SPECTRAL CHARACTERISTICS OF SURFACE–LAYER TURBULENCE OVER THE SUBURBS OF TIANJIN *

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ABSTRACT

The paper computed the spectra of velocity and temperature, and the cospectra of velocity and temperature by the observational data of July, 1990 in the suburbs of Tianjin. The results show that the characteristics of the atmospheric turbulence spectra over the suburbs are basically in accordance with some typical results over the flat terrain. But the scale, on which turbulence can satisfy the isotropic condition, over the suburbs is larger than over the flat terrain. The spectrum peak frequency range is a bit narrower. The feature of the spectrum range in low frequency (LF) is out of accordance with that of the flat terrain either.

Key words: atmospheric boundary layer, atmospheric turbulence, turbulence spectrum

I. INTRODUCTION

Since 1960s, with the rapid development of observational technology and computing capability, analysis of spectrum characteristics of atmospheric turbulence has been making progress. Different researchers obtain different models for atmospheric turbulence in the boundary layer because spectrum equations in describing turbulence are not strictly inferred according to hydrodynamical equations and it is difficult to make duplicative measurement. But the main conclusions are still consistent. As far as flat terrain, there have been many expperiments and clear theoretical analyses in the field of turbulence study (Haugen 1973; Zhou et al. 1979). Take spectrum of velocity as an example, it is generally identified that the turbulence spectrum in the inertial area complies with Monin–Obukhov's similarity theory and the spectrum density meets the power law of $-5/3$. Under the conditions of various stabilities, the distribution of spectra in LF range shows larger dissociation. Under the near neutral stability conditions, spectrum curves appear to be regular distribution with the variation of z/L, while under unstability conditions the arrangement of spectrum curve shows some uncertainties. The research on turbulent characteristics over the underlying surface with larger roughnees is not as much as over flat terrain. Roth et al. (1989) have got some illuminating results. Observation results of Wang et al. (1985) in Beijing suburbs show that there is larger fluctuation of spectral density in LF range of turbulent spectrum near ground in the region. Zhang et al. (1991) think that dynamic effect over the surface layer is significantly strengthened because of the existence of urban buildings, and this causes the response of turbulent spectrum curve to the change of stability extremely

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insensitive in neutral stratification. By analysing the data of one observational experiment in Lanzhou, Wang (1992) suggests that there is no essential difference in the structure of turbulence spectrum between city and flat terrain. In this paper, by analysing observational data in the suburbs of Tianjin, we try to illustrate the difference between the spectral features of turbulence over suburbs and concluded by other people over flat terrain.

II. METEOROLOGICAL PLATFORM AND DATA

The meteorological observational tower is located in the southern verge of the suburbs of Tianjin. The neighborhood within 50 m of the tower is an open area. Beyond this range, there is a building about 6 m away in the north. The heights of buildings in various directions vary from 3 to 30 m in the region 300 m out of the tower. The sounding apparatus is a supersonic velocity-temperature instrument. The sampling frequency is 10 times per second; the length of data is 55—60 minutes and the sounding height is 35 m from surface. In this paper, the observational data in July 28—30, 1990 were analysed.

III. DATA HANDLINGS AND COMPUTATIONAL METHODS

In order to remove as much as possible the effects of outliers and tendency variation which probably exist in the data, it is necessary to remove outliers and determine if there is a need for detrending or not. First, change the coordinates of observational data by adjusting the components of longitudinal-, cross- and vertical-wind to the axes of x, y and z coordinates respectively. Then perform the centralization processing on the data of velocity and temperature in order to obtain fluctuating series u', v', w' and T' . The following methods are used to get rid of the outlier probably existed in the data.

