第十章 脉动风的概率特性
Chapter 10 Probabilistic Characteristic of fluctuating wind

10.1 脉动风的概率分布
10.1 Probabilistic distribution of fluctuating wind

- 脉动风反映了大气边界层中自然风的湍流特性 Fluctuating wind reflects the fluctuating characteristics of natural wind turbulence in the atmospheric boundary layer
- 风速的脉动特性对工程结构的作用十分重要 The fluctuation characteristic of wind is very important to engineering structures
- 刚性结构要受到脉动风速所产生的阵风荷载 Rigid structures are subject to gust loading generated by fluctuating wind
- 柔性结构在脉动风速作用下会发生动力响应 Flexible structures produce dynamic response under fluctuating wind

Chapter 10 Probabilistic Characteristic of fluctuating wind

10.1 Probabilistic distribution of fluctuating wind

- 柔性结构的空气动力特征的参数可以分为能量特征参数和空间特征参数

The aerodynamic characteristic parameters of flexible structures can be described by energy characteristic parameters and spatial characteristic parameters.

- 能量参数：湍流度、脉动风功率谱

Energy parameters : turbulence intensity, wind power spectrum

- 空间参数：湍流积分尺寸、空间相关性。

Space parameters : turbulence integral dimension, spatial correlation.

10.1 Probabilistic distribution of fluctuating wind

- **对风速记录的分析表明，如果忽略初始阶段的严重非平稳区域，脉动风十分接近于平稳随机过程，它的概率密度很接近于正态分布**
- **Wind speed record analysis shows that if the serious non-stationary parts is ignored in the initial phase，the fluctuating wind is very close to stationary random process, the probability distribution is very close to normal distribution**

纵向 longiudinal

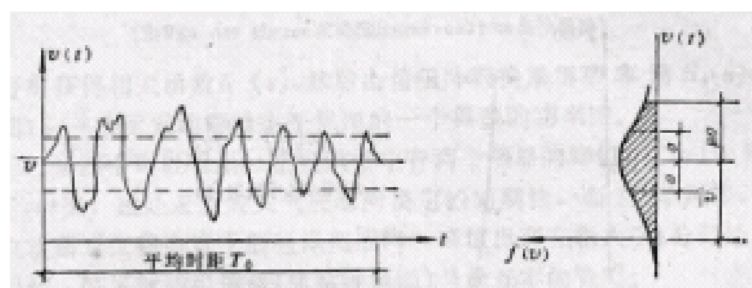
$$\sigma_u = \left\{ \frac{1}{T} \int_0^T [U(t) - \bar{u}]^2 dt \right\}^{\frac{1}{2}} = \left\{ \frac{1}{T} \int_0^T u(t)^2 dt \right\}^{\frac{1}{2}}$$

横向 lateral

$$\sigma_v = \left\{ \frac{1}{T} \int_0^T v(t)^2 dt \right\}^{\frac{1}{2}}$$

竖直向 vertical

$$\sigma_w = \left\{ \frac{1}{T} \int_0^T w(t)^2 dt \right\}^{\frac{1}{2}}$$

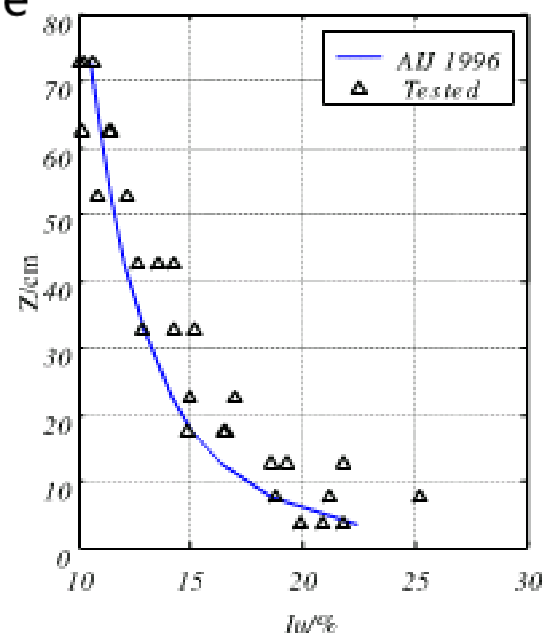


10.1 脉动风的概率分布
10.1 Probabilistic distribution of fluctuating wind

湍流度（Turbulence intensity）
描述脉动风强度的重要参数，是衡量脉动风能量大小的标志
The Factor that descripts the strength of fluctuating wind. It is a criteria for measuring the energy of fluctuating wind.

