Lecture 2: *Error Sources & Error Properties of Instruments (Part 1)*

王代华，博士，教授，博士生导师

Dr. Dai-Hua, Wang, Professor

PILab 精密與智能實驗室
Precision and Intelligence Laboratory

重庆大学, 光电工程学院, 重庆 40004

http://www.pilab.coe.cqu.edu.cn/

Email: dhwang@cqu.edu.cn

Tel: 023-65112105, 65102511, Fax: 65112105

Outline

- Part 1
  - 仪器误差及其来源
  - Principle errors
- Part 2
  - Manufacturing errors
  - Running errors
- Summary

仪器误差及其来源

- 仪器误差
  - 指仪器本身固有的误差
- 为了有效进行精度分析，必须对影响仪器精度的各种误差源进行分析、归纳
- 在仪器的设计、制造、使用的各个阶段都可能产生误差
- 类型
  - 原理误差/Principle errors
  - 制造误差/Manufacturing errors
  - 运行误差/Running errors

Contents

- Definition
- *Examples*
  - *Ex 1: Principle of the laser shadow gauge*
  - *Ex 2: Quantization error*
  - *Ex 3: Mechanical structure error*
  - *Ex 4: Fourier transformation error*
- Analyzing methods
- Minish and eliminate

Definition

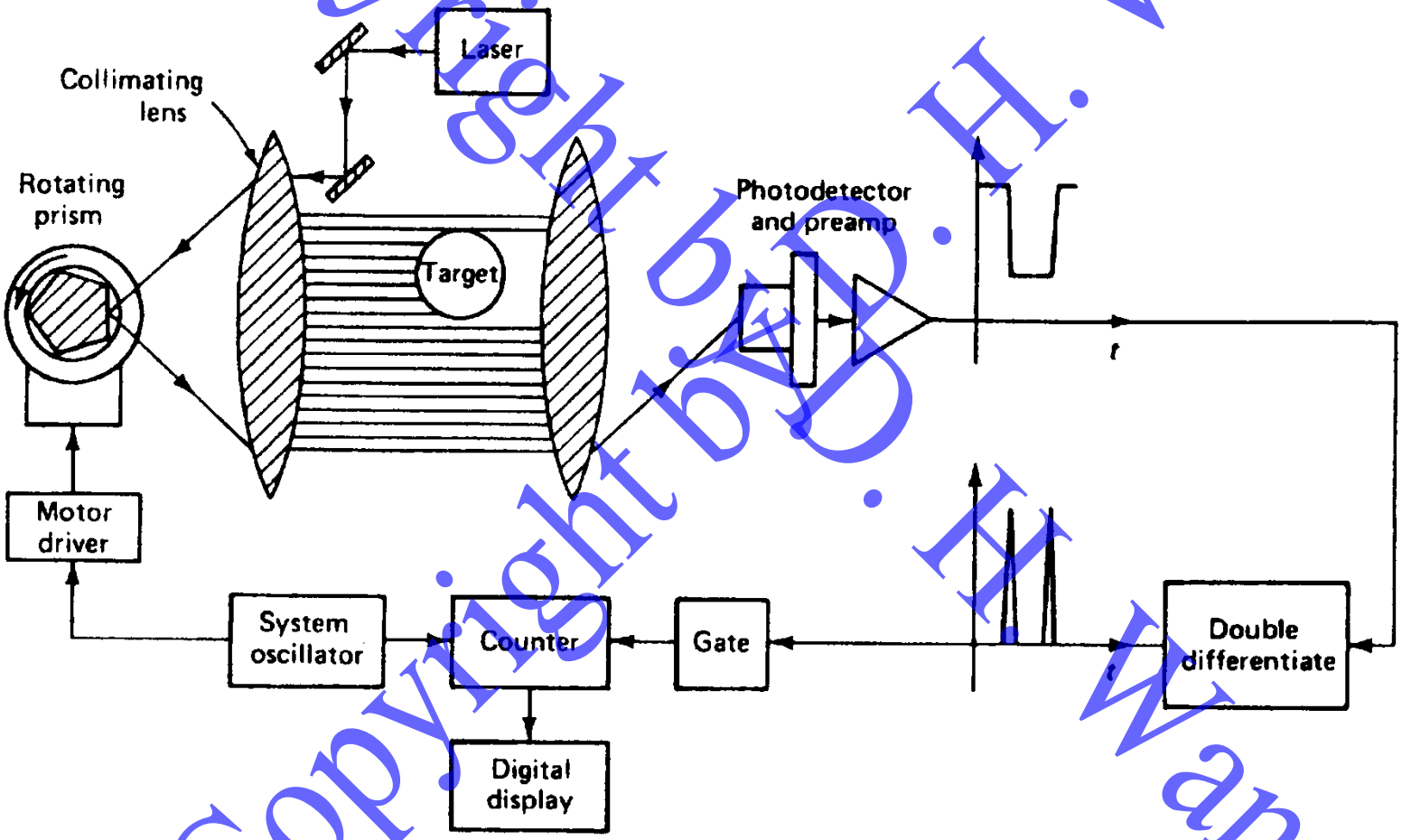
- 原理误差是由于在仪器设计中采用了近似的理论、近似的数学模型、近似的机构和近似的测量控制电路所造成的。
  - 原理误差只与仪器的设计有关，而与制造和使用无关。
  - 在一般情况下，采用近似的理论和原理进行设计是为了简化设计、简化制造工艺、简化算法和降低成本。
  - 在有些情况下，是由于理想的原理在设计中难以实现。
- 原理误差的特点
  - 产生在仪器的设计过程中，可看成是仪器原理上的固有误差，从数学特征上看属于系统误差。
  - 原理误差的存在使仪器的准确度下降，应予重视。

