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"Wind Speeds Statistics"

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Wind speed statistics

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1 Introduction

The probabilistic analysis of wind speed at a site or in an area of a given size forms the essential premise for dealing with numerous problems involving various disciplines including, in the first place, physics, engineering and architecture. Associated with this context are the studies concerning atmospheric diffusion of polluting gases, production of aeolic energy, utilization and destination of the territory and the design and verification of structures.

The topics indicated above are usually tackled according to a dual phase approach. In the first phase all the meteorological stations able to provide data inherent to the problem under consideration are initially identified; the data recorded are later corrected and transformed in order to assemble a homogeneous data base for each station. In the second phase, the individual data bases are subjected to a statistical analysis with the object of evaluating the probability distribution of wind speed at the instrumented sites. In the context of certain classes of problems, especially those relating to the study of structural safety, the treatment is further developed at a third level aimed at appraising, at the individual sites, the probability distribution of the maximum wind speed over a fixed period of time. The collection of the statistical data thus acquired is then elaborated from a local or territorial point of view, according to the problem under consideration.

This text is based on the lecture given at the *College on Atmospheric Boundary Layer Physics*, 2nd Workshop on Modelling of the Atmospheric Flow Fields, 21 May - 1 June 1990.

Within the ambit of these subjects, this chapter deals initially with the selection and preparation of aeolic data bases (paragraph 2) and later illustrates the principles currently better known and more reliable for the probabilistic analysis of the data population (paragraph 3). The analysis of the probability distribution of the maximum wind speed over a fixed period of time is the subject of the next chapter of this book.

2 Wind speed data bases

In order to ensure that an aeolic data base can be correctly submitted to statistical analysis, it is necessary that it is representative, reliable and homogeneous. A representative data base is one acquired over a sufficiently extended period of time by an adequately located station (paragraph 2.1). A reliable data-base is error-free (paragraph 2.2). A homogeneous data base is composed of values recorded under uniform conditions (paragraphs 2.3 and 2.4).

2.1 Representativeness of data bases

Consider a station aimed at acquiring meteorological data and equipped, in particular, with anemometric instruments. The station records, either continuously or discontinuously, time-histories of the wind direction α and speed V. From these diagrams a series of partial data is extracted including, in principle, mean values (generally averaged on 10-60 minutes, selected with continuous or discreet scanning) and peak values (averaged on time intervals in the order of 1-5 s, the daily maxima for example). These data, together with other metereological data (pressure, temperature, visibility, ...) are collected on cards and then recorded on magnetic supports. The collection of wind speed and direction records available in digital form is defined as initial data base.

The representativeness condition inspiring the choice of a data base is of the relative type. The duration of the recording period which makes the data base representative depends on the quality of the statistical procedures used and accuracy sought. The concept of adequate location should be considered from both a local and territorial viewpoint. From a local viewpoint, the data recorded by instruments placed in the vicinity of perturbing elements (fig. 1) [Gill et al., 1967; Wieringa, 1983] are representative to the degree in which the conversion procedures successively employed are effective. From a territorial viewpoint, the selected anemometric stations form a representative