$I_u = \frac{\sigma_u}{\bar{u}}$ $I_v = \frac{\sigma_v}{\bar{u}}$ $I_w = \frac{\sigma_w}{\bar{u}}$

σ为脉动风速的根方差；$\bar{u}$为平均风速
σ is the standard deviation of fluctuating wind and $\bar{u}$ is the mean wind speed
无量纲的湍流度随高度增加而减小
The turbulence intensity without dimension decreases with increasing altitude
其具体分布规律与地貌有关
The specific distribution rule is related to the landforms
靠近地面一般可达20%以上。
The intensity can exceed 20 percent close to the ground



10.1 脉动风的概率分布
10.1 Probabilistic distribution of fluctuating wind

一些国家的规范（如日本、澳大利亚）中给出了不同地貌条件下纵向脉动风湍流度随高度的变化

The codes in other countries such as Japan and Australia gives the longitudinal fluctuating wind turbulence under different geomorphological conditions varying with height

我国《建筑物荷载规范》并没有明确规定，但隐含采用下式

Chinese Load Code for the design of building has no specific regulations but implicitly recommends adopting the following formula

$$I_u = 0.1(z/H_G)^{-\alpha-0.05}$$

《公路桥梁抗风设计指南》给出了建议值

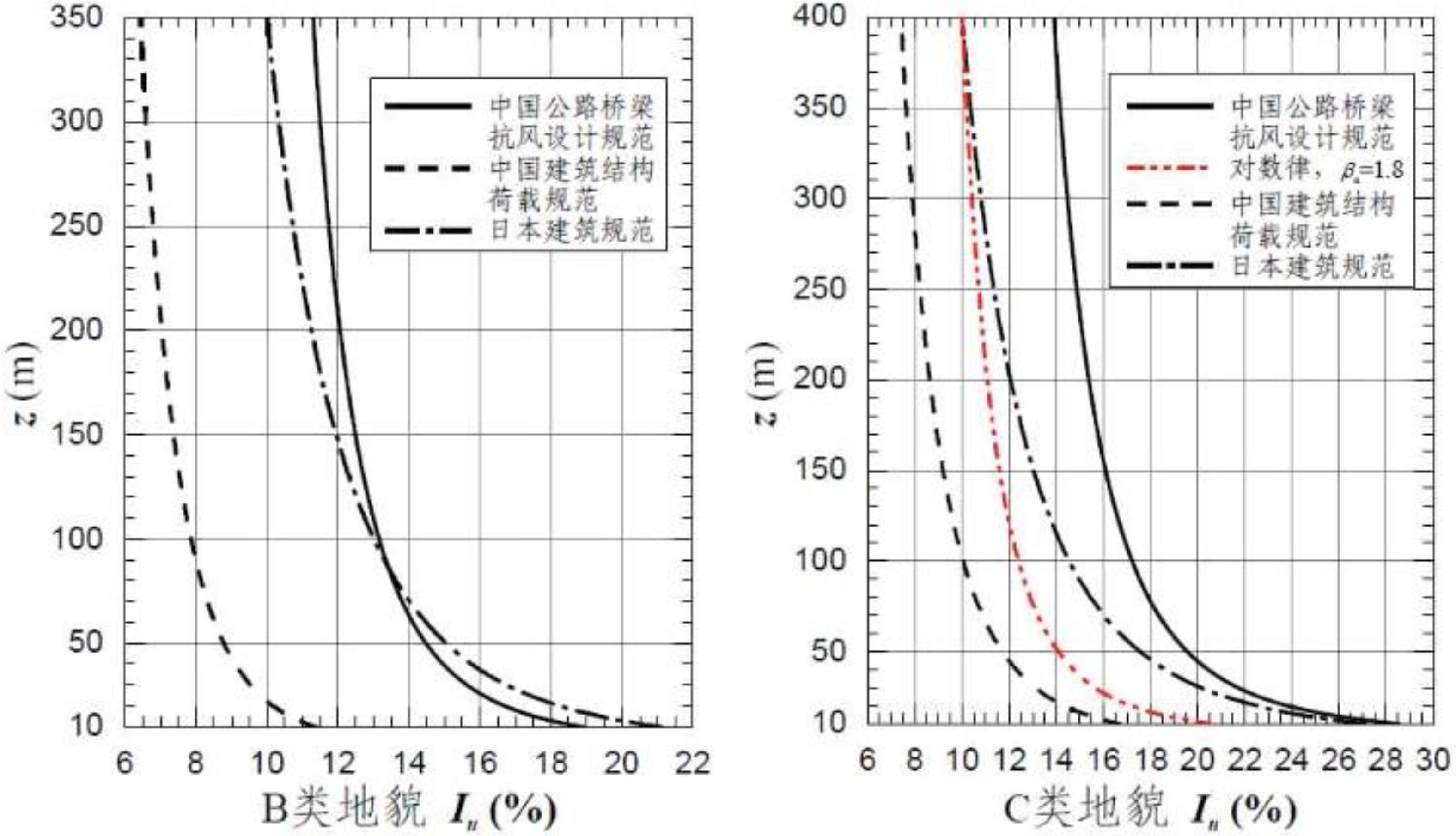
Wind-resistent Design Specification for Highway Bridges gives the recommend values