For the mth data, the mean of x'_m and the other 5 before and 5 after it is computed

$$\overline{x'_m} = \frac{1}{11} \sum_{j=-5}^{5} x'_{m+j}.$$

So the seesaw variance of this point among the 11 points is

$$\sigma_m^2 = \frac{1}{11} \sum_{j=-5}^{5} (x'_{m+j} - \overline{x'_m})^2.$$

$x'/m \quad \pm 5\sigma_m$ is used as the discriminant. If $\overline{x'_m} \in [\overline{x'_m} - 5\sigma_m, \overline{x'_m} + 5\sigma_m]$, x'_m is regarded as normal data, or as an outlier and replaced by $\overline{x'_{m-1}}$. This method has certain defects. For example, the first five and the last five data cannot be distinguished, and the effectiveness of the data handling in which there are many outlier (over several times as many as 11) to process, is worse.

Theoretically, the sum of data series having been centrally processed should be zero, or it is thought to have tendency variation. In the actual computation, the fluctuating series are thought to be stationary time series as long as the sum is not greater than 10^{-2}, so there is no need for removing tendency, or detrending must be done. The method of tendency removing can see also reference (Wang 1988).

The series of fluctuating data having been processed as mentioned are truncated sequentially in units of length of 4096 data. The data at each observation time can be divided into 8 sections. After the spectrum distribution of each section is computed separately by using FFT, the estimated spectrum of this time, mainly part in high frquency (HF) wanted, can be obtained by computing the mean value of the spectrum densities with same frequency. By computing the mean value of the undivided data of the time, in units of 16 data, a new series of data is obtained. After this series is computed by employing FFT, the estimated spectrum, mainly in LF part, is obtained and is combined with the estimated spectrum obtained above. The outcomes produced by simply flating the combined spectra will be given in the next section of this paper. Results show that for the turbulence spectra computed in this method, low cut-off frequency is 2.4×10^{-4} Hz, high cut-off frequency is 5 Hz and band width is over 4 orders of magnitude. The computed stability shows that the variation range of z/L is not wide enough. Here z is the height of detecting point, L is Monin-Obukhov length and it is expressed as

$$L = -u_*^3 / (k\frac{g}{\theta}\overline{w'T'}),$$

where $k = 0.4$, $g = 9.8$ m s^{-2}, θ is replaced by mean temperature T, and u_* is friction velocity

$$u_*^2 = [\overline{u'w'}^2 + \overline{v'w'}^2]^{1/2}.$$

Another important statistical characteristic element is $T_* = \overline{w'T'} / u_*$. The dissipation rates of non-dimensional velocity fluctuation ψ_ε and temperature fluctuation ψ_H, involved when the coordinates of energy spectrum curve are non-dimensionally normalized, and the normalized factors $G(z/L)$, $H(z/L)$, $K(z/L)$, involved when the cospectrum curves are non-dimensionally normalized, are computed by employing the empirical formula given by Kamal (1972).

IV. RESULTS AND ANALYSES

In this paper, the coordinate system in each figure is double logarithmic coordinate the horizontal coordinate f (or n) is non-dimensional compressed frequency (or frequency). S_u, S_v, S_w or S_t in the vertical coordinate is densities of power spectra or temperature spectra, and their normalized formulas are given in figures.

1. *The Effect of Stability on Turbulent Spectra*

Stability is an important restrictive factor to atmospheric turbulent motion. Figure 1 shows that the variation of stability has varying effect in degrees in different frequency range. The positions of spectrum curve were independent of the change of z/L in HF range (inertial range) and turbulence spectra meet the changing rule of the $nS(n) \propto f^{-2/3}$. Here $f = nz/\bar{u}$; $\bar{u}$ is mean velocity. However, the position of spectral curve is affected clearly by the change of L/z in LF range (energy-laden area), and the turbulence spectra approximately meet $nS(n) \propto f^{+1}$. Those indicate that the dynamic factor plays the major role in the turbulent motion in HF range. In LF range, the peak frequency of turbulence spectra becomes higher, however, spectrum density becomes smaller when stability increases or when unstability decreases. On the one hand, it indicates that the mean scale of turbulent motion decreases with stability strengthening. On the other hand, it indicates that the energy of atmospheric turbulence reduces with stability strengthening. In Fig. 1, the effect degree of the change of z/L on the density of spectra in varying frequency range and the position relation between spectrum curves show that the change of stability only affects the energy of vortexes on the scale of energy-laden range.

