Problem of prediction of wind forces on engineering structures and application to practice

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Problem of Prediction of Wind Forces on Engineering Structures and Application to Practice

Problèmes de l'estimation des charges de vent sur une construction et application à la pratique

Probleme der Voraussagung von Windkräften auf Bauwerke und die Anwendung in der Praxis

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• INTRODUCTION

Principles of maximum entropy is used to develop minimally biased probability distribution functions for maximum value of the horizontal components of wind velocities. An attempt is made to throw some fresh ideas on the formulation of a sound statistical model for the evaluation of wind velocities and wind pressures on engineering structures.

Since wind velocities vary with time and space, it is shown that wind force on a structure is not static in nature, and as such cannot be obtained from instantaneous wind velocity by a simple formula of a static wind force. An attempt is made to obtain a design wind force, only by changing numerical values of gust factors referring to size, and structural characteristics.

In order to obtain the gust factors for determining the wind loading on various structures, the space correlation of velocity fluctuations is considered in addition to power spectrum. Moreover, the essential procedures used in arriving at the gust factors are outlined. This evaluation is not intended to be rigorous, however, it does describe the practical procedures and the essential assumptions and approximations that can be used to simplify the results into usable form.

2. PRINCIPLE OF MAXIMUM ENTROPY AND ITS APPLICATION IN THE DEVELOPMENT OF STATISTICAL MODELS FOR WIND VELOCITIES AND WIND PRESSURES

The static wind pressure can be taken to be

$$\bar{p}(z) = \frac{1}{2} \rho \bar{U}^2 C_p(z) \qquad (2.1)$$

where $\bar{p}(z)$ is the mean pressure at a point z above the ground, $\bar{U}$ is the mean velocity at the level at the top of the structure in the place where the structure will serve, ρ is the density of the air, and $C_p(z)$ is the pressure co-efficient of point z. Of course in design, the maximum wind velocity should be used in place of the mean wind velocity in order to obtain the maximum wind pressure from equation (2.1).

The maximum wind velocity for a given place should be obtained by statistical means from a long record of annual maximum wind velocities. For a given averaging time of the annual maximum wind velocity record for any place, it is possible to use the principle of maximum entropy for the estimation of the instantaneous maximum wind velocity and hence the evaluation of the maximum wind pressure. The uncertainty in the value of the maximum wind velocity at any given height can be evaluated by the specification of its entropy, which can be expressed mathematically (1) by

$$H = -K \sum_i \bar{g}_i(U) \ln \bar{g}_i(U) \qquad (2.2)$$

where H is the entropy or uncertainty in the value of maximum wind velocity, K is an arbitrary constant, $\bar{g}_i(U)$ is the probability density function of the maximum wind velocity U for the ith possible outcome of the maximum value of the wind velocity. Equation (2.2) gives a measure of the uncertainty or ignorance of the true state of the maximum value of the wind velocity. Maximizing equation (2.2) leads to the condition of maximum uncertainty, from which can be derived the minimally biased probability density function for the maximum wind velocity. The form of the minimally biased probability density function, can be shown to be given (2, 3, 4, 5) by expression (2.3) for any given prior estimates of the mean $\bar{U}$ and the standard deriviation σ_μ of the maximum value of the wind velocity.

$$\bar{g}(U) = \exp\left(-a_0 - a_1 U - a_2 U^2\right) \quad (2.3)$$

In equation (2.3); a_0, a_1, and a_2 are Lagrangian multipliers. Furthermore, it can be shown that, (4,5)

$$a_0 = \frac{a_1^2}{4a_2} - \frac{1}{2}\ln a_2 + \ln\left[1 - \mathrm{erf}\left(\frac{a_1}{2\sqrt{a_2}}\right)\right] + \ln\frac{\sqrt{\pi}}{2\Delta U}. \quad (2.4)$$