Ex 1: Principle Errors of the Laser Shadow Gauge

- 扫描测径原理
  - 扫描是图象工程中进行图形采集、传送、显示、再现的基本方法，它的主要应用是图象的分解和合成。
  - 利用精确而稳定的同步扫描可以得到与被测物体光强空间分布成比例的电量时序变化。
  - 在这种光电信号中，时序间隔与空间坐标间的严格定量关系是图形几何量测量的重要依据。
  - 基于这种原理逐渐发展出一种图象测量的新技术。
- Characteristics

Ex 1: Principle Errors of the Laser Shadow Gauge

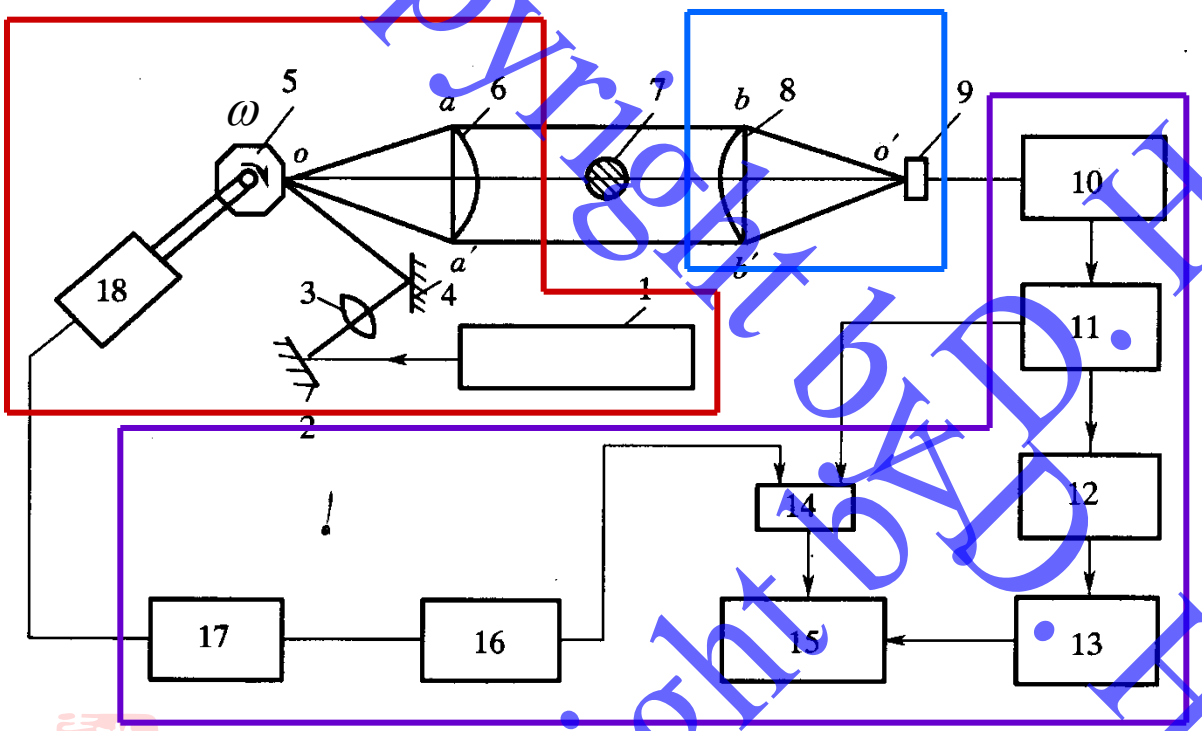
❒ **Schematic of laser shadow gauge**



Ex 1: Principle Errors of the Laser Shadow Gauge

- Schematic of laser shadow gauge
- Characteristics
  - Contact-less operation
  - High accuracy
  - High speed

Laser Shadow Gauge: Components and Principle



1 – He-Ne laser 2,4 - Reflector 3 - Lens
5 – five-sided prism

- Components
  - a transmitter (containing laser scanner)
  - a receiver (photo detector)
  - a processor unit

