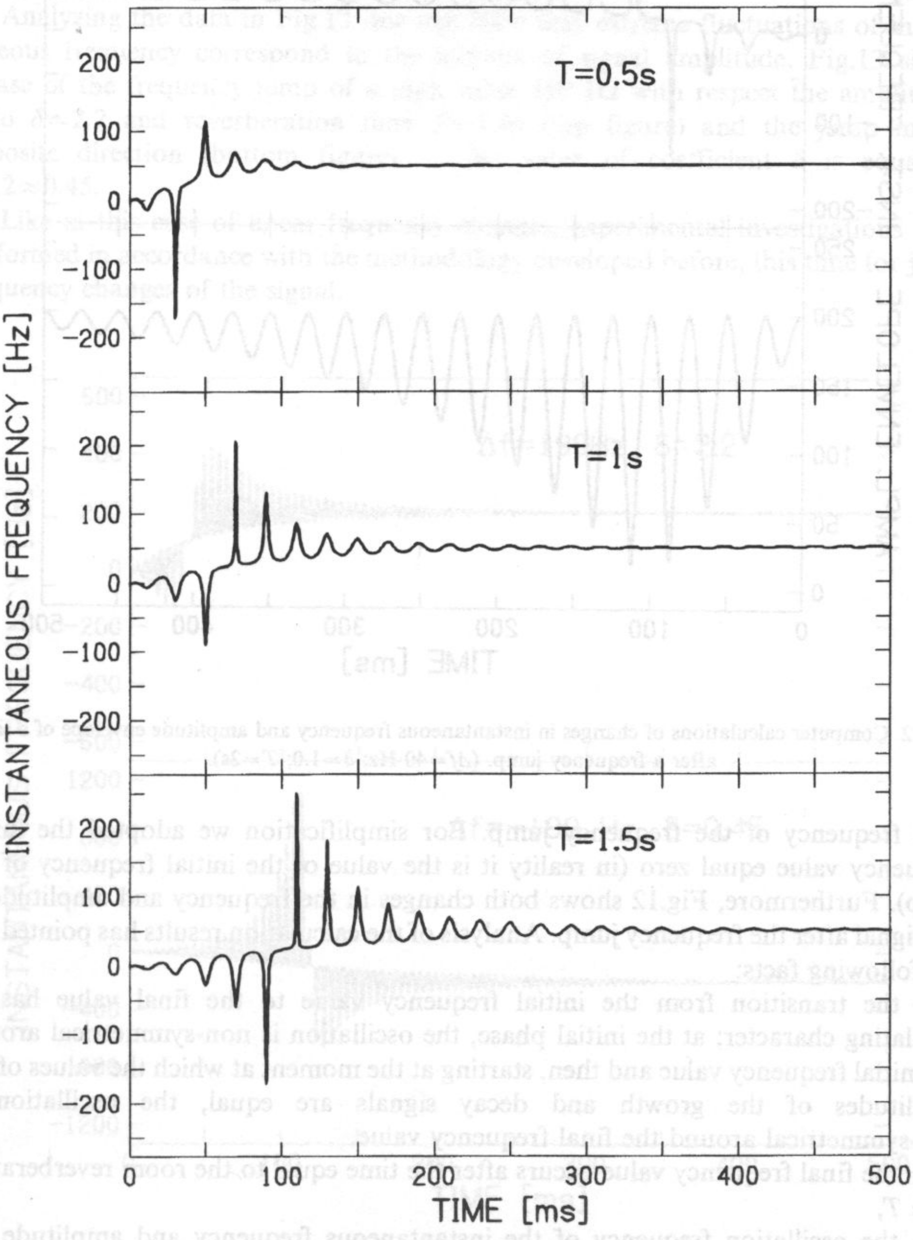

Fig. 11. Computer calculations of changes in instantaneous frequency of a signal, due to a frequency jump, for selected values of reverbation time T.($\Delta f = 50$ Hz; $\delta = 0.6$).

