STUDY OF STATISTICAL PROPERTIES OF THE WIND AND TEMPERATURE FIELDS IN THE ATMOSPHERIC SURFACE LAYER WITH ULTRASONIC SENSORS

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To study the three-dimensional small-scale turbulence in the atmospheric surface layer complex experimental measurements of fluctuations of the meteorological quantities were carried out with six acoustic sensors spaced apart in the horizontal and vertical planes. Based on the data obtained the spatial anisotropy of turbulence is considered as well as the differences in behavior of the statistical characteristics of wind and temperature fluctuations caused by different dependence of the coefficients of the turbulent heat exchange and momentum on the stability state of the surface layer.

At present to develop and substantiate theoretically the lidar and acoustic methods of sounding the atmospheric parameters normally the Kolmogorov model of turbulence for locally isotropic medium is used. In this case a spatiotemporal structure of wind velocity field is described using the hypothesis of "frozen" turbulence, and temperature is considered as a conservative and passive impurity. But, as known, in the atmospheric surface layer the turbulence is essentially anisotropic. Moreover, there are differences in the behavior of the wind and temperature fluctuations depending on the stability state of the atmosphere.[1]

In this paper we consider some results of a series of experiments to study in detail the structure of turbulence in the atmospheric surface layer using six ultrasonic sensors of wind velocity and temperature fluctuations. The primary goal of the study was to elucidate a dependence of statistical characteristics of fluctuations of the wind velocity and temperature on a variety of parameters: the distance between the measurement points, direction of separation with respect to average velocity, frequency, and thermal stratification conditions in the surface layer.

Measurements were carried out during twenty four hours every half an hour. Spatially the ultrasonic sensors were placed along one line at a distance of 1 m between them. Measurements of fluctuations of the longitudinal wind velocity component and temperature were made with all the six sensors. Moreover, the acoustic weather station,[2] which measured the fluctuations of three wind velocity components, temperature, humidity, and average value of air pressure, was used as one of the sensors. The measurements were made synchronously at a rate of 4 Hz. The length of a single data sample was 4096 points, i.e. the averaging time equaled about 17.1 min.

The study was carried out in three successive stages in accordance with the longitudinal, vertical, and transverse disposition of the sensor linearly arranged set, relative to the average wind direction. At each stage the experiment was carried out in an automated mode of operation controlled using two personal computers. These computers also recorded and partially processed the data on a real time scale. Thus recorded data have then been subjected to a more detailed analysis and statistical processing.

We have analyzed 35 measurement sessions. For each run the following statistical characteristics were determined: for the longitudinal wind velocity component and temperature we calculated the average values, variances, asymmetry and excess, autocorrelation functions, and auto spectra at each sensor point, and also the mutual correlation functions, spectra of coherence and phase were calculated for the sensors placed at the distance 1–5 m from each other. Besides, based on the data of the weather station we calculated the single-point moments and spectra for the transverse and vertical wind velocity components and the scales of velocity (friction velocity), temperature, specific humidity, length (Obukhov scale), vertical turbulent flux of the momentum, water vapor, explicit and latent heat were also calculated.

Although the question on similarity of temperature fluctuations to the wind ones has been widely discussed,[3] at present an assumption about the identical nature of the turbulent heat and momentum exchange in the surface layer of the atmosphere is a hypothesis and needs for the further experimental tests. In this paper we, however, are limited by a comparative analysis of the behavior of spatiotemporal correlation functions and coherence spectra of fluctuations of the temperature and wind velocity components.

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The range of variation of the thermal stratification conditions during the experiment, in terms of the parameter z/L (where L is the Obukhov scale, z is the observation altitude), was quite broad, i.e., the state of the surface layer changed from a very stable state (1 class, by Terner) at night to a very unstable one (7 class) during day-time. Change of the surface layer state is shown in Fig. 1.