$$I_v = 0.88 I_u \quad I_w = 0.50 I_u$$

Chapter 10 Probabilistic Characteristic of fluctuating wind

10.1 脉动风的概率分布

10.1 Probabilistic distribution of fluctuating wind



10.1 脉动风的概率分布
10.1 Probabilistic distribution of fluctuating wind

- 湍流积分长度（Turbulence integral length）

通过某一点气流中的速度脉动可以认为是由平均风所运输的一些理想涡旋叠加而引起的，若定义涡旋的波长就是涡旋大小的量度，紊流积分尺度则是气流中湍流涡旋平均尺寸的量度。

The velocity fluctuation passing through a point can be recognized as the Superposition of the ideal vortex transported by mean wind. If the wavelength is defined as the measurement of vertex size, Turbulence integral length is the measurement of average size of the turbulent vortex in the airflow.

10.1 脉动风的概率分布
10.1 Probabilistic distribution of fluctuating wind

湍流积分长度从数学上可定义为 The mathematical definition of turbulence integral can be defined as follow:

$$L_u^x=\frac{1}{\sigma_u^2}\int_0^\infty C_{u_1u_2}(x)dx \quad L_u^y=\frac{1}{\sigma_u^2}\int_0^\infty C_{u_1u_2}(y)dy \quad L_u^z=\frac{1}{\sigma_u^2}\int_0^\infty C_{u_1u_2}(z)dz$$

$$L_v^x=\frac{1}{\sigma_v^2}\int_0^\infty C_{v_1v_2}(x)dx \quad L_v^y=\frac{1}{\sigma_v^2}\int_0^\infty C_{v_1v_2}(y)dy \quad L_v^z=\frac{1}{\sigma_v^2}\int_0^\infty C_{v_1v_2}(z)dz$$

$$L_w^x=\frac{1}{\sigma_w^2}\int_0^\infty C_{w_1w_2}(x)dx \quad L_w^y=\frac{1}{\sigma_w^2}\int_0^\infty C_{w_1w_2}(y)dy \quad L_w^z=\frac{1}{\sigma_w^2}\int_0^\infty C_{w_1w_2}(z)dz$$

函数C分别表示两个脉动风速的互协方差函数 Function C respectively represents covariance functions of two pieces of fluctuating wind.

如果互协方差函数是相隔距离的快速递减函数，则湍流积分长度很小，紊流影响也很小。反之如果互协方差函数随相隔距离的增大递减很慢，则湍流积分长度很大，紊流的影响也大。

If the covariance function is a fast decreasing function of the distance, then the interval of turbulence integral is small, correspondingly the effect of turbulence is small. Conversely, If the covariance function decreases slowly with distance, the interval of turbulence integral is large, the effect of turbulence is also large.

10.2 脉动风的功率谱
10.2 Power spectra of fluctuating wind

脉动风功率谱（Power Spectra）

表现了脉动风能量在整个频率范围内的分布特征

It describes the energy distribution of fluctuating wind over full frequency range.