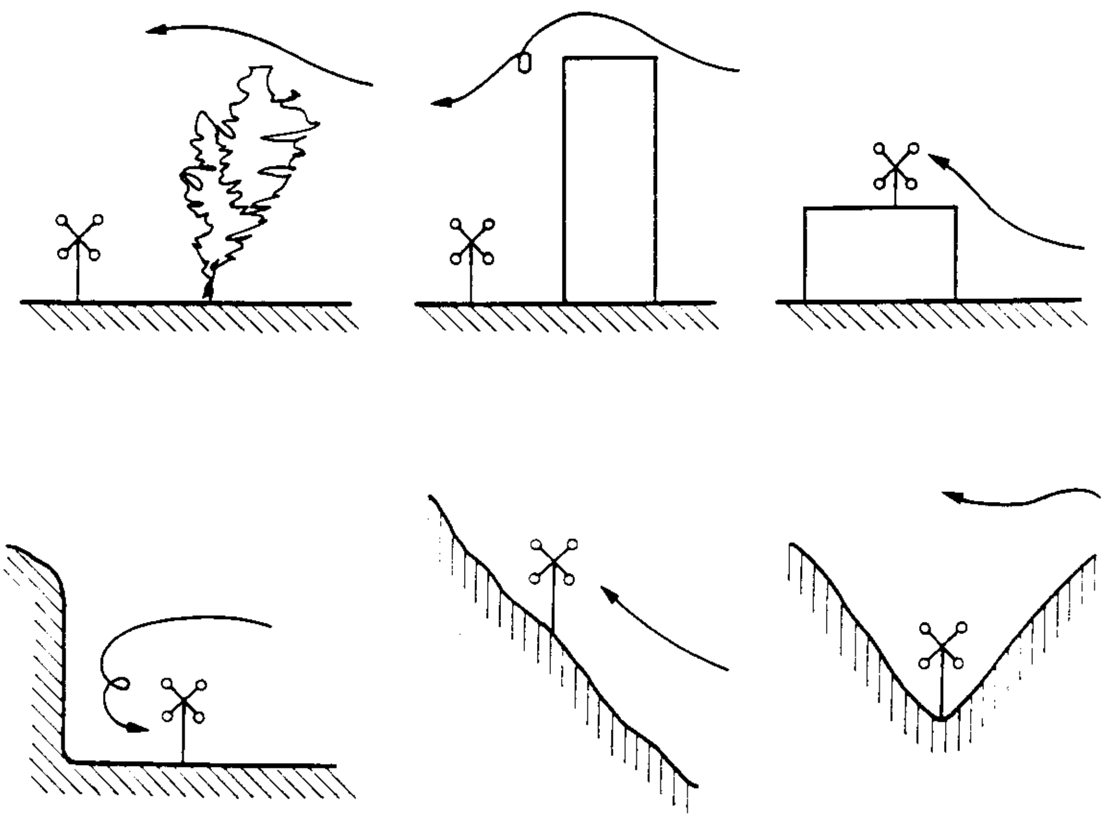

Figure 1: Perturbing elements in the vicinity of instrument.

network if closely-woven and uniform in proportion to the level of detail required for mapping the area.

2.2 Correction of data bases

The initial data bases, however representative in principle, contain five fundamental categories of errors [Ballio et al, 1991]:

1. measurements made with poor-functioning instruments due, for instance, to lack of maintenance or wear;
2. measurements made outside the reading interval (v_1, v_2), such as during wind-calms $(0 \leq v < v_1 \sim 0.5 - 2m/s)$ or aeolic phenomena of exceptional intensity $(v > v_2 \sim 50m/s)$;
3. recording of events extraneous to the problem under consideration (for instance, airport measurements concurrent with aircraft landing or take-off operations);
4. data losses due to instrument shutdown caused by natural events (tornadoes, shock phenomena, lightning, ...) or by operators (maintenance, replacement or transfer of anemometers, prohibitive atmospheric conditions, ...);
5. manual errors which have arisen in the transfer of data either from graph to card or from card to magnetic support.

The collection of anemometric measurements made reliable by suitable debugging or correction of erroneous data is defined as corrected data base.

The passage from an initial data base to a corrected data base requires different elaboration according to the values of the data in question. Elaborating data below the lower threshold of anemometric reading is meaningful in the analysis of the probability distribution of the data population; being practically inseparable, these aspects will be dealt with in paragraph 3.3. Elaborating data concerning the central body of the initial data bases does not generally influence the results of the statistical analysis, and as such, is unnecessary. Elaborating the maximum values is a fundamental element in the study of extreme winds and proceeds in harmony with the two sequential phases described herein after.

The potentially erroneous values are distinguished in the first phase. This operation calls for the preliminary selection of data to be used in the statistical analysis of the maxima. These data are compared with the immediately preceding and subsequent data (over one day, for instance). Data homogeneous with neighbouring measurements are assumed as being correct; those not having regular tendencies are deemed as potentially erroneous.

The potential erroneous data, from hereon called singular values, are eliminated or corrected in the second phase on the basis of three techniques of increasing difficulty and accuracy:

1. the singular values are directly suppressed using the following principle: they are effectively erroneous, and in this case suppression is correct, or they denote phenomena which are intense but limited in space and time, and as such significative at the most in relation to very small exceedence probability;

2. the set of data including the singular value is compared with the corresponding sets of data inherent to other meteorological parameters strictly associated with wind velocity (atmospheric pressure at ground level, temperature, ...); the singular data not correlated with these parameters are deemed erroneous and as such are suppressed;

3. singular data are directly compared with the original diagrams or with the original cards and then suitably corrected.

2.3 Transformation of data bases

The corrected data bases, although representative and reliable, are affected in principle by two fundamental categories of heterogeneity:

1. the presence of averaged values over different time periods;

2. the presence of values acquired under different micrometeorological conditions.

The heterogeneity due to the presence of measurements averaged over different time periods is particularly important in the United States, where the "fastest mile wind speed" v_f is still used (wind velocity averaged over a time interval equal to the ratio between one mile and v_f, variable therefore from value to value), in territories where acquired data are processed differently (in Italy, for instance, the Air Force stations record means over 10 minutes, rarely in mountain-top localities; the Italian Broadcasting Corporation, on the other hand, possesses a network of anemometers, located on mountain tops which record peak values), when, at different stations or at the same station but at different times, different instruments are operating (it is a topic of great importance with respect to peak values, very sensitive to instrument response time).

Reliable methods for transforming wind speeds into new values referring to different averaging time intervals have been developed by Durst [1960], Deacon [1965], Shellard [1967], Brook and Spillane [1970], Weringa [1973], Greenway [1980], Wood [1983], Solari [1993].

When considering a single corrected data base, the micrometereological heterogeneity is due to three concurrent fundamental causes:

1. the variation of wind direction α and the consequent different structure of the incident flow as a function of the terrain characteristics and presence of disturbing bodies upstream from the anemometer (fig. 2a);

2. the variation over time t in the above conditions [Tamura and Suda, 1988] (fig. 2b);

3. possible shifting of sensor.

In addition to these heterogeneity conditions, the overall analysis of the corrected data bases introduces the different geographic positions of the individual stations considered.

The collection of data made homogeneous by multiplying the corrected values by suitable conversion factors is defined as transformed data base. It is to be noted that by attributing a definition to the transformed velocity common to the entire territory analyzed (for instance the geostrophic wind speed, or the mean wind velocity at ten meters height over an ideally flat and homogeneous terrain with an assigned roughness coefficient), the data pertaining to different stations are also homogeneous.