$$\bar{U}a_1 = -2X^2 + Z. \quad (2.5)$$

$$\left(\frac{\sigma_\mu}{\bar{U}}\right)^2 = \frac{2X^2 + 2X^2 Z - Z^2}{4X^4 - 4X^2 Z + Z^2}, \quad (2.6), \quad \text{where } Z = \frac{2}{\sqrt{\pi}}\frac{X\exp(-X^2)}{(1-\mathrm{erf}(X))}. \quad (2.7)$$

$$\text{and } X = \frac{a_1}{2\sqrt{a_2}}. \quad (2.8)$$

Thus, using the results of equations (2.4 to 2.9), and Figures 1 and 2, the values of the Lagrangian multipliers a_0, a_1 and a_2 can be determined in terms of $\bar{U}$ and σ_μ; and then the minimally biased probability distribution function for the maximum wind velocity can be evaluated from equation (2.3). The results given by this approach are satisfactory enough for the normal range of wind velocities which are of interest in civil engineering applications. It has been found that actual data (5) are well-fitted by this type of distribution. The great advantage of this type of analysis is that all the recorded extreme values are used and that the best available estimate can be obtained of the speed which is likely to be exceeded on the average only once in any specified number of years.

Furthermore, it should be realised that wind speeds are affected by such factors as variations in height, averaging times and topographical effects. Some of the well-known results, concerning the effects of these factors, on the maximum velocity distribution which are of interest in civil engineering applications, can be directly applied, in conjunction with the results obtained in this paper.

3. DYNAMIC CONSIDERATIONS IN STRUCTURAL DESIGN AGAINST WING

In equation (2.1) for mean wind pressure, it can be assumed that both $\bar{U}$ and $C_p(z)$ are affected by the roughness of the surface of the ground, and in fact several expressions have been developed to show the relationships between the variations of $\bar{U}$ and $C_p(z)$, and other essential parameters such as height above the ground, gradient velocity, and the ground roughness coefficient.

In design, the gust pressure factor is intended to take account of the superimposed dynamic effects of gusts. The gust factor is used in conjunction with the mean load, so that the total design wind load should satisfy the condition,

$$p(z)_{max} \geq G\bar{p}(z) \quad (3.1)$$

The value of (p(z) max) is chosen such that it corresponds to the value of maximum design wind velocity, by the help of equation (2.1).

. In equation (3.1), G the gust factor can be expressed as,

$$G = 1 + gr\sqrt{(B+R)} \qquad (3.2)$$

where g is the peak factor which depends on the fundamental frequency of vibration of the structure and time over which the mean velocity is averaged (see Figure 3); r is the roughness factor which depends on the location of the structure and the height of the structure above the ground (see Figure 4); B is the excitation by background turbulence which depends only on the height of structure above ground (see Figure 5); and R is the excitation by turbulence resonant with structure. The quantity R can be expressed as

$$R = \frac{sF}{\beta} \qquad (3.3)$$

where F is the gust energy ratio (see Figure 6); S is the size reduction factors which depends on the breadth b and the height h of the structure, and other important parameters (see Figure 7); and β is the critical damping ratio of the structure, this critical damping ratio, β , comprises contributions to damping from both mechanical and aerodynamic factors.

Other essential factors which sould be taken into account in design are the problems arising from unsymmetrical loading, vortex excitation, and aeroelastic instability. Moreover, wind tunnel testing and meteorological tests at the site should be conducted, in order to take necessary cognizance of aeroelastic model testing in the wind tunnel and of making meteorological measurements at the site in all instances in which dynamic factors are likely to be significant.

4. THE VARIATION OF GUST FACTOR

The wind velocity $U(z,t)$ in a place at a given height z and time t, can be divided into two parts, namely the mean velocity $\bar{U}(z)$ and the fluctuating velocity $\mu(z,t)$ as follows:

$$U(z,t) = \bar{U}(z) + \mu(z,t) \qquad (4.1)$$

The mean square of the fluctuating velocity can be expressed in terms of its power spectral dènsity, F(n), which is a function of the frequency n,

$$\bar{\mu}^2(z,t) = 2\int_{\frac{1}{2}T}^{\infty} F(n)\,dn \qquad (4.2)$$

Equation (4.1) shows that since the wind velocity is a varying quantity, the value of the actual wind pressure on the structure will also vary, and as such the value of the gust factor G can also be shown to vary.