脉动风功率谱需由强风观测记录得出，一般有两种方法：

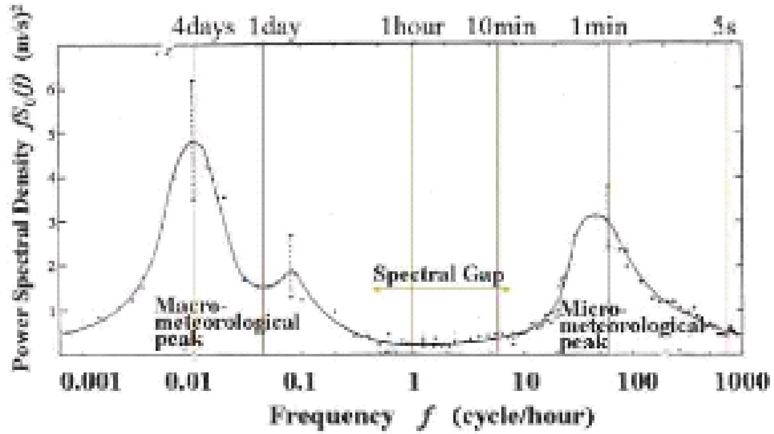
Power spectra is obtained by observing strong winds. Generally there are two methods:

把强风记录通过超低频率滤波器，直接测出风速的功率谱曲线；

Directly measure the power spectrum of wind speed by letting strong wind records go through ultra-low frequency filter.

把强风记录经过相关性分析，获得风速的相关曲线，建立相关函数的数学表达式，然后通过傅里叶变换得到功率谱。

Obtain the correlation curve by analyzing strong wind records and establish expressions of correlation function. And finally, the power spectrum is obtained through Fourier transformation



（1）在中心频率为0.01（1/小时）出现第一个峰值，对应于天气系统整个运转的变化周期4天通常称为宏观气象峰值；

The first peak corresponding to the whole period of the weather system appears at where the center frequency is 0.01(1/h), which is usually called macro meteorological peak

（2）第二个峰值出现在12小时周期处，相当于昼夜间的温度变化

The second peak occurs at the period of 12 hours, which is equivalent to the change in temperature between day and night.

（3）第三个峰值出现在1分钟周期处，反映了大气湍流的脉动，即与边界层湍流作用有关的从十分钟到小于3秒周期的高频作用，通常称为微观气象峰值

The third peak occurs at the period of 1 minute, reflecting the fluctuation of atmospheric turbulence, which is the high frequency action of a period of 3 seconds to 10 minutes and is usually called micro meteorological peak.

10.2 脉动风的功率谱
10.2 Power spectra of fluctuating wind

- **在结构风工程领域，低频部分（包含宏观气象峰值）远离结构自振频率，对结构仅起静力作用；高频部分（包含微观气象峰值）与结构自振频率较为接近，需要考虑对结构的动力效应；并且，这两部分的相互作用可以忽略，可分开进行研究。**
- **In the wind engineering field, the low frequency component (including macro metrological peak) is far from the structural natural frequency and its action is static. While the high frequency component (including micro metrological peak) is close to the natural structural frequency, thus the dynamic action of the wind must be taken into consideration. Meanwhile, the mutual action of this two components can be neglected and discussed separately.**