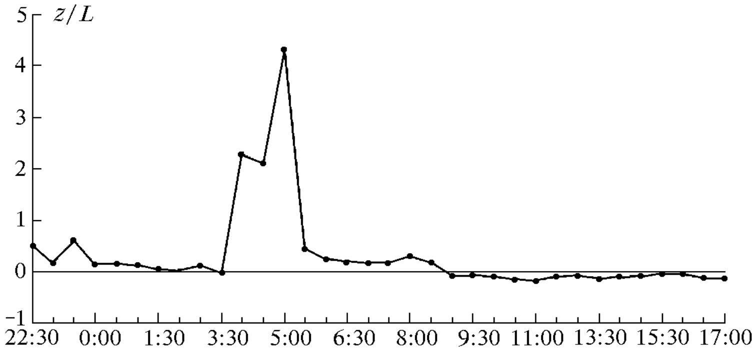

FIG. 1.

As known,[4] the temperature fluctuations arise in the atmosphere only if the height stratification of the potential temperature occurs. According to Ref. 4 no temperature fluctuations are generated in the presence of adiabatic gradient of the potential temperature (neutral stratification conditions). When the vertical temperature gradient deviates from the adiabatic one, vertical motion of the elementary volumes of air by fluctuations of the vertical velocity leads to local temperature fluctuations. Reduction of the variance of these fluctuations σ_t^2 to a dimensionless form is done using the temperature scale T^* determined by the equality $\langle t'w' \rangle = -u^* T^*$, where t' and w' are the fluctuations of temperature and wind velocity vertical component, u^* is the friction velocity.

Figure 2 shows the normalized variance of temperature fluctuations as a function of stability according to data from our measurements. One can see that at the stratification close to neutral the magnitude $\sigma_t/|T^*|$ increases. On the whole the dependence presented well agrees with the theoretical statements and known experimental data.

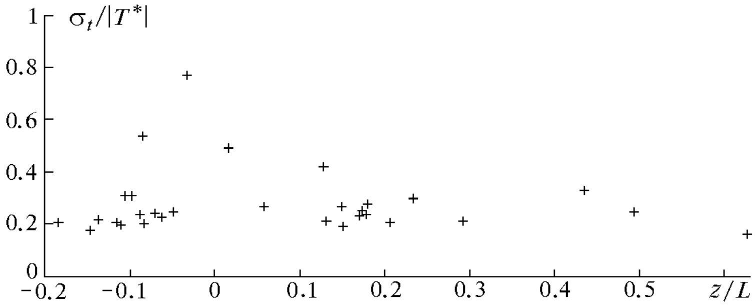

FIG. 2.

In Ref. 3 the similarity principle of temperature fluctuations spectra to wind ones is used. However, there is a difference between these spectra connected with the temperature field may not be stretched itself, but it is transferred by the velocity field. In this case the inertia intervals of these two fields overlap partially, but their coincidence is not necessary.[4] A possible cause of the difference in temperature and wind velocity spectra may be different behaviors of the turbulent exchange coefficients. At present the difference between the turbulent exchange coefficients depending on the stratification is established quite reliably.[1] In accordance with the Monin–Obukhov similarity theory in the atmospheric surface layer the ratio between the turbulent exchange coefficients α for the heat K_h and momentum K_m is a function of the stability parameter (dimensionless height) $\xi = z/L : \alpha = K_h/K_m = \varphi_m(\xi)/\varphi_h(\xi)$, but it is impossible to determine the functions $\varphi_m(\xi)$ and $\varphi_h(\xi)$ with the similarity theory. To do this one needs for corresponding experimental data. In accordance with the results of numerous measurements of the velocity and temperature profiles, including the laboratory conditions, the value α was found to be 1.16 at $\xi = 0$. Since, by definition, $\varphi_m(0) = 1$ the function $\varphi_h(0) = 0.86$. However, many authors consider that the relations of φ_m and φ_h to ξ obtained by processing of the experimental data requires further refinement.[1]

