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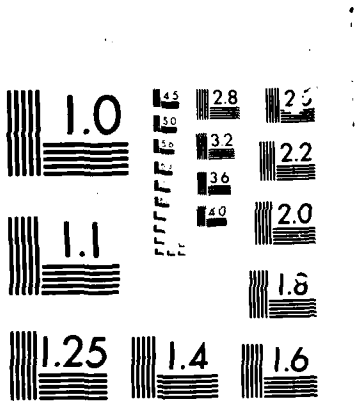

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USAFETAC/PR-86/001

DESIGN WIND ANALYSIS

(PROJECT 387402)

BY

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MARCH 1986

UNITED STATES AIR FORCE
AIR WEATHER SERVICE (MAC)
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19. Abstract: Provides a comprehensive literature review on methods of design wind analysis. The report notes that there is no "best way" to raise winds from one level to another, pointing out that meteorologists and engineers have separate preferences. Notes also that while one method may work well for one investigation, it may result in false conclusions when used for another.

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SUMMARY

In this report, prepared by USAFETAC's Operational Applications Development Section (DNO) in response to a request by the Engineering Meteorology Section (ECE), readers will find a comprehensive literature review on methods of design wind analysis. As will be noted in the introduction, meteorologists and engineers do not agree on a single "best" method for raising winds from one level to another; each group has its own preference or preferences.

There is no "best" way for presenting data to be used in this type of investigation. All the studies in this literature review use some type of "average" windspeed to describe steady state winds and an "average" gust to describe fluctuations in the steady winds; there is no agreement between studies, nor is there agreement on how the averages are determined.

Given the limitations of the 1/7 power law as noted in this literature review: The 1/7 power law appears best in an applications sense, simply because it is the most convenient method to use. Other methods (such as boundary-layer similarity theory, power spectral density functions, and the use of Weibull statistics) used to describe wind speed distributions are much more cumbersome; as such, they are seldom used. Also, the results of these types of studies are much more site specific in that it is much more difficult to make comparisons from one site to another, or from one study to another. While one method may work well in one investigation, it might fall completely apart in another. Worse, it could even result in false conclusions when applied to another situation.

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Introduction:

A physical model of a windstorm may consist of a mean flow and superimposed fluctuations generated by surface roughness. The shear action of the surface roughness retards the velocity of the mean flow so that it is practically zero at the surface and gradually increases with height until reaching a nearly constant value, the gradient velocity V_g at the gradient height z_g (Gould and Abu-Sitta, 1980)

The simplest form of a periodic fluctuating windspeed is one in which the amplitude is constant with respect to time and there is a single frequency present. Analytically, this can be expressed:

$$u(t) = \sin wt \tag{1}$$

A more complex variation can be visualized in which the wind speed is a compound of two constant-amplitude fluctuations of different frequencies. This would be expressed as:

$$u(t) = a_1 \sin w_1 t + a_2 \sin w_2 t \tag{2}$$

A different form of a deterministic fluctuating wind speed could be produced if the amplitude varied with time in a known fashion:

$$u(t) = a(t) \sin wt \tag{3}$$

Where a(t) is a known function of time. The windspeed in the atmosphere varies in a random fashion, not deterministically, similar to that depicted in Fig. 1. It is impossible to express this variation quantitatively by an equation such as eqn. (2), even if the coefficients are functions of time as in eqn. (3), because the future behavior is unknown and cannot be predicted (Lawson, 1980).

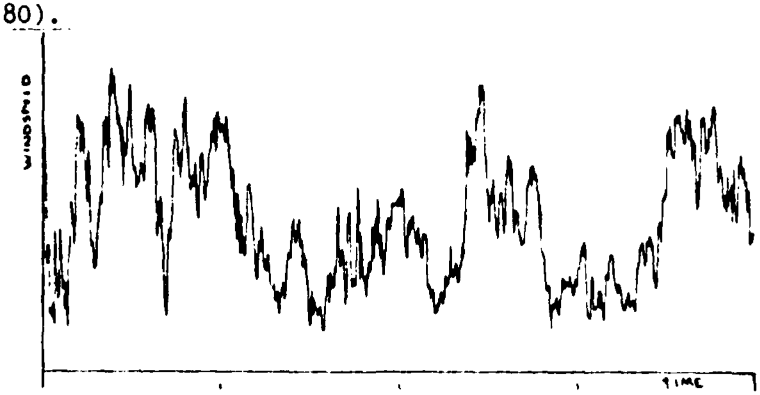

Fig. 1. Random variable

It is convenient to split the time-varying wind speed V(t) into a mean speed ($\bar{u}$) and a fluctuating (u(t)) part. This is illustrated in Fig. 2 and is defined by eqn. 4:

