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Turbulence spectral characteristics of surface boundary layer

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ABSTRACT: A spectral analysis from wind tunnel and near-neutral atmosphere data was realized. The measurement spectra are compared with von Kármán and Kaimal expressions and a complementary evaluation based on the previous work of Arbage and Degrazia et al. was realized. A comparison of the vertical component with atmospheric values is also considered and the atmospheric stability effects on full-scale measurements are also analyzed. Parameters used to obtain dimensionless spectra including mean velocity, the variance of velocity fluctuations, the longitudinal integral length, local friction velocity and the mean turbulent kinetic energy dissipation.

KEY WORDS: Wind Engineering; Turbulence Spectra, Atmospheric Boundary Layer.

1 INTRODUCTION

Understand the dynamics and transport processes of fluids and gases in natural environments and technological settings is important for innumerable reasons. In wind engineering, one research area aims at reproducing in laboratory the physics phenomena of the atmospheric surface layer. For this field of research, two important challenges can be highlighted. First, the technical challenge of producing a realistic simulation of the atmospheric turbulence in reduced scales and, second, how to determine a suitable mathematical model describing relevant physical characteristics of the turbulent flow. Regarding this later problem, many wind engineering studies rely on the spectral analysis of turbulence. In particular, small scale models of the atmospheric surface layer simulated in laboratory are typically analyzed through expressions describing non-dimensional spectrum of the real atmospheric surface layer. Atmospheric wind data are often obtained from anemometers normally located at the range of 1-50 m height, and sampling frequency within the range of 1-20 Hz. Typical atmospheric turbulence records are non-stationary and contains low frequency components due to micrometeorological and meso-scale motions, superimposed to the scales of the boundary layer turbulence. Consequently, the wind spectrum is very broad, containing time scales of several hours up to fractions of a second.

The Van der Hoven spectrum, obtained in Brookhaven, Long Island, NY, USA [1] is a well-known experimental result reporting the spectrum of the longitudinal velocity component characteristics in the complete frequency domain. Micro-meteorological and macro-meteorological peaks can be distinguished in the Van der Hoven spectrum and a low energy spectral "valley" between these two peaks can be identified, which is broadly used to discriminate micro-meteorological and macro-meteorological aspects. Fluctuations of periods less than one hour define the micro-meteorology region and determine atmospheric turbulence spectra. In 1948, von Kármán suggested an expression to model the turbulence spectrum, and 20 years later began to be used in wind engineering. Harris [2] showed drawbacks of this formula by fitting it to wind atmospheric experimental data. More recently, a model for the turbulent spectra in a shear driven planetary boundary layer was proposed by Degrazia et al. [3].

In this work a spectral analysis from laboratory data, obtained in two wind tunnels of different sizes, and data measured directly in a near-neutral atmosphere is realized. Firstly, the obtained measurements spectra are compared with von Kármán and Kaimal expressions. Later, a complementary evaluation based on the previous work of Arbage et al. [4] is realized. The present study is focused on the analysis of the longitudinal velocity component; however, comparisons of the lateral and vertical components with atmospheric values are also considered. The impact of the atmospheric stability on full-scale measurements is also addressed. Parameters used to compare the von Kármán and Kaimal expressions includes the mean velocity and its variance, the longitudinal integral length or local friction velocity; which are commonly used in Wind Engineering. The parameterization proposed by Degrazia et al., on the other hand, also considers the mean turbulent kinetic energy dissipation. In this case, the frequency of the spectral peak in the surface for neutral conditions is used to define the spectral model; therefore, the spectral model can be better adapted to field measurements.

