Aerodynamic characteristics and wind direction above a spruce forest stand

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Abstract: In this paper an analysis of the wind direction and wind speed profile measurements in and above young spruce forest stand is presented. The needed experimental data were obtained by measurements during the growing season of the year 2004 (May to October) in the locality Bílý Kříž (49°30′17″ N, 18°32′28″ E, 898–908 m a.s.l.) in Moravian-Silesian Beskydy Mts, Czech Republic. The experimental site consisting of two plots Fd and Fs with different tree density is created by the monoculture of a Norway spruce stand. The wind direction was measured continuously by the InSituFlux system (Sweden). It was found out that the prevailing wind above the investigated spruce forest stand came from the SSW direction, in more than 50% of all analysed wind directions. The reason is in the local orographic broken terrain. The analysed wind speed profiles were measured in Fs plot continuously at levels 7, 9, 10, 12, 16, and 21 m in May and June and from July at higher levels 7, 9, 10, 13, 18, and 26 m. The spruce stand in Fs plot with density 1880 trees per ha had the mean tree height (h) in the period from May to June 9.9 m and from July to October $h = 10.4$ m. For the analysis 837 profiles were selected, which fulfilled the condition: $u(9 \text{ m}) > 1.0 \text{ m s}^{-1}$. In that case we can assume, that the wind speed profiles were analysed in the conditions of the turbulent development.

Key words: spruce forest stand, wind speed profiles, wind direction, zero-plane displacement, roughness length

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1. Introduction

The impact of the climate change is considered for the most significant problem in the present history of the human race. Forest ecosystems with respect to their area and structure play a significant role in production, modification, and microclimate protection (*Intribus, 1977*). Most climate models are very sensitive to the exchange of momentum, heat, and water at the boundary between the earth's surface and the atmosphere (*Garratt, 1993*). Atmospheric processes significantly influence the growth and the development of vegetation. On on the other side, the vegetation has important influence on the field of airflow, temperature and humidity stratification in the surface layer of the atmosphere. It modifies the processes in this atmosphere layer and forms its own microclimate (*Matejka, 1991, 1998*).

The forest stands signify a very important component in this interaction (*Halldin and Gryning, 1999*). Therefore the study of the interactions between the forest stand and the atmosphere was one of the objectives of several international experiments, for example NOPEX (*Halldin et al., 1999*).

The majority of forest ecosystems in the Czech Republic are composed of Norway spruce stands which have more than 80% share. The extensive research of the climate of the Norway spruce monoculture is carried out at the Experimental Ecological Study Site at Bílý Kříž in the Moravian-Silesian Beskydy Mts, Czech Republic (*Kratochvílová et al., 1989*; *Havránková and Janouš, 2000*; *Matejka et al., 2000*).

This paper presents the analysis of the influence of the airflow direction above the spruce forest stand on the aerodynamic characteristics of the air layer affected by this forest. Aerodynamic characteristics play a significant role in the interaction between the vegetation and the surface atmosphere layer (*Brutsaert, 1982*).

2. Experimental site and methods

The analysed wind direction and wind speed profiles were measured during the whole growing season of the year 2004 in and above the Norway spruce (*Picea abies* L., Karst) monoculture at the Experimental Ecological

Study Site (EESS) at Bílý Kříž (lat. 49°30′17″ N, long. 18°32′28″ E). This forest is situated on a mild slope with SW orientation, which is in the highest part of the Moravian-Silesian Beskydy Mts (898–908 m a.s.l.) (*Janouš and Schulzová, 1995)*.

Bílý Kříž, by climatic classification, is a cool and humid region with abundance of precipitation. The mean annual air temperature is 4.9° C, the mean annual precipitation total is 1100 mm, and the mean air humidity is 80% (*Rožnovský, 1998*).

The prevailing wind direction above the investigated spruce forest stand is south, in spite of this, generally in this part of the Beskydy Mts north and west airflow predominates. It is a result of the orographic broken terrain (*Havránková and Janouš, 2000; Havránková et al., 2001*).