Some of the important factors which can contribute to this variation include the effects of analysis time, averaging time, length of the structure, mechanical characteristics of the structure and the variation of the turbulent energy of the wind with frequency which can be described conveniently by the power spectral density F(n).

The rate of decrease of the gust factor G with the length of the structure, can be obtained by referring to differences of phase in velocity fluctuations between two points which are apart by more than the scale of mean eddies in the wind. In other words, it suffices to show statistically that the air flow with maximum instantaneous velocity will not act on the whole length of the structure. For the purpose of mathematical formulation, space correlation between two points must be used in addition to spectral density, F(n).

For a long structure, wind load will be greatest in the wind direction perpendicular to the axis of the structure. The space correlation $\Pi(x)$ is obtained simply from the velocity fluctuations $\mu(x_0, t)$ and $\mu(x_0 + x, t)$, at two points separated horizontally by a distance x in the perpendicular direction to the wind, as follows:

$$\Pi(x) = \overline{\mu(x_0, t) \cdot \mu(x_0 + x, t)} \qquad (4.3)$$

As shown in (4.3), the space correlation is only a function of distance between two points, and can be shown to be:

$$\Pi_1(x) = \bar{\mu}^2(x_0) \exp\left[-\frac{x}{L}\left(1 - \frac{x}{2L}\right)\right] \qquad (4.4)$$

where L is the lateral scale of turbulence. When the turbulence is isotropic, space correlation along mean wind becomes,

$$\Pi_2(x) = \bar{\mu}^2(x_0) \exp\left(-\frac{x}{L}\right) \qquad (4.5)$$

The space correlation can now be expressed as a function of the frequency n,

$$\Pi(x) = 2\int_0^\infty |S(x,n)|\, dn \qquad (4.6)$$

where $|S(x,n)|$ is the absolute value of the cross spectral density. In homogeneous wind field, the spectral densities at two horizontal points x_0 and $(x_0 + x)$ are the same; and the correlation coefficient of fluctuating velocity of frequency n between two points separated by a distance x can be defined as follows,

$$R(x,n) = |S(x,n)| / F(n) \qquad (4.7)$$

Finally, for this case, equation (4.3) and (4.6) can be expressed as:

$$\Pi(x) = 2\int_0^\infty F(n)\,R(x,n)\,dn \qquad (4.8)$$

It is now possible to use the above results to develop necessary maximum velocity which is likely to be exceeded on the average only once in any specified number of years: and also to compute the necessary gust factor G for any long structure, (see Figure 8) for typical results. Also the use of the size reduction factor **S** in equation (3.3), (see Figure 7), has also taken the effect of the size of the structure into account, in the practical evaluation of the gust factor G for various structures.

5. CONCLUSION

The problem of estimating maximum design wind forces and pressures on structure can be divided into the assessments of,(a) the maximum design wind velocity,(b) the shape and pressure coefficients which are incorporated in the parameter (11), Cp (Z), and (c) the final evaluation of gust factors and wind pressures.

A considerable degree of uncertainty exists in the estimates of both the design wind speeds, the coefficients and other essential parameters of this problem. A method of obtaining the design wind speed is described, which is based on the application of maximum entropy technique; and an attempt is made to obtain the design wind force of various structures from the formula of static wind force, only by changing numerical values of gust factors, refereing to size and structural characteristics. Codes of practice are often used for relevant information on factors which are essential in this problem. However, for many structures the design demands more detailed and specific wind-loading data than are given in codes. The conditions under which wind-tunnel tests to obtain more specific data are carried out required careful consideration. Properties of the local natural wind, such as shear and turbulence, the Reynolds number of the flow, and the influence of local topographical factors, grouping of buildings, etc., may have to be reproduced in the wind tunnel to ensure full confidence in the accuracy of the data.