2 TURBULENCE SPECTRA EXPRESSIONS

Atmospheric spectra are represented by expressions obtained by fitting spectra of experimental data. A typical expression is the von Kármán formula that appears in the ESDU -Wind Engineering Data Sheet 74031- manual as follows:

$$\frac{nS_u}{\sigma_u^{\,2}} = \frac{4X_u(z)}{\left[1+70{,}78X_u(z)^2\right]^{5/6}} \tag{1}$$

where S_u is the spectral density function of the longitudinal component, n is the frequency [Hz], $\sigma_u^{\,2}$ is the velocity fluctuation variance and the dimensionless frequency $X_u(z)$ is:

$$X_u(z) = \frac{n\,L_u(z)}{\bar{U}(z)} \tag{2}$$

This formulation satisfies Wiener-Khintchine relations and considers the Kolmogorov balance in the spectrum range. However, Harris [2] indicates situations where experimental values are not properly fitted by this expression. On the other hand, the Kaimal spectrum is given by the expression:

$$\frac{nS_u}{\sigma_u^{\,2}} = 33{,}3\frac{Y_u(z)}{\left[1+50Y_u(z)\right]^{5/3}} \tag{3}$$

The dimensionless frequency $Y_u(z)$ is calculated using the height z, being:

$$Y_u(z) = nz/U(z) \tag{4}$$

The equation (5) gives the dimensionless frequency spectra of lateral component of velocity fluctuations and was obtained fitting Kansas experiments measured data[5].

$$\frac{n\,S_v}{u_*^{\,2}} = \frac{17Y_u(z)}{1+9{,}5Y_u(z)^{5/3}} \tag{5}$$

Kaimal expression associated to the vertical component at neutral stability atmospheric condition is given by (6). The spectral density of vertical velocity fluctuations S_w, is normalized by the local friction velocity u_*^2 [5].

$$\frac{n\,S_w}{u_*^{\,2}} = \frac{2Y_u(z)}{1+5{,}3Y_u(z)^{5/3}} \tag{6}$$

The atmospheric stability effect over the spectrum of vertical velocity fluctuation it is possible to analyze with the stability parameter variations z/LMO where LMO is the Monin-Obukhov length.

Degrazia et al. [3] developed a model for turbulent spectra in both purely shear and buoyancy dominated atmospheric boundary layer. This model use Taylor's diffusion theory together with a model for turbulent spectra in a shear-buoyancy driven atmospheric boundary layer, in order to generate a turbulence parameterization applicable to all stability conditions with the exception of very stable cases since the Monin-Obukhov scaling does not apply in these condition. In this analysis we are interested in a model that describes the turbulence associated with a neutral atmospheric boundary layer, the model derived by Degrazia et al. which describes turbulent spectra generated by shear mechanism is:

$$\frac{n S_i}{u_*^2} = \frac{1{,}5 c_i \phi_\varepsilon^{2/3} f}{\left\{1 + \frac{1{,}5 f^{5/3}}{\left[(fm)_i\right]^{5/3}}\right\}\left[(fm)_i\right]^{5/3}} \tag{7}$$

where $i = u, v, w$, $(fm)_i$ is the dimensionless frequency of the neutral spectral peak, and $c_i = \alpha_i \alpha_u (2\pi k)^{-2/3}$, $\alpha_u = 0{,}5 \pm 0{,}05$, and $\alpha_i = 1, 4/3, 4/3$ for u, v and w components, respectively. The dimensionless frequency is $f = nz/U$ and the dimensionless dissipation rate ϕ_ε is obtained by

$$\phi_\varepsilon = kz\,\varepsilon / u_{*0}^3 \tag{8}$$

where ε is the mean turbulent kinetic energy dissipation, k is the von Kármán constant, and u_{*0} is the surface friction velocity [4]. The local friction velocity u_* for a neutral PBL is

$$u_*^2 = u_{*0}^2 (1 - z/h)^{1.7} \tag{9}$$

according [3], where h is the depth of the neutral planetary boundary layer and it could be obtained by

$$h = 0{,}2 u_{*0} / |f_c| \tag{10}$$

and $fc = 10^{-4} s^{-1}$ is the Coriolis parameter.

The peak frequencies $(fm)_u$, $(fm)_v$ and $(fm)_w$ characterizing the energy-containing eddies, can be calculated by the expression

$$(fm)_i = (fm)_{0i} (1 + 0{,}03 a_i f_c z / u_{*0}) \tag{11}$$

where $(fm)_{0i}$ is the frequency of the spectral peak in the surface.