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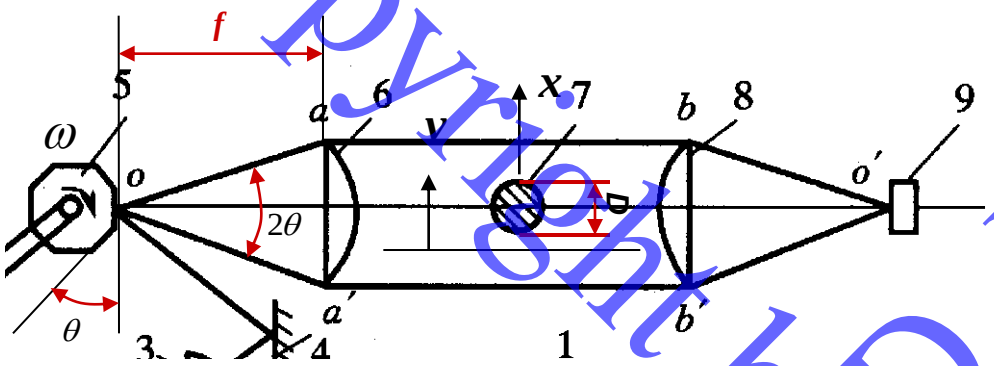
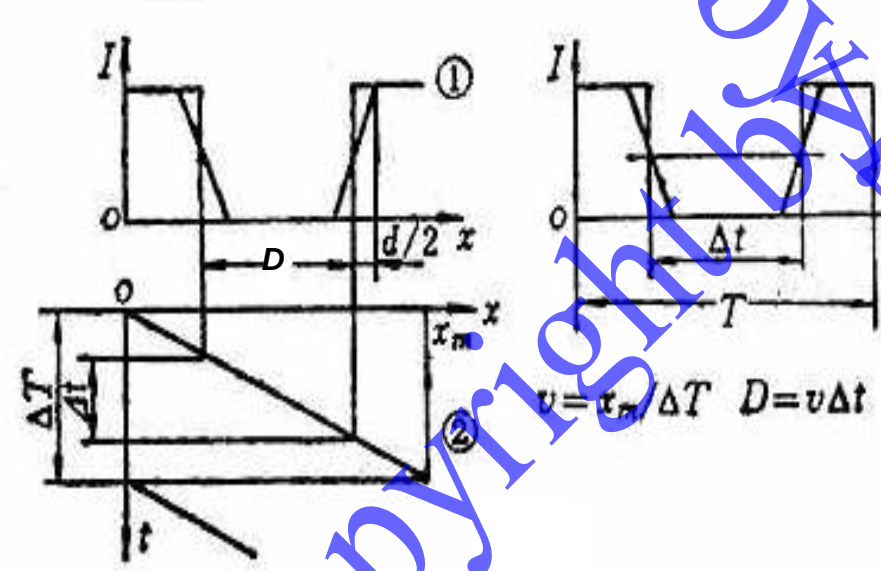
Laser Shadow Gauge: Principle (1)



$$v \approx 2\omega f = 4\pi n f$$



$$D = v\Delta t$$

$$\approx 4\pi n f \Delta t$$

1 - Density variation
2 - Laser beam scanning
3 - Time series

Laser Shadow Gauge: Principle Error (1)

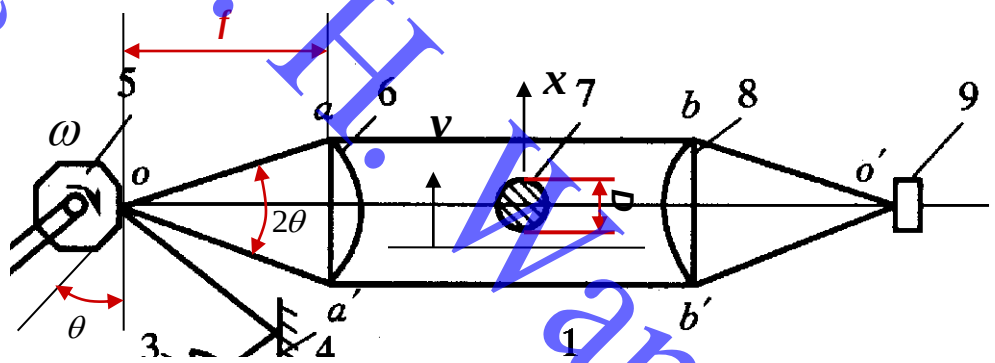
❒ Assumption

- 在设计中近似地认为在与光轴垂直方向上激光光束的扫描速度是均匀的，即

$$v \approx 2\omega f = 4\pi n f$$

- 被测工件的直径

$$D = v\Delta t$$
$$\approx 4\pi n f \Delta t$$



Laser Shadow Gauge: Principle Error (2)