A detailed discussion of engineering methods at present available for computing conversion factors is given by Ballio et al [1991]. The use of numerical models for transforming wind speeds is the subject of Chapters ????? of this book.

2.4 Enucleation of exceptional aeolic phenomena

The data bases, corrected and transformed according to the procedures illustrated in paragraph 2.3, are affected by a heterogeneity still to be eliminated: the presence of data relative to different aeolic phenomena (extra-tropical cyclones, tropical cyclones, monsoons, breezes, foehn winds, downbursts, tornadoes, ...). Therefore, in order to correctly carry out the statistical analysis,

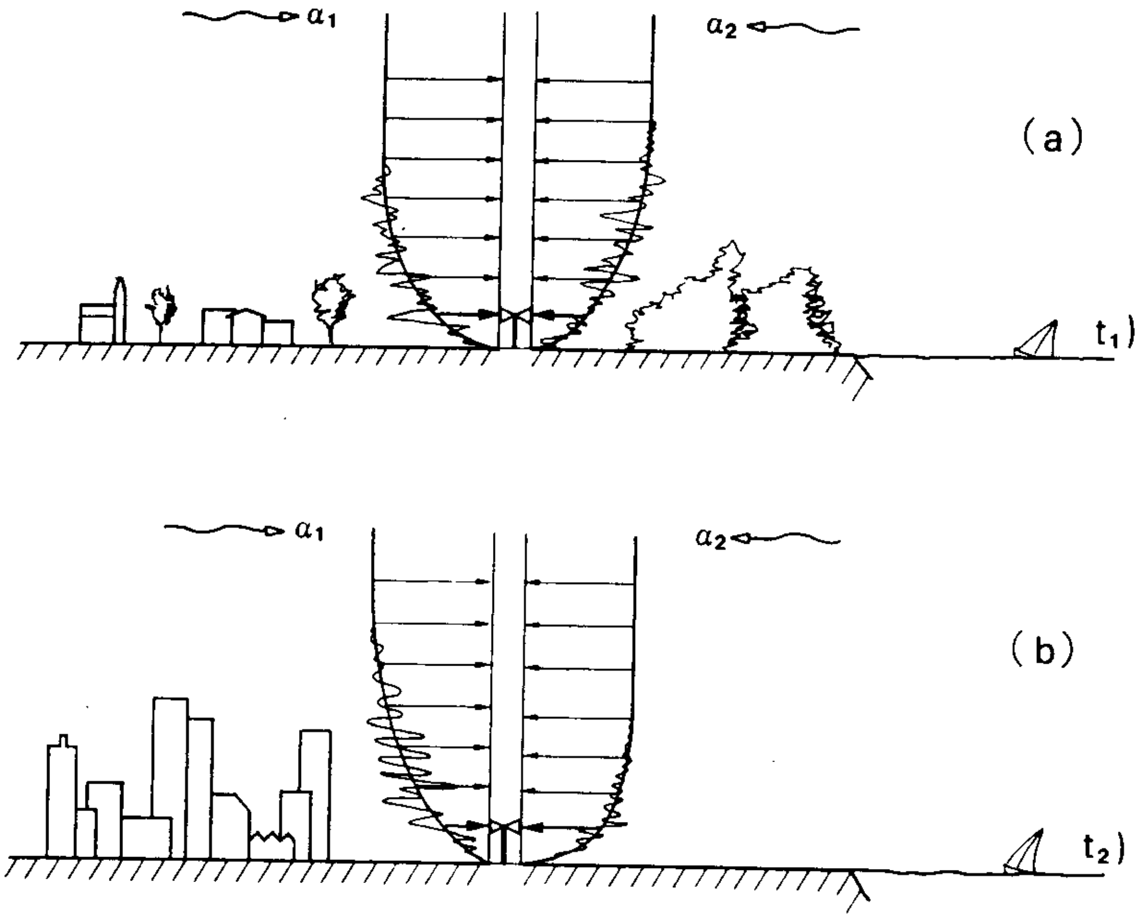

Figure 2: Examples of micrometeorological heterogeneities.

it is necessary to partition the individual data bases into L sub-data bases including values homogeneous in the sense previously indicated. This operation, which can be exceptionally complex if carried out in general terms, in practice consists in the simple enucleation, from each data base, of the measurements corresponding to exceptional aeolic phenomena and as such rare and easily recognizable. High intensity tropical cyclones (called hurricanes in America, typhoons in the Far East, simply cyclones in Australia and in the Indian Ocean) and tornadoes belong to this category. All other winds are defined as ordinary winds.

As exceptional winds are extremely sporadic phenomena, they are quite uninfluential as far as the probabilistic analysis of the data population is concerned. They have instead a role often essential in the context of the study of the probability distribution of the maximum value (Chapter ???).