3 WIND DATA DESCRIPTION

Atmospheric boundary layer wind data were collected using a 3-D sonic anemometer at 10 m height. Data were measured at Paraíso do Sul, Rio Grande do Sul (S 29º 44’ 39,6”, W 53º 09’ 59,8”), in southern Brazil, employing a sample rate of 16 Hz. The micrometeorological tower is located in an almost flat terrain, which is relatively homogeneous (Figure 1). The meteorological station is part of a Brazilian project developed with the purpose of investigating the surface conditions for distinct ecosystems in the country. Two partial time series, Atm-M1 and Atm-M2, representing strong winds in a constant direction and low turbulence intensity were selected and each series consisted 216= 65.536 points (≈68 min). The wind data were first rotated to refer them to a streamline system [6-8] and linear trends were removed from the series by the least square method.

Laboratory data used for this analysis were obtained from two wind tunnels at the Universidad Nacional del Nordeste (UNNE), Argentina (Figure 2). One of these, the larger called Jacek P. Gorecki wind tunnel (TVG), has a test section of 2,4 m × 1,8 m (cross-section) and 22,8 m long. The other wind tunnel, the smaller (TV2), is also an open circuit with dimensions 4,45 m × 0,48 m × 0,48 m (length, height, width).

In TVG wind tunnel, the atmospheric surface-layer was simulated using the Counihan method, and employing roughness elements and mixing devices showed in Figure 3 [9]. Measurements on a full-depth Counihan simulation [10] with velocity distributions corresponding to a class III terrain were realized. According to Argentine Standards CIRSOC 102 [11], this type of terrain is designed as “ground covered by several closely spaced obstacles in forest, industrial or urban zone”. The mean height of the obstacles is considered to be about 10 m, while the boundary layer thickness is 420 m. The boundary layer thickness in TVG wind tunnel was δ = 1200 mm and measurements were performed at height z = 170 mm. The average wind velocity of the time series employed in this analysis was 14,86 m/s.

In the TV2 wind tunnel, a simulation of natural wind on the atmospheric boundary layer was performed by means of the Standen method [12], with velocity distributions also corresponding to a forest, industrial or urban terrain. A part-depth simulation with a boundary layer thickness of δ = 350 mm was obtained by means of spires and roughness elements (Figure 3) and measurements were made at height z = 80 mm. The mean wind velocity corresponding to TV2 measurement is 13,73 m/s.

Wind tunnel measurements were made using a hot-wire anemometer connected to a data acquisition system. Data was obtained with acquisition frequency of 3000 Hz and the anemometric signal previously was filtered by a low-pass filter set at 1000 Hz. Each time series registered in the wind tunnels consisted of 120.000 points (TVG) and 90.000 points (TV2).

Figure 1.Micrometeorological tower and 3-D sonic anemometer.

Figure 2. Jacek P. Gorecki wind tunnel (TVG) (left) and TV2wind tunnel (right).

Figure 3. Full-depth Counihan vortex generators in Jacek P. Gorecki wind tunnel (TVG) (left) and part-depth Irwin spires in TV2 wind tunnel (right).

Table 1 shows wind data characteristics of the time series used in this analysis; mean velocity U , the variance of longitudinal velocity fluctuations σ_u^2 , sample rate f_{aq} , and the longitudinal integral length L_u . Velocity fluctuations of u , v and w were obtained from atmospheric data. The longitudinal component u was only measured by the one-channel hot-wire anemometer in the laboratory experiments. The local friction velocity u_* was experimentally obtained for laboratory measurements and was calculated with the expression $C_{as} = u_*^2 / U^2$ for atmospheric data. The C_{as} value was adopted considering an opened area. The mean turbulent kinetic energy dissipation ε was determined by the fit of the structure function (four-fifths law) in the inertial range.