- 激光扫描光束距透镜光轴距离为 $\pm x$的位置与时间t 的关系式

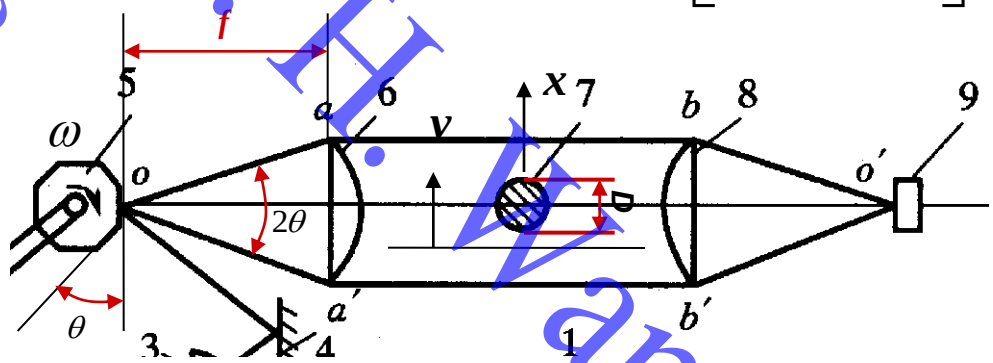
$$x = f\tan(2\omega t) = f\tan(4\pi n t)$$

- 在 $\pm x$ 位置上，激光光束在与光轴垂直方向上的扫描速度

$$x = f\tan(2\omega t) = f\tan(4\pi n t)$$

$$v_0 = \frac{\mathrm{d}x}{\mathrm{d}t} = 4\pi n f \sec^2(4\pi n t)$$

$$= 4\pi n f\left[1+\tan^2(4\pi n t)\right] = 4\pi n f\left[1+\left(\frac{x}{f}\right)^2\right]$$



Laser Shadow Gauge: Principle Error (3)

❒ 被测工件的直径

$$v_0 = 4\pi nf\left[1+\left(\frac{x}{f}\right)^2\right] \Rightarrow D_0 = v_0\Delta t = 4\pi nf\left[1+\left(\frac{x}{f}\right)^2\right]\Delta t$$

❒ **Conclusion**

- 可见实际激光扫描速度*v0* 随着光束离光轴的距离 *x* 的不同而变化，且离光轴垂直距离越大，扫描速度越高。
- 这就使得该仪器的测得值总是小于被测直径的实际值，从而引起了原理误差。

Laser Shadow Gauge: Principle Error (4)

❒ **Principle error**

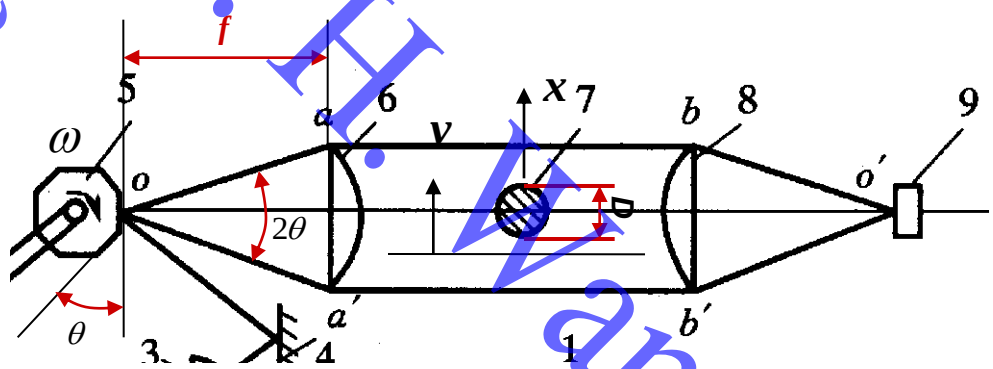
$$\Delta D = D_0 - D = (v_0 - v)\Delta t$$

$$= \left\{ 4\pi nf \left[1 + \left(\frac{x}{f} \right)^2 \right] - 4\pi nf \right\} \Delta t$$