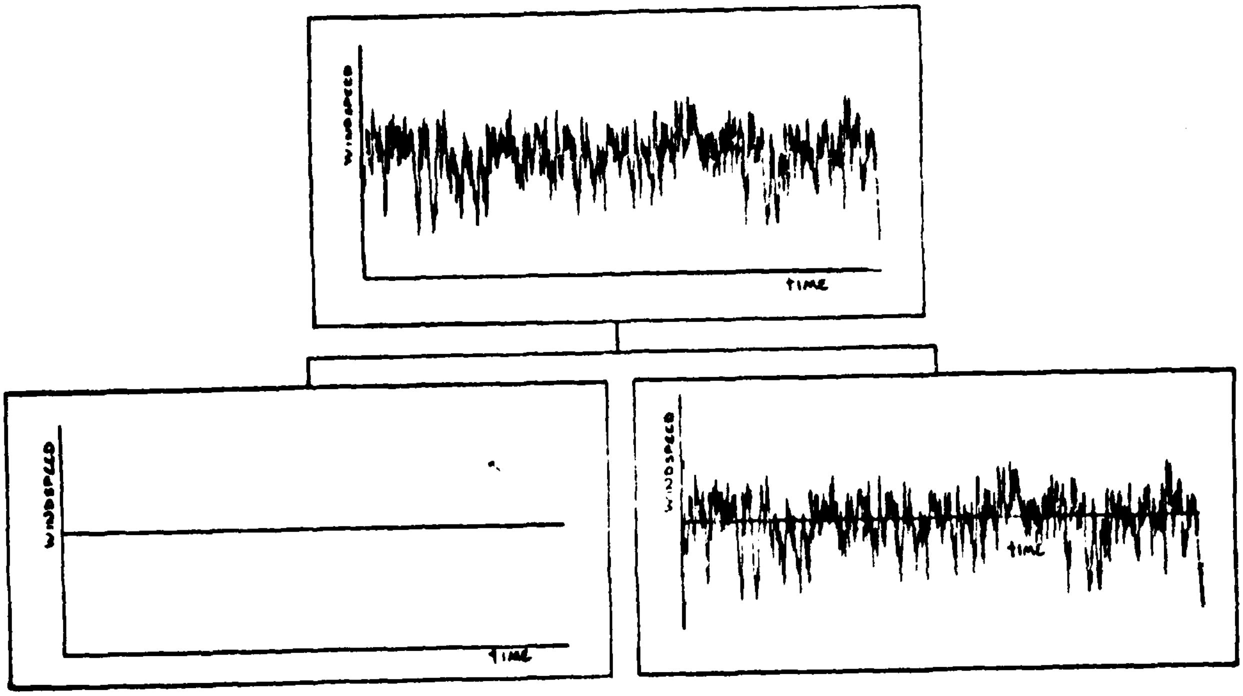

Fig. 2. Separation of windspeed into mean and fluctuating parts

$$V(t) = \bar{u} + u(t) \tag{4}$$

The term 'mean' denotes an average over a time interval which for some variables may tend to a constant as the averaging time increases. In the case of the windspeed it is conventional to define a mean windspeed as the average over one hour. There is a good reason for the choice of this value in that the spectrum of wind turbulence (Fig 3) shows very little energy over the frequency range 1/1200 Hz to 1/7200 Hz. This is called the "spectral gap", and means that the hourly average windspeed is a very stable quantity to calculate between these averaging times.