The wind speed and direction was measured continuously by the system InSituFlux (Sweden). It is a system to measure the fluxes of energy and substances between a surface and boundary layer of the atmosphere using the eddy-covariance method. Simultaneously the microclimatic profile measurements of the wind speed, air temperature and humidity in and above investigated forest stand were realized on 26 m high tower. The values of wind speed were continuously measured by automatic measuring equipment with data logger (DL3000, Delta-T, U.K.) and anemometers (AN1, Delta-T, U.K.) in the 10-minute intervals and records of data.

The experimental site consists of two plots Fd and Fs with different trees density. The analysed vertical wind speed profiles were measured in Fs plot in and above the investigated spruce stand during all growing season, from May to October 2004. In this time the investigated spruce forest stand was 23 years, and on the area of 2500 m^2 the stand density in Fs plot was 1880 trees/ha. It was shown, that airflow in May was different as during June and therefore we analysed the wind speed profiles in these months separately. The mean forest height h in period from May to June was 9.9 m and the wind speed profiles were measured at levels 7, 9, 10, 12, 16, and 21 m. From July to October $h = 10.4$ m and measured levels were 7, 9, 10, 13, 18, and 26 m.

The aerodynamic characteristics of an air layer affected by vegetation can be described using parameters like the roughness length z_0 and the zero plane displacement height d. The d values were determined by processing the vertical wind speed profiles measured at the neutral thermal stratification of the atmosphere (*Brutsaert, 1982*). The values of z_0 can be obtained from the analysis of the vertical wind speed profiles measured above an active vegetation surface under different atmospheric thermal stratification (*Monin and Obukhov, 1954; Matejka et al., 2000*). Following from the Monin-Obukhov similarity theory, each vertical wind speed profile $\bar{u}_k(z_i)$ can be approximated by the relation

$$u_k(z_i) = A_k(\gamma + \log z_i) + C_k z_i, \tag{1}$$

where k is the profile number. The values of A_k, γ, and C_k parameters are calculated by the least squares method for every profile. Then the values of z_0 are obtained from following relationship (*Monin and Obukhov, 1954*)

$$z_0 = 10^{-\gamma}. \tag{2}$$

Further using these parameters the friction velocity u^* and β/L, where β is the Monin-Obukhov‘s universal constant and L is the Obukhov‘s stability length, can be obtained from the relationships

$$u^* = \frac{\kappa A_k}{\ln(10)}, \tag{3}$$

$$\frac{\beta}{L} = \frac{C_k}{A_k}\ln(10). \tag{4}$$

Above the vegetation, the roughness-sublayer extends, in which surface elements directly influence the turbulence. There is some evidence that it can reach 3–8 times the stand height (*Garratt, 1980*). *Cellier and Brunet (1992)* obtained about 2 times the canopy height. In our analysis the roughness-sublayer height z_r was estimated using the relationship (*Verhoef et al., 1997*)

$$z_\mathrm{r} \approx 15 z_0 + h. \tag{5}$$

3. Results and discussion

For the analysis of the wind speed profiles a selected set was used, which fulfilled the condition $\bar{u}(h-1) > 1.0$ m s^{-1}, where $h - 1 = 9.0$ m. In this case the conditions of turbulent development can be supposed. Then the analysed set contained 167 profiles in May, 90 in June and 580 ones during the period July - October. These profiles were divided into six ranges in accordance with the value of $u(h)$, Fig. 1.

$$\begin{array}{ll} \mathrm{I} & 1.0 \leq u(h) < 2.0 \\ \mathrm{II} & 2.0 \leq u(h) < 3.0 \\ \mathrm{III} & 3.0 \leq u(h) < 4.0 \\ \mathrm{IV} & 4.0 \leq u(h) < 5.0 \\ \mathrm{V} & 5.0 \leq u(h) < 6.0 \\ \mathrm{VI} & 6.0 \leq u(h) < 7.0 \end{array} \tag{6}$$

It was shown, that most of the analysed profiles were measured in the range values II and III: 67% during May - June and 72% during period July - October. In the first months of this growing season (May – June) the investigated forest stand with $h = 9.9$ m had the mean zero plane displacement $d \approx 6.7$ m, the mean roughness length $z_0 = 0.8$ m, and the roughness sublayer height $z_r = 22.4$ m. During the period July – October, $h = 10.4$ m, $d \approx 7.1$ m, $z_0 = 0.9$ m, and $z_r = 24.1$ m.