3 Wind speed statistics

3.1 Bivariate Gaussian and derived distributions

Studies carried out since 1946 [Brooks et al.] have demonstrated that the density function of wind speed aloft can be adequately represented by the following bivariate Gaussian model:

$$\begin{aligned} f_{V_xV_y}(v_x, v_y) &= \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-r_{xy}^2}} \exp\{-\frac{1}{2(1-r_{xy}^2)} \cdot \\ &\cdot [\frac{(v_x-\overline{V}_x)^2}{\sigma_x^2} - \frac{2r_{xy}(v_x-\overline{V}_x)(v_y-\overline{V}_y)}{\sigma_x\sigma_y} + \\ &+ \frac{(v_y-\overline{V}_y)^2}{\sigma_y^2}]\} \end{aligned} \quad (1)$$

where x, y are orthogonal axes parallel to the earth's surface, directed respectively from East to West and from North to South; V_x, V_y are the wind speed components according to x, y; v_x, v_y are the state variables of V_x, V_y; $\overline{V}_x$, $\overline{V}_y$ and σ_x, σ_y are respectively the mean values and standard deviations of V_x, V_y; r_{xy} is the cross-correlation coefficient of V_x, V_y.

Eq. (1) may be suitably developed [Weil, 1954; Yadavalli, 1967] in order to obtain the following non-directional density function:

$$f_V(v) = A_o v e^{-A_1 v^2}[I_o(A_2 v^2) I_o(A_3 v) +$$

$$+ \quad 2\sum_{j=1}^{\infty} I_j(A_2 v^2) I_{2j}(A_3 v)\cos 2j\psi] \quad , \quad v \geq 0 \qquad (2)$$

in which:

$$V = \sqrt{V_x^2 + V_y^2}, \quad v = \sqrt{v_x^2 + v_y^2} \qquad (3)$$

$$A_o = \frac{1}{\sigma_a \sigma_b} exp\{-\frac{1}{2}(\frac{\overline{V}_x^2}{\sigma_a^2} + \frac{\overline{V}_y^2}{\sigma_b^2})\} \qquad (4)$$

$$A_1 = \frac{\sigma_x^2 + \sigma_y^2}{4(1 - r_{xy}^2)\sigma_x^2 \sigma_y^2} \qquad (5)$$

$$A_2 = \frac{\sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4 r_{xy} \sigma_x^2 \sigma_y^2}}{(1 - r_{xy}^2)\sigma_x^2 \sigma_y^2} \qquad (6)$$

$$A_3 = \sqrt{\frac{\overline{V}_x^2}{\sigma_a^4} + \frac{\overline{V}_y^2}{\sigma_b^4}} \qquad (7)$$

$$\psi = arctg(\frac{\overline{V}_y \sigma_a^2}{\overline{V}_x \sigma_b^2}) \qquad (8)$$

$$\sigma_a^2 = \frac{1}{2}[\sigma_x^2 + \sigma_y^2 + \sqrt{(\sigma_x^2 + \sigma_y^2)^2 - 4\sigma_x^2\sigma_y^2(1 - r_{xy}^2)}] \qquad (9)$$

$$\sigma_b^2 = \frac{1}{2}[\sigma_x^2 + \sigma_y^2 - \sqrt{(\sigma_x^2 + \sigma_y^2)^2 - 4\sigma_x^2\sigma_y^2(1 - r_{xy}^2)}] \qquad (10)$$

I_j is the j-th Bessel function of the first type.

This formulation may be simplified substantially by introducing the following two hypotheses:

$$r_{xy} = 0 \qquad (11)$$

$$\sigma_x = \sigma_y = 0 \qquad (12)$$

Eq. (11) corresponds to admitting V_x and V_y as uncorrelated, which is usually found to be fully satisfactory. Eq. (12) is equivalent to assuming wind speed aloft to be isotropic; as such, it is quite acceptable on meteorologically homogeneous territories, whereas it partly fails in frontier zones such as large mountain chains and oceanic coasts [Baynes, 1974].

On the basis of eqs. (11) and (12), eq. (2) identifies itself with the following chi-squared non-central density function [Patnaik, 1949]:

$$f_V(v) = \frac{v}{\sigma^2} exp\left[-\frac{(v^2+\overline{V}_r^2)}{2\sigma^2}\right] I_o\left(\frac{\overline{V}_r v}{\sigma^2}\right) \quad , \quad v \geq 0 \qquad (13)$$

where:

$$\overline{V}_r = \sqrt{\overline{V}_x^2 + \overline{V}_y^2} \qquad (14)$$

Eq. (13) may be further simplified, this time radically, by assuming the absence of preferential directions:

$$\overline{V}_r = 0 \qquad (15)$$

In this case the density function of V assumes the well-known expression of Rayleigh:

$$f_V(v) = \frac{v}{\sigma^2} exp\left[-\frac{v^2}{2\sigma^2}\right] \quad , \quad v \geq 0 \qquad (16)$$

to which corresponds the distribution function:

$$F_V(v) = 1 - exp\left[-\frac{v^2}{2\sigma^2}\right] \quad , \quad v \geq 0 \qquad (17)$$

In fact, although the applicative advantages linked with use of eqs. (16) and (17) are substantial, they do give rise to approximations which are very often too inaccurate. Add to this the fact that eq. (15) precludes all possibility of applying the Rayleigh model close to the ground, where the effect of the roughness and topography tend instead to strengthen the importance of the wind direction.