Wind effects are important considerations for the design of safe and economic structures, but their estimation remains subject to considerable uncertainties. These uncertainties will become better understood as improvements in the experimental facilities and wind tunnel techniques develop, and also as more meteorological data effect improvements in the experimental facilities and wind tunnel techniques develop, and also as more meteorological data effect improvents in the statistical evaluation and reliability of the long range prediction of maximum wind speeds and pressures; and in our knowledge of the turbulence and shear characteristics of the wind.

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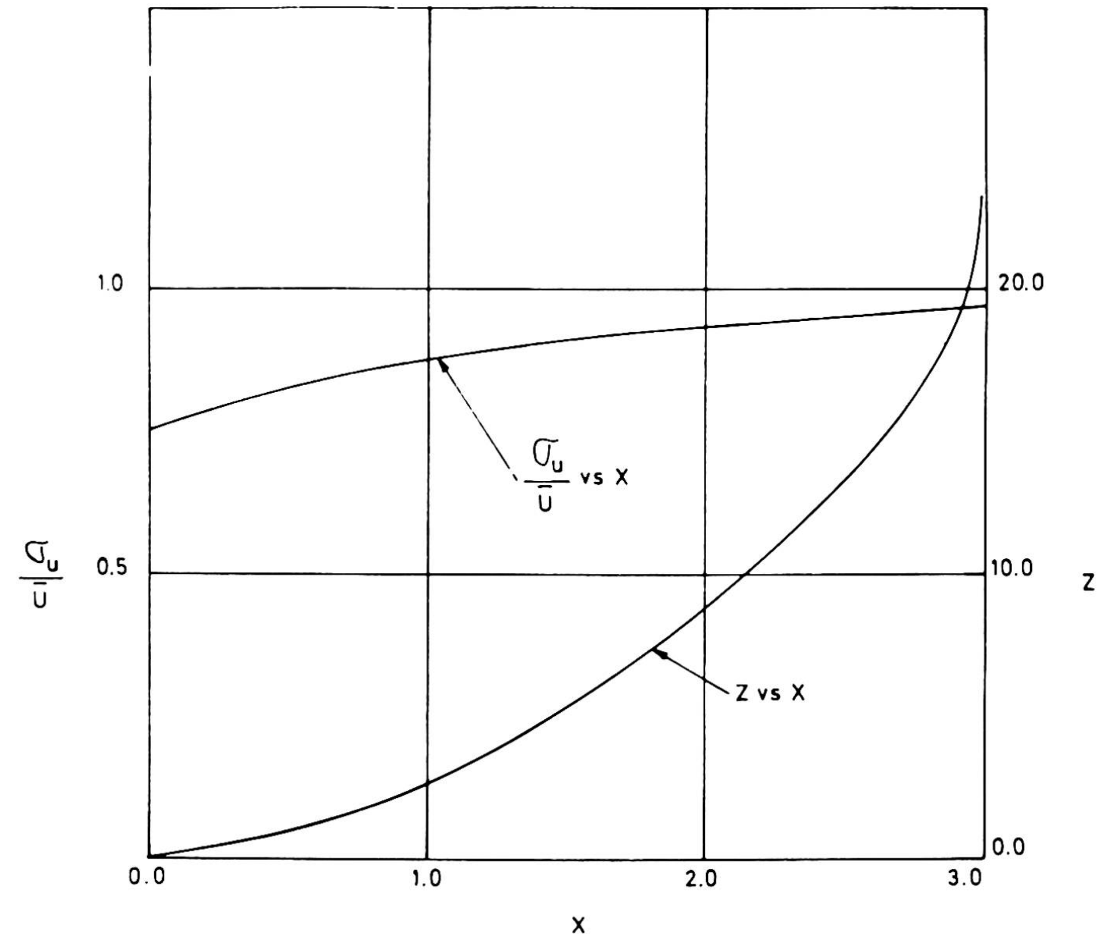
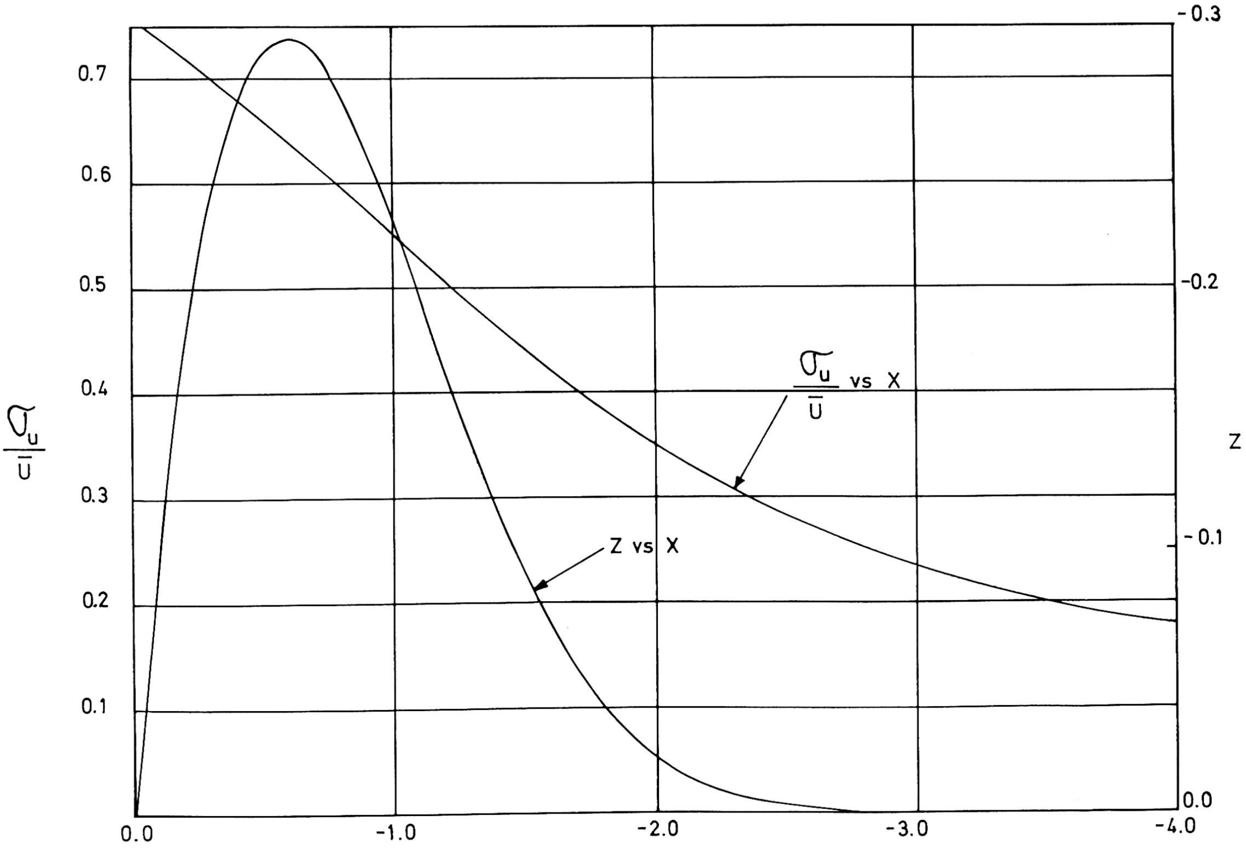