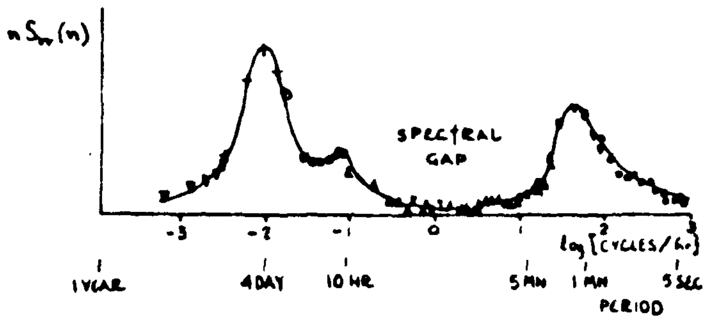

Fig. 3. Spectral density function for windspeed due to Van der Hoven

It should also be noted that the texture and roughness of the terrain, as well as its surface contours and topography, have a profound effect on the variation of the mean flow and height of the turbulence generated in the boundary layer. These features of the wind structure, in turn, have a significant influence on the structure loads. A structure in open country outside a city is likely to see substantially higher mean wind loads than one situated in the center of the city, but a smaller proportion of the gust loading (Plate, 1982).

Engineers and meteorologists use a variety of ways to express the variation of wind speed with height. The most popular are the logarithmic law, the power law, Deacon's Law and similarity theory in the case of a diabatic atmosphere. There is no real agreement on which of these methods are best. According to DeWinkel (1979), it is customary for engineers to rely on the simple '1/7 power law' for extrapolating windspeed from measurements at anemometer height (near 8m) to z-values of up to 50m above ground for the purpose of assessing wind energetics. Meteorologists, on the other hand, tend to prefer the logarithmic law. The logarithmic wind profile in adiabatic surface layers is one of the cornerstones of micrometeorology (Tennekees, 1973).

The Power Law

The power is one of the simplest descriptions of flow-speed profiles above a solid boundary. For many years engineers have preferred to use a power law for the variation of hourly average windspeed with height. A common form of the power law is:

$$\bar{u} = u_1 \, (z/z_1)^p \qquad (5)$$

Where $\bar{u}$ is the mean flow velocity at height z and u_1, is the velocity at height z_1. For both laboratory and atmospheric studies, the value of p is approximately 1/7 with adiabatic conditions and small pressure gradients. It's use follows the original work of von Karman on turbulent boundary layers in ducts, about which he postulated the "seventh-power law" (Lawson, 1980). Von Karman's work formed a cornerstone in the education of many engineers, and as such, the power law is still favored by them.

According to Sisterson et al. (1983), the use of this relationship, while perhaps appropriate in a climatological sense for daytime wind profiles in the lower atmosphere, frequently results in serious underestimates of wind speeds aloft at night. Sutton (1953) showed that eqn. (5) with a value of $p=1/7$ described atmospheric wind profiles between heights of 1.5m and 122m fairly well during near-neutral (adiabatic) conditions. However, his data indicated the value of p decreases with heating from below (unstable conditions) and increases with surface cooling (stable conditions).

The night-time case of strong surface cooling and thus very stable atmospheric conditions are of interest because then the value of p seems to deviate most strongly from 1/7. Sisterson and Frezen (1978) found power law exponents as large as 0.50 for heights between 30 and 150m, apparently in association with the occurence of nocturnal low-level wind maxima. They found that these nocturnal low-level jets formed more frequently than had been supposed. The maxima seem to be associated with near-zero wind velocities at the surface and large vertical gradients above.

According to Sterns and Kuffel (1981), such observations are not uncommon. Table 1 has been constructed to show that wind maxima are wide-spread, particularly in the Midwest and Great Plains areas of United States.

Table 1. Table of nocturnal, low-level wind investigation observations found in the literature

INVESTIGATOR	LOCATION	METHOD OF INVESTIGATION	HEIGHT OF MAX	TIME OF MAX	SEASONAL DEPENDENCE	PERIOD OF OBSERVATION
Barad (1961)	O'Neil, Nebraska 42° N	Loeser balloon technique	250–600 m	0300 L.T.	not available	6 weeks in the fall of 1953
Sisterson and Frenzen (1978)	Springfield, Illinois 40° N	WHAT system pilot balloons	150 m	0500 L.T.	not available	July-August 1975, July-August 1976
Crawford and Hudson (1970)	Oklahoma City, Oklahoma 35°N	1602 ft. tower 445 m	335	0000–0100 L.T.	not available	June 1966 May 1967
Jehn and Durie (1963)	Dallas, Texas 33° N	1400 ft. tower 435 m	91–	0300 L. T.	most frequent in July (80%) least frequent in winter (40%)	606 days in January 1961 December 1962
Rider and Armendariz (1971)	White Sand Missile Range, New Mex. 33° N	radar-tracked balloons	100–600 m	1900–0700 L.T.	most frequent in March-June secondary in November least in July-Sept.	1969-1970 91 jets occurred on 154 nights
Farguharson (1939)	Khartoum, Africa 14° N	single theodolite pilot balloons	300 m	0600–0900 L.T. secondary in July	most in January-March	315 days over 11 months
Goualt (1938)	Fort Lamy, Africa 12°N	single thendolite pilot balloons	500 m	0500 L.T.	most frequent in winter	April 1936 March 1937