3.2 Weibull distribution

The choice of the Weibull distribution [1951] as the probabilistic model of wind speed aloft and at ground level originates from mere empiricism:

$$f_V(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad , \quad v \geq 0 \qquad (18)$$

$$F_V(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad , \quad v \geq 0 \qquad (19)$$

The Weibull distribution makes use of two parameters, k and c, which replace the single parameter σ of the Rayleigh model. This ensures greater flexibility in the data regression, without foregoing the formal simplicity characterizing eqs. (16) and (17). Eqs. (18) and (19) coincide with eqs. (16) and (17) for $k = 2$ and $c = \sigma\sqrt{2}$. The degree of how much k differs from 2 provides, therefore, an estimate of how much the Weibull distribution strays from the Rayleigh distribution. Experience teaches that this deviation tends to increase near the ground, being minimum in the undisturbed atmosphere [Davenport, 1968].

It can also be seen that if V is distributed according to the Weibull model with parameters k and c, and if moreover $W = aV^p (a, p > 0)$ is assumed to be approximately distributed with the Weibull model, this model has parameters k/p and ac^p. On the basis of this property, with the distribution of speed V known, it is immediate to derive the approximate distributions of the kinetic pressure $Q = \rho V^2/2$ and aeolic power $P = \rho V^3/2$ (ρ being the density of air), which represents the fundamental elements for the analysis of structural behaviour and energy sources. For these reasons the Weibull distribution ever increasing has received consent over the years, to the point of being currently employed, except on rare occasions, for any statistical study whatsoever associated with aeolic phenomena [Davenport, 1968; Hannessey, 1977; Jestus et al., 1978; Cook, 1982; Conradsen et al., 1984].

The estimate of parameters k and c is generally made utilizing the moments, maximum likelihood out least squares methods; a systematic treatment of these and other procedures is carried by Conradsen et al. [1984]. The moments method and the maximum likehood method are found to be clearly inadequate by virtue of the Weibull asymmetric distribution. The efficiency of the least squares method, due to its biased nature [Benjamin and Corneil, 1970], may be substantially improved by making recourse to BLIE (Best

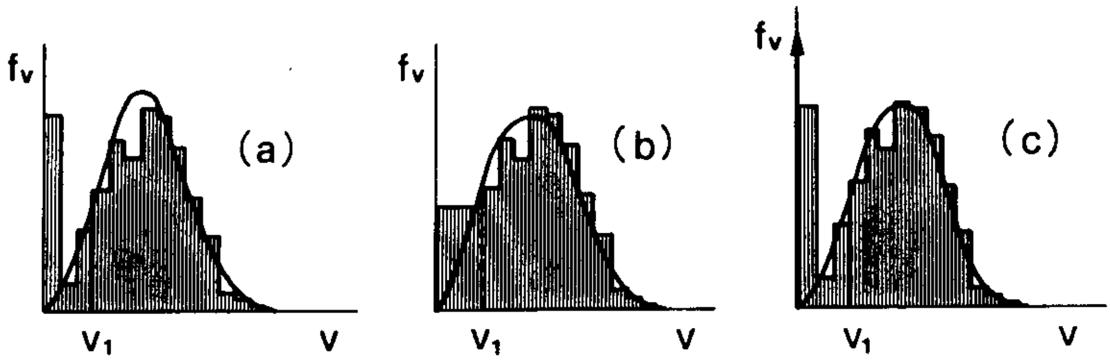

Figure 3: Fitting of Weibull model to data histogram.

Linear Invariant Estimators) or BLUE (Best Linear Unbiased Estimators) techniques [Conradsen et al, 1984]. The precision with which the distribution tail is modelled, essential in the prospective of the extreme analysis, can be increased through the use of two procedures which may be applied jointly. The first, the so-called "weighted regression", attributes gradually increasing importance to the higher values utilizing V^α type weights (with $\alpha \geq 1$). The second only regresses values greater than a suitably assigned v_r threshold.

3.3 The problem of the wind calms

The probability distribution expressed by eqs. (18) and (19) imposes the condition $f_V(0) = F_V(0) = 0$. The anemometric records, on the contrary, according to locality, report more or less long periods of wind calms (Fig. 3a). This incongruity may be eliminated by applying the censored technique or the hybrid technique.

The censored technique [Conradsen et al, 1984] considers speeds v less than the lower instrumental v_s threshold as being unreliable; it modifies the values contained in the $[0,v_s)$ interval, attributing an opportunely varied distribution to them (e.g. constant as in fig. 3b); the k and c parameters of the model are estimated on the basis of modified data.

The hybrid technique [Takle and Brown, 1978] accepts the instrumental response, substituting eqs. (18) and (19) with the following expressions:

$$f_V(v) = F_o\delta(v) + (1 - F_o)\frac{k}{c}(\frac{v}{c})^{k-1}exp[-(\frac{v}{c})^k] \quad , \quad v \geq 0 \qquad (20)$$

$$F_V(v) = F_o + (1 - F_o)\{1 - exp[-(\frac{v}{c})^k]\} \quad , \quad v \geq 0 \qquad (21)$$

where F_o is the probability that $v = 0$ and $\delta(\ )$ is the Dirac operator (fig. 3c). Parameters k and c are regressed solely on the basis of values greater than zero. F_o may be identified as the ratio between the number of the values $v = 0$ and the total number of data.