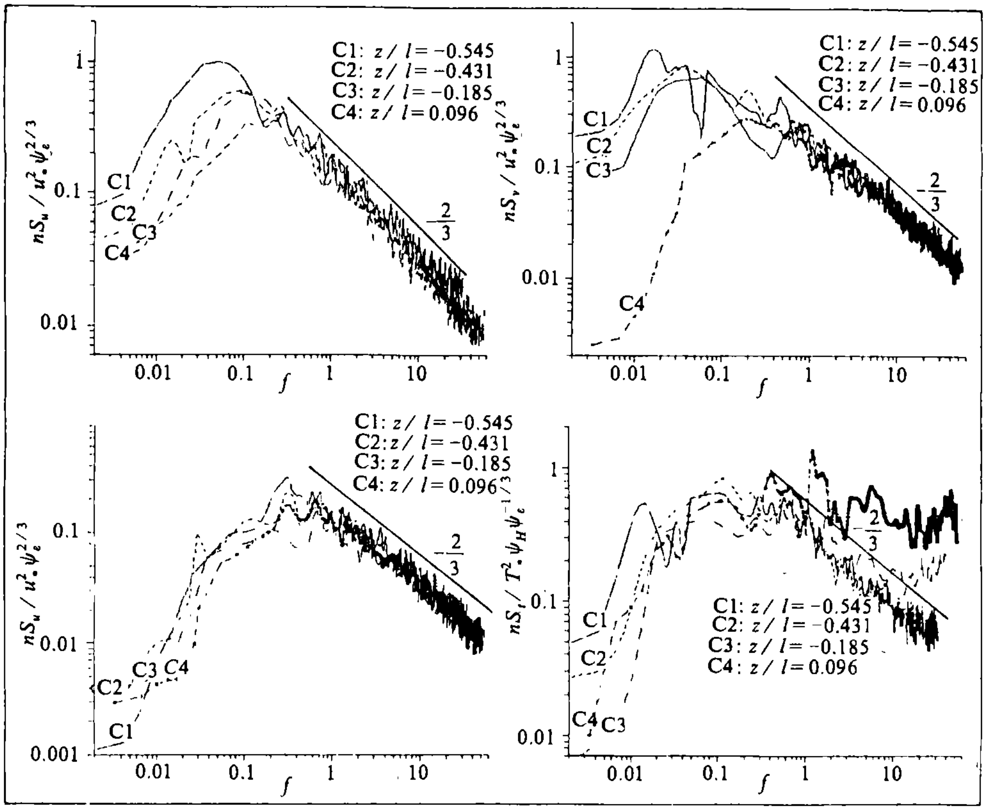

Fig. 1. Comparison of velocity spectra and temperature spectra corresponding to varying value of z/L.

From Fig. 1 we can see that the effect of z/L changing on spectrum density in LF range in w-direction is not so clear as in horizontal direction. It makes known that the response of the change of turbulence spectra to the change of z/L in vertical direction is not so sensitive as in horizontal direction due to the effect of surface restrictive and roughness. Table 1 shows the comparison between the peak frequency of turbulence spectra over the suburbs of Tianjin (f_{mt}) and what was concluded by previous researches (Haugen 1973; Li et al. 1986) over flat terrian (f_{mp}). f_{mx} in Table 1, where x takes the directions of u, v, w respectively, is the non-dimensional frequency corresponds to the maximum spectrum in x direction.