Wind speeds measured during a 4 year period at heights of 6 and 23m have been analyzed by Moses and Bogner (1967). They found that the best-fitting values of p have a wide distribution and clear seasonal variation. Daily medians ranged from 0.14 in winter to more than 0.20 in summer, a difference of 30%; the annual median is 0.17. Not only is there a wide seasonal variation of the power-law exponent, but there is also a considerable deviation between daytime and night-time values of p (Fig. 4) They were able to conclude that during the day, a 1/7 power law describes wind profiles in the lowest 23m faily well. At night, however, no single value of the power-law exponent can accurately describe the wind profiles.

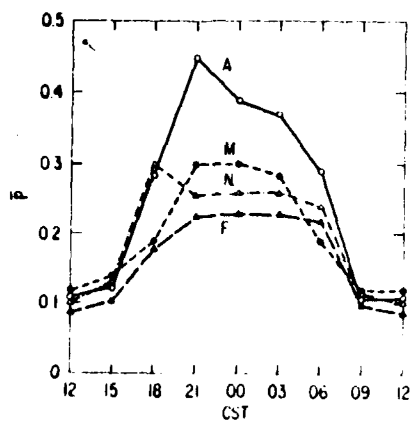

Fig 4. Median power-law exponent as a function of the time of day of Feb (F), May (M), Aug (A), and Nov (N)

In a similar study by Sisterson et al. (1983), it was determined that a simple 1/7 power law cannot accurately describe a complete wind profile, particularly in stable conditions. Winds estimated at 44.5m by application of the 1/7 power law to velocities measured at 6m were 15% too low. The corresponding wind power potential (the cube of the wind speed) would be underestimated by about 45%. For this reason, they concluded that the unrestricted use of the power law cannot be supported. However, with proper consideration of the effects of stability and surface roughness, a power law might be used as a simple estimate of wind power potential and wind shear.

The results of Sisterson et al. do not seem unreasonable when compared with other studies. Touma (1977) concluded that the 1/7 power law is generally a good approximation only under neutral conditions. The true power law relationship is highly variable and is dependent upon stability class at each site. Table 2 lists the Pasquill stability classes used in the Touma study which are based on the vertical temperature gradient criteria given in the National Regulatory Commission (NCR) Regulatory Guide 1.23. The NRC requires that stability should be based on direct measurement of temperature differences between two levels. A summary of the power law exponents, computed in the Touma study are shown in Table 3. Because of the variable nature of the power law exponent, it is suggested that a site specific power law profile be developed and used when it is necessary to extrapolate wind speed data at another level.

Stability class	Range of vertical temperature gradient		Turbulence
	°F/1000 ft	°C/100 m	
A = Very unstable	$\Delta T < -10.4$	$\Delta T < -1.9$	High
B = Moderately unstable	$-10.4 \leq \Delta T < -9.3$	$-1.9 \leq \Delta T < -1.7$	
C = Slightly unstable	$-9.3 \leq \Delta T < -8.2$	$-1.7 \leq \Delta T < -1.5$	
D = Neutral	$-8.2 \leq \Delta T < -2.7$	$-1.5 \leq \Delta T < -0.5$	Moderate
E = Slightly stable	$-2.7 \leq \Delta T < 8.2$	$-0.5 \leq \Delta T < 1.5$	Low
F = Moderately stable	$8.2 \leq \Delta T < 22.0$	$1.5 \leq \Delta T < 4.0$	
G = Very stable	$22.0 \leq \Delta T$	$4.0 \leq \Delta T$	