Fig. 4 illustrates some distribution functions obtained by applying the censored technique and the hybrid technique for four different estimation criteria. The coordinated scales of the diagrams are such that linearize eq. (19) ("Weibull probability paper"). The results confirm that the moments method and the maximum likelihood method are inadequate for estimating parameters. The least squares method and the weighted least squares method offer decidedly better and substantially coincident results. The first appears preferable to the second by virtue of the arbitrariness of the choice of the weight factors.

Fig. 5 compares results obtained with the censored technique and with the hybrid technique, estimating the parameters with the least squares method using the order statistics [Benjamin and Cornell, 1970]. As may be readily observed, the greater the probability F_o of wind calms, the better is the hybrid technique than the censored technique. In all the situations illustrated, it appears evident, moreover, that the hybrid technique also allows more confident estimates of the values in the tail of the distributions.

3.4 Advanced models

Even though the Weibull distribution model, applied using the censored technique or hybrid technique, has been increasingly accepted over the years, proposals do still exist for improving its quality. One of these is the generalised three parameter Weibull distribution [Stewart and Essenwager, 1978;

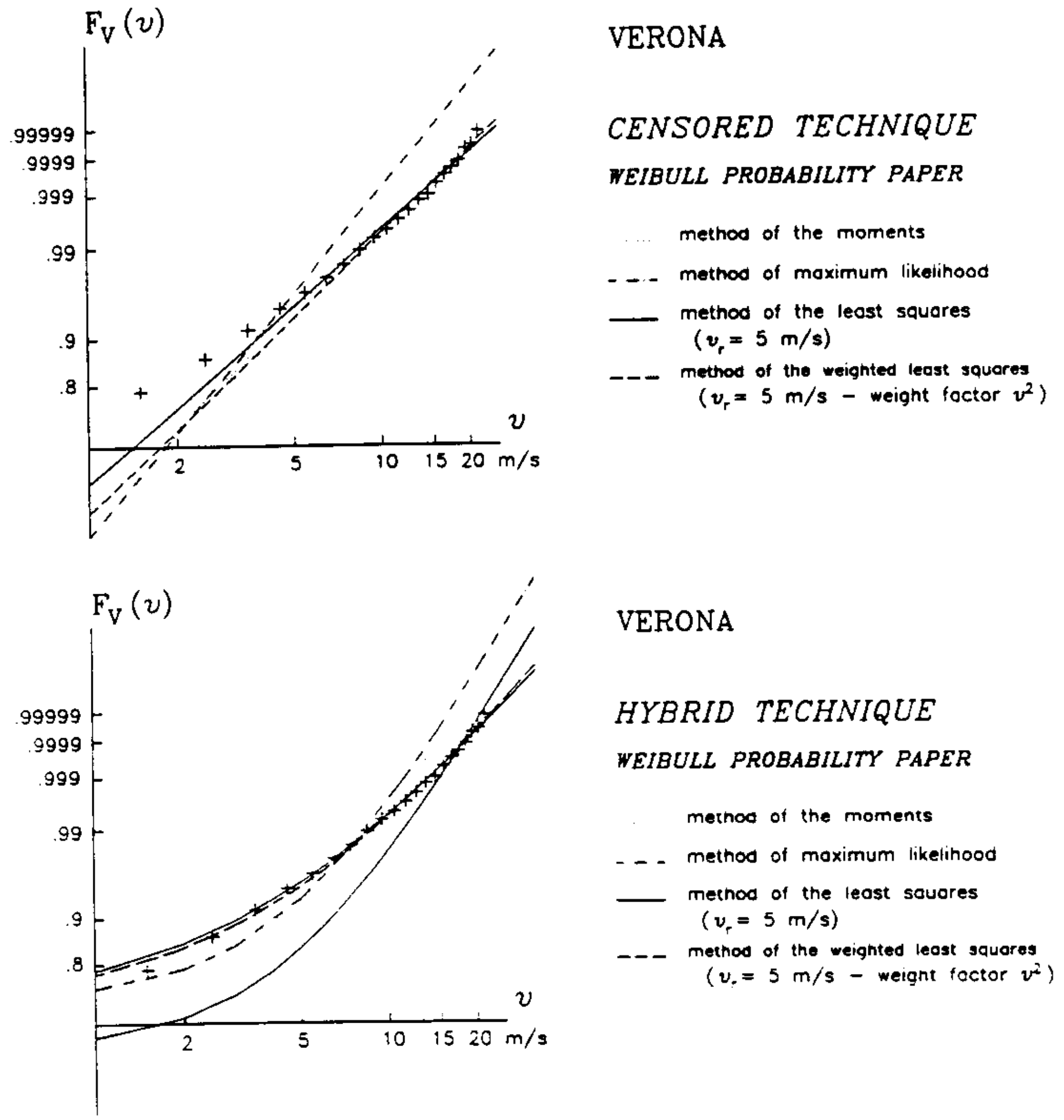

Figure 4: Examples of wind speed statistics.

