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Innovation Intelligence®

OptiStruct

随机振动分析

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振动分类—按载荷形式和响应类型
Classification of vibration

线性系统Linear system

Dynamic response

自由振动

Free Vibration

(f=0)

正则模态分析

Real Eigen/Modes

复模态分析

Complex Eigen/Modes

强迫振动(外力、压强)
Enforced Vibration
(Force, Pressure)

强迫运动(加速度、位移)
Enforced Motion

精确分析

瞬态响应
Transient
response

频率响应

Frequency
response

统计分析

随机振动响应

**Random
Response**

峰值分析

响应谱等

(Acceleration, Displacement) SRS, DDAM

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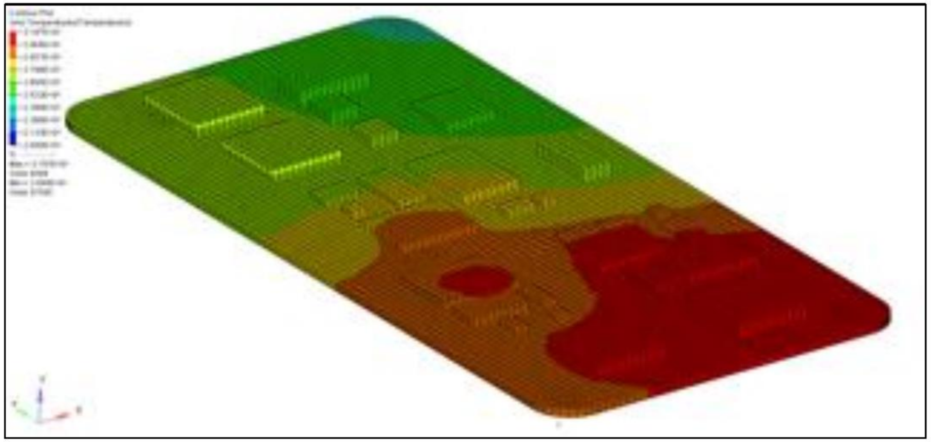
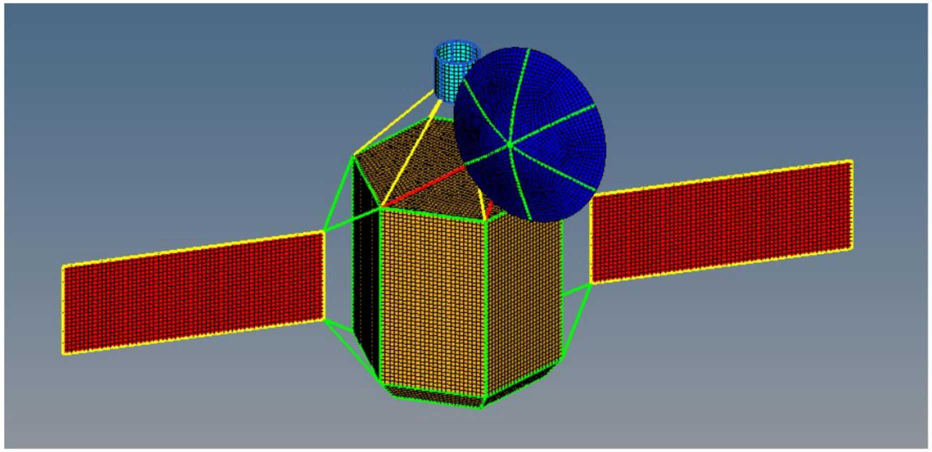
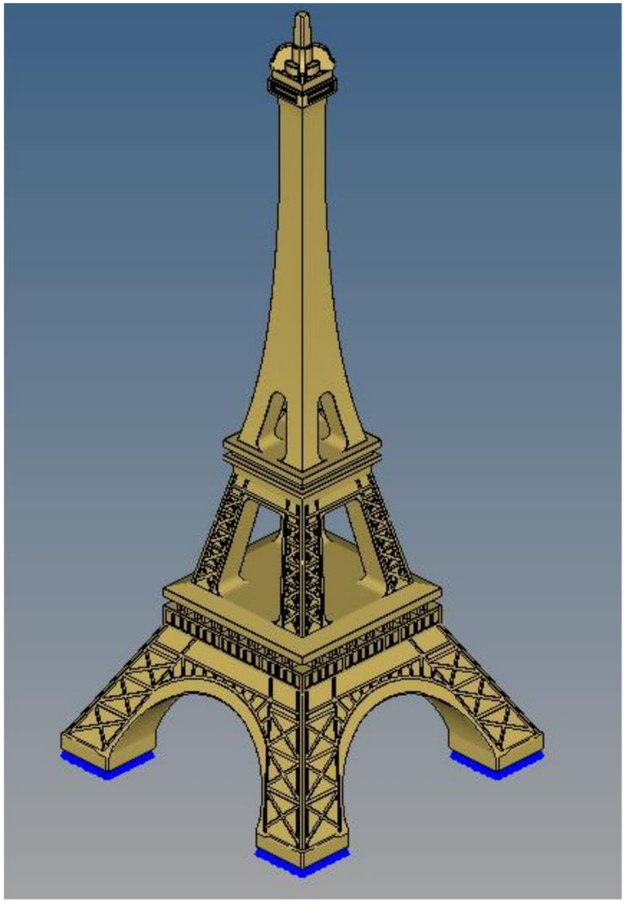
强迫振动？强迫运动激励？