Table 1. Comparison of the Peak Frequency of Turbulence Spectra over the Suburbs of Tianjin and over Flat Terrian

Stability condition	Peak frequency					
	f_{mt}			f_{mp}		
	f_{mu}	f_{mv}	f_{mw}	f_{mu}	f_{mv}	f_{mw}
Near neutral stability	0.18	0.20	0.35	0.05	0.30	0.47
$-0.545 < z/L < 0.096$	0.04—0.20	0.02—0.25	0.20—0.40			

According to Table 1, compared with the case over flat terrain, the peak frequency of turbulence spectra obtained over Tianjin's suburb increases in u direction while decrease in v and w

directions, so the reduced value of $f_{mw}-f_{mu}$ means that the 3-D peak frequency of turbulence spectra becomes narrower. When the value of z/L varies from -0.545 to 0.096, the peak frequency moves towards HF. The shifting amount in each of the three directions is about 0.2. That is to say, the degree in which the change of stability affects peak frequency, is similar in three directions. Together with the analysis on Fig.1, it shows that with the unstability increasing, the scales of major vortexes in turbulence are increasing.

Haugen (1973) concluded that the spectra of velocity over flat terrian began to drift off its neutral condition toward LF when $f=0.18f_{max}$ over flat terrian. According to the estimation of Fig. 1, when the ratio of f to f_{max} is 0.3—0.5, the spectra drift off its neutral condition, in three directions, i. e. the shape of spectra is not as flat as that over flat terrain. It is illuminated that the increase of roughness of the underlying earth' s surface due to the existence of buildings makes the peak frequency band of spectra narrower.

With the change of z/L, the regularity in the distribution of temperature spectra is not as good as in that of velocity spectra. It may be caused by the noise pollution. If the several curves when $z/L<0$ are analysed, we found that the shapes and the basic features of temperature spectra are similar to those of velocity spectra, except that the spectra of temperature are flatter than the spectra of velocity.

2. *Comparison of Power Spectra in Three Directions*

Although they are very similar in HF, the spectra in three directions differ in LF due to the thermodynamical condition, topographic condition and surface restriction. It is usually thought that the 3-D spectrum density over flat area satisfies the relationship $S_u(n)>S_v(n)>S_w(n)$ and has the feature $f_{mu}<f_{mv}<f_{mw}$, in the stable and near-netural conditions. In the unstable condition, it is difficult to find the relationship of u- and v-spectra and it is also difficult to determine which peak frequency is bigger and which is smaller. For $z/L=0.096$, Figure 3 shows that the features of spectra density and peak frequency are connected over flat terrain. But $f_{mv}<f_{mu}<f_{mw}$ is always being satisfied and the feature $S_v(n)>S_u(n)>S_w(n)$ is also very clear, if $z/L<0$. It is different from the situation over flat terrain. The results narrated above show that rough surface may increase the variability in wind direction and the fluctuation of cross wind, so that there always is the relationship $S_v(n)>S_v(n)$ in LF range under the unstable condition. Moreover, the change of peak frequency and its magnitude in different directions may be related to the roughness of surface.

Figure 2 shows that fluctuation energy is the highest in the direction u, the second is in the direction v and the smallest in the direction w, when $z/L=0.096$. If $z/L<0$, the fluctuation energy is the highest in the direction v.

3. *Analysis of Local Isotropy*

Many observational analyses show that the turbulence spectra meet the isotropic hypothesis in inertial range and the values of S_v/S_u and S_w/S_u are $4/3$ in inertial range. Haugen (1973) thought that above mentioned conclusion can be verified when $n>10\bar{u}/z$. According to Haugen' s results, we set the $\bar{u}$ (actual observational wind speed) to be 3.5 m s^{-1} and the z (height of the observational point) to be 35 m. Therefore, the values of S_v/S_u and S_w/S_u can not be $4/3$ until n is greater than 1 Hz. Figure 3 shows that the value of S_w/S_u is $4/3$ in the area when $n>0.4$, the value of S_w/S_u is close to $4/3$ and the value of S_v/S_u is $4/3$ in