Now, the wind direction during the growing season of 2004 is analysed. The wind roses of the analysed profiles separately in May, June, and period July - October are presented in Fig. 2. In May the analysed wind directions ranged in the SSE – WSW interval with two maxima: in S direction 37.4% and SSW 45.2%, while in June these ranged in the narrow interval with the expressive maximum in SSW direction (S direction 12.2%, SSW 68.9%, and SW 18.9% from the whole analysed profiles). It is interesting that the highest values of the wind speed occurred also during the S–SSW wind directions, Fig. 3. It is evidently the result of the local orographicaly broken terrain.

During the period July – October the prevailing wind directions were in SSW direction, 67.5%, 30.0% in S direction, and only about 1.0% in SSE and SW ones.

The aim of this contribution is the wind direction influence on the aerodynamic characteristics of the air layer affected by investigated forest stand. Therefore first the relation between the friction velocity u^* and the wind speed $u(h)$ will be found empirically from the analysed wind speed profile measurements during the investigated growing season. Assuming z_0 and d are constant with the wind speed, the linear equation, $u^* = au(h)$, where a is constant, is rewritten from the log low. In this case the vegetation is in

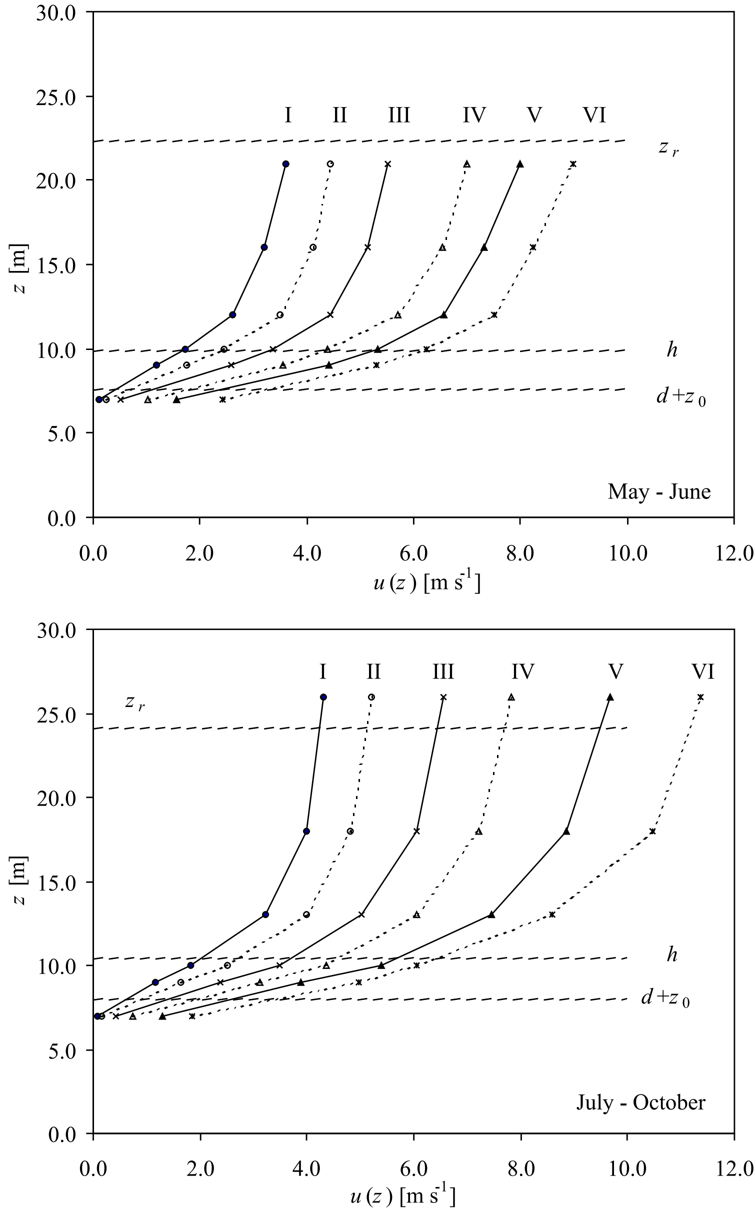

Fig. 1. Mean vertical wind speed profiles in the range of I-VI (Eqs. 6). Symbol h means the mean stand height, d is the mean zero plane displacement, z_0 the mean roughness length, and z_r the roughness sublayer height.

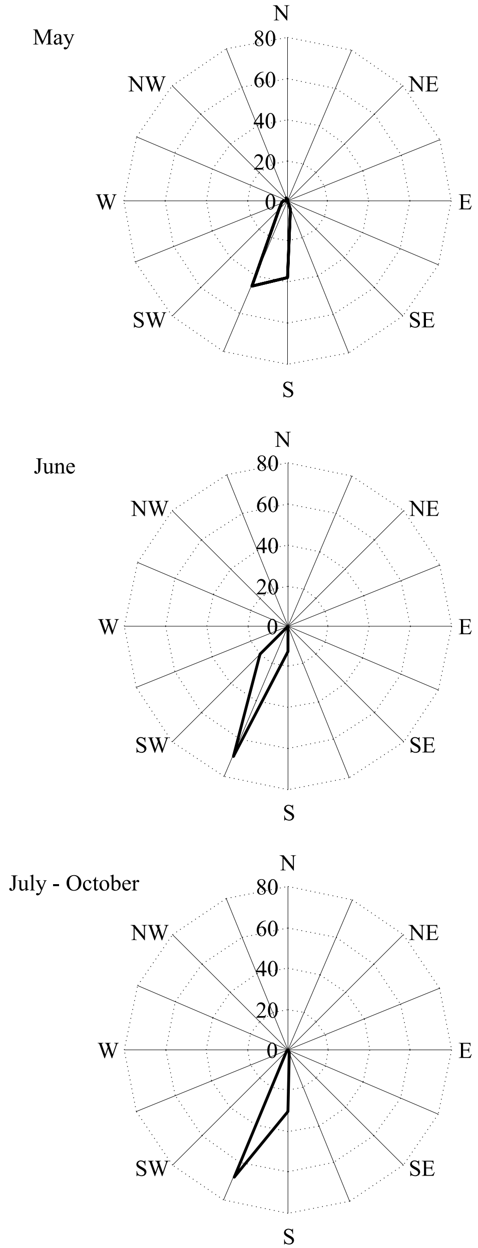

Fig. 2. Wind roses of the selected profiles above investigated spruce forest stand in May, June, and July – October 2004.

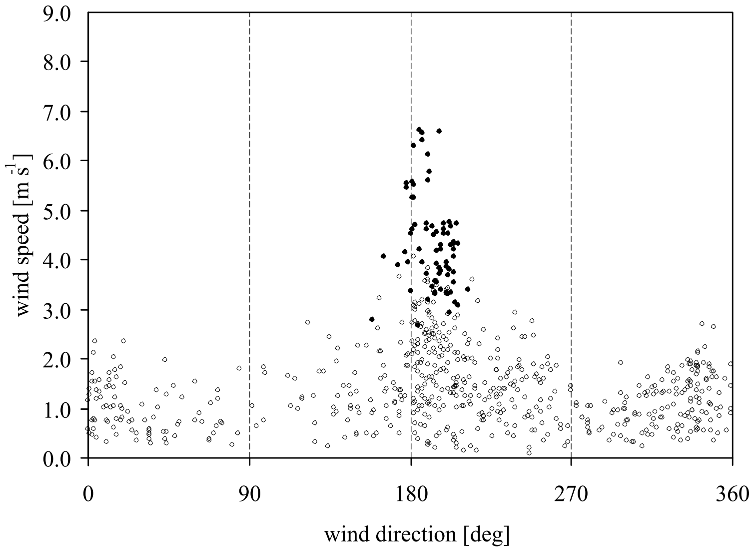

Fig. 3. Dependence of the wind speed (all speed values measured by InSituFlux system at level 13.5 m) on the wind direction for EESS Bílý Kříž in June 2004. Solid points represent the wind speed of analysed profiles.