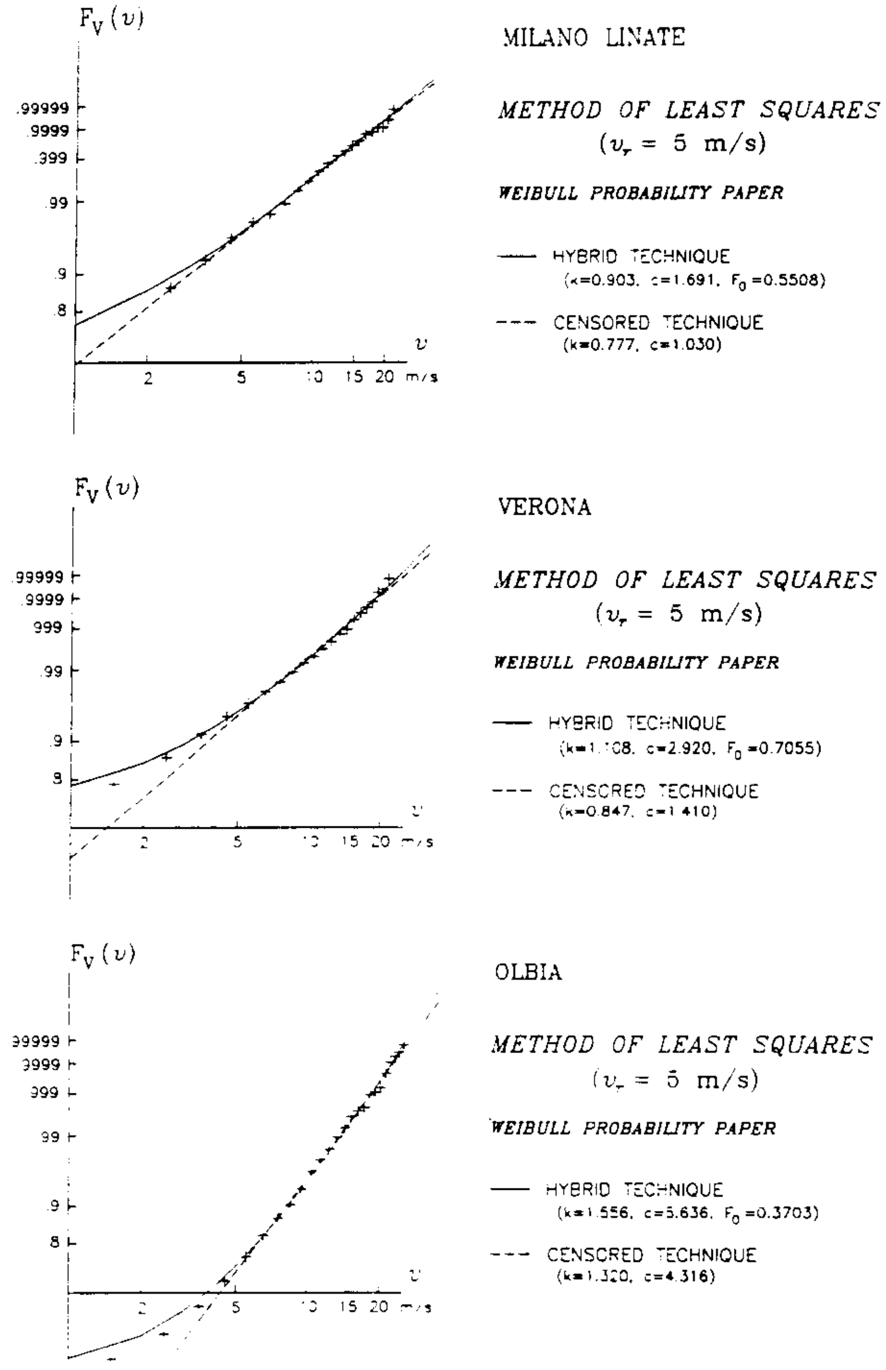

Figure 5: Examples of wind speed statistics.

Van Der Auwera et al., 1980]. This, however, leads to relevant analytical complications, giving rise to improvements often irrelevant.

Simpler and more effective, instead, is the use of composite models obtained assembling Weibull distribution families individually applied to micro - meteorologically uniform data portions.

Expressing the density and distribution functions of non-null wind speeds coming from the i-th sector ($i = 1, 2, \dots m$) during the j-th time period of the year ($j = 1, 2, \dots n$) by the original Weibull model (eqs. 18 and 19):

$$f_{V_{ij}}(v) = \frac{k_{ij}}{c_{ij}} \left(\frac{v}{c_{ij}}\right)^{k_{ij}-1} \exp\left[-\left(\frac{v}{c_{ij}}\right)^{k_{ij}}\right], \; v > 0, i = 1, \dots m, j = 1, \dots n \qquad (22)$$

$$F_{V_{ij}}(v) = 1 - \exp\left[-\left(\frac{v}{c_{ij}}\right)^{k_{ij}}\right], \; v > 0, i = 1, \dots m, j = 1, \dots n \qquad (23)$$

the density and distribution functions of global data population are given by the expressions:

$$f_V(v) = F_o \delta(v) + \sum_{1}^{m}{}_{i} \sum_{1}^{n}{}_{j} A_{ij} \frac{k_{ij}}{c_{ij}} \left(\frac{v}{c_{ij}}\right)^{k_{ij}-1} \exp\left[-\left(\frac{v}{c_{ij}}\right)^{k_{ij}}\right], v \geq 0 \qquad (24)$$

$$f_V(v) = 1 - \sum_{1}^{m}{}_{i} \sum_{1}^{n}{}_{j} A_{ij} \exp\left[-\left(\frac{v}{c_{ij}}\right)^{k_{ij}}\right], v \geq 0 \qquad (25)$$

in which:

$$A_{ij} = P_{ij} \gamma_j, \quad i = 1, \dots m, j = 1, \dots n \qquad (26)$$

$$\sum_{1}^{m}{}_{i} \sum_{1}^{n}{}_{j} A_{ij} = 1 - F_o \qquad (27)$$

where P_{ij} is the probability that during the j-th period of the year the wind comes from the i-th sector with non-null speed; γ_j is the ratio between the number of data recorded in the j-th period of the year and the total number of data.