Examples of the temperature and wind velocity fluctuation spectra normalized to the variance we have obtained under conditions of stable, neutral, and unstable stratification are presented in Figs. 3, 4, and 5, respectively. Unfortunately for the stable and neutral states of the surface layer stratification the intensity of turbulent fluctuations was very weak, and the spectral characteristics were close to those of pure noise. At large z/L values the short–duration sporadic manifestations of the turbulence lasting 0.5–5 min were observed in certain cases only. Since the averaging time was about 17 min this led to a disturbance of the stationary conditions during the sampling time. It is clear from Figs. 3 and 4 that the inertia interval in spectra is small, and a rise in the spectral curves in the high frequency region is explained by noise. These results agree with the conclusions from Ref. 3 that in the night surface layer the turbulence is intermittent. Also these results agree with the data of similar experiments described in Ref. 1 where it was shown that at $Ri \approx 0.2$ in some observational series the slope of the dimensionless spectra multiplied by the frequency was close to zero and had the values from −1.2 to −2.5 in the other ones.

Measurements of temperature fluctuations under unstable stratification showed that almost all disturbance energy concentrates near the spectral maximum that is clearly observed in the low frequency region, and in the inertia interval the spectra really obey the “2 thirds law” (see Fig. 5).

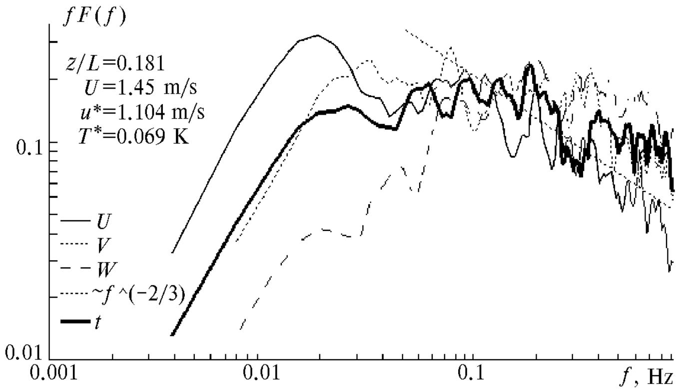

FIG. 3.

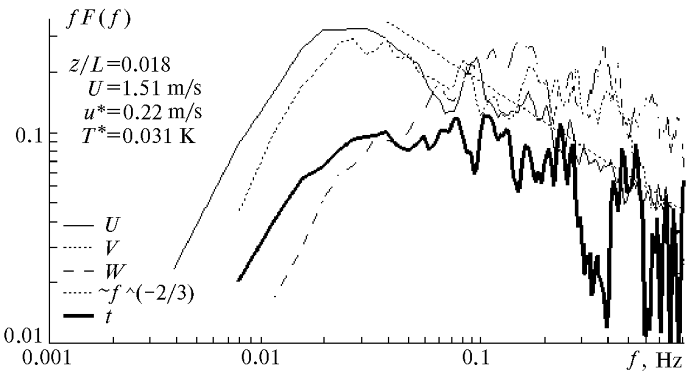

FIG. 4.

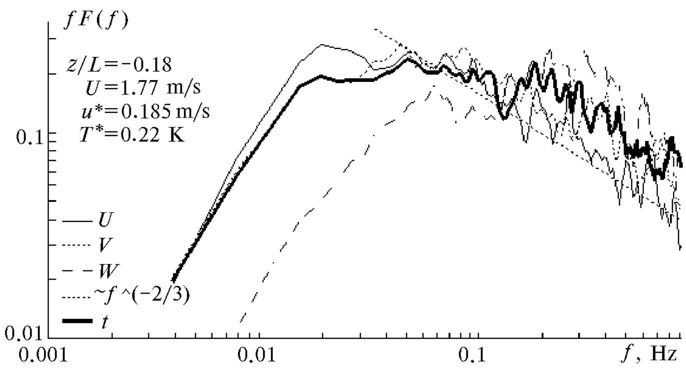

FIG. 5.