Table 1. Wind data characteristics

	U [m/s]	z [m]	σ_u^2 [m²/s²]	f_{aq} [Hz]	L_u [m]	ε [m²/s²]	u_*^2 [m²/s²]
Atm-M1	7,22	10	2,77	16	36,30	0,045	0,245
Atm-M2	6,76	10	2,68	16	37,00	0,041	0,215
TVG	14,86	0,17	8,11	3000	0,43	33	4,196
TV2	13,73	0,08	3,49	3000	0,14	48,8	0,884

4 RESULTS

Results include atmospheric and wind tunnel turbulence spectra, and comparisons of dimensionless spectra. Atmospheric data were obtained using a Campbell 3D sonic anemometer [13], for which the resolution is 0,01 m/s for velocity measurements, while the wind tunnel time series describing in section 3 were measured by a constant temperature hot-wire anemometer. The Fast-Fourier transform was used to compute the spectra and the spectral estimates are block-averaged over non-overlapping frequency bands.

4.1 *Atmospheric turbulence spectra*

Figure 4 shows spectral density functions S_u, S_v and S_w corresponding to each component (u longitudinal, v lateral and w vertical) obtained from Atm-M1 and Atm-M2 series. It is possible to perceive the inertial region characterized by -5/3 slope, and lower energy levels associated to vertical velocity fluctuations w. It is not possible to confirm the neutral atmospheric stability condition, but fluctuations associated to thermal or convective effects are not significant. The results are similar for both series and small differences appear only in the lowest frequency narrow. That is, the flow characteristics correspond to strong wind for both cases but the condition of non-stationary flow occurs at low frequencies. In general, values are in accordance with Kansas experiments for near-neutral atmosphere [5]. Non-filtered signal effects appear at high frequencies.

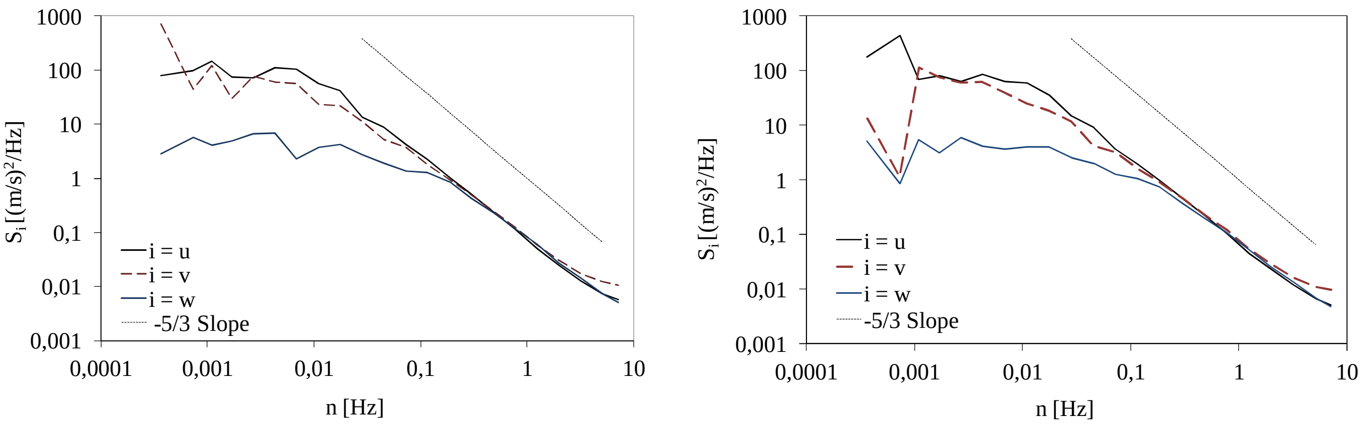

Figure 4. Spectral density functions of the wind velocity fluctuations u, v and w corresponding to Atm-M1 (left) and Atm-M2 (right) atmospheric series. The -5/3 slope indicates the inertial region.

4.2 *Wind tunnel turbulence spectra*

The spectra of the longitudinal component u corresponding to laboratory measurements are shown in Figure 5. One measurement on each wind tunnel is analyzed being possible to perform controlled and repeatable laboratory measurements. It is clearly defined the inertial region (-5/3 slope), but the frequency narrow is greater for the TVG wind tunnel measurement. In the low frequency region, there is greater regularity of spectral values than in the case of atmospheric spectra indicating more stationary flow. The low-pass filter effect is perceived at the frequency of 1000 Hz where the high frequency components are removed.