Fig. 1


0.7
0.6
0.5
0.4
0.3
0.2
0.1
$\frac{\sigma_u}{\bar{U}}$
- 0.3
-0.2
- 0.1
0.0
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$\frac{\sigma_u}{\bar{U}}$ vs X
Z vs X
0.0
-1.0
-2.0
-3.0
-4.0

Fig. 2

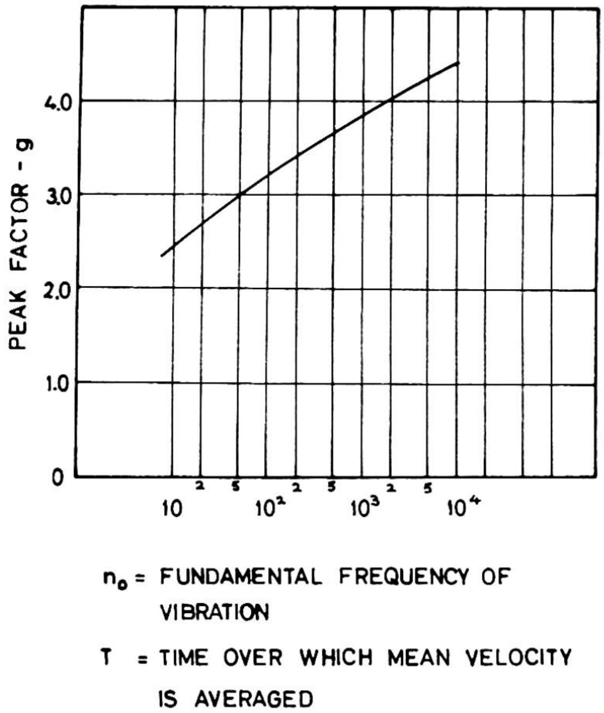

Fig. 3: Peak Factor

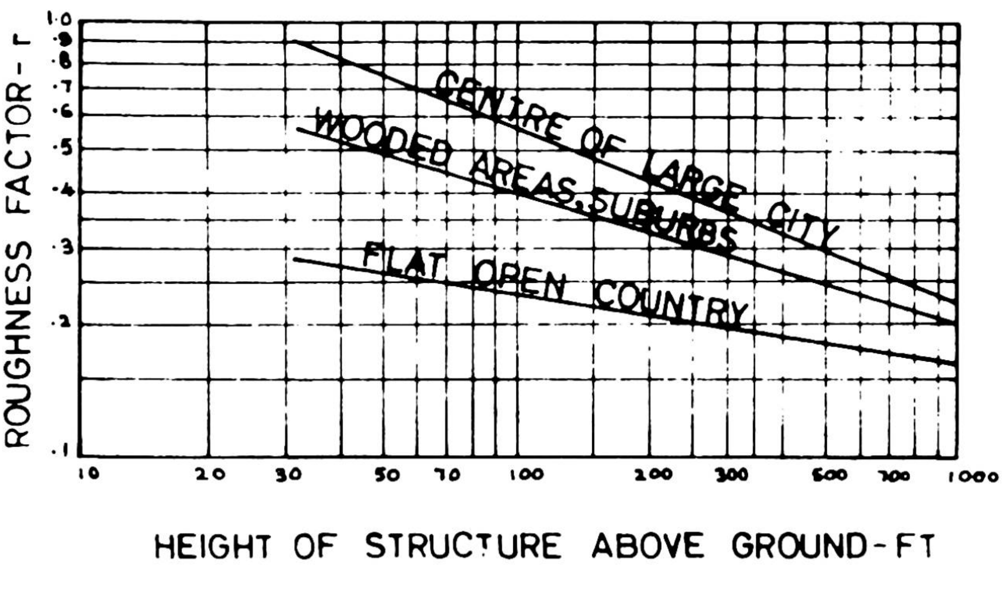

Fig. 4: Roughness Factor

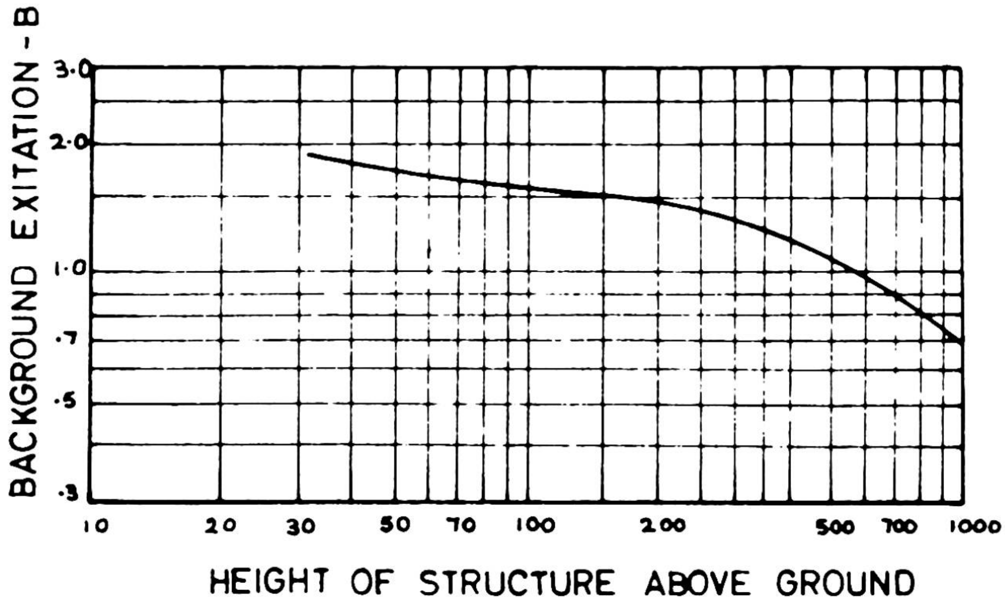

Fig. 5: Exitation Caused by Background Turbulence

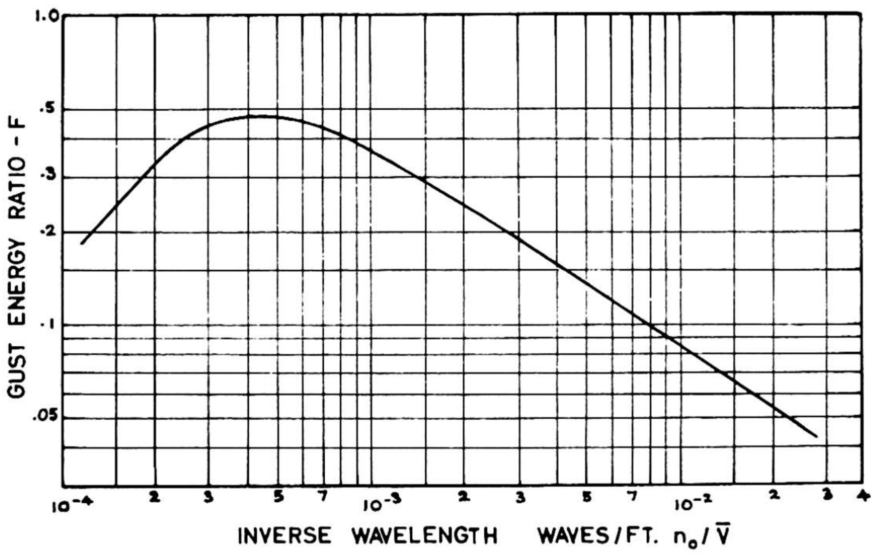

Fig. 6: Gust Energy Ratio

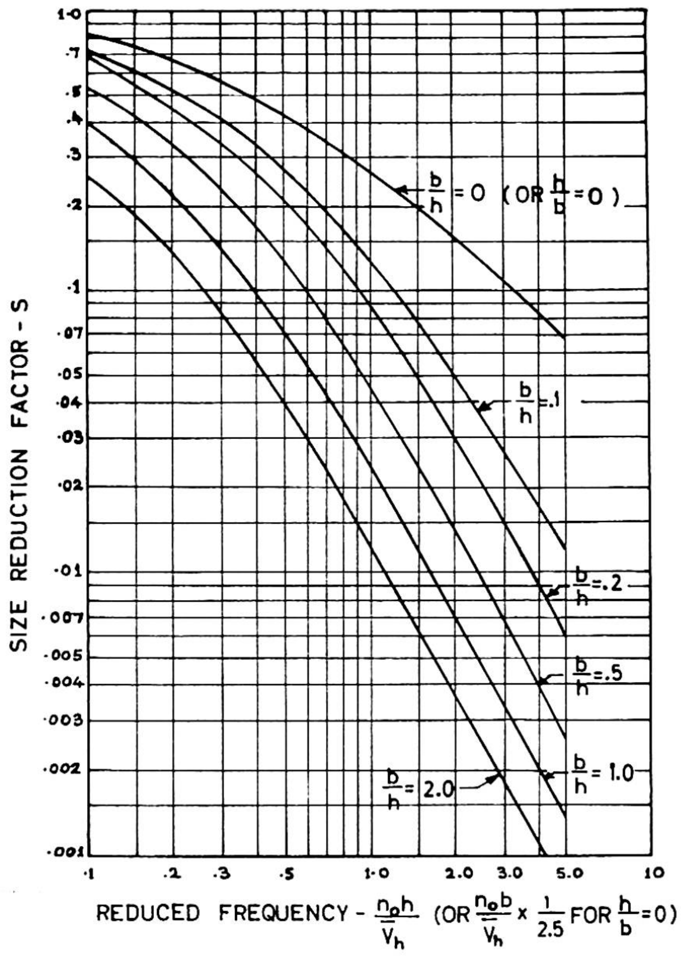

Fig. 7: Size Reduction Factor

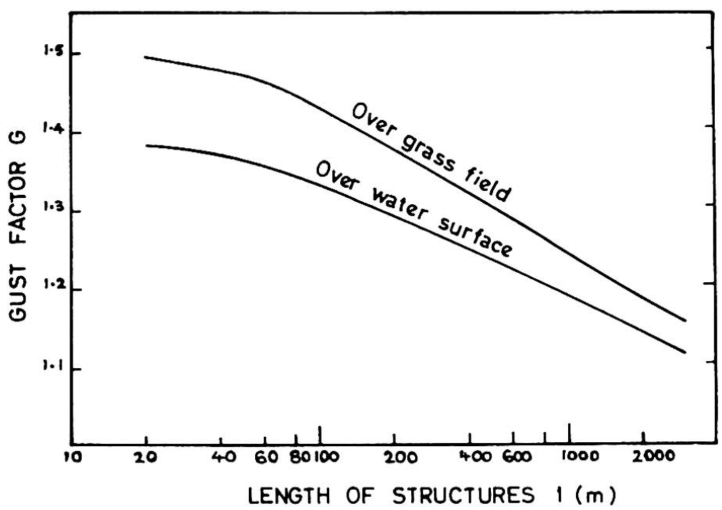

Fig. 8: Variation of Gust Factor of Long Structures with Length of Structures

SUMMARY

Minimally biased probability distribution functions for maximum value of the horizontal components of wind velocities and