It is known[1,3,4] that in the surface layer the turbulence is essentially anisotropic. Let us consider some manifestations of the anisotropy in the example of spatiotemporal correlation functions of fluctuations of the longitudinal wind velocity component and temperature measured under the condition of unstable stratification, which are shown in Figs. 6, 7, and 8 for the longitudinal, transverse, and vertical separations between the sensor points of the acoustic meters, respectively.

The most slow drop of the correlation maxima takes place in the longitudinal direction both for the velocity fluctuations (the curves *1–4*) and for temperature ones (the curves *1′–4′*). Moreover when the spatial separation of points increases (the curves *1* to *4* correspond to the separations 1, 3, 4, and 5 m), the natural decrease of the correlation maxima and rise in the time delay of their location are observed, i.e. a satisfactory fulfillment of the hypothesis of "frozen" turbulence takes place in this direction.

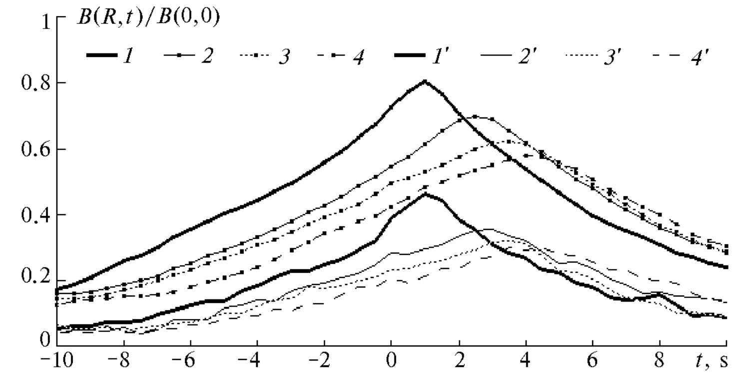

FIG. 6.

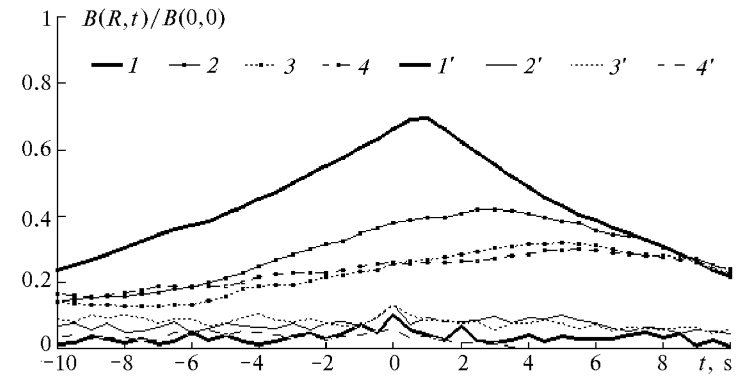

FIG. 7.

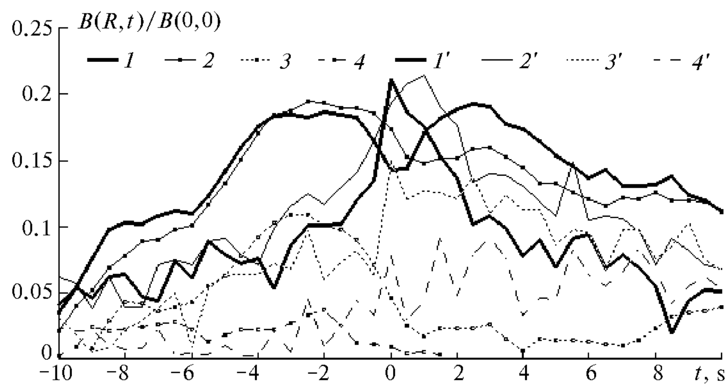

FIG. 8.

In the transverse direction the drop of the wind fluctuation correlation occurs considerably more quickly then in the longitudinal direction, and the level of the temperature correlation is considerably lower then for wind. Moreover, if for fluctuations of the longitudinal velocity a correspondence of the maximum values and their temporal delays to the values of spatial separations is still traced, then for the temperature fluctuations this dependence is broken, and a shift of maxima is absent at all.