4.3 *Comparison of dimensionless spectra with von Kármán and Kaimal expressions*

In Figure 6, the dimensionless spectra of the longitudinal component from TVG, TV2, Atm-M1and Atm-M2 series are compared with von Kármán and Kaimal spectrum expressions. Spectra obtained from TVG and TV2 wind tunnel series show a good agreement with the von Kármán spectrum. Atmospheric values are in better correspondence with the Kaimal spectrum, especially in the lower frequencies.

Teunissen warns that the values of the von Kármán expression are not reliable for $f\,L_u/U < 0{,}1$ [14]. The spectra obtained from TVG and TV2 wind tunnel series present a better approximation to the von Kármán spectrum. In general, the experimental spectra peak values are similar to von Kármán peaks and the frequencies corresponding to these peak values present displacements that depend on the series and are different on having considered the von Kármán or Kaimal expression.

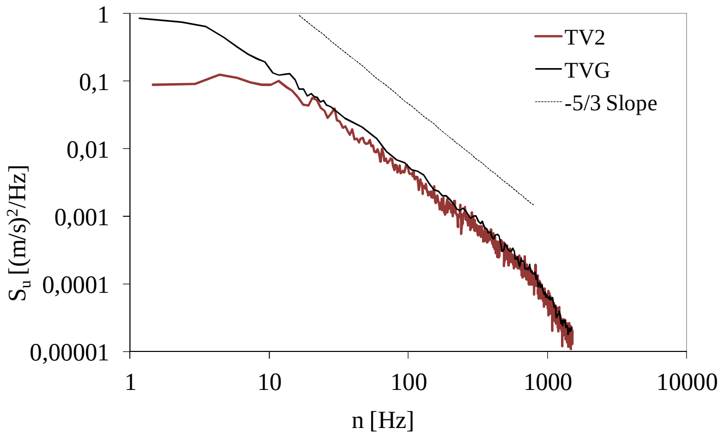

Figure 5. Spectra of the longitudinal velocity fluctuations u for TV2 and TVG wind tunnel series.

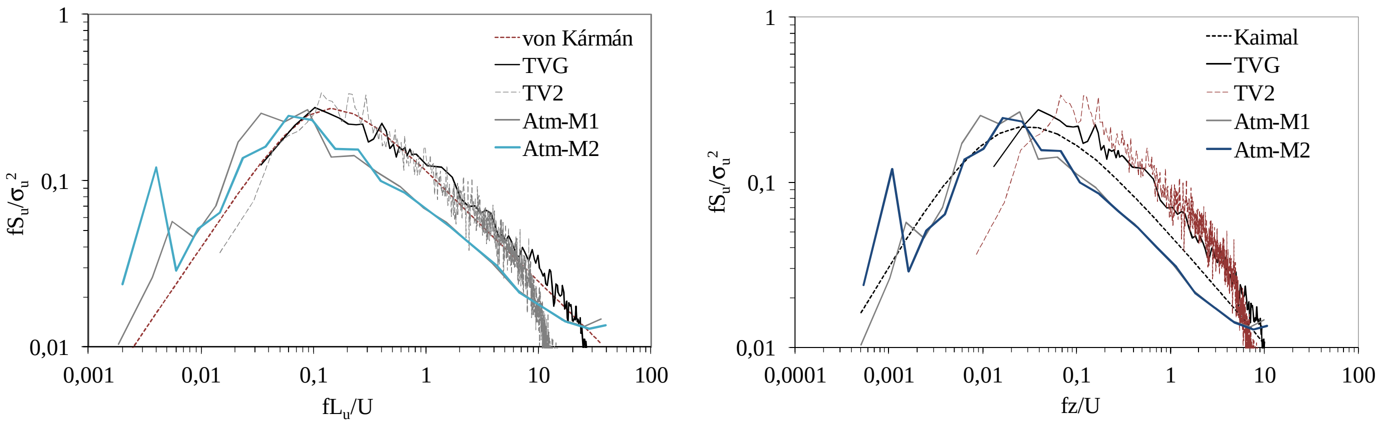

Figure 6. Comparisons of dimensionless spectra corresponding to TVG, TV2, Atm-M1, and Atm-M2 series with von Kármán and Kaimal, respectively.