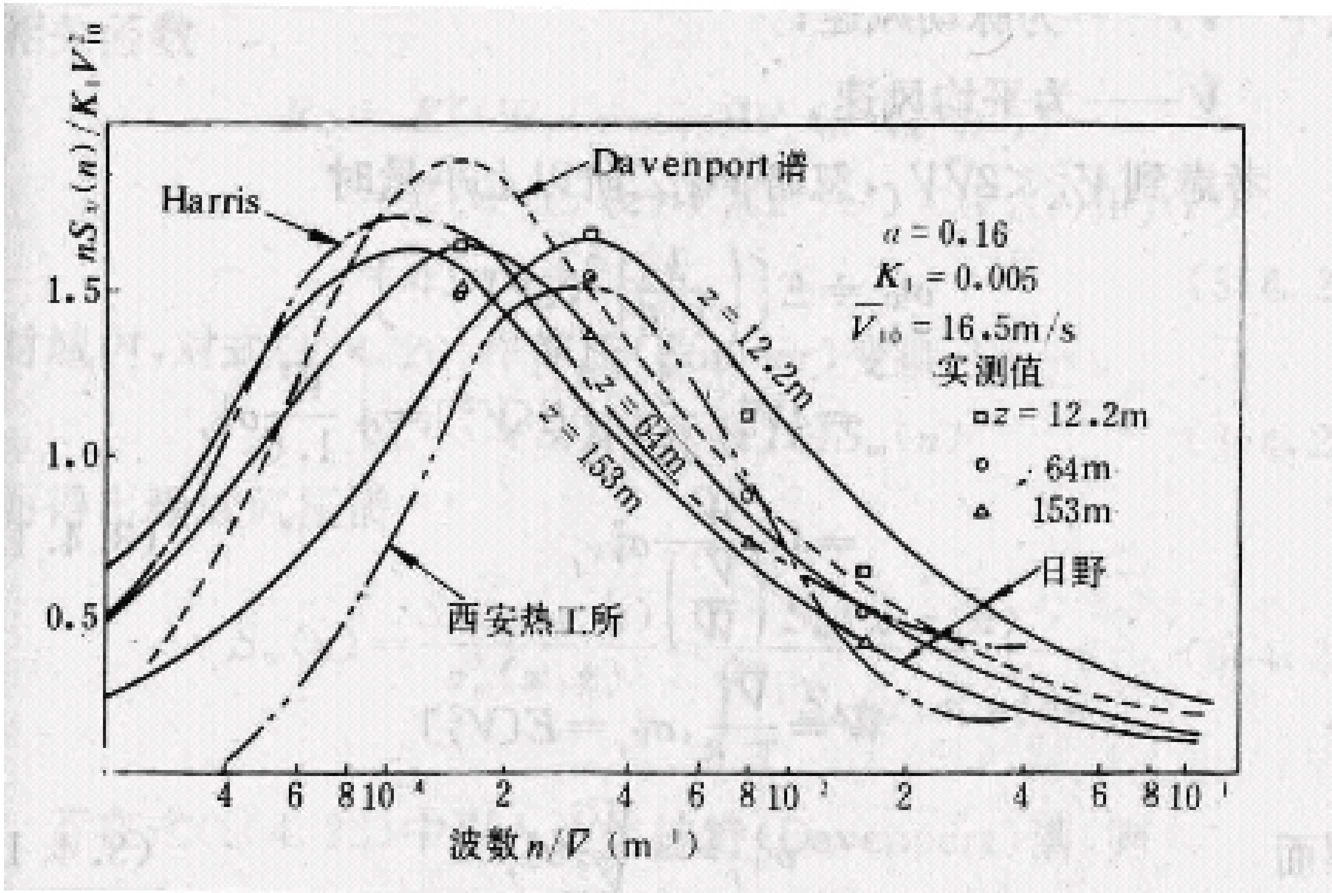
10.2 脉动风的功率谱
10.2 Power spectra of fluctuating wind

- 结构风工程中常用的脉动风功率谱可分为纵向风谱，横向风谱和竖直风谱。
- **Fluctuating wind power spectrum commonly used in structural wind engineering can be classified as longitudinal, horizontal and vertical wind spectrum.**
- 纵向脉动风谱中比较重要的有**Davenport**谱、**kaimal**（**Simu**）谱、**Hino**谱
- **More important longitudinal wind spectrum are Davenport spectrum, Kaimal (Simu) spectrum and Hino spectrum.**
- **Davenport**谱与高度无关，是大气边界层顺风向脉动风谱的近似表达式，也是目前应用的最多的脉动风谱。
- **The mostly common used Davenport spectrum is independent of height and it is the approximate expression of downwind fluctuating wind spectrum**

$$\frac{nS_u(n)}{u_*^2} = \frac{4f^2}{\left(1+f^2\right)^{4/3}} \qquad f = \frac{1200n}{\overline{u}_{10}} \qquad u_*^2 = K\overline{u}_{10}^2$$

10.2 脉动风的功率谱
10.2 Power spectra of fluctuating wind

- **纵向风谱**



10.2 脉动风的功率谱
10.2 Power spectra of fluctuating wind

◆横向脉动风功率谱常采用如下形式的Kainmal谱

Kainmal Spectrum is often adopted as horizontal wind spectrum

$$\frac{nS_v(z,n)}{u_*^2}=\frac{15f}{(1+9.5f)^{5/3}} \qquad f=\frac{nz}{\overline{u}(z)}$$

◆竖直向脉动风功率谱则常采用Lumley-Panofsky谱

And Lumley-Panofsky spectrum is often adopted as vertical wind spectrum

$$\frac{nS_w(z,n)}{u_*^2}=\frac{3.36f}{(1+10f)^{5/3}} \qquad f=\frac{nz}{\overline{u}(z)}$$