As is clear from Fig. 8 for the separation of meters in the vertical direction (here the curves *1–4* correspond to the separations 1, 2, 3, and 4 m) the correlation of the longitudinal velocity fluctuations was most low. However, here a decrease of the statistical relation of fluctuations is traced as far as the difference of heights increases. The peculiarity of the fluctuation correlation with the vertical separation is that the correlation maximum between the levels (for example, the levels at 2 and 3 m apart – the curves *2* and *3*, respectively) is observed not for the positive time delay, as for the cases of the longitudinal and transverse separations, but for the negative ones, i.e. when the observations at the upper level precede to observations at the lower level. Such a shift of the cross-correlation function maximum in accordance to Ref. 4 means a slope of turbulent eddies towards the average motion due to their interaction with the positive (upward) gradient of the average velocity.

It is interesting, that when the distance between the levels is not too large ($R = 1$ m, the curve *1*), in the given realization a presence of two weakly pronounced local maxima with the time delay opposite in sign is observed. It is possible, that the right-hand side maximum with the positive delay is connected with the vertical component of the average wind velocity caused by the air flows from heated underlying surface occurs in the surface layer under conditions of unstable stratification. It must be so, that the regular vertical transfer of inhomogeneities by this component leads to appearance of maximum at a positive delay. Since this component is small (in this case $\langle w \rangle = 0.1$ m/s) its influence on the maximum shift is detected only for close levels, where the influence of corresponding difference of the longitudinal velocities caused by the presence of the logarithmic profile is less important. As one can see from Fig. 8 the right-hand side maximum practically disappears at the separation $R = 2$ m already (owing to the influence of ordinary processes of the evolution of inhomogeneities of the velocity and turbulent mixing).

As regards the temperature fluctuations although the correlation is also low, as in the case of the transverse separation, one can notice, that the maximum of functions is reached not at negative time shift, as for the longitudinal velocity fluctuations, but for a positive one, i.e. by the transfer of temperature inhomogeneities upwards by the average vertical component of the wind velocity.

On the whole Figures 6–8 show that during the measurements under moderately unstable stratification conditions of the surface layer the velocity vortexes were most strongly stretched along the direction of average motion. Typical dimension of the vortexes in the transverse direction was smaller than in the longitudinal one, but it was considerably larger than in the vertical direction. Spatial correlation of the temperature inhomogeneities drops most slowly for the horizontal position of the sensors linear array along the average wind direction also. However, in the transverse and vertical directions the behavior of the correlation functions of the temperature fluctuations essentially differs from that of corresponding correlation functions of the longitudinal velocity fluctuations. All this shows that the essential distinctions in the structure of turbulent fields of wind velocity and temperature which are expressed in different manifestations of the spatial anisotropy of their statistical characteristics.

To study the detailed structure of turbulent fields of the velocity and temperature information on the degree of statistical relation of fluctuations in different spatial points for the specific values of frequency is of certain interest. Such information is in the coherence functions

$$\mathrm{Coh}^i(f, R_j) = [\mathrm{Co}^2(f) + Q^2(f)] \,/\, [F_A^i(f)\, F_B^i(f)], \quad i, j = 1, 2, 3, \qquad (1)$$

where f is the frequency; $F_A^i(f)$ and $F_B^i(f)$ are the power spectra at the points A and B, respectively; R_j is the distance between the points A and B; $\mathrm{Co}(f)$ is the cospectrum, and $Q(f)$ is the quadrature spectrum; indices i, j = 1, 2, 3 mean the longitudinal, transversal, and vertical wind components and longitudinal, transversal, and vertical disposition of the sensor array relative to the average wind direction, respectively.

The coherence (1) is a statistical characteristic determining the contribution of fluctuations of different frequencies into the correlation between the fluctuations of meteorological quantities at two spatially separated points. As applied to the wind velocity the coherence can be treated as a measure of the velocity vortex stability.