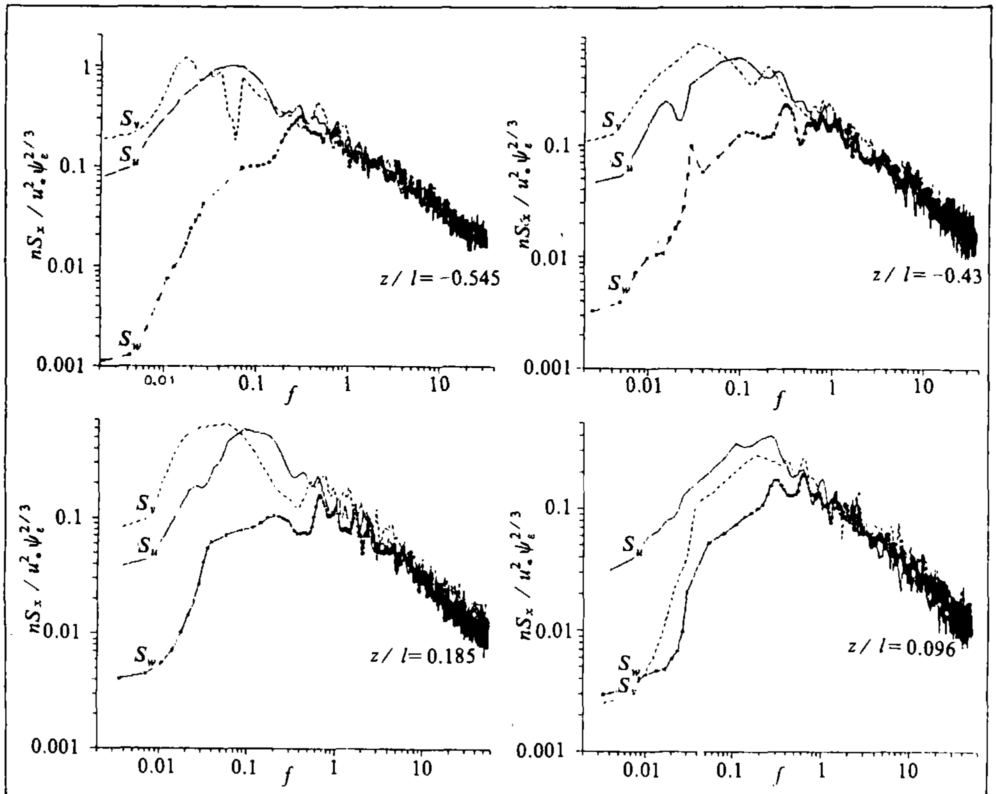

Fig. 2. Comparison of velocity spectra in three directions under different stability conditions.

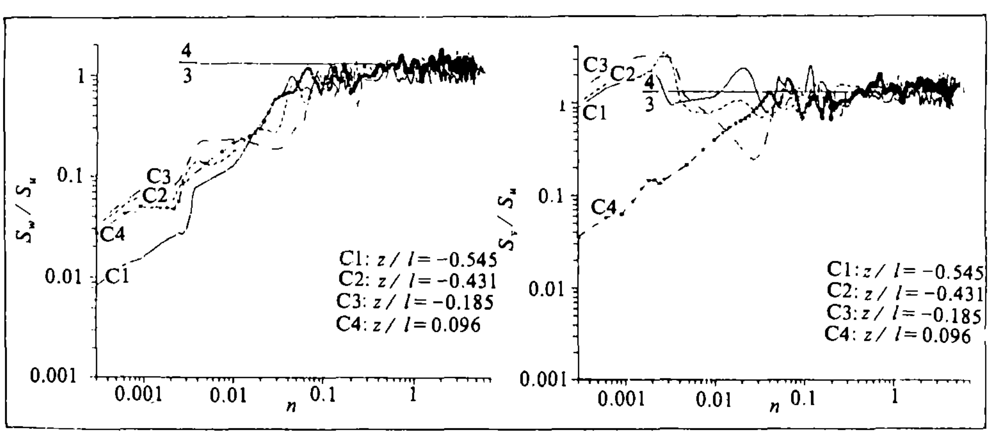

Fig. 3. The distributions of S_w/S_u and S_v/S_u with n (unit of n is Hz).