an aerodynamic steady state, the friction velocity is in the direct proportion to the wind speed. From experiments it follows that in a lot of cases above flexible vegetation the u^* value settles down and deviates from the liner relation. Accordingly, the relation between u^* and $u(h)$ is fitted as follows, $u^* = a[u(h)]^b$, a, b are constant *(Brutsaert, 1982; Hayashi, 1983).* Then the vegetation is in an aerodynamic unsteady state and z_0 and d vary with the wind speed *(Hayashi, 1983; Hurtalová and Matejka, 1999).* In this contribution the dependence of the z_0 values on the wind speed is parameterized.

The wind speed profile analysis shown, that the dependence of the friction velocity on the wind speed measured at $z = h$ can be approximated by the following relationship, solid lines in Fig. 4:

$$u^* = 0.469[u(h)]^{0.47}, \quad r_{xy} = 0.59 \text{ in May,} \tag{7}$$

$$u^* = 0.490[u(h)], \quad r_{xy} = 0.74 \text{ in June.} \tag{8}$$

The dispersion of experimental points, Fig. 4, can be explained only by the partial dependence of u^* values on the wind speed. It follows from these relationships that in May the investigated spruce forest stand was in an aerodynamic unsteady state, Eq. (7), while in June it was in an aerodynamic steady state, Eq. (8). It can be expected, that it is the result of the different wind direction of analysed profiles above this stand during these months. It means that in May the z_0 values change systematically with the wind speed, and in June z_0 is independent of the wind speed. The dependence of the roughness length on the wind speed measured at level 21 m in May and June confirmed this result, Fig. 5. In May this relation was significant and can be approximated by

$$z_0 = 0.167 \exp[-0.217u(z)] \tag{9}$$

with the correlation coefficient between experimental z_0 and z_0 values calculated by this relation, $r_{xy} = 0.71$. In June this relation was not significant, Fig. 5.

During the period July – October the wind rose was similar to that of May. The analytical expression of the dependence of u^* on $u(h)$ was

$$u^* = 0.628[u(h)]^{0.39} \tag{10}$$

with the correlation coefficient $r_{xy} = 0.62$. So, the investigated forest stand during this period was in an aerodynamic unsteady state and the z_0 values during this period changed systematically with the wind speed.

The dependence of z_0 values on the wind speed can be determined empirically also as the dependence of relative roughness length $\xi_0 = z_0/h$ on the nondimensionless wind speed $\Gamma = u(h)/u^*$. This experimental dependence is graphically presented in Fig. 6 for period May – June and in Fig. 7 for July – October. An analytical expression of these dependencies can be approximated by the following relationships, solid lines in Figs. 6 and 7:

$$\xi_0 = 0.210\exp(-0.342\Gamma), \quad r_{xy} = 0.97 \quad \text{in May – June}, \tag{11}$$

$$\xi_0 = 0.213\exp(-0.345\Gamma), \quad r_{xy} = 0.98 \quad \text{in July – October}. \tag{12}$$

The dependence $\xi_0 = f(\Gamma)$ was highly significant, and was not dependent on the wind direction.