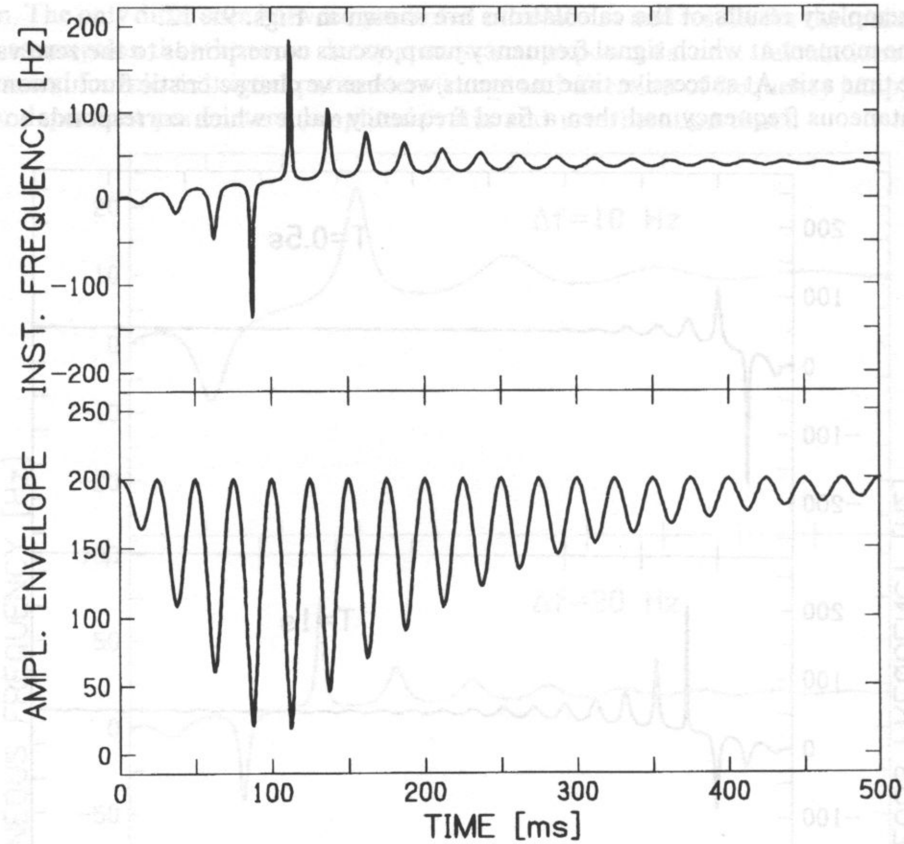

Fig. 12. Computer calculations of changes in instantaneous frequency and amplitude envelope of a signal after a frequency jump. ($\Delta f = 40$ Hz; $\delta = 1.0$; $T = 2$s).

final frequency of the frequency jump. For simplification we adopted the initial frequency value equal zero (in reality it is the value of the initial frequency of the jump). Furthermore, Fig.12 shows both changes in the frequency and amplitude of the signal after the frequency jump. Analysis of the calculation results has pointed out the following facts:

• the transition from the initial frequency value to the final value has an oscillating character; at the initial phase, the oscillation is non-symmetrical around the initial frequency value and then, starting at the moment at which the values of the amplitudes of the growth and decay signals are equal, the oscillation is non-symmetrical around the final frequency value,

• the final frequency value occurs after the time equal to the room reverberation time T,

• the oscillation frequency of the instantaneous frequency and amplitude envelope is equal to the value of the frequency jump,

• for the value of coefficient $\delta > 1$ the oscillation time around the initial frequency value is shortened,

• changes in time of the amplitude envelope have an oscillatory character, however without the change in the oscillation direction, which is characteristic of changes in instantaneous frequency.

Analyzing the data in Fig.12 one can state that extreme fluctuations of instantaneous frequency correspond to the minima of signal amplitude. Fig.13 shows a case of the frequency jump of a high value 199 Hz with respect the amplitudes ratio $\delta = 2.2$ and reverberation time $T = 1.4$s (top figure) and the jump in the opposite direction (bottom figure) — the value of coefficient δ is equal to $1/2.2 \approx 0.45$.

Like in this case of linear frequency changes, experimental investigations were performed in accordance with the methodology developed before, this time for jump frequency changes of the signal.