4.4 *Comparison of dimensionless spectra with Degrazia et al. model*

The spectral model developed by Degrazia et al. (Eq. 6) is defined using the parameters ϕ_ε , the dimensionless dissipation rate, and u_* , the local friction velocity. The dimensionless frequencies of the neutral spectral peak $(fm)_i$ were defined according [4] with a_u = 500, a_v = 1094, and a_w = 3889. The peak frequencies in the surface are $(fm)_{0u}$ = 0,040, $(fm)_{0v}$ = 0,10 and $(fm)_{0w}$ = 0,33. These estimated values of the spectral peak frequencies were obtained from the north wind phenomenon in southern Brazil and they are in fair agreement with the values obtained from the data measured in Kansas experiments. The expression given by Degrazia depends on each measurement due to parameter $(fm)_i$, then the comparison of dimensionless spectra should be done individually. For wind tunnel measurements, peak frequencies were directly obtained from the dimensionless spectral density functions.

Atmospheric spectra show good agreement in the inertial zone (Figure 7). The spectral peak frequency of the measured spectra appear shifted to the low frequency region with respect to the peak of the spectral model. It is possible that low-frequency spectral components occurring by the presence of atmospheric convective turbulence components. The deviation of the high frequency values with respect to the spectral model are the result of anemometer non-filtered signal and, consequently, of the aliasing effect. Wind tunnel spectra show good agreement in the entire frequency range up to the cut-off frequency of the low-pass filter (Figure 8).This result is good news being that the model was completely derived from atmospheric results.

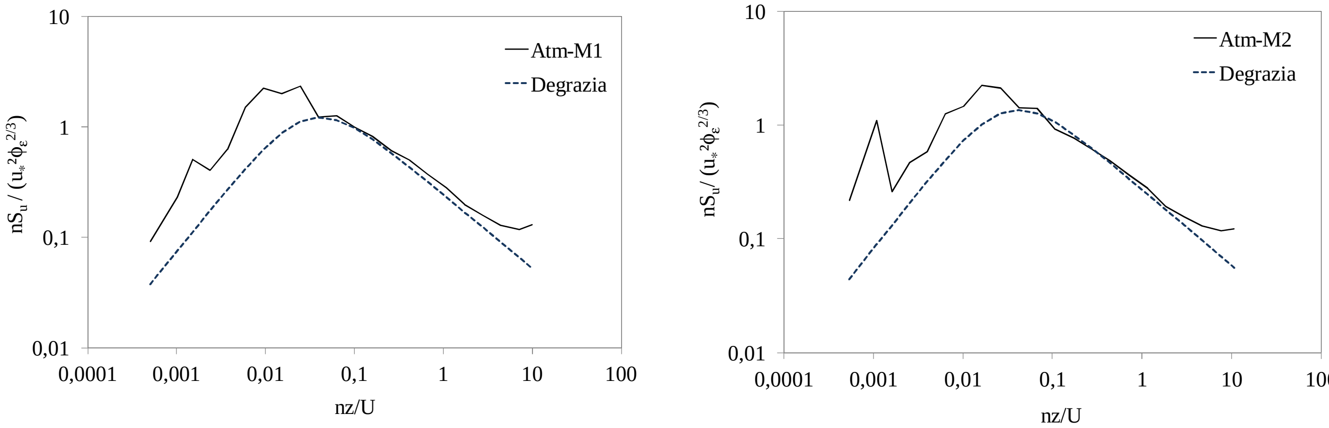

Figure 7. Comparisons of dimensionless spectra corresponding to Atm-M1 and Atm-M2 series with Degrazia et al. model (the spectral model is defined for neutral atmospheric condition).