- 强迫运动激励首先一定是固定在某些“基础”之上的。





Lunch load



地震波

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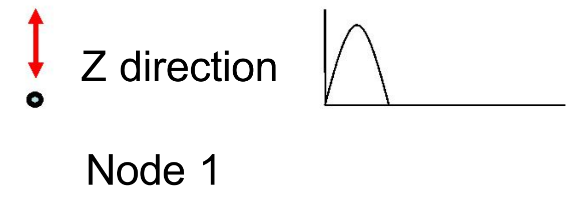
强迫运动 – 虚拟约束法SPCD

- 定义节点1的位移时间历程的自动强迫运动
- HyperMesh中定义两个约束：
  - SPCD 定义节点1的强迫运动位移
  - SPC定义节点约束
    - SPC必须约束住加载自由度
    - SPC是否需要约束其它自由度？



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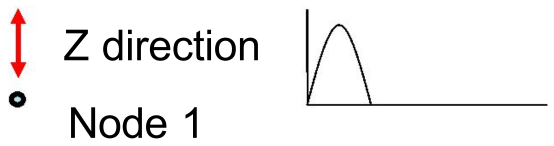
强迫运动 – 虚拟约束法**SPCD**

- SPCD 定义节点1的强迫运动量
- SPC 定义节点1的约束，这是一个虚拟约束



对于**SPCD**方法，虚约束自由度同时又是运动加载自由度！

```
TLOAD1    4         5                   ACCE      1
LSEQ      1         5         6
SPCD      6         1         3         386.1
DLOAD     2         1.        1.        4
$ Displacement Constraints of Load Set : acceleration
SPC1      1         123       1
$ Referenced Dynamic Load Tables
$ Dynamic Load Table : field
TABLED1   1
          0.        0.        .1        0.        .11       1.        .49       1.
          .5        0.        1.        0.        ENDT
```

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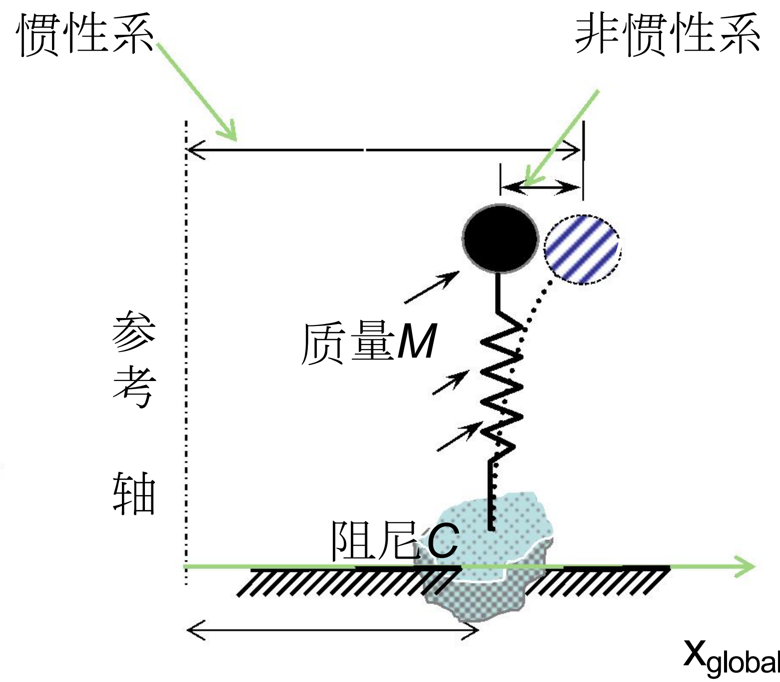
强迫运动的绝对响应和相对响应



质点位移 $u(t) = u_r(t) + u_g(t)$

质点加速度 $\ddot{u}(t) = \ddot{u}_r(t) + \ddot{u}_g(t)$

惯性力 $f_I = -m\ddot{u}_r(t) - m\ddot{u}_g(t)$

弹性恢复力 $f_s = k u_r(t)$

阻尼力 $f_d = c\dot{u}_r$

运动方程

$$\boxed{m\ddot{u}_r + c\dot{u}_r + k u_r = -m\ddot{u}_g = -p_{eff}}$$

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PARAM,ENFMOTN

- ENFMOTN参数控制绝对位移和相对位移的输出

- PARAM,ENFMOTN,ABS
  - ABS的缺省值表示分析结果是模型的绝对运动

- PARAM,ENFMOTN,REL
  - 假如值被定义为 REL, 那么运动相对于强迫运动的基础。在模态振动分析中，这等效于用大质量法和从分析中排除刚体运动。