the area when $n>0.06$. So the scale on which turbulence meets isotropy over the surface of Tianjin's suburb is several times larger than the turbulent scale concluded by Haugen over flat terrain. Haugen also thought that the two-thirds law, horizontal component can be verified very dependable in the area of $n>0.133$. However, from Fig. 4, it can be seen that the two-thirds law can be met if horizontal component is in the area of $n>0.03$ and vertical

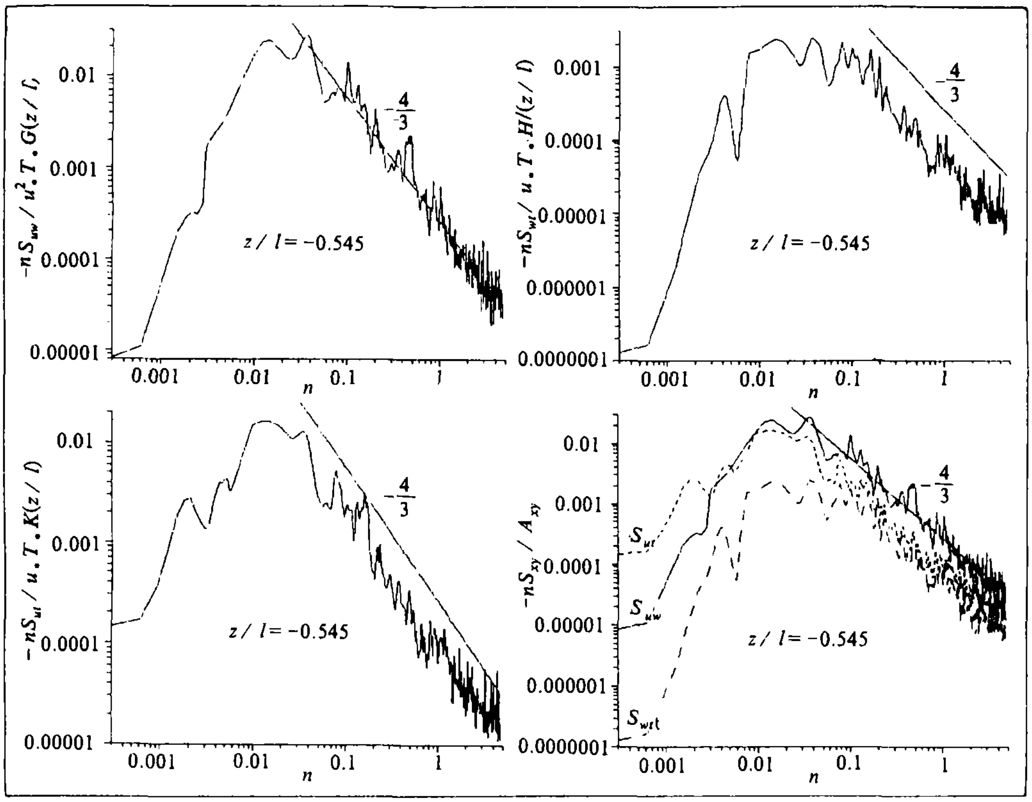

Fig. 4. The cospectra with $z / L = -0.43$.