pressures, acting on engineering structures, are developed using maximum entropy concepts. In order to evolve a meaningful design wind force, it is found important to consider the dynamics of the problem, by considering among other factors, relevant changes in the numerical values of the gust factors referring to size, structural characteristics, and the space correlations of velocity fluctuations in addition to power spectrum.

RÉSUMÉ

A l'aide de conceptions d'entropie maximale on a développé des fonctions de répartition de la probabilité les moins vagues possibles pour les valeurs maximales des composantes horizontales de la vitesse et de la pression du vent. Pour trouver une force utile au dimensionnement, il est important de considérer le côté dynamique du problème, en tenant compte entre autres des changements importants du facteur de rafales, dépendant des dimensions et des caractéristiques de la structure, ainsi que des relations dans l'espace des fluctuations de vitesse en addition aux variations de puissance.

ZUSAMMENFASSUNG

Mit Hilfe Maximal-Entropie-Prinzipien werden Verteilungsfunktionen kleinster Schiefe für den grössten Wert der waagrechten Windgeschwindigkeits- und Winddruckkomponente auf Bauten hergeleitet. Um eine sinnvolle Kraft für die Bemessung zu bestimmen, muss die dynamische Wirkung unbedingt berücksichtigt werden, indem unter anderem die erheblichen Aenderungen des Böenfaktors in Funktion der Abmessungen und der baulichen Charakteristiken der Konstruktion sowie die räumlichen Zusammenhänge der Geschwindigkeits- und Kraftvariationen in Betracht gezogen werden.

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