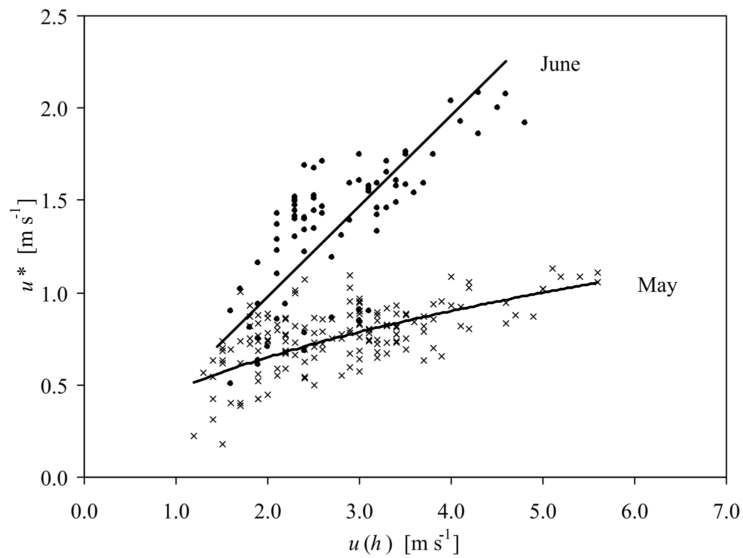

Fig. 4. Dependence of the friction velocity u^* on the wind speed $u(h)$ in May and June. Solid lines are analytically expressed by Eqs. (7) and (8).

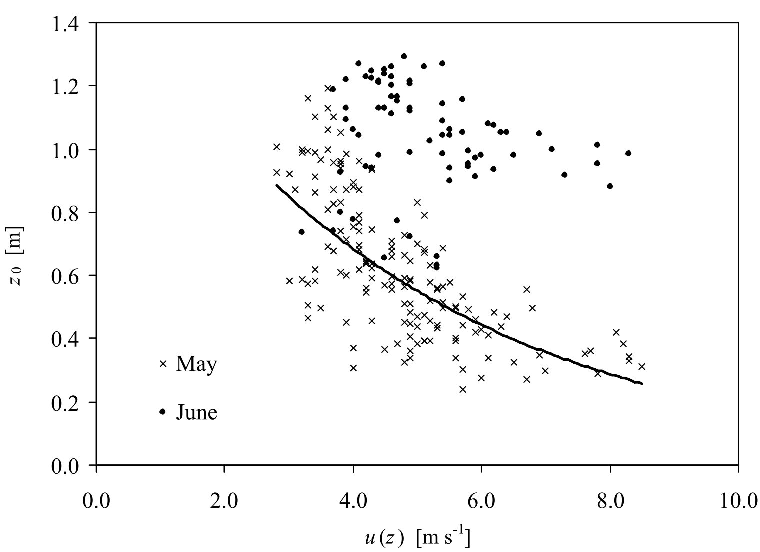

Fig. 5. Dependence of the roughness length z_0 on the wind speed $u(z)$, where $z = 21.0$ m in May and June. Solid line is expressed by Eq. (9).

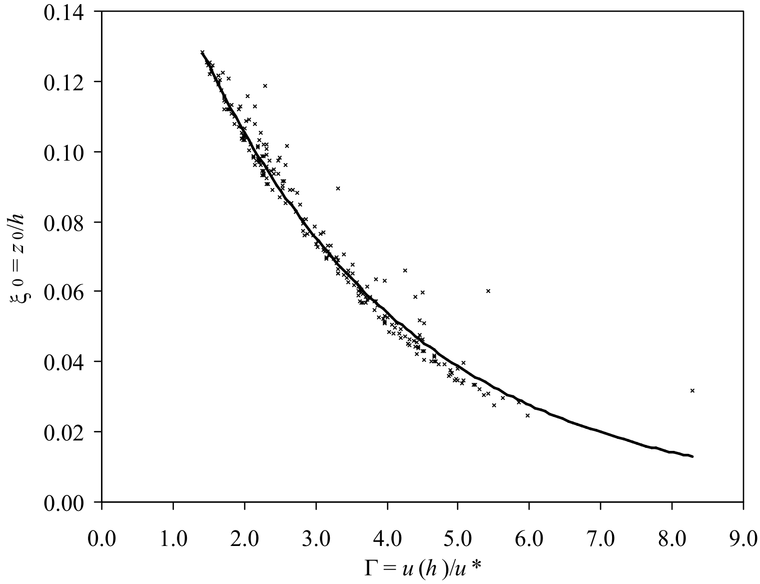

Fig. 6. Dependence of the relative roughness length ξ_0 on the nondimensioless wind speed Γ during period May to June. Solid line is expressed by Eq. (11).