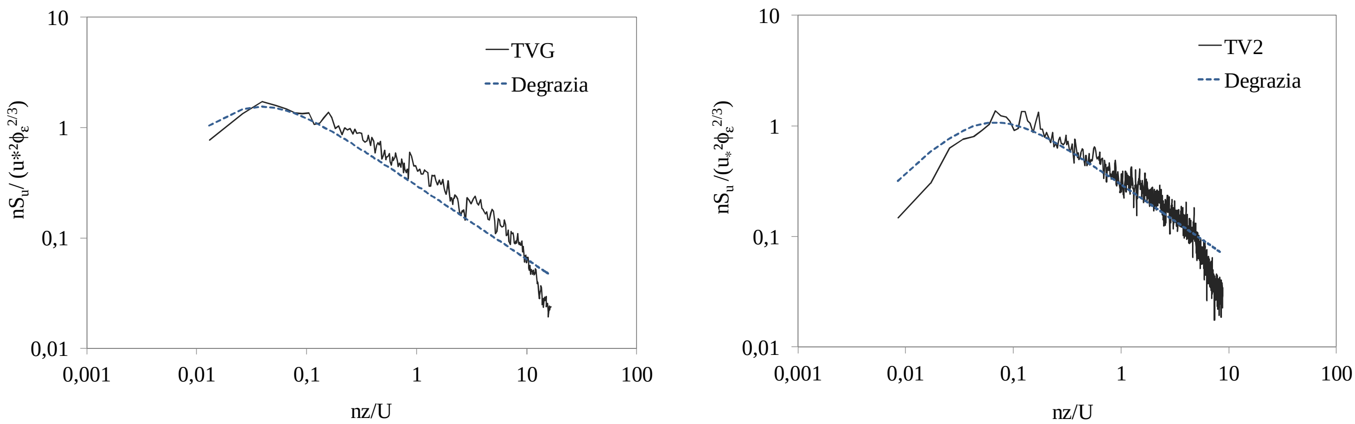

Figure 8. Comparisons of dimensionless spectra corresponding to TVG and TV2 series with Degrazia et al. mode (the spectral model is defined for neutral atmospheric condition).

4.5 Comparison of S_v and S_w atmospheric spectra

The atmospheric lateral component spectrum is compared with the expressions given by Degrazia et al. and from Kansas experiments (Figure 9). Experimental values are more approximate to Degrazia et al. model. The same considerations made for S_u respect to low-frequency spectral components are valid for S_v.

An additional consideration with regard to the atmosphere stability was realized with the dimensionless spectra of the vertical component S_w from atmospheric data. Kaimal et al. [15] associate the S_w spectrum with the stability atmospheric condition using the Monin-Obukhov's parameter. In Figure 10, the dimensionless spectrum of the vertical component S_w is compared with Kaimal expression for the neutral stability condition. The friction velocity u_* was calculated considering an opened area. The adopted value was $10^3 C_{as} = 4,7$ in concordance with Blessmann data [14]. For the neutral condition the S_w spectrum peak should match with Kaimal spectrum peak. In this case a displacement of the peak exists, possibly because the atmospheric boundary layer stability was not exactly neutral.

In Addition, from Kansas experiments, Kaimal [7] establishes curves that relate the adimensional frequency with the spectral peak with the z/LMO parameter. For the analyzed case, the spectral peak corresponds to Ym = 0,26 and allows the estimation of $z/LMO \approx -$ 0,35. The Monin-Obukhov length, also can be determined from the friction velocity u_* and the heat flow in the surface, resulting $z/LMO = -$ 0,010 [16], value that indicates a situation more closer to neutral stability condition.

5 CONCLUSIONS

In the present paper, spectra obtained from atmosphere and wind tunnel measurements are analyzed. In all cases it is possible to verify the existence of the Kolmogorov region characterized by the -5/3 slope. Laboratory spectra show better correspondence with von Kármán expression while the atmospheric spectra present a better agreement with the Kaimal formula. The displacement of frequency peak, however, suggests that the atmosphere may not be sufficiently neutral. Further comparisons are still needed to confirm the present conclusions. Moreover, the Degrazia spectral seems an interesting approach to be further explored in wind tunnel applications.