Table 2. Pasquill stability classes in terms of vertical differences (T)

Stability class	Missouri[a] 1973–74	Missouri[a] 1974–75	Kansas[a] 1973–74	Kansas[a] 1974–75	Iowa[a] 1973–74	Texas[a] 1973–74	Michigan[a] 1975–76	Missouri[b] 1973–74
A	0.103	0.099	0.124	0.091	0.104	0.120	0.109	0.111
B	0.079	0.092	0.145	0.103	0.101	0.123	0.085	0.119
C	0.082	0.080	0.152	0.122	0.114	0.128	0.078	0.104
D	0.115	0.144[c]	0.199	0.172	0.188	0.174	0.116	0.136
E	0.271	0.273	0.341	0.282	0.313	0.330	0.261	0.272
F	0.423	0.385	0.480	0.412	0.466	0.562	0.425	0.424
G	0.504	0.417	0.506	0.452	0.444	0.624	0.516	0.447
Terrain	Rolling	Rolling	Rolling	Rolling	Rolling	Rolling	Hilly	Rolling

[a] Stability class based on a ΔT of 10 to 60 m.
[b] Stability class based on a ΔT of 10 to 90 m.
[c] For 1/7 power law $p = 0.143$.

Table 3. Power law exponents for various sites computed from annual average windspeed at two levels

DeMarris (1959) used meteorological data from a 125m tower at the Brookhaven National Laboratory to determine the power law profile. The power law exponents varied from 0.1 to 0.3 during the day when superadiabatic and neutral lapse rates prevail and from 0.2 to 0.8 during night-time conditions when stable and isothermal conditions exist.

In a study on gust variation with height up to 150m, Deacon (1955) showed the increase of gust speeds with height to be markedly less than that of mean wind speed. He found that at times of occurrence of wind gust maxima, the wind speed is proportional to the height raised to the power 0.085 and the corresponding index for mean speed is 0.16. Other studies on the relationship of gusts to the steady wind and their variation with speed, height, stability, and terrain include Davis and Newstein (1968), Camp (1968), Fichtl et al. (1969), Brooks and Spillane (1970), Peterson and Hennessey (1978), and Lettau (1979) However, although all these studies are in general agreement about the nature of these relationships, their quantitative results have varied depending on the data and analytical methods used.

The Logarithmic Wind Profile.

The Logarithmic wind profile in adiabatic surface layers is one of the cornerstones of micrometeorology. Because the logarithmic law appears to be insensitive to the manner of its derivation (Lumely and Panofsky, 1964), a great deal of folklore on its accuracy and applicability has become entrenched in the subject over the forty-odd years since it was derived (Tennekes, 1973).

In the simplest case of neutral boundary layer flow near the surface, the assumption of constant momentum flux leads to the relation

$$\tau = \tau_0 = \rho u_*^2$$

or (6)

$$K_m \frac{\partial \bar{u}}{\partial z} = u_*^2$$

where τ is the surface stress per unit area, u_* is the friction velocity, and K_m is the eddy viscosity or a diffusivity of momentum. In the surface layer, the velocity scale is u_* and the length scale is z. Then from dimensional considerations

$$K_m \propto u_* z$$

or (7)

$$K_m = k u_* z$$

in which k is the von Karman's constant. After substituting from eqn. (7) into eqn. (6), one obtains

$$\frac{\partial \bar{u}}{\partial z} = u_*/kz \qquad (8)$$

which predicts the wind shear to be directly proportional to u_* (velocity) and inversely proportional z. This also follows from dimensional arguments if one assumes that the wind shear ($\partial u/\partial z$) and other flow characteristics in a neutral layer depend only on u_* and z. The integration of eqn. (8) yields.

$$\bar{u}/u_* = 1/k \ln(z/z_0) \qquad (9)$$

which is the well-known lograthmic wind profile. Here z_0 is introduced as a constant of integration, and is known as the roughness parameter. In practice, z_0 is determined by plotting the measured values of $\bar{u}$ against ln z_0 or log z_0, and extrapolating the best-fitted straight line down to the axis where $\bar{u}$=0, the intercept on the ordinate axis being ln z_0 or log z_0. The assumptions made in deriving eqn. 9 cannot be justified for $z < h_0$, where h_0 is the average height of roughness elements (Plate, 1982).