10.2 脉动风的功率谱
10.2 Power spectra of fluctuating wind

脉动风压谱 Fluctuating wind pressure spectrum

任一高度处，任一瞬时的风压压强 *W（t）*，平均风压 *W*，脉动风压为$\mathbf{W_f}$，

Let W(t) be the wind pressure of an any height and any time, W is mean wind pressure and fluctuating wind pressure is $\mathbf{W_f}$

$$\sigma_{Wf}^{\ 2} = E[W_f^{\ 2}] = E[(W(t) - \overline{W})^2]$$

$$\gamma = 0.012018 KN/m^3, \qquad g = 9.8 m/s^2$$

$$W = \frac{\gamma}{2g} v^2 = \frac{0.012018}{2 \times 9.8} v^2 \approx \frac{v^2}{1630} (KN/m^2) \approx \frac{v^2}{1.6} (N/m^2)$$

10.2 脉动风的功率谱
10.2 Power spectra of fluctuating wind

脉动风压谱 Fluctuating wind pressure spectrum

$$\sigma_{Wf}^{\ 2} = E\{(\frac{1}{1.6})^2[(v_f+\bar{v})^2-\bar{v}^2]^2\} = E[(\frac{1}{1.6})^2(2\bar{v}v_f+v_f^{\ 2})^2]$$

$$\because v_f^{\ 2} << 2\bar{v}v_f \ \therefore \sigma_{Wf}^{\ 2} \approx E[(\frac{1}{1.6})^2(2\bar{v}v_f)^2] = 4\bar{v}^2(\frac{1}{1.6})^2E[v_f^{\ 2}]$$

$$= 4\frac{\overline{W}}{1.6}\sigma_{vf}^{\ 2} = 4\frac{\overline{W}\bar{v}^2}{1.6\bar{v}^2}\sigma_{vf}^{\ 2} = 4\frac{\overline{W}^2}{\bar{v}^2}\sigma_{vf}^{\ 2}$$

$$\because \sigma_{vf}^{\ 2} = \int_0^\infty S_{vf}(n)dn \ \therefore \sigma_{Wf}^{\ 2} = \int_0^\infty S_{Wf}(x,z,n)dn$$

$$\Rightarrow S_{Wf}(x,z,n) = 4\frac{\overline{W}^2}{\bar{v}^2}S_{vf}(n)$$

(wind pressure spectrum)

10.2 脉动风的功率谱
10.2 Power spectra of fluctuating wind

规格化脉动风压谱 Normalized fluctuating wind pressure spectrum

设脉动风压强W_f（ x , z , t ）可按时间、空间分离变量

Let fluctuating wind pressure be $W_f (x , z , t)$, then the variables can be separated by time and space

$$W_f(x,z,t) = W_f(x,z)W_f(t)$$

自相关函数

$$R_{wf} = E[(W_f(x,z,t)W_f(x',z',t')] = E[W_f(x,z)W_f(x',z') \bullet W_f(t)W_f(t')]$$

$$= R(x,z)R(t)$$

$$\Rightarrow S_W(x,z,n) = \sigma_W{}^2(x,z)S_W(n)$$

$$S_W(n) = \frac{S_W(x,z,n)}{\sigma_W{}^2(x,z)} = \frac{x^2}{n(1+x^2)^{4/3}} \Big/ \int_{-\infty}^{\infty} \frac{x^2}{n(1+x^2)^{4/3}}\,dn = \frac{2}{3}\frac{x^2}{n(1+x^2)^{4/3}}$$

10.3 风压脉动系数 fluctuating wind pressure coefficient

定义：任意点的脉动风压与该点的平均风压的比值

Definition: the ratio of the fluctuating wind pressure of an arbitrary point to the mean wind pressure of the point.

$$\mu_f(z) = \frac{W_f(z)}{\overline{W}(z)} = \frac{\mu\sigma_{Wf}(z)}{\overline{W}(z)}$$

$$\sigma_{Wf}(z) = 2\frac{\overline{W}}{\overline{v}}\sigma_{vf} = 2\frac{\overline{W}}{\overline{v}}\left(\int_0^{\infty} S_v(n)dn\right)^{1/2} = 2\frac{\overline{W}}{\overline{v}}\sqrt{6K}\,\overline{v}_{10}$$

$$\because \overline{v}(z) = \overline{v}_{10}\left(\frac{z}{z_{10}}\right)^{\alpha} \quad \therefore \sigma_{Wf}(z) = 2\sqrt{6K}\,\overline{W}\left(\frac{z}{z_{10}}\right)^{-\alpha}$$

$$\Rightarrow \mu_f(z) = \mu 2\sqrt{6K}\left(\frac{z}{z_{10}}\right)^{-\alpha}$$

规范经验公式 Empirical formula by the code

$$\mu_f(z) = 0.5 \times 35^{1.8(\alpha-0.16)}\left(\frac{z}{z_{10}}\right)^{-\alpha}$$