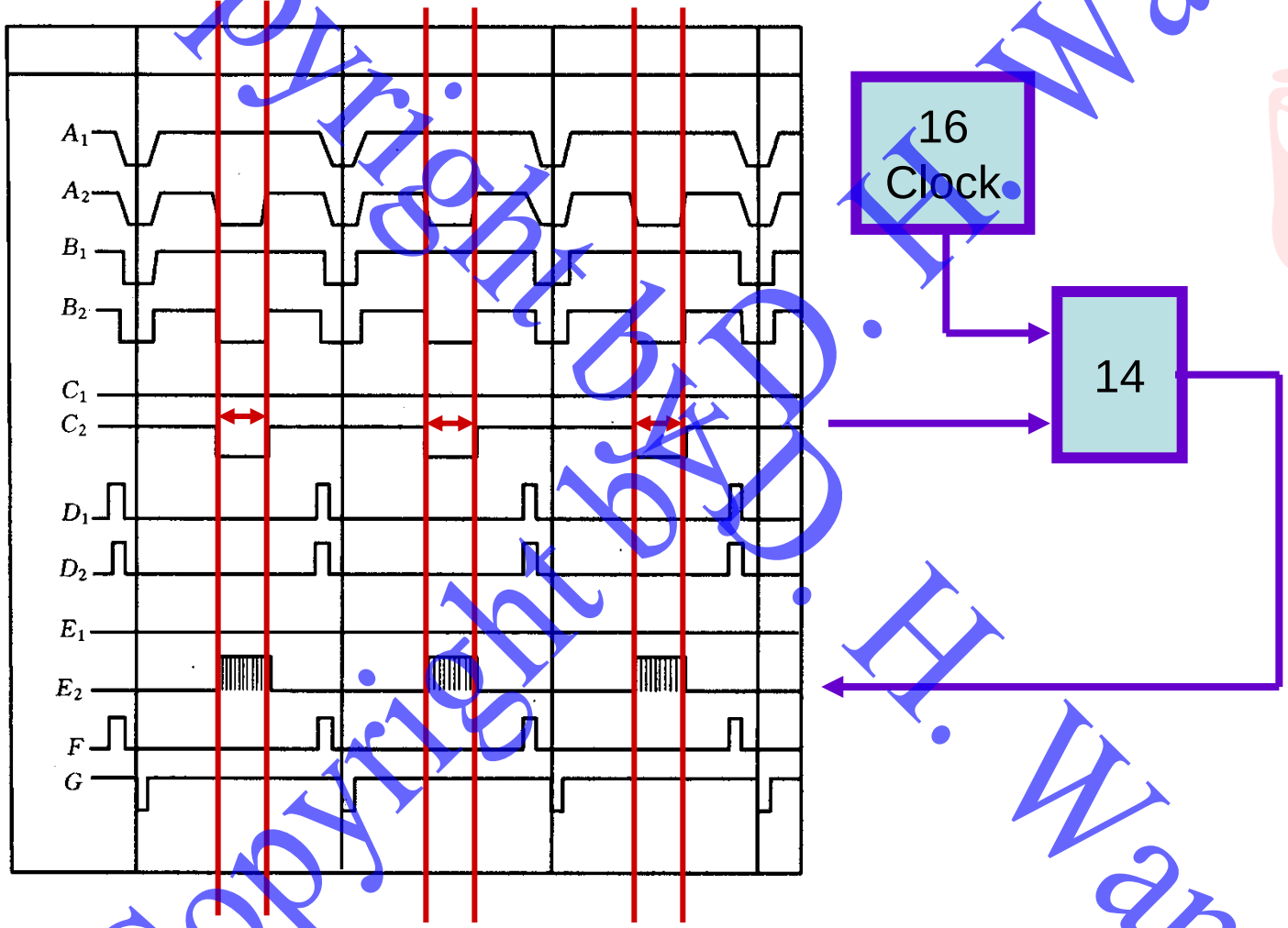
$$= 4\pi n \frac{x^2}{f} \Delta t$$

$$\Delta D \propto x^2$$

$$\Delta D \propto \frac{1}{f}$$



Laser Shadow Gauge: Principle (2)



Laser Shadow Gauge: Principle (3)

- 电路采用同步供电的方式，选用10 MHz 的晶体振荡器作为基频，利用晶体振荡源分频到50 Hz，控制同步电机转速。这样即使基频有若干改变，仍能使计数器数值变化和电机转速的变化两者保持一定的同步性，有利于消除测量误差。
  - 设晶体的振荡频率为 γ，一个时钟脉冲所代表的距离