For a very rough surface such as a corn crop, forest, or an urban area, the most appropriate datum for determining the heights in the boundary layer is not the ground level, but displaced above by a distance d_o, called the zero-plane displacement. Introducing d_o into eqn. (9), the logarithmic profile equation becomes

$$\bar{u}/u_* = 1/k \ln[(z'-d_o)/z_0] \qquad (10)$$

in which z' is the height measured from the ground surface. In practice, both z_o and d_o are empirically determined from a least-squares fitting of eqn. 10 to the observed wind profiles under neutral stability conditions.

Numerous observations have been made of mean wind profiles in the atmospheric boundary layer over a variety of natural and artificial surfaces. These have been used to verify the logarithmic wind profile law, as well as for determining the roughness parameters z_o and d_o as functions of roughness height h_o (see Plate, 1971). Although z_o varies over five orders at magnitude (from about 10^{-4} for smooth water surfaces to several meters for forests and urban areas), the ratio z_o/h_o falls within a narrow range between 0.03 and 0.25 and increases slowly with increasing h_o. An average value of z_o/h_o=0.15 may be used for most natural surfaces. An extensive discussion of the relationship between z_o and the surface geometry is given by Plate (1982).

Tennekes (1973) explored the practical consequences of the asymtotic nature of the logarithmic wind profile for neutral, barotropic, atmospheric boundary layers. He noted that recent developments in boundary layer theory have shown that the von Karman constant, pegged at 0.4 since the Depression, is now allowed to float anywhere between 0.33 (Tennekes, 1968; Tennekes and Lumley, 1972) and 0.40, with a current value of 0.35 over smooth terrain (Bussinger et al., 1971; Frenzen, 1972). The consequences of this uncertainty for the determination of stress from wind profiles are evident: in many experients, the computed wind shear stress may have been some 20% above its true value, and the inferred surface friction velocity may have been off by as much as 10%. Tennekes (1973) concluded that the logarithmic law is valid over a restricted range of heights and that a cautious micrometerologist should not assume that he can determine u_* within 1% from a wind profile; systematic errors of 5% or more are quite likely. Futhermore, thermal wind, inhomogeneous or nonstationary boundary conditions, and the presence of a vertical heat flux all may, or may not, affect the logarithmic slope and other features of the wind profile in the inertial sublayer.

Tennekes conclusions only echo those of Munn (1966), who noted that although the logarithmic wind profile is important in wind tunnel studies of shear flow, it is not particularly useful in the atmosphere. The lapse rate is rarely adiabatic and buoyancy forces must be considered.

Monin - Obukhov Similarity Theory

- The diabatic wind profile:

The most widely used theory for the stratified surface layer is that proposed by Monin - Obukhov (1954). Their basic hypothesis is that in the surface layer, mean flow and turbulent characteristics depend only on four independent variables: The height above the surface z, the friction velocity u_*, the surface kinematic heat flux Q_o, and the buoyancy variable g/T_o. From these variables, one can form only one independent dimensionless group, traditionally defined as the stability parameter

$$\zeta = z/L \tag{11}$$

where

$$L = -[u_*^3/k(g/T_o)Q_o] \tag{12}$$

is the buoyancy length scale known as the Monin - Obukhov length after its originators. Note, the von Karman constant k was introduced in the definition of L by Obukhov (1946); a length scale defined without k would be preferable in view of the present controversy or uncertainty in the value of k.

The similarity prediction that follows from the M-O hypothesis is that any average turbulence characteristic $\bar{f}$ in the surface layer when normalized by an appropriate combination or scale f_o, having dimensions of f, and formulated from the independent variables z, u_*, Q_o, and g/T_o, must be a universal function of z/L only.

