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Abstract

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EXPERIMENTAL STUDY OF THE FREQUENCY SPECTRA OF THE VERTICAL COMPONENT OF WIND VELOCITY IN THE SURFACE LAYER OF THE ATMOSPHERE

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The processes of transfer of heat, moisture, and momentum in the surface layer of the atmosphere are associated with vertical motions of air. Therefore, of great interest is the study of the statistical characteristics of the vertical component of wind velocity and the elucidation of the relations of these characteristics to the profiles of the mean wind velocity and temperature. A convenient method for the experimental study of wind-velocity fluctuations is the measurement and analysis of energy frequency spectra ([1]), which give an idea of motions of different scales. Processing the results of spectrum measurements on the basis of similarity theory ([2]) makes it possible to generalize the experimental data and to find universal spectral functions of dimensionless frequencies and parameters characterizing the state of the surface layer of the atmosphere.

The instantaneous value of the vertical component of wind velocity, averaged over a base of 2.5 cm, was measured with a specially developed acoustic microanemometer ([3]). The electrical signal from the output of the microanemometer, proportional to the measured quantity, was fed to the input of a frequency analyzer intended for simultaneous analysis ([4]). The analyzer contained a set of 30 half-octave filters, spaced at half-octave intervals in the range from $\omega_n/2\pi = 0.05$ Hz to $\omega_v/2\pi = 1000$ Hz. At the output of each filter a detector and an integrating cell with a time constant of 100 sec were connected. The energy spectrum $F(\omega)$ was obtained by processing the record on the tape of a self-recorder, which was connected in turn to the output of each integrating cell. Interrogation of the 30 cells lasted 2 min. Sufficiently stable averages were obtained with a 5-fold interrogation of the filters, which corresponds to 10-min averaging.

Measurements of the spectra of the vertical component of wind velocity were carried out in August–September 1958 in the vicinity of the settlement of Tsimlyanskii on a level area of open steppe. Over the entire measurement period about 100 spectra were obtained at heights of 1 and 4 m. As the characteristic of stratification, the Richardson number was taken,

Fig. 1

Figure 1: Fig. 1

$$\mathrm{Ri} = \frac{g}{T}\,\frac{\partial \overline{T}(z)}{\partial z} \Big/ \left(\frac{\partial \overline{u}(z)}{\partial z}\right)^2$$

($\overline{T}(z)$ is the mean temperature, $\overline{u}(z)$ is the mean velocity at height z, $g = 981$ cm/sec^2). The values of $\overline{T}$ and $\overline{u}$ were obtained from periodic (every half hour) measurements of the vertical profiles of temperature and wind velocity. The sensors for $\overline{T}$ and $\overline{u}$ were installed at heights of 0.5, 1, 2, 4, 8, and 12 m. From the vertical profiles of the mean velocity the value of the dynamic velocity $v_* = \varkappa du(\overline{z})/d\ln z$ ([5]) at the measurement height* was also determined ($\varkappa = 0.43$, the von Kármán constant).

* Measurements of the profiles and the calculations of v_* and Ri were carried out under the direction of A. V. Perepelkina.

The similarity theory ([2]) for the temporal energy spectra $F(\omega, z)$ of the vertical component of velocity gives the relation

$$F(\omega, z) = \frac{v_*^2 z}{\bar{u}}\,\bar{F}\left(\frac{\omega z}{\bar{u}}, \mathrm{Ri}\right); \tag{1}$$

$\bar{F}$ is a dimensionless universal function.

In processing the experimental results, all spectra were grouped by identical heights and close values of the Richardson numbers and normalized according to (1). Fig. 1 gives an example for one of the groups. It is seen from the figure that normalization by $v_*^2 z/\bar{u}$ and the transition to dimensionless

Fig. 1. I –frequency spectra $F(\omega, z)$, Ri $= -0.09$, $z = 4$ m; II –spectra normalized according to (1), Ri $= -0.09$, $z = 4$ m; III –spectra averaged for close values of Ri, Ri $= -0.09$: a –$z = 1$ m, b –$z = 4$ m

frequencies $\Omega = \omega z/\bar{u}$ makes it possible to find the mean spectrum $\bar{F}(\omega z/\bar{u}, \mathrm{Ri})$ for close values of the numbers Ri.

The averaged spectra $\bar{F}$ for each of the groups are shown in Fig. 2 on a logarithmic scale. It is seen from Fig. 2 that, in form, the spectra are similar for different meteorological conditions and that there is a monotonic dependence on the number Ri: with increasing instability (Ri < 0), the spectra $\bar{F}$ lie higher. This is easily explained by the fact that, at identical friction stresses ($v_* =$ const), under instability, fluctuations of convective origin are added to fluctuations of dynamic origin. In all spectra, in the high-frequency region, there is a linear dependence of $\ln\bar{F}$ on $\ln\Omega$, which corresponds to a power-law dependence of $\bar{F}$ on Ω. This portion corresponds to the inertial interval of the turbulence spectrum.

Fig. 2 and Fig. 3

Figure 2: Fig. 2 and Fig. 3

The exponent calculated over all spectra for the inertial interval was found to be -1.64, which is very close to the theoretical value -1.67 given by Kolmogorov-Obukhov' s "2/3 law." The boundary of the inertial interval was determined by the value of the frequency Ω_i at which the power-law dependence in the low-frequency region is violated. To find the values of Ω_i, graphs of the functions $\Omega^{2/3}\bar{F}(\Omega, \mathrm{Ri})$ were constructed, on···

for which the inertial interval is represented by a horizontal line. The values of Ω_i depend on the stratification conditions: for $\mathrm{Ri} = -0.76$, $\Omega_i = 2.5$; for $\mathrm{Ri} = 0.0$, $\Omega_i = 4.5$; for $\mathrm{Ri} = +0.28$, $\Omega_i = 12$, i.e., with increasing stability the lower boundary of the inertial interval shifts toward higher frequencies. The scales $l_i = 2\pi z/\Omega$, corresponding to the boundary of the inertial interval, thus turn out to be of the order of the observation height. In the region of the very lowest frequencies, a maximum of the spectral function is indicated; for Ri numbers close to zero (neutral stratification), it lies at values $\Omega \sim 0.05 \div 0.1$.