Eqs. (22) and (23) have a very important application significance. The knowledge of the sectorial distribution of the wind speed is in fact essential for the study of structural behaviour, for example in the orientation of urban layouts, airport runways and aeolic power stations, siting of industrial plants, etc. The analysis of the wind speed distribution over pre-established periods of the year is just as important for studying the behaviour of temporary structures and all the problems in which wind is linked to time variable environmental phenomena (snow accumulation, ice formation, fire spreading, physiological tolerance, etc.).

Eqs. (26) and (27) constitute some progress with respect to eqs. (20) and (21). In principle, these imply that, the greater the number $n \times m$ of micro-meteorologically uniform data sub-bases, the better is the regression of the global data base. In practice, this does not happen: the increment of the product $m \times n$, on the one hand, increases the flexibility of the model, while, on the other, impoverishes the single data sub-bases, making the estimates of the parameters of the model's components less reliable. The need, therefore, is to find a correct balance by working on the values of m and n in order to minimise the errors.

Figure 6 shows a comparison between results supplied by eq. (21) and those obtained from eq. (25) for $m = 12$ and $n = 1$. As can be clearly seen, not always eq. (25) produces effectively better regressions. As such, it may be particularly useful only if applied through strict reliability checks.

4 Conclusions and perspectives

A synthetic outline has been furnished of the methods at present most accredited for analyzing wind speed statistics. In addition to these methods some recent results are also described of a series of researches carried out, on the same subject, by the Author together with his co-workers prof. ing. Giulio Ballio, dr. ing. Sergio Lagomarsino and dr. ing. Giuseppe Piccardo.

From an examination of the methods under discussion and the results illustrated, it emerges that it is possible to carry out an extremely reliable statistical analysis of wind speed. The choice of the most suitable method, however, must be compatible with the aims of the study and the level of accuracy required.

Acknowledgements

The present paper is a summary and compendium of a number of works concerning an extensive research program being carried out by the Author

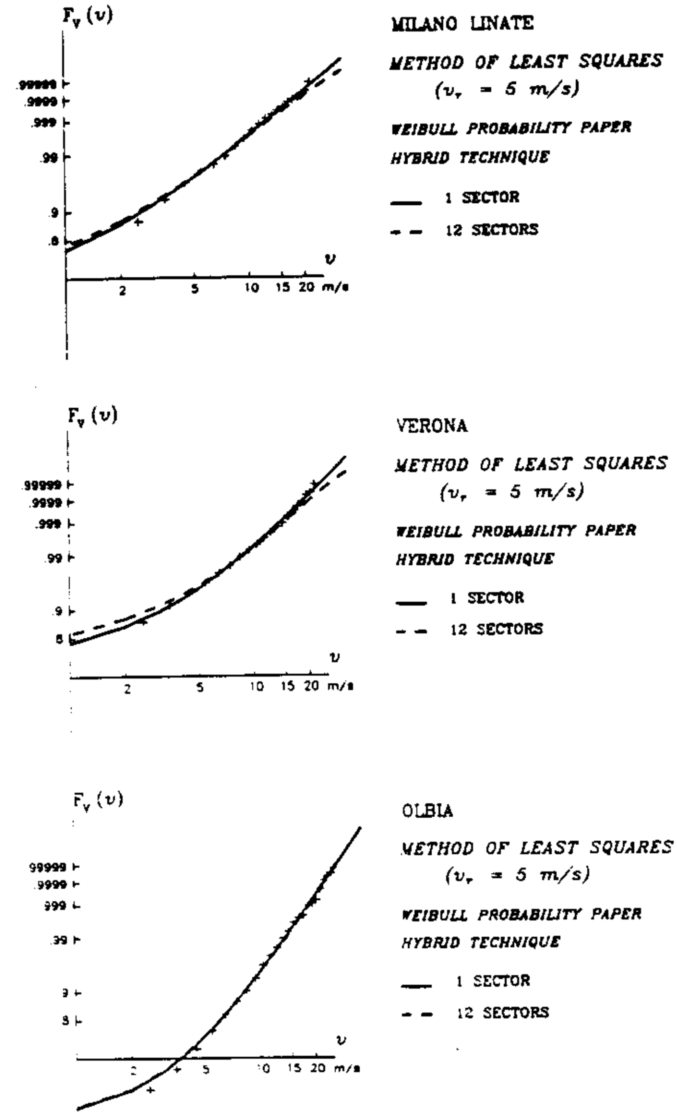

Figure 6: Examples of wind speed statistics.

in cooperation with Prof. Ing. Giulio Ballio of the Department of Structural Engineering of Milan Polytechnic, and with Dr. Ing. Sergio Lagomarsino and Dr. Ing. Giuseppe Piccardo of the Institute of Construction Science of Genoa University.

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