Table 2. The Relationship of Momentum and Thermal Fluxes to n

Frequency range	Relation between S_{uw}, S_{ut} and S_{wt}	Corresponding vortex scale
$n < 0.03$	$S_{wt} < S_{uw} < S_{ut}$	$\lambda > 130$ m
$0.03 < n < 0.1$	$S_{wt} < S_{ut} < S_{uw}$	40 m $< \lambda <$ 130 m
$n > 0.1$	$S_{uw} > S_{ut}$, S_{ut} close to S_{wt}	$\lambda < 40$ m
All frquency area	$S_{wt} < S_{uw}$	

component in the area of $n > 0.3$. Studying shapes of spectrum curves and the distributions of spectrum density in 3–D, we find that the increase of roughness of surface makes the scale on which turbulence meets isotropy increase. Figure 3 shows that S_w / S_u drift off the 4 / 3 is farther than S_v / S_u in LF area. The value of n while S_v / S_u strikely drift off 4 / 3 is 0.03 under the stable condition, but the value n is much smaller under the unstable condition.

4. *Cospectra*

Figure 4 shows that the change of cospectra as n changes satisfies the four–thirds law in inertial area, and the peak frequencies all lie nearby $n = 0.01$ Hz or $f = 0.1$. This is in agreement with Kamal' s result. Compared with power spectra, the fluctuation of cospectrum curve is

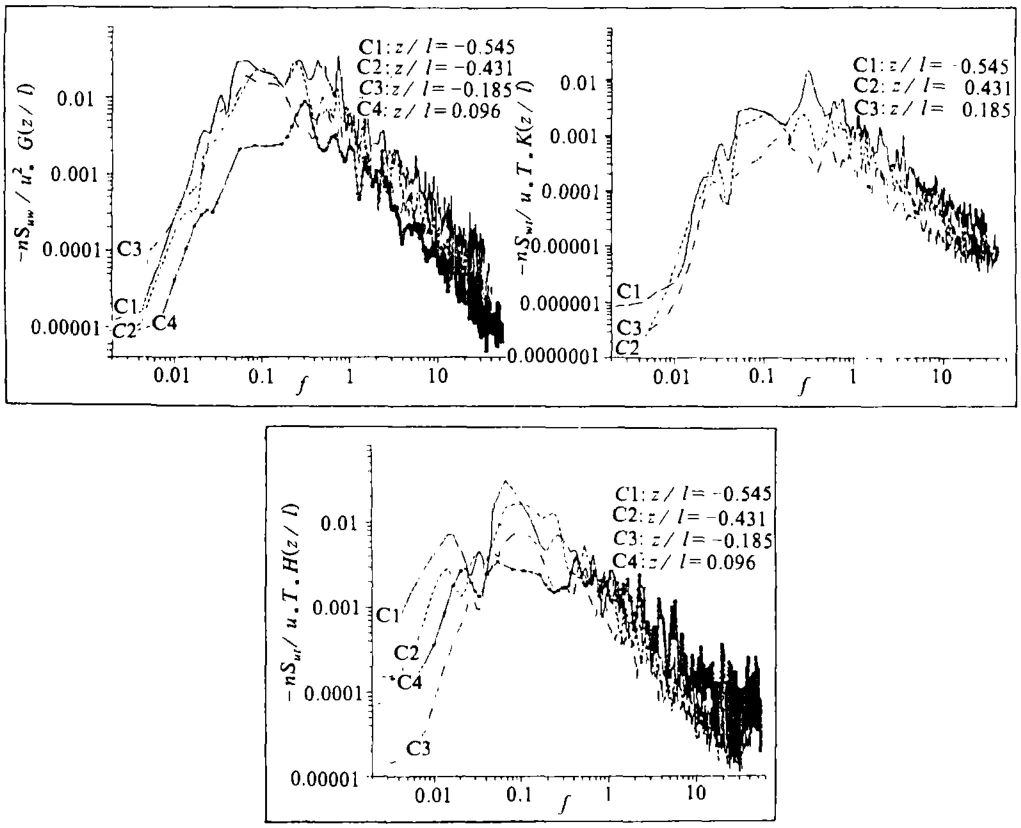

Fig. 5. Cospectra coresponding to different z/L.

larger. Among all frquency bands, S_{uw} (momentum flux) is always above S_{wt} (thermal flux), while the curve of S_{uw} crosses with curve of S_{ut} (horizontal thermal flux). Table 2 gives the comparison between S_{uw}, S_{ut} and S_{wt}.