10.4 脉动风的相关性 Correlation of fluctuating wind

空间相关性（Spatial Correlation）

空间不同位置上的脉动风速通常并非同时达到最大值，这种性质称为脉动风速的空间相关性；The fluctuation wind speeds of different locations usually do not reach their maximum value at the same time. The property is called spatial correlation of fluctuation wind speed

在时域内，脉动风空间相关性一般可采用协方差或相关系数来描述. In the time domain, the spatial correlation of fluctuating wind can generally be described by Covariance or Correlation coefficient.

在频域内，脉动风空间相关性可采用交叉谱、互谱以及相干函数来描述。In the time domain, the correlation can be described by cross-spectra, co-spectra and coherence.

10.4 脉动风的相关性 Correlation of fluctuating wind

时域 Time Domain

不同高度处纵向脉动风沿高度、宽度方向的协方差可以表示为：
The **covariance** of longitudinal fluctuating wind of different height along the height and the width can be expressed as：

$$C_{u_1u_2}(z)=\overline{u'(z_1)u'(z_2)}=\frac{1}{T}\int_0^T[U(z_1,t)-\bar{u}(z_1)][U(z_2,t)-\bar{u}(z_2,t)]dt$$

$$C_{u_1u_2}(x)=\overline{u'(x_1)u'(x_2)}=\frac{1}{T}\int_0^T[U(x_1,t)-\bar{u}(x_1)][U(x_2,t)-\bar{u}(x_2,t)]dt$$

纵向脉动风沿高度方向、宽度方向的相关系数可以表示为：
The **correlation coefficient** of longitudinal fluctuating wind along the height and the width can be express as：

$$\rho_z(z_1,z_2)=\frac{\overline{u'(z_1)u'(z_2)}}{\sigma_u(z_1)\sigma_u(z_2)} \qquad \rho_x(x_1,x_2)=\frac{\overline{u'(x_1)u'(x_2)}}{\sigma_u(x_1)\sigma_u(x_2)}$$

脉动协方差、相关系数是确定各类结构风压的重要参数

10.4 脉动风的相关性 Correlation of fluctuating wind

时域 Time Domain

- **在工程上一般采用沿距离远近呈指数衰减的函数来近似表示脉动风纵向相关系数。**
- **In practical engineering we generally adopt functions that decays exponentially with the distance to approximately descript the longitudinal correlation coefficient of fluctuating wind**

$$\rho_x(n, x_1, x_2) = \exp\left[-C_x \frac{n|x_1 - x_2|}{\bar{u}_{12}}\right] \qquad \rho_z(n, z_1, z_2) = \exp\left[-C_z \frac{n|z_1 - z_2|}{\bar{u}_{12}}\right]$$

$$\rho_{xz}(n, x_1, x_2, z_1, z_2) = \exp\left[-\frac{n}{\bar{u}_{12}}\sqrt{C_x^2(x_1 - x_2)^2 + C_z^2(z_1 - z_2)^2}\right]$$

Davenport： $C_x = 8 \quad C_z = 7$ Emil： $C_x = 16 \quad C_z = 10$

第十章 脉动风的概率特性

Chapter 10 Probabilistic Characteristic of fluctuating wind

10.5 阵风因子 Gust factor

- 极值风速（Peak gust wind）、阵风因子（Gust factor）
- 根据随机振动理论，具有一定保证率的极值风速可以表示为:

$$u' = \bar{u} + g\sigma_u$$

通过左式可以方便得到不同地貌、不同高度处的极值风速。需要注意的是，各个高度处的极值风速并不是同时出现，因此，上述方法得到的并不是极值风速风剖面。而是极值风速沿高度的包络线。

- 阵风因子G：极值风速与平均风速的比值，据此，纵向风速阵风因子可以表示为：

$$u' = G\bar{u}$$

$$G = \frac{u'}{\bar{u}} = \frac{\bar{u} + g\sigma_u}{\bar{u}} = 1 + g\frac{\sigma_u}{\bar{u}} = 1 + gI_u$$

- 对A、B类地貌取1.38；对C、D类地貌取1.7。