Figures 9 and 10 show the behavior of the coherence functions for the horizontal velocity components (curves *1* and *2*) and for temperature (curves *1′* and *2′*) measured for the separations between the observation points $R = 1$ m (curves *1* and *1′*) and $R = 5$ m (curves *2* and *2′*) along the average wind velocity direction for conditions of unstable and stable stratifications, respectively. One can see from Fig. 9 high values of the coherence between fluctuations at the points of sensor locations in the low frequency region for unstable stratification, as it could be expected from the known conceptions of the turbulent motion in the near surface layer.[4]

When the frequency increases, i.e. when going to smaller scales of turbulent inhomogeneities, a decrease in the coherence takes place as in the case when a distance between the measurement points increases. In this case obvious distinctions in the behavior of temperature and wind fluctuations are not revealed in the case when the correlation functions at the longitudinal separation of sensors.

When the stratification is stable (Fig. 10), a drop of the coherence with increasing frequency and distance between the points is more quick than it occurs under unstable one. This fact can be explained by a general decrease in the turbulence energy due to the buoyancy Archemedes force and corresponding decrease of all scales.[1] Moreover, a certain distinction in the behavior of temperature and wind coherence is observed in the low frequency region. If for the longitudinal wind velocity component the coherence increases with a decrease in the frequency as in the case for an unstable stratification, then the temperature fluctuation coherence, when going to larger spatial scales first reaches its maximum value and then begins to decrease. The presence of such a low-frequency maximum in the coherence spectra of temperature fluctuations means that the main contribution into their spatial correlation is introduced by the inhomogeneities with the scale, which is smaller than the typical scale of the longitudinal velocity.

If one takes into account that the mechanism of temperature fluctuation generation for the stratification different from neutral is, on the whole, caused by the vertical velocity component fluctuations, then such a scale must be certain typical size of the turbulent inhomogeneities along the vertical direction. Under stable stratification conditions the turbulent eddies of velocity are compressed along the vertical direction by the buoyancy force.

Thus, the aforesaid distinctions of the turbulent exchange coefficients and spatial anisotropy of the turbulent inhomogeneities is also a factor causing the difference in the behavior of spectral characteristics of the longitudinal velocity component and temperature in the low-frequency region. At higher frequency time scales are smaller and the eddies are more isotropic.

For a theoretical generalization of the experimental data of wind coherence the following model representations[5] are often used

$$\mathrm{Coh}^i(f, R_j) = \exp\,(-K_j^i\, n_j) \quad i, j = 1, 2, 3, \qquad (2)$$

where $n_j = f R_j / V_i$ is the dimensionless frequency; K_j^i is the attenuation parameter. The curves *1a* and *2a* in Figs. 9 and 10 are the exponential approximation of the corresponding experimental coherence functions of the longitudinal velocity component. The values of attenuation coefficients obtained qualitatively obey the relationships determined in Ref. 5 based on a comparison of a large number of the experimental investigations performed by different authors in different sites.

According to the conclusions from Ref. 5, under unstable stratification no noticeable dependence of K_1^1 on R exists. Really, the values of attenuation parameter K_1^1 for $R = 1$ and 5 m obtained from our measurements have close magnitudes of 5.03 and 4.01, respectively (the curves *1a* and *2a* in Fig. 9). At the same time, under stable stratification (curves *1a* and *2a* in Fig. 10) these parameters are 4.92 and 10.1 for the same separations. These values well agree with the conclusions from Ref. 5 that the growth of K_1^1 is observed at the increase of R under stable stratification. Moreover, if at large separations ($R = 5$) the growth of K_1^1 is observed when the stability increases (the values 4.92 and 10.1 for the unstable and stable conditions), at small separations ($R = 1$) the attenuation parameter can even decrease (the values 5.03 and 4.01, respectively). Such a dependence agrees with the results of some investigations described in Ref. 5.