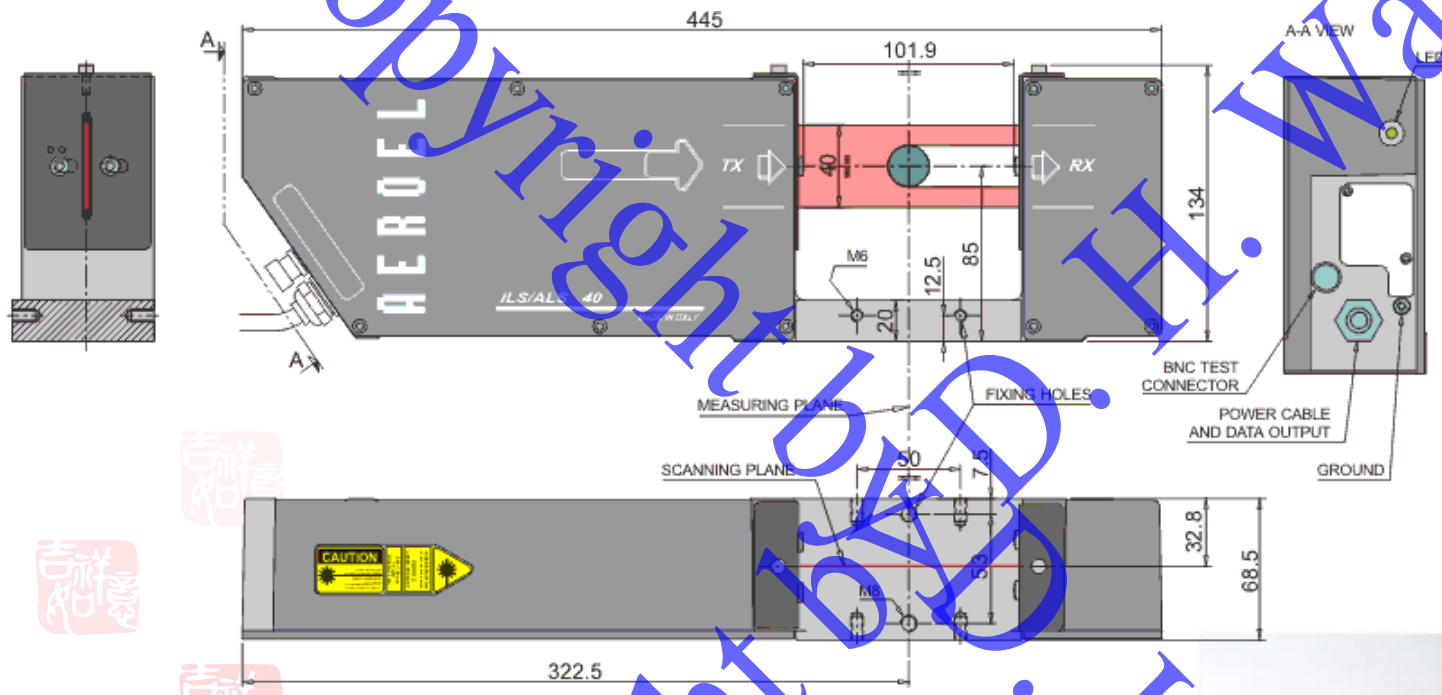
$$\delta = \frac{4\pi nf}{\gamma}$$

  - 若被测件直径为D，则数码管显示的脉冲数

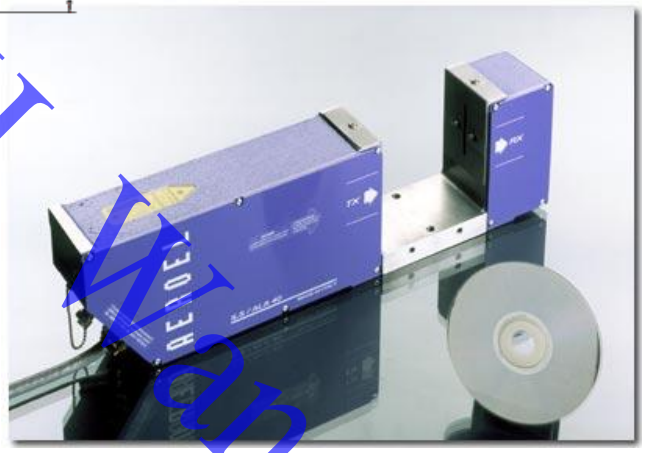
$$N = \frac{D}{\delta} = D\frac{\gamma}{4\pi nf}$$

  - **Conclusion:** 为提高灵敏度，δ越小越好，γ越大越好。

Laser Shadow Gauge: ILS40 Laser Sensor



From http://www.aeroel.it/eng/ils/ils40.htm



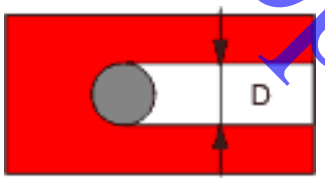
Laser Shadow Gauge: Questions?

- How to measure the large size, such as Φ110~Φ180 mm?
- How to measure the small size, such as Φ<0.5 mm?
- How to measure the thickness of a flexible film?

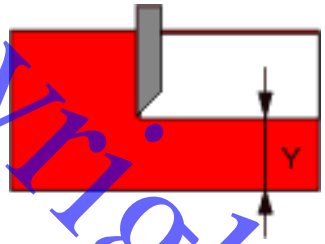
"We reason deeply, when we forcibly feel"

-- Mary Wollstonecraft

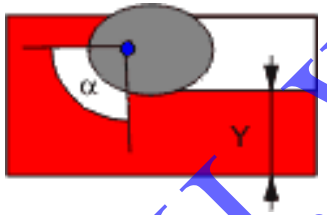
Laser Shadow Gauge: Typical Applications