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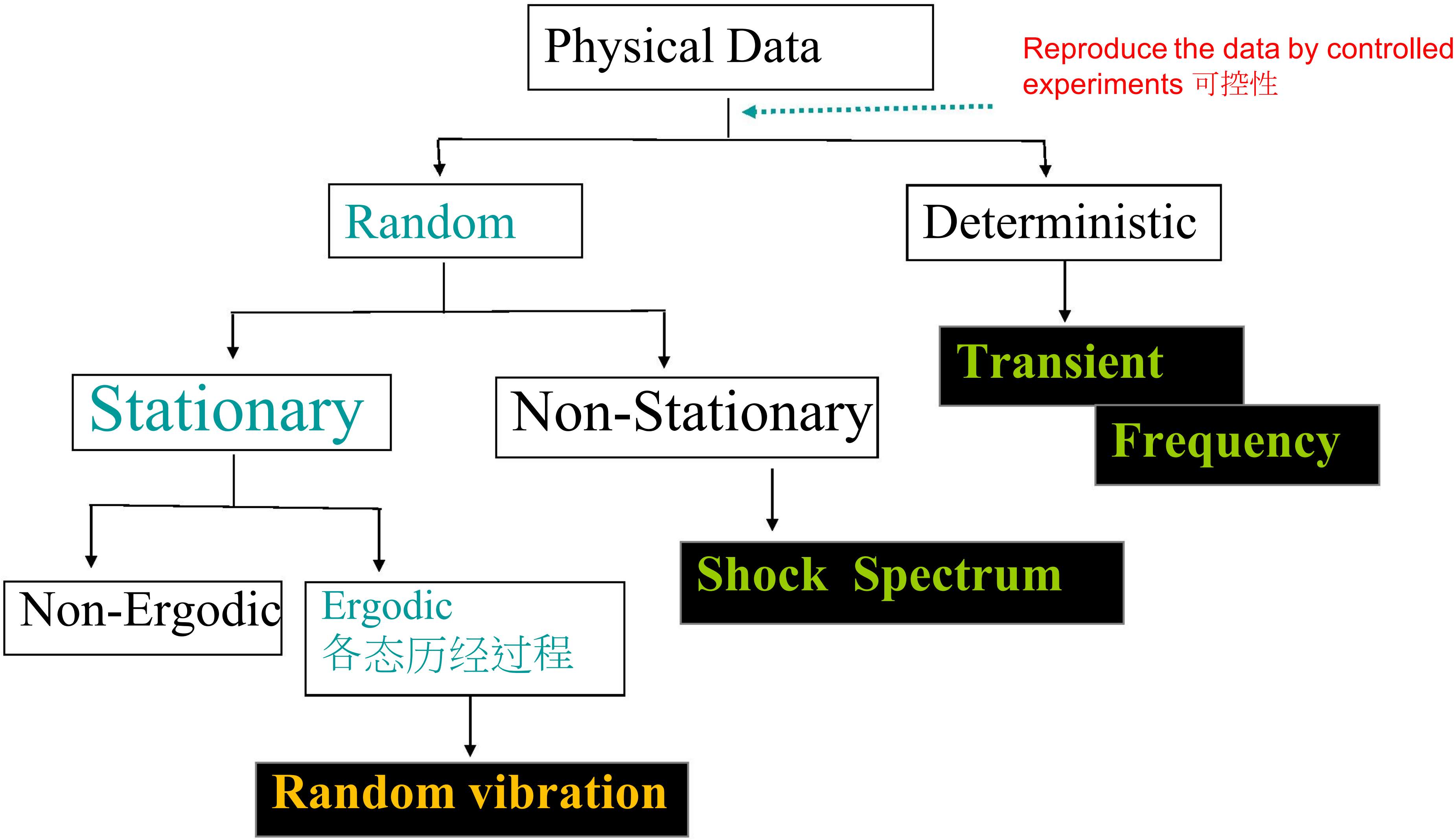
数据分类
Classification of Physical Data



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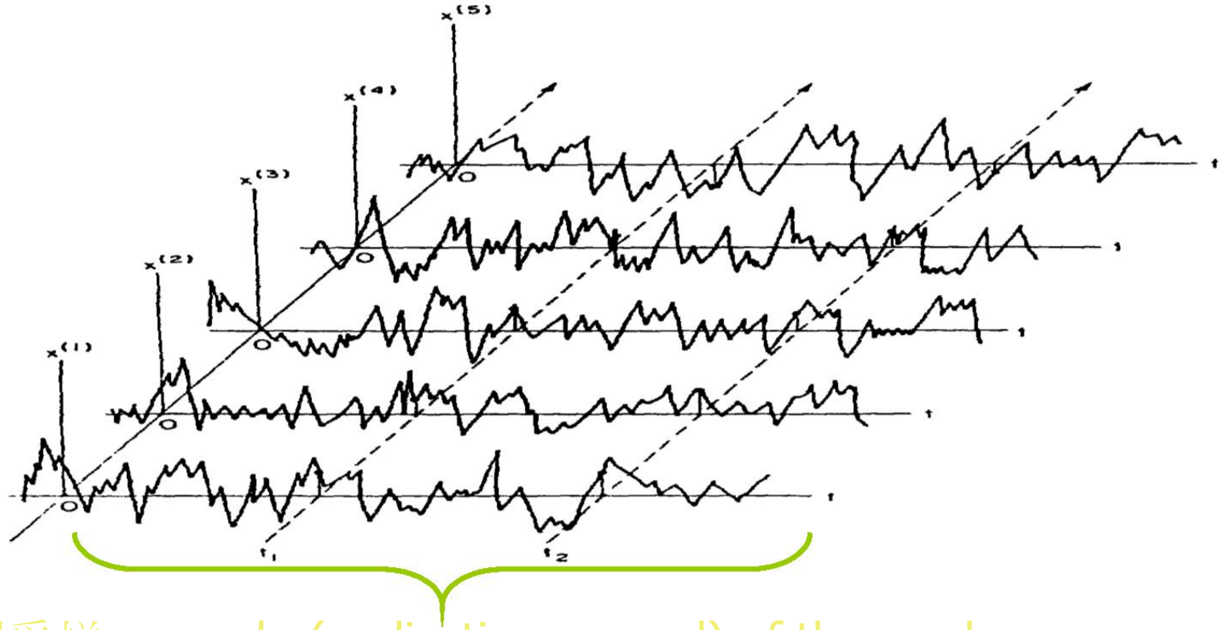
Stationary and Ergodic
稳态数据和各态历经过程