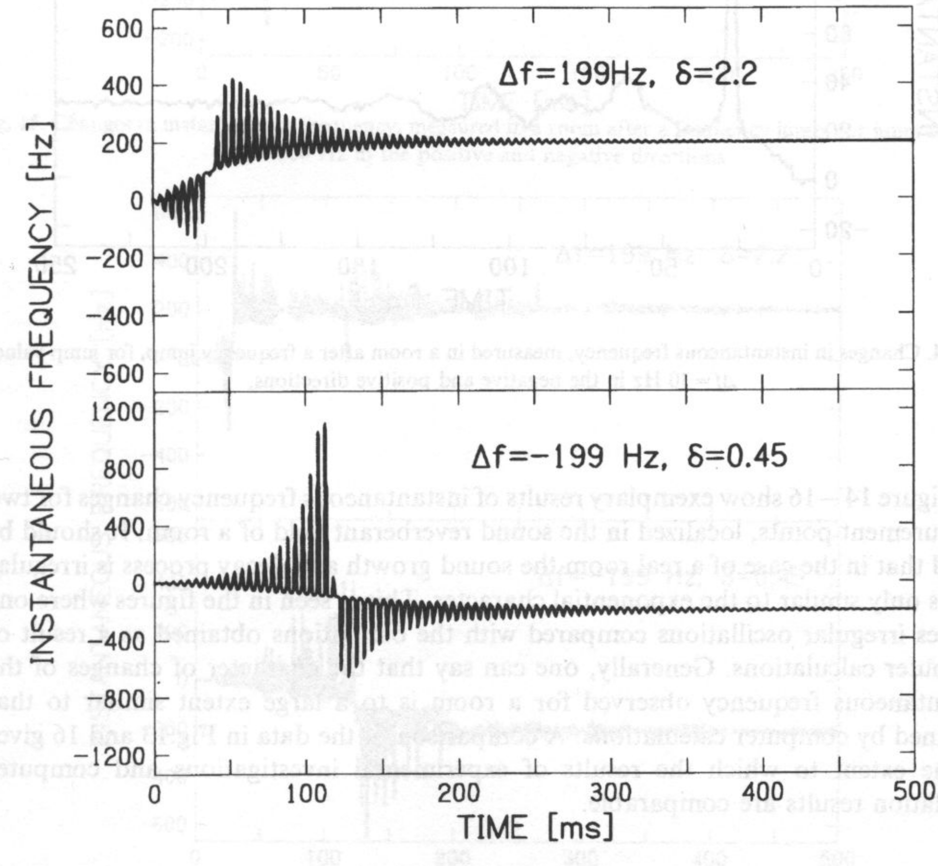

Fig. 13. Computer calculations of changes in instantaneous frequency of a signal after a frequency jump, for jump values $\Delta f = 199$ Hz in the positive and negative directions. ($T = 1.4$ s).