That is,

$$\bar{f}(z)/f_o = F(\zeta) \tag{13}$$

For diabatic surface layers, M-O theory states that substitution of actual height z by a dimensionless height ζ,

$$\zeta = -gkzw'T' \;/\; T_o u_*^3 \tag{14}$$

(where g = acceleration due to gravity, T_o = Kelvin temperature of the active surface, and w'T' is a thermo-kinematic equivalent of the vertical eddy flux of heat), yields wind shear as a universal function of ζ provided that the wind shear is made dimensionless as $\phi(\zeta)$ where

$$\phi = (k/u_*)\partial u/\partial \ln\zeta = (k/u_*)\partial u/\partial \ln z \tag{15}$$

Integration of the shear equation (15) yields the diabatic wind profile for $z_o \leq z \leq h$

$$ku/u_* = \ln (z/z_o) - \Psi = \ln (\zeta-\zeta_o) - \Psi \tag{16}$$

where

$$\Psi = \int_{z_o}^{z} (1-\phi)\; d \ln\zeta \tag{17}$$

This approach has been used in studies by Panofsky <u>et al.</u>, (1955), Businger (1959), Oke (1978) and Lettau (1979).

Military Applications

Windspeed design goals for military equipment developed for worldwide usage over land are included in MIL-STD 210B. The goals are: (1) the speed up to which "operations" are expected to proceed, (2) the speed that equipment should "withstand" without irreversible damage even though the critical speed for operations is exceeded. The withstanding capability can be attained through the basic integrity of the designed equipment or through the use of auxillary "tie-down" kits (Sissenwine et al., 1973). Note, however, design wind speeds implicit in wind loading specifications have been in the past and are still made on an empirical, largely subjective basis (Simiu and Scanlan, 1978).

Guidance provided by the Special Assistant for Environmental Services (SAES) of the Joint Chiefs of Staff (JCS) indicates that the speed for operations will be a value that is exceeded only 1 percent of the time in the windiest month at the windiest geographical area over which military operations are conceivable. JCS (SAES) further suggests that for "withstanding" there should be a family of speeds which have only a 10 percent probability of being attained in geographical areas subject to strong winds during an exposure life of 2, 5, 10, or 25 years considered applicable to the spectrum of field lives of military equipment (Sissenwine et al., 1973).

The design wind speed at any given station in the contiguous U.S. is defined by Breckke (1959) as the peak gust at 30 ft above ground recorded at the station in the period 1944 - 1952. It is assumed that the maximum gust is equal to 1.3 times the fastest-mile wind. Breckke's definition was adopted in the Uniform Building Code in 1974. The design wind speeds specified by the American National Standard ANSI A58.1 (1972) are 50-year fastest miles for most permanent structures, 100-year fastest miles for structures with an unusually high degree of hazard to life and property in case of failure, and 25-year fastest miles for structures having no human occupants or where there is negligible risk to human life.

It is difficult to make comparisons between the 39-year peak gust of Breckke and the 50-year fastest miles specified by ANSI because of the inhomogeneity of the data used by Breckke. However, both criteria result is wind loads that appear to ensure a reasonable degree of structural safety (Simiu and Scanlan, 1978).

Sissenwine et al., in a study of gustiness and variations of wind with height during strong wind regimes, give a complete discussion of design wind analysis directed toward military applications. Their analysis, based on power-law relationships, presented factors for adjusting wind speed to a common height to describe wind speed and gusts over the vertical extent of military usage. Their recommendations included: (1) equipment designed for worldwide surface level deployment must be able to operate when the steady wind at 10ft is 43 knots and gusts are 48 to 62 knots, depending upon the horizontal dimension of equipment, (2) equipment designed for worldwide deployment must also be able to "withstand", without irreversible damage, steady speeds of 119, 140, 156, and 176 knots at a 10ft. height for estimated durations of exposure of 2, 5, 10, and 25 years respectively.

Conclusions

1) There is not a "best" method for raising winds from one level to another. Meteorologists prefer the logarithm approach for an adiabatic atmosphere and similarity theory for a diabatic atmosphere. Engineers prefer the power-law approach.

2) The power-law method "appears" best in an applications sense, however, an exponent of $p = 1/7$ can only be supported under ustable atmospheric conditions.

3) The value of the power-law exponent deviates most strongly from 1/7 under very stable conditions. In an atmosphere characterized by a nocturnal inversion and a low-level wind maxima, the value of p can approach unity.

4) The format of data used in design wind analysis studies varies from one study to another. An "average" wind speed is used to describe steady state winds and an "average" gust is used to describe fluctations; there is no agreement between studies as to how long the averaging period should be.

5) With respect to military applications, power-law relationships adequately describe wind speed and gusts in the vertical.

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