数据采样a sample (realization, record) of the random process

- **Stationary:** For every t, PDF (Probability Density Function), μ_x and σ_x^2 of every record are constant. 对每个采样数据，概率密度函数，μ_x和σ_{x2} 是恒定的。

- **Ergodic:** If the random process is stationary , and the characters of any single record are the same as the ensemble of records.对所有的采样数据，任意时间段内都是稳态的

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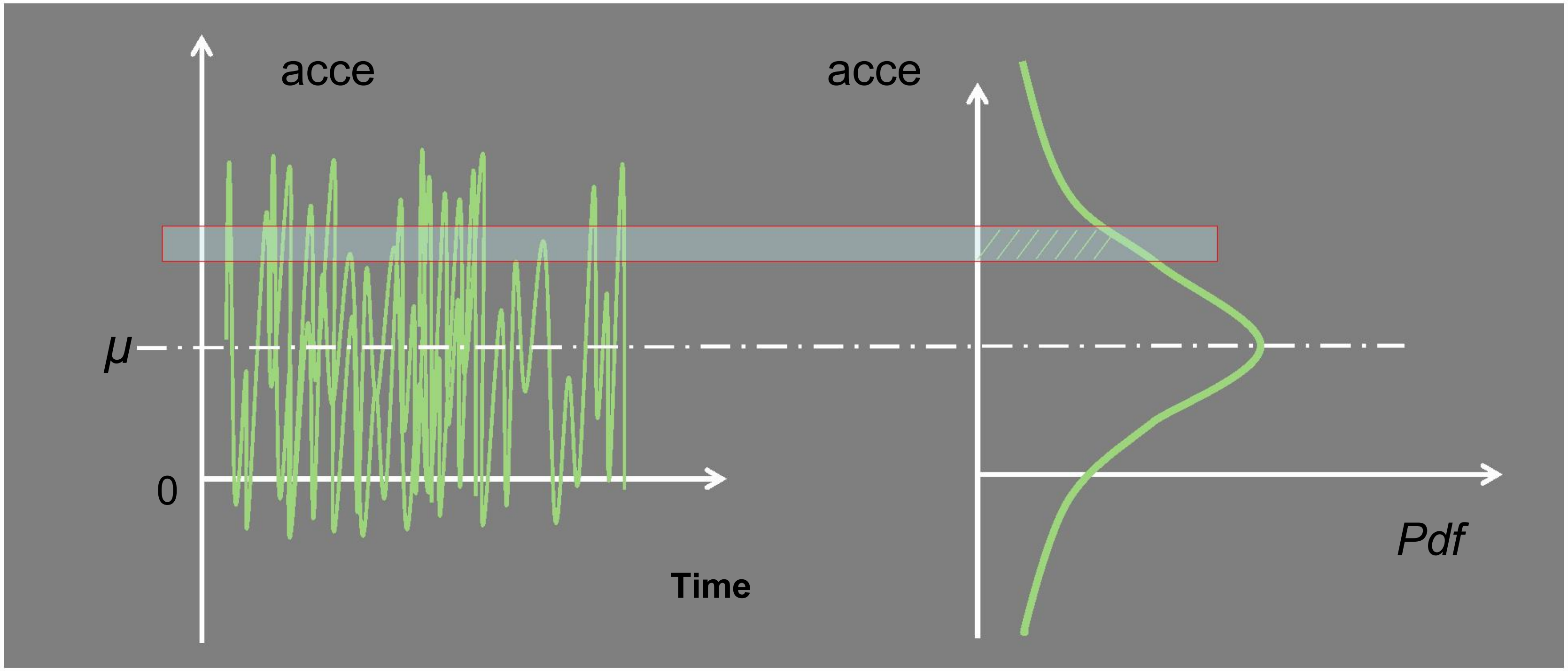
各态历经随机信号，N(μ,σ)
Ergodic Random signal