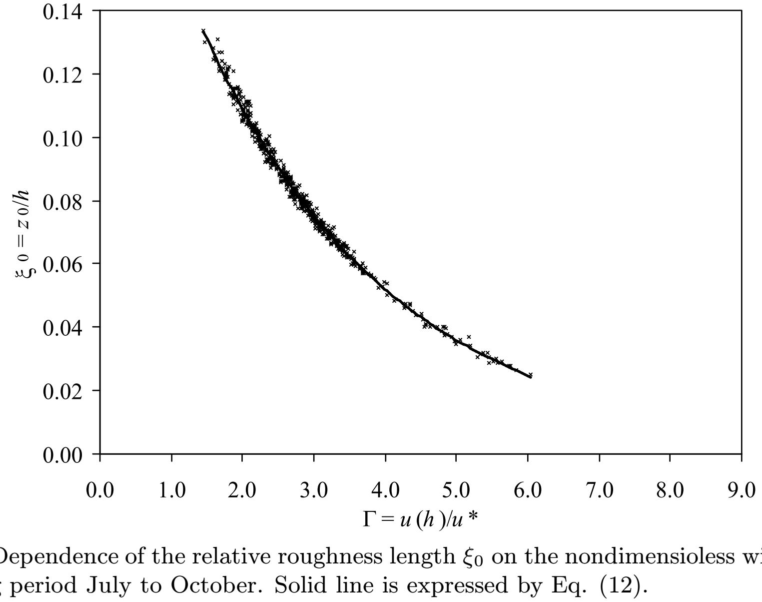

Fig. 7. Dependence of the relative roughness length ξ_0 on the nondimensioless wind speed Γ during period July to October. Solid line is expressed by Eq. (12).

4. Conclusions

When the vegetation surface is exposed to airflow, it is deformed with the increase of wind speed. This deformation may be associated with streamlining effects. When the wind reaches an inherent speed, it may turn into wave motion. Under these conditions the vegetation surface becomes smoother and the momentum transport decreases just over the surface. Consequently, at a certain wind speed an aerodynamic regime may appear and then the friction velocity approaches a minimum. Similar situation was described earlier by *Hayashi (1983)*.

In this contribution the investigated surface was created by a young spruce forest stand with an age of 23 years. As it was written before, this forest is situated on a mild slope with SW orientation. So the wind speed values depend on the airflow direction above this experimental site. With the aim to analyse the influence of the wind direction on the aerodynamic parameters, the selected wind speed profiles measured in and above this forest stand during all growing season (May – October 2004) were analysed. The analysed set contained 257 profiles in the period May - June and 580 profiles during the period from July to October, which fulfilled the condition $\bar{u}(h-1) > 1.0$ m s^{-1}.

It was shown, that the most analysed profiles ranged in the interval values $2.0 \leq u(h) < 4.0$ m s^{-1}, 67% in the period May - June and 72% in the period July - October. From the wind direction analysis it follows, that airflow direction above the investigated forest stand in May was different than in June. In May, the analysed directions ranged in the SSE – WSW interval with two maxima, 37.4% in S and 45.2% in SSW direction, and in June these ranged in the narrow interval with a pronounced maximum in SSW direction, 68.9% of the whole analysed profiles, Fig. 2. This fact caused that in May the investigated spruce forest stand was in an aerodynamic unsteady state, while in June it was in an aerodynamic steady state. It followed from the relation between u^* and $u(h)$ analysis. It means that in May the z_0 values change systematically with the wind speed, and in June z_0 was independent of the wind speed, Fig. 5. In May, the dependence of the z_0 values on the wind speed measured at level 21 m can be approximated by relation $z_0 = 0.167\exp[-0.217u(z)]$.

During the period from July to October, this forest stand was in an aerodynamic unsteady state and z_0 values varied with the wind speed.

The dependence of the relative roughness length $\xi_0 = z_0/h$ on the nondimensionless wind speed $\Gamma = u(h)/u^*$ did not depend on the wind direction, and Eqs. (11) and (12) approximated well this dependence with the high value of the correlation coefficient.

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