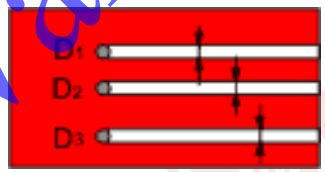
D=OUTSIDE DIAMETER



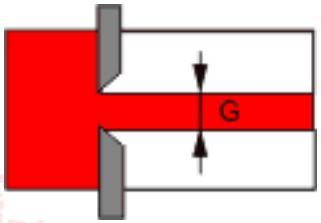
Y=EDGE POSITION



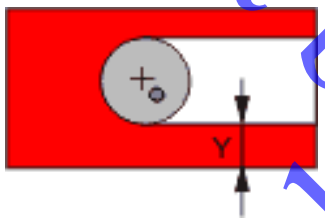
Y(a)=CAM PROFILE



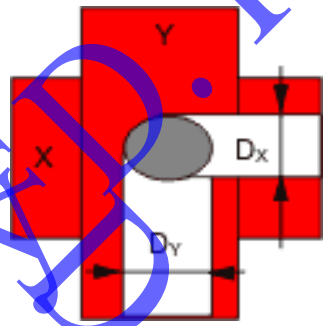
D= MULTIPLE WIRE DIAMETER



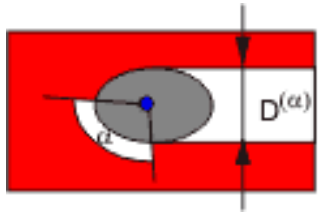
GAP MEASUREMENT



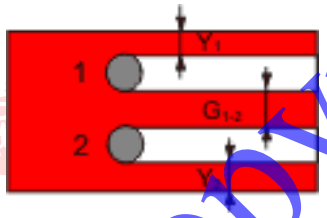
Ymax-Ymin=RUNOUT



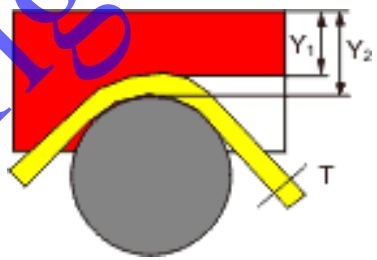
(Dx+Dy)/2=AVERAGE DIAMETER
[Dx+Dy]=OVALITY



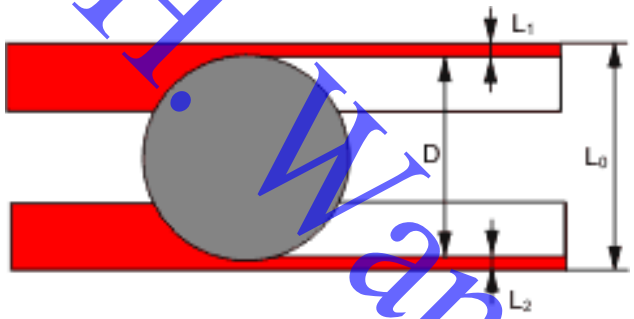
Dmax-Dmin=OVALITY



POSITION AND GAP

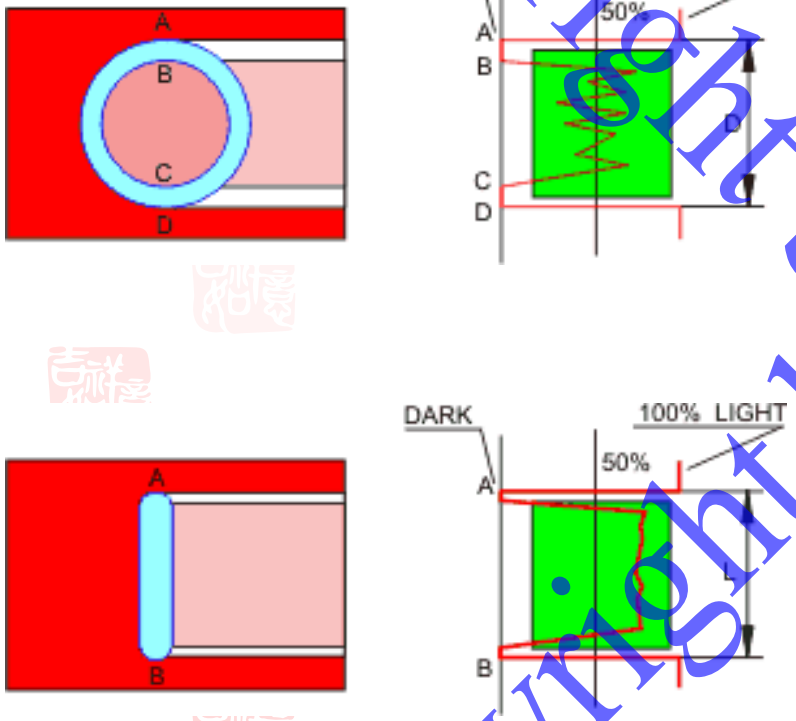


Y2-Y1= FILM THICKNESS



LARGE DIAMETER D = L0-L1-L2

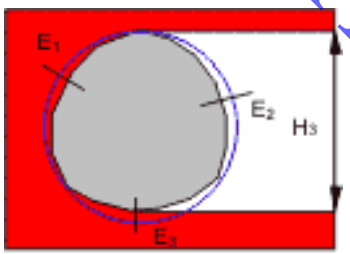
Laser Shadow Gauge: Measuring the transparent materials (Glass logic)



- The separation surfaces between glass and air are opaque and can be detected
- The distance between the first and the last edge is the external diameter dimension.
- A special signal processing software (glass logic) ignores all signal included within these extreme edges.
- The internal diameter cannot be reliably detected and it is impossible to be measured.