$$F(x)=\frac{1}{\sqrt{\;}}\int^{x} e^{-(x-\mu)^2}\,dx$$

$$\sigma=\sqrt{\frac{1}{n}\sum(a_i-\mu)^2}=RMS$$

$=$ $\int$ n $i=1$

σ 2

2

2

$\pi\sigma$

$-\infty$

工程上常见的随机信号， 可以用高斯分布，即正态分布来表示。

均方根(标准差Standard deviation)：每个样本点到平均值的平均距离。

μ_x, σ_x 只能反映载荷的幅值或者强度变化， 但是完全不能反映频谱特性

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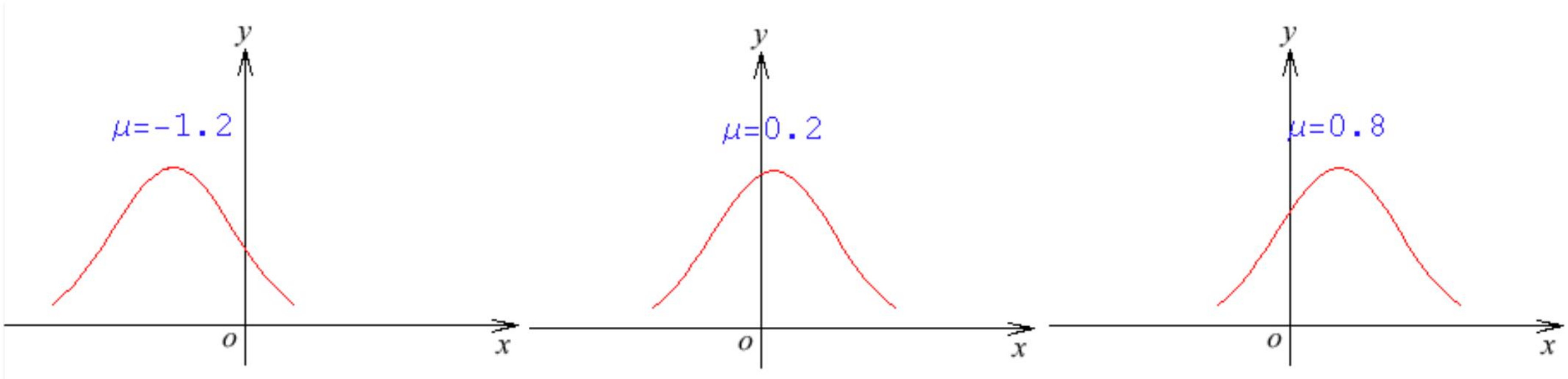
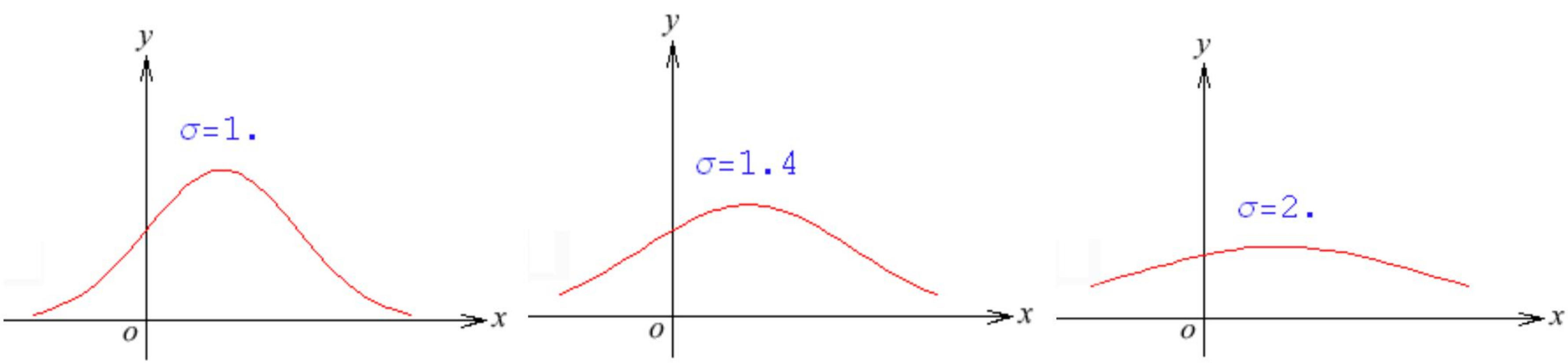
正态分布的特征
characters of normal distribution



平均值的影响



标准差的影响

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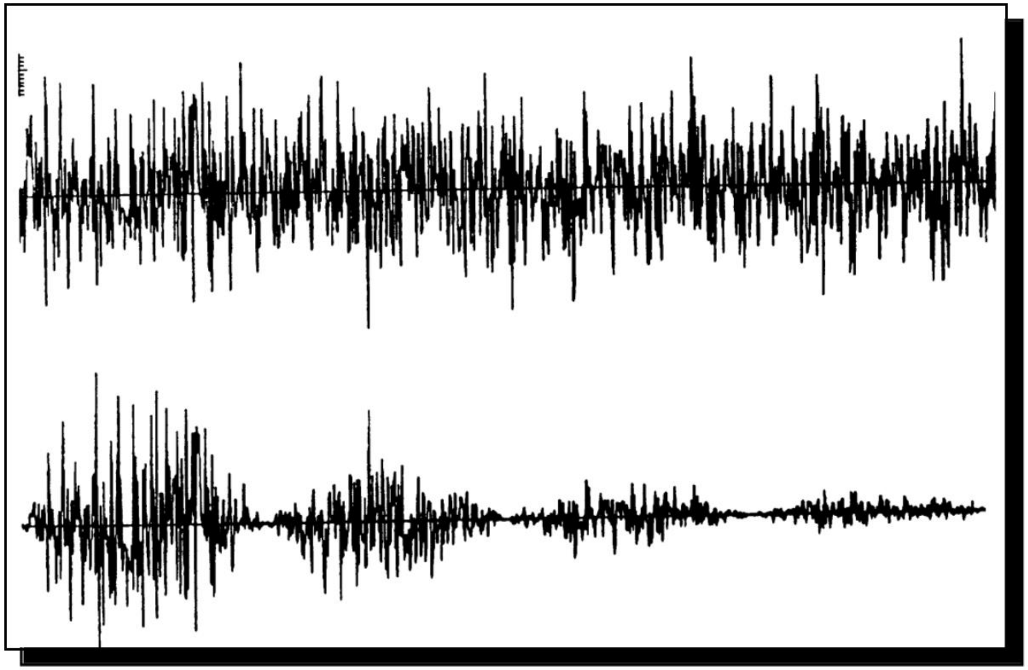
随机振动响应的两个基本假设