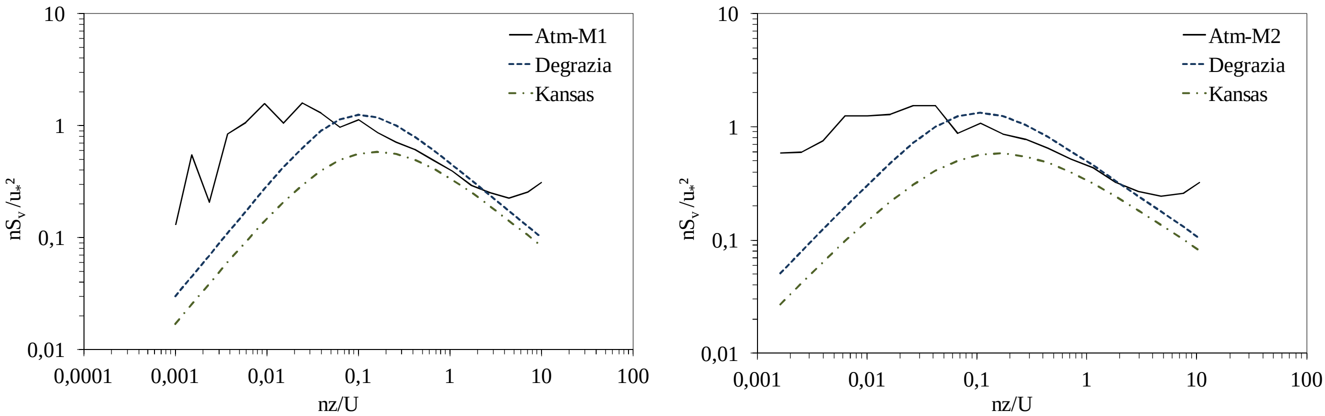

Figure 9. Comparisons of dimensionless spectra corresponding to Atm-M1 and Atm-M2 series with Kansas and Degrazia et al. models (spectral models are defined for neutral atmospheric condition).

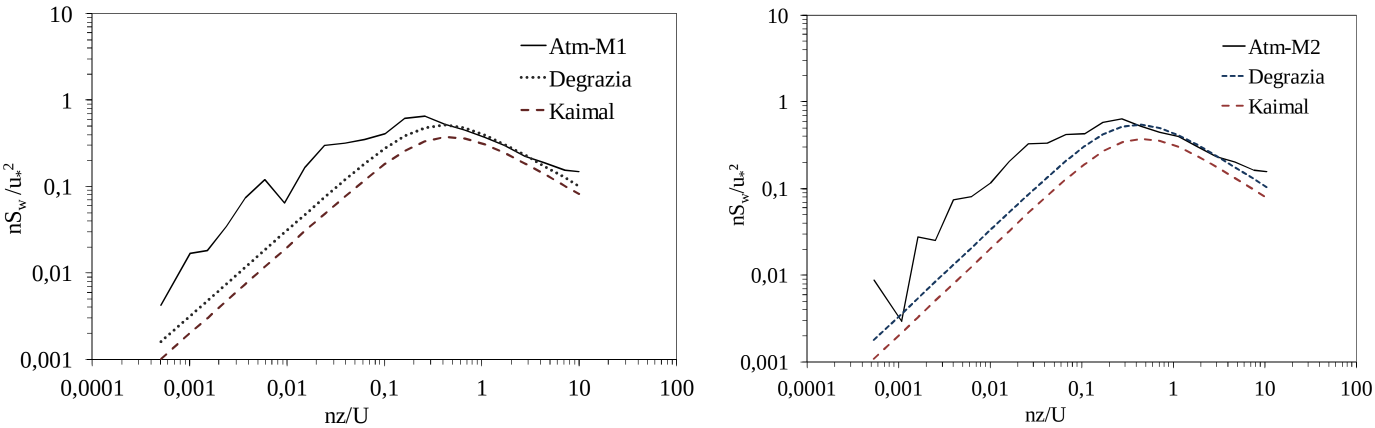

Figure 10. Comparisons of dimensionless spectra corresponding to Atm-M1 and Atm-M2 series with Kaimal expression and Degrazia et al. model (spectral models are defined for neutral atmospheric condition).

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