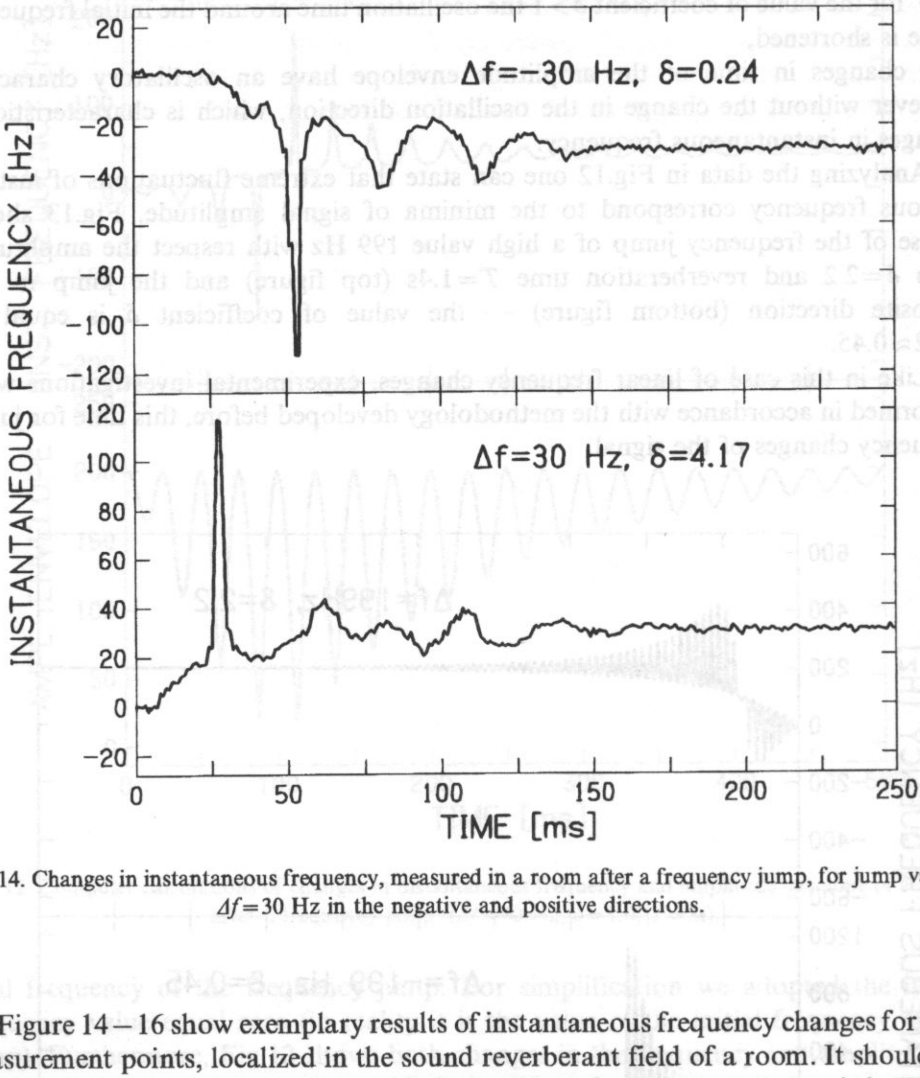

Fig. 14. Changes in instantaneous frequency, measured in a room after a frequency jump, for jump values $\Delta f = 30$ Hz in the negative and positive directions.

Figure 14 – 16 show exemplary results of instantaneous frequency changes for two measurement points, localized in the sound reverberant field of a room. It should be noted that in the case of a real room the sound growth and decay process is irregular and is only similar to the exponential character. This is seen in the figures where one notices irregular oscillations compared with the oscillations obtained as a result of computer calculations. Generally, one can say that the character of changes of the instantaneous frequency observed for a room is to a large extent similar to that obtained by computer calculations. A comparison of the data in Fig.13 and 16 gives us the extent to which the results of experimental investigations and computer simulation results are comparable.

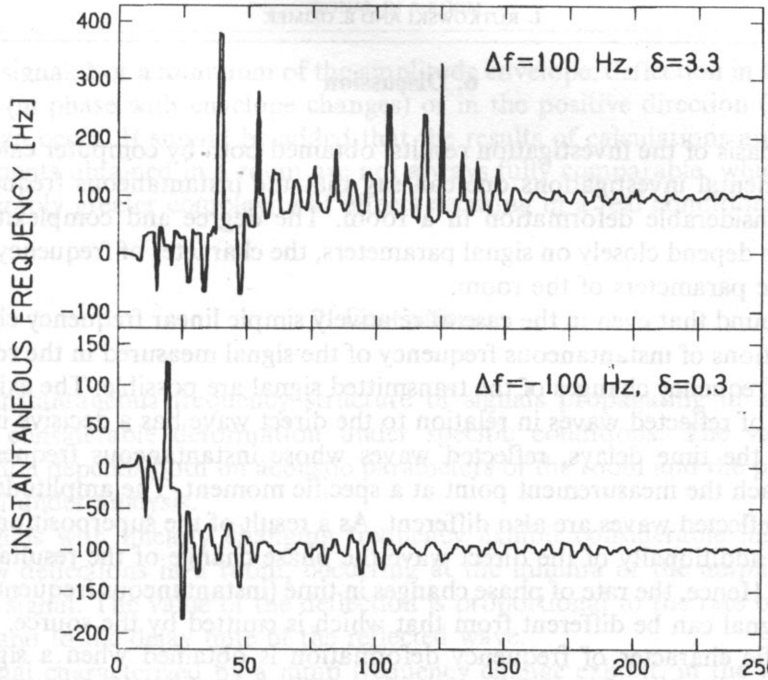

Fig. 15. Changes in instantaneous frequency, measured in a room after a frequency jump, for jump values $\Delta f = 100$ Hz in the positive and negative directions