- 随机振动分析方法有两个基本假设：
  - 载荷和响应 满足正态分布假设
  - 载荷和响应 满足零平均值假设



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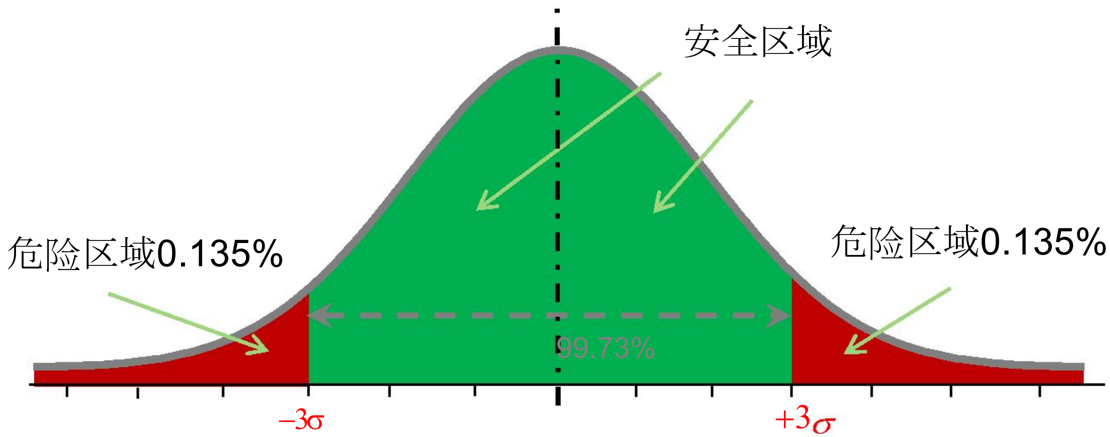
正态分布的置信水平
1σ~3σ



$$F(x)=\frac{1}{\sqrt{2}\,\sigma}\int_{-}^{x} e^{-\frac{(x-\mu)^2}{2\sigma^2}}\,dx$$

λσ	P(|x|≤λσ)	P(|x|>λσ)	Per Million/每百万
1σ	68.27%	31.7%	317,300
2σ	95.45%	4.55%	45,500
2.5σ	98.76%	1.24%	12,400

$\pi\,\sigma$

$-\infty$

$$\sigma = RMS = \frac{1}{n}\sum_{i=1}^{n}(a_i-\mu)^2$$

随机振动采用双边置信水平

3σ	99.73%	0.27%	2,700
3.5σ	99.953%	0.047%	470
4σ	99.9937%	0.0063%	63
5σ	99.999943%	0.000057%	0.57
6σ	99.9999998%	0.0000002%	0.002

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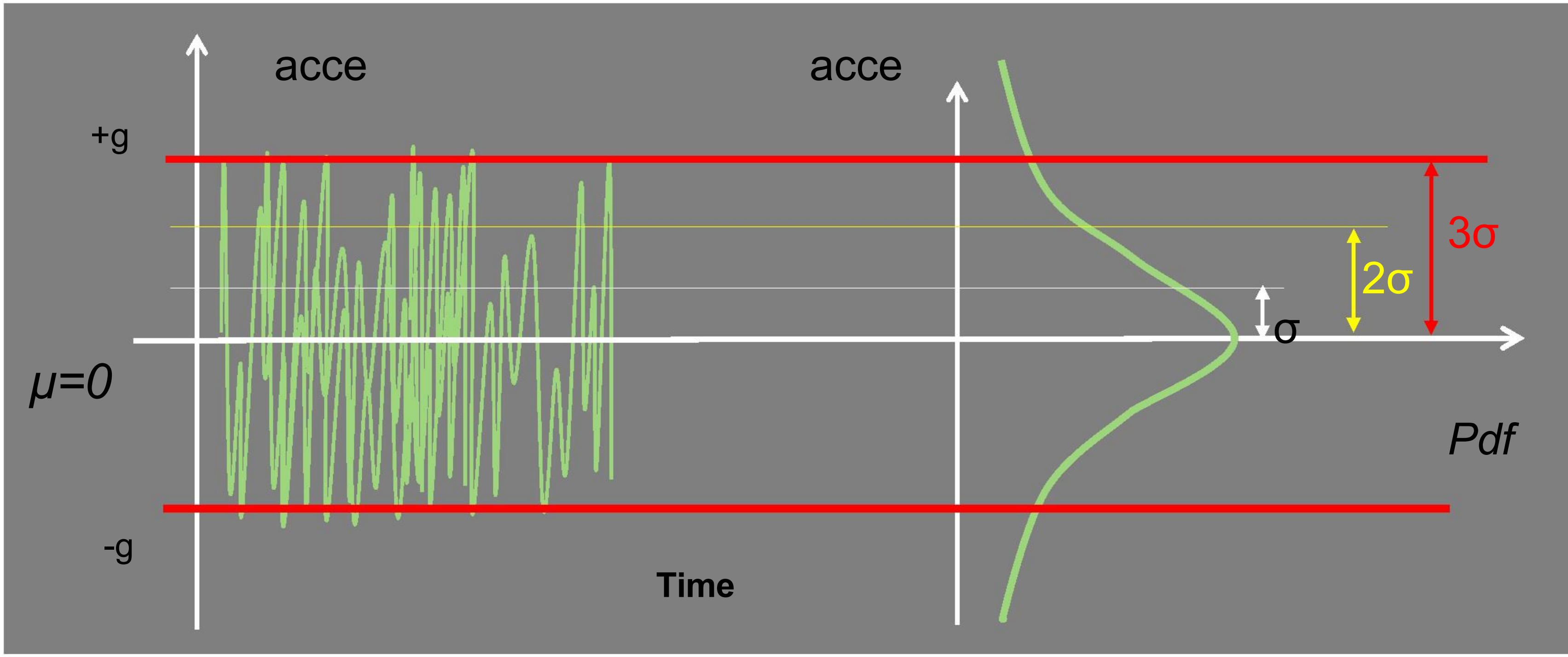
随机振动结果的常用置信水平