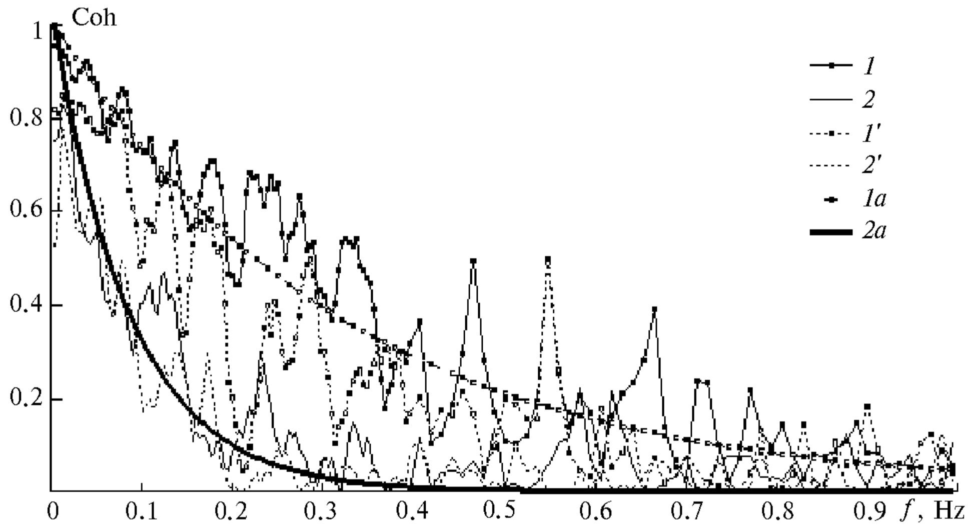

FIG. 9

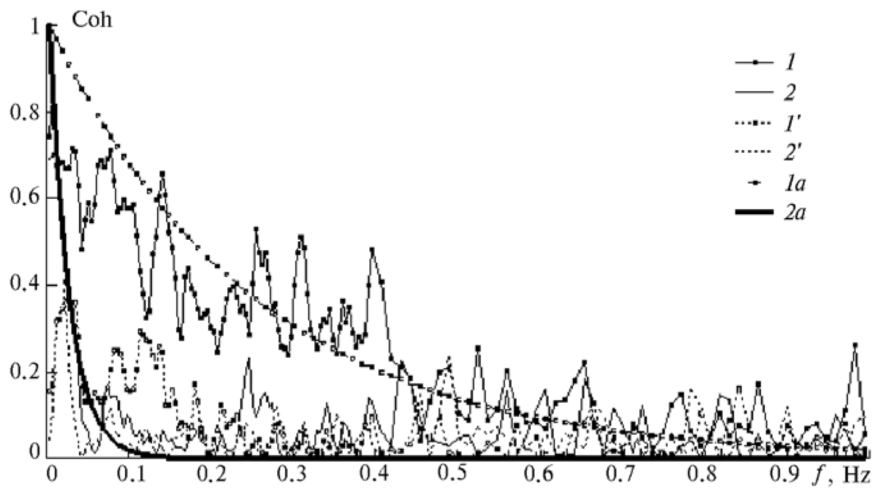

FIG. 10

To obtain a more detailed quantitative conclusions about the influence of the stability conditions in the surface layer on the degree of the turbulence spatial anisotropy more long experiments are needed allowing for the influence of a set of additional factors like the boundary layer height, underlying surface roughness, etc. Nevertheless, it is obvious from the analysis presented that similar complex automated measurements are a good possibility to study the surface layer turbulence where the synchronous data sampling is needed for a large number of hydrometeorological parameters. The cases of weak and intermittent turbulence[5] require additional study. A positive aspect applying the acoustic meters[2] from this point of view is high accuracy and high rate of recording velocity and temperature fluctuations allowing the fine effects in structure of turbulent fields to be investigated. The data obtained can be used for theoretical generalization and identification of new relationships of the behavior of small-scale turbulence in the atmospheric surface layer.

ACKNOWLEDGMENT

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