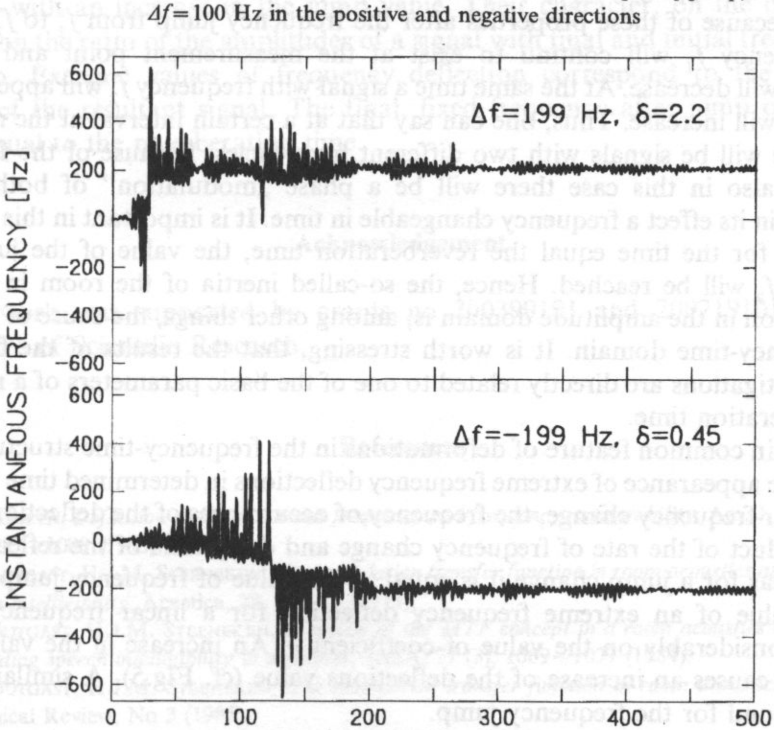

Fig. 16. Changes in instantaneous frequency, measured in a room after a frequency jump values $\Delta f = 199$ Hz in the positive and negative directions.

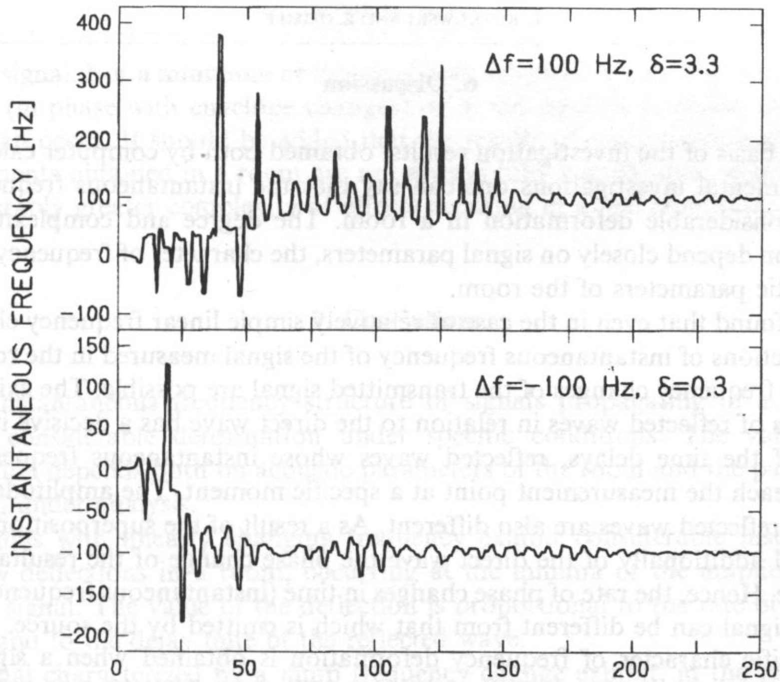

Fig. 15. Changes in instantaneous frequency, measured in a room after a frequency jump, for jump values $\Delta f = 100$ Hz in the positive and negative directions