Common confidence level for random vibration



$$F(x) = \frac{1}{\sqrt{1}} \int^{x} e^{-\frac{x^{2}}{\sigma}} \, dx$$

λσ	安全率	失效率
2.5σ	98.76%	1.24%
3σ	99.73%	3‰

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2

2

2

$\pi\sigma$

$-\infty$

3.5σ 99.953% 0.047%

随机振动结果通常使用3σ双边置信，即±3σ

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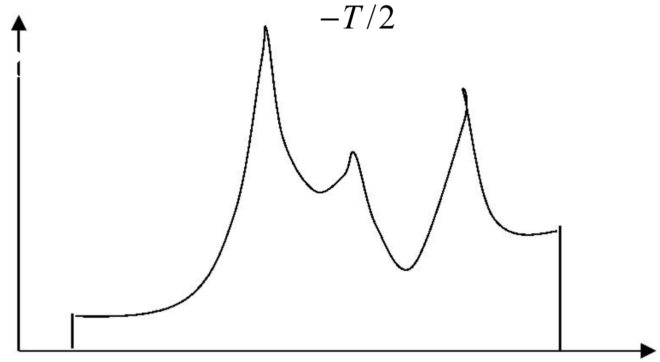
PSD定义公式
PSD Function definition

自相关函数：
(Auto)correction

$$R_{xx}(\tau) = E[x(t)x(t+\tau)] = \lim_{T\to\infty} \frac{1}{T}\int_{-T/2}^{T/2} x(t)x(t+\tau)\,dt$$



自功率谱密度函数定义
(Auto)PSD

$$1 \quad = \int^{\infty} \quad - \quad i$$

$$S_{xx}(\omega) \qquad R_{xx}(\tau)\, e^{\omega\tau}\, d\tau$$

$$2 \quad \pi \quad -\infty$$

PSD

$$\tau = \int_{-\infty}^{\infty} \omega \quad e^{i\omega\tau} \quad \omega =$$

$$R_{xx}(\;) \qquad S_{xx}(\;) \quad d \quad A$$

A

$$RMS \qquad A$$

$=$

f_1 f_2

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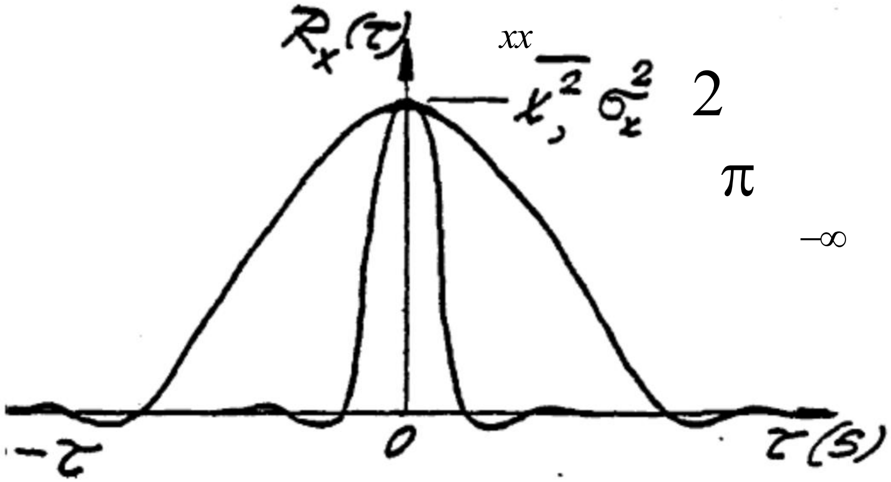
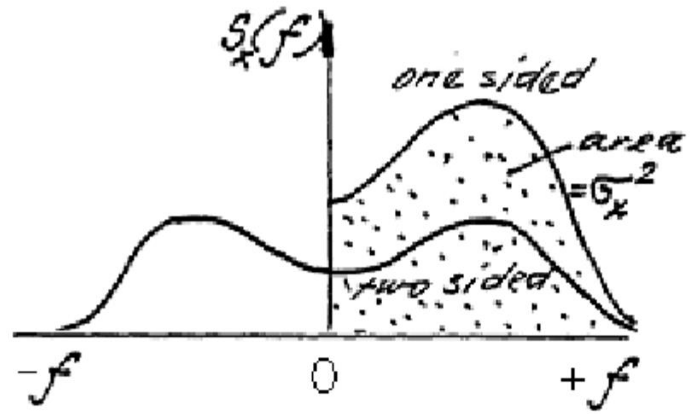
PSD计算公式
PSD Function Calculation

双边谱

$$S_{xx}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R_{xx}(\tau)\, e^{-i\omega\tau}\, d\tau$$





PSD使用单边谱

$$G_{xx}(\omega) = \begin{cases} 2S_{xx}(\omega) & \omega \geq 0 \\ 0 & \omega < 0 \end{cases}$$