Fig. 2. Universal functions $F\left(\frac{\omega z}{\bar{u}}, \mathrm{Ri}\right)$.
a—for $\mathrm{Ri} = -0.76$; *b*—$\mathrm{Ri} = -0.36$; *v*—$\mathrm{Ri} = -0.09$;
g—$\mathrm{Ri} = 0.02$; *d*—$\mathrm{Ri} = 0.0$; *e*—$\mathrm{Ri} = +0.02$;
zh—$\mathrm{Ri} = +0.28$.

Fig. 3. Distribution of energy over the spectrum.
a—for $\mathrm{Ri} = -0.76$; *b*—$\mathrm{Ri} = 0.00$; *v*—$\mathrm{Ri} = +0.28$.

The investigated portion of the spectrum occupies about 10 octaves, and therefore, because of the use of a logarithmic scale, Fig. 2 does not give a clear representation of the distribution of energy over the spectrum. From the identity

$$\sigma_w^2 = \int_0^\infty F(\omega)\, d\omega = \int_{-\infty}^\infty \omega F(\omega)\, d\ln\omega$$

we obtain that $(\ln 2)\omega F(\omega)$ is the power of the pulsations per octave, while the area under the curve $\omega F(\omega)$, plotted on a semilogarithmic scale, is equal to the total power or variance σ_w^2 of the pulsations.

In Fig. 3 are plotted the dimensionless functions, averaged by groups,

$$\psi = \frac{\omega}{2\pi}\,\frac{F\left(\omega z/\bar{u}, \mathrm{Ri}\right)}{\sigma_w^2}$$

for different stratification conditions. From this graph it is seen that the main part of the pulsation energy is concentrated in the region of frequencies close to

Fig. 4. Dependence of σ_w/v_* on stratification. On the abscissa axis the scale $\mathrm{Ri}^{*1/3}$ is used

Figure 3: Fig. 4. Dependence of σ_w/v_* on stratification. On the abscissa axis the scale $\mathrm{Ri}^{*1/3}$ is used

Ω_m, which depends on stratification: for $\mathrm{Ri} = -0.76$

$\Omega_m \sim 1.5$, for $\mathrm{Ri} = 0.0$ $\Omega_m \sim 2$, for $\mathrm{Ri} = +0.28$ $\Omega_m \sim 5 \div 6$. This result is readily explained by the fact that, with increasing stability, motions of large scales $L > L_m = 2\pi z/\Omega_m$ are hindered. From the graphs in Fig. 3 it may be estimated that about 30% of the energy falls in the inertial interval. It is seen from Fig. 3 that in the portion of the spectrum investigated the main part of the energy of the pulsations σ_w^2 is contained.

The similarity theory [2] indicates that σ_w/v_* is a function of the Richardson number. In order to find the form of this function for each spectrum, the values

$$\sigma_w^2 = \int_\omega^\omega F(\omega)\,d\omega.$$

were determined by numerical integration. The dependence of σ_w/v_* on Ri is presented in Fig. 4, where values averaged by groups are given. From Fig. 4 it is seen that, with increasing instability, the ratio σ_w/v_* increases, which is apparently associated with an increase in the pulsations of the vertical component of velocity due to convection. Using the relation between the spectral function $F(\omega)$ and the structure function $D(\rho)$:

Fig. 4. Dependence of σ_w/v_* on stratification. On the abscissa axis the scale $\mathrm{Ri}^{*1/3}$ is used

$$D(\tau) = 4\int_0^\infty (1-\cos\omega\tau)F(\omega)\,d\omega$$

one can find the structure constant c^2, entering the "2/3 law" :

$$D(\rho) = c^2\frac{v_*^2}{(\chi z)^{2/3}}\rho^{2/3}, \qquad \tau = \frac{\rho}{u}\ ^{(2)}.$$

The values of c^2, calculated from the spectra using the values $v_* = \chi\, d\overline{u}(z)/d\ln z$, are given in Table 1. These data can be used in calculating the structure constants from profiles of the mean velocity.

Table 1

Ri	−0.76	−0.36	−0.09	−0.02	0.00	+0.028	+0.28
c^2	7.56	4.33	1.95	1.09	1.04	0.88	0.47
c_0^2	1.90	2.48	1.72	1.09	1.04	0.88	0.69

An attempt was made to find the values of the structure constant c_0^2 taking into account the deviation of the profile from the logarithmic one. According to [(5)], as the approximating function $f(\zeta) = \ln|\zeta| + 0.6\zeta$ was taken. The values c_0^2 calculated using this function show, as is seen from Table 1, a smaller dependence on stratification, and this, in essence, confirms the possibility of constructing a universal spectral function $\overline{F}$ for the inertial interval,

$$\overline{F}(\lambda) = \frac{c_0^2}{3\Gamma(1/3)}\lambda^{-5/3}.$$

The value c_0 for $R = 0.0$ is close to that calculated by A. M. Obukhov [(6)].

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Note: Figure translations are in progress. See original paper for figures.