Figure 4 and Table 2 show that the transport of momentum flux is always higher than that of thermal flux in vertical direction when $z/L=0.04$ and $z=35$ m. Transports of momentum flux and horizontal thermal flux are higher than transport of vertical thermal flux in LF range. This conclusion is contrary Haugen' s (1973), and the reason needs further studying in future. Thermal flux in horizontal direction is same in vertical direction, but momentum flux is higher.

Figure 5 shows that cospectra are affected by stability. As the z/L changes, the change tendency of peak frequencies and shapes of cospectra similar to that of the velocity spectra. The difference is that cospectra are also affected by the change of the value of z/L in HF range. The cospectrum curve for responding to small value of z/L is usually above the cospectrum curve corresponding to large value of z/L. It shows that unstability strengthening leads to increasing thermal and momentum fluxes. The effect of the stability changing on the momentum and thermal fluxes in vertical direction is less than in horizontal direction. In the area where $f>0.2$, the changing magnitude of S_{wt} increases clearly. In the area where $f>0.1$, the changing magnitude of S_{uw} increases clearly. It indicates that for greater turbulence, owing to the effect of surface limitation and roughness, the magnitude of flux increased in vertical direction decreases with increasing unstability.

IV. CONCLUSIONS

The turbulence over the terrain of Tianjin suburb satisfies with Monin–Obukhov's similarity theory, and some basic features of the turbulence spectra are similar to those over flat terrain. For the existence of buildings on the underlying surface leads the roughness to increase, the characteristics of turbulence spectra under the conditions of the suburb terrain are different from those over flat terrain. These characteristics are concluded as:

(1) The average scale of turbulence and the scale which meets the two–third law increase.

(2) f_{mu} extends towards the HF range, while f_{mw} extends towards the LF range. The common relationship $f_{mu} < f_{mv} < f_{mw}$ over the flat terrain does not fit the case, and the peak frequency becomes narrower.

(3) Fluctuations of spectra density in v direction are bigger and double–peak characteristics of that are evident, in LF range. Spectra densities in u direction are bigger than in vertical direction.

By analysing cospectra, we find that transports of momentum and thermal fluxes are obviously affected by stability, and increase with increasing unstability. Transports of momentum and thermal fluxes in horizontal direction are higher than in vertical direction over low frquency range, and there is on obvious difference in HF. It shows that the bigger scale turbulence is restricted clearly by the surface.

REFERENCES

Haugen, D. A. (1973), *Workshop on Micrometeorology*, Amer. Meteor. Soc.

Kamal, J. C. (1972), Spectral characteristics of surface layer turbulence, *Q. J. R. Meteor. Soc.*, **98**.

Li Zhongkai et al. (1986), *Principle and Application of Air Pollution Meteorology*, China Meteorological Press (in Chinese).

Roth, M. et al. (1989), Velocity and temperature spectra and cospectra in an unstable suburban atmosphere, *Boundary Layer Meteor.*, **47**: 309—320.

Wang Hongyu (1988), *Processing of Random Digital Signal*, Sciences Press (in Chinese).

Wang Jiemin (1992), Characteristics of the surface layer turbulence spectra over valley city, *Chinese J. Atmos. Sci.*, **16**: (in Chinese).

Wang Lizhi et al. (1985), Studying of the surface boundary layer turbulence over the suburbs, *Chinese J. Atmos. Sci.*, **9**: (in Chinese).

Zhang Aishen et al. (1991), Characteristics of turbulent structure over Beijing suburb and margin of city, *Chinese J. Atmos. Sci.*, **15**: (in Chinese).

Zhou Mingyu et al. (1979), Advance of research in atmospheric boundary layer physics, *Chinese J. Atmos. Sci.*, **3**: (in Chinese).