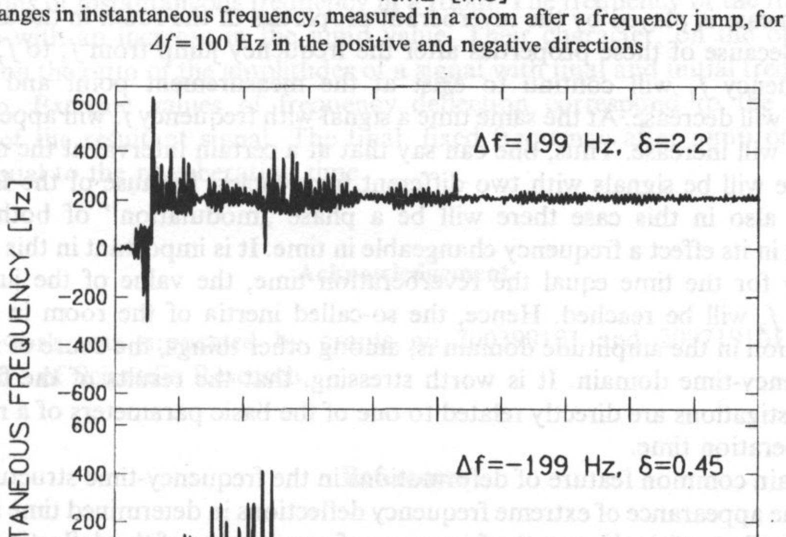

Fig. 16. Changes in instantaneous frequency, measured in a room after a frequency jump values $\Delta f = 199$ Hz in the positive and negative directions.

6. Discussion

On the basis of the investigation results, obtained both by computer calculations and experimental investigations one can say that the instantaneous frequency can undergo considerable deformation in a room. The degree and complexity of the deformation depend closely on signal parameters, the character of frequency changes and acoustic parameters of the room.

It was found that even in the case of relatively simple linear frequency changes in time, deflections of instantaneous frequency of the signal measured in the room with relation to frequency changes of the transmitted signal are possible. The existence of time delays of reflected waves in relation to the direct wave has a decisive influence. Because of the time delays, reflected waves whose instantaneous frequencies are different reach the measurement point at a specific moment. The amplitude ratio of successive reflected waves are also different. As a result of the superposition of these waves, and additionally of the direct wave the phase change of the resultant signal takes place. Hence, the rate of phase changes in time (instantaneous frequency) of the resultant signal can be different from that which is emitted by the source.

A specific character of frequency deformation is obtained when a signal with a constant amplitude and jump frequency changes is emitted into the room. The basic role in this case is played by the reverberant properties of the room in the amplitude domain. Because of these properties after the frequency jump from f_1 to f_2 a signal with frequency f_1 will continu to exist at the measurement point and only its amplitude will decrease. At the same time a signal with frequency f_2 will appear whose amplitude will increase. Thus, one can say that at a certain interval at the measured point there will be signals with two different frequencies. Because of the frequency difference also in this case there will be a phase „modulation" of both signals, producing in its effect a frequency changeable in time. It is important in this case that practically for the time equal the reverberation time, the value of the jump final frequency f_2 will be reached. Hence, the so-called inertia of the room in terms of reverberation in the amplitude domain is, among other things, the cause of inertia in the frequency-time domain. It is worth stressing, that the results of the frequency jump investigations are directly related to one of the basic parameters of a room, i.e. the reverberation time.

A certain common feature of deformations in the frequency-time structure of the signal is the appearance of extreme frequency deflections in determined time intervals. For a linear frequency change, the frequency of occurrences of the deflection is equal to the product of the rate of frequency change and delay time of the reflected wave $\alpha \Delta t$, whereas for a jump change it is equal to the value of frequency jump Δf.

The value of an extreme frequency deflection for a linear frequency change depends considerably on the value of coefficient δ. An increase in the value of the coefficient causes an increase of the deflections value (cf. Fig.5). A similar relation was not found for the frequency jump.