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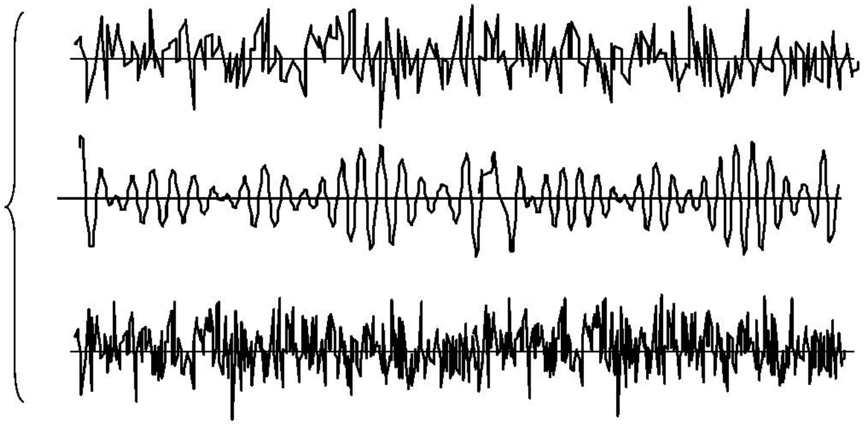
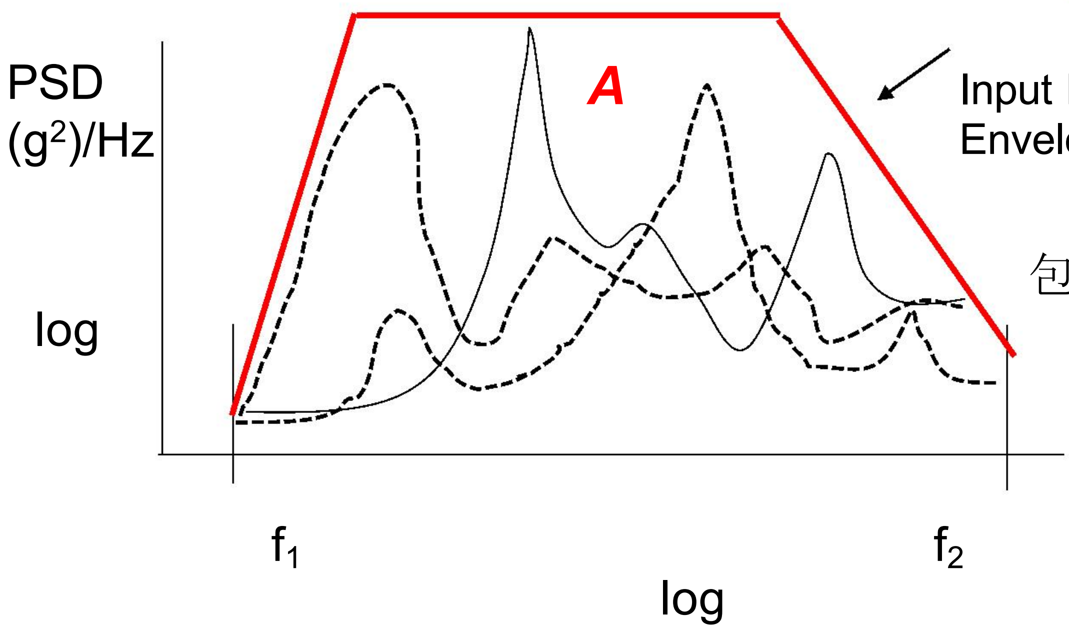
如何生成**PSD**载荷
Convert time records to PSD

不同路面的时域数据

Zero mean



取包络线



Input PSD =
Envelope curve包络线

包络线下的面积为A

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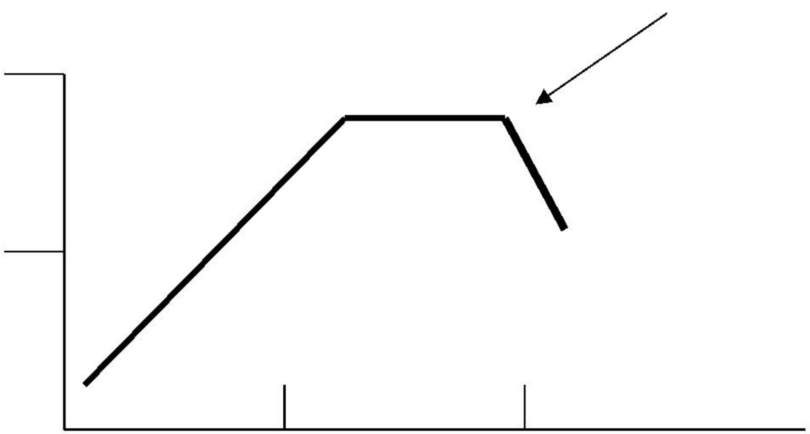
PSD输入谱的典型定义

Example 1 of random loading:	
20-160 Hz	+5 dB/oct (+ slope)
160-800 Hz	0.06 g^2/Hz
800-2000 Hz	-6 dB/oct (- slope)
Overall	xxx g_{rms}

二倍频*octave* $= \log_2 (f_2/f_1) = \dfrac{\lg(f_2/f_1)}{\lg 2} = \dfrac{\lg(f_2/f_1)}{0.30103}$

十倍频*decade* $= \lg(f_2/f_1)$



G_{xx}

.1 g^2/Hz

.01 +5 dB/oct (+ slope) -6 dB/oct (- slope)

$\log_{10}(a)$

.001

10 100 1000 $\log_{10}(f)$

$$dB = 10 \cdot \log_{10} \frac{G_x(f_2)}{G_x(f_1)}$$

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