Irrespective of the type of frequency change used, the extrema of instantaneous frequency deflection correspond to the minima of the amplitude envelope of the resultant signal. For a minimum of the amplitude envelope, deflection in the negative direction (in phase with envelope changes) or in the positive direction (in opposite phases) can occur. It should be added that the results of calculations and results of measurements obtained in a room are not always fully comparable, which indicates a considerably greater complexity of effects occuring in a real conditions.

7. Conclusions

The instantaneous frequency structure of signals propagating in a room can undergo considerable deformation under specific conditions. The value of the deformation depends both on acoustic parameters of the room and the paramters of the signal under analysis.

• Signals with linearly changing frequency exhibit considerable instantaneous frequency deflections in a room, occurring at the minima of the amplitude of the resultant signal. The value of the deflection is proportional to the rate of frequency changes and to the delay time of the reflected wave.

• Signal characterized by a jump frequency change exhibit, in the jump range, fluctuations of instantaneous frequency in a room. The frequency of the fluctuations increases with an increase in the jump value. Their character, on the other hand, depends on the ratio of the amplitudes of a signal with final and initial frequencies of the jump. Extreme values of frequency deflection correspond to the amplitude minima of the resultant signal. The final, fixed frequency after jump occurs after a time equal to the reverberation time.

Acknowledgement

The work was supported by grants no 200399101 and 200719101 from the Committee of Scientific Research.

References

[1] M.S. Gupta, *Definition of instantaneous frequency and frequency measurability*, Am. J. Phys., **43**, No 12, 1087–1088 (1975)

[2] T. Houtgast, H.J.M. Steeneken, *The modulation transfer function in room acoustics as a predictor of speech intelligibility*, Acustica, **28**, 66–73 (1973).

[3] T. Houtgast, H.J.M. Steeneken, *A review of the MTF concept in a room acoustics and its use for estimating speech intelligibility in auditoria*, JASA, **77** (3), 1069–1077 (1984).

[4] T. Houtgast, H.J.M. Steeneken, *The modulation transfer function in room acoustics*, Bruel-Kjaer Technical Review, No **3** (1985).

[5] H. Kuttruff, *On the audibility of phase distortions in rooms and its significance for sound reproduction and digital simulation in room acoustics*, Acustica **74**, 3–7 (1991).

[6] H.N.H. Miyata, T. Houtgast, *Speech intelligibility and modulation transfer function in non-exponential decay fileds*, Acustica, **69**, 151 – 155 (1989).

[7] E. Ozimek, *Investigations into the change in the spectral structure of sound propagating in a room* (in Polish with a summary and figure captions in English) Wydawnictwo Naukowe UAM — Poznań 1977, p. 248.

[8] E. Ozimek, *Problem of the sound spectral changes propagating in a room in the aspect multidimensional space*, Archives of Acoustics, **12**, 251 – 272 (1987).

[9] E. Ozimek, *Transformation of the space of room acoustic states into space of sound deformation*, Journal of Sound and Vibration, **113**, 417 – 423 (1987).

[10] E. Ozimek, L. Jugowar, L. Rutkowski, *Problem of the instantaneous sound frequency measurement*, Archives of Acoustics, **9**, 325 – 339 (1984).

[11] E. Ozimek, A. Sęk, *Perception of irregular frequency changes of sinusoidal signal*, Acustica, **66**, 146 – 152 (1988).

[12] E. Ozimek, L. Rutkowski, *Deformation of frequency modulated signals (FM) propagating in a room*, Applied Acoustics, **26**, 217 – 230 (1989).

[13] S.O. Rice, *Mathematical analysis of random noise*, Bell System Tech. J., **23**, 24 (1944/45).

[14] L. Rutkowski, E. Ozimek, *Changes of the deviation of FM signals in a room*, Proceedings of the International Symposium on „Architectural Acoustics" (2). Strbske Pleso, 202 – 205 (1985)

[15] T. Tohijama, R. Lyon, T. Koike, *Reverberent phase in a room and zeros in the complex frequency plane*, JASA, **89**, 1701 – 1707 (1991).