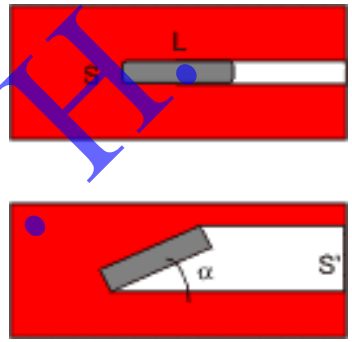
Laser Shadow Gauge: Very Difficult or Impossible Applications

- **ROUNDNESS**

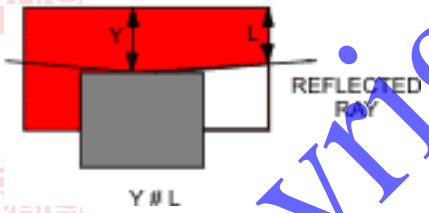


$E_3 = D(??) - H_3$

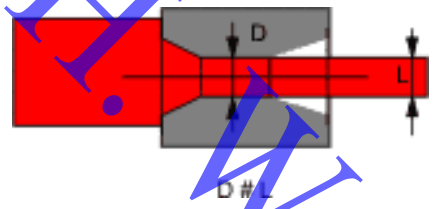
- **THICKNESS**



- **POSITION OF A FLAT SURFACE**



- **HOLE OR DIE DIAMETER**

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The End

Thank you very much for your attention !

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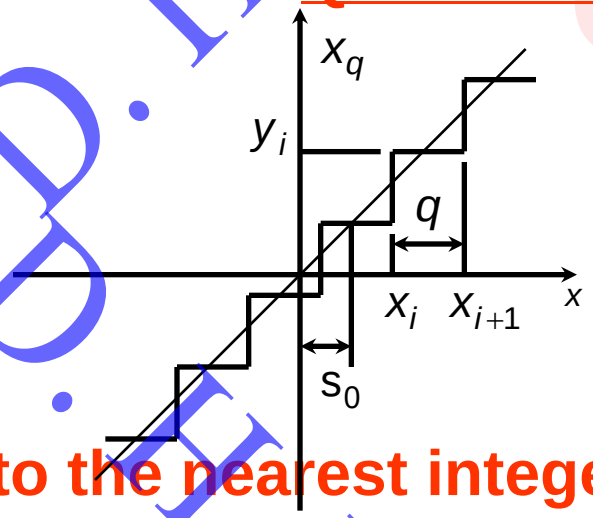
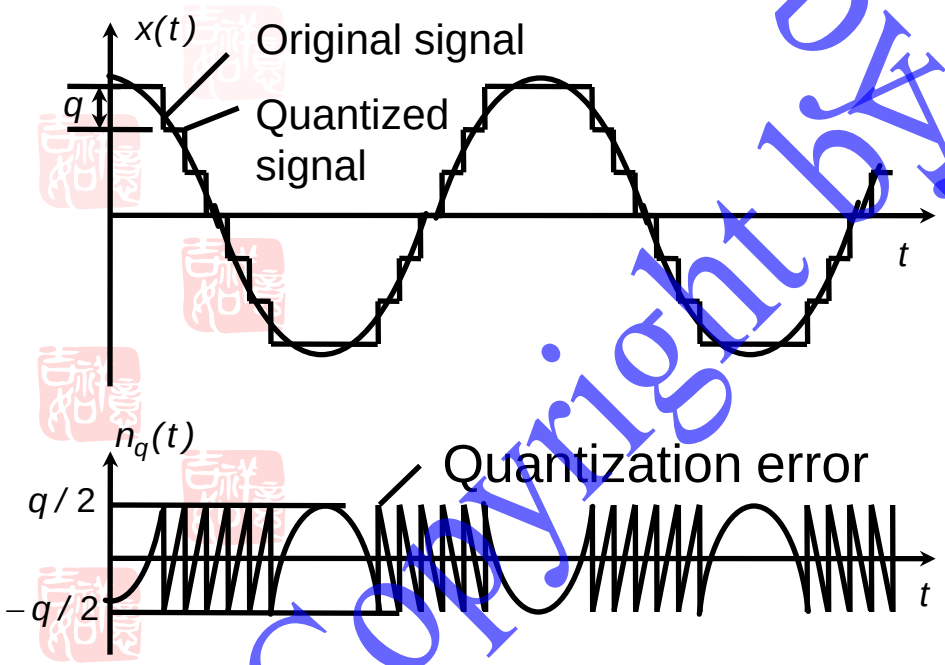
Sampling and Quantization

- Digital waveform are discrete in time and in amplitude.
  - The discrete in time is called SAMPLING.
  - The discrete in amplitude is called QUANTIZATION.
- Uniform quantizer
  - all steps are equal
  - So: shifting parameter
- Rounding quantizer
  - each sample is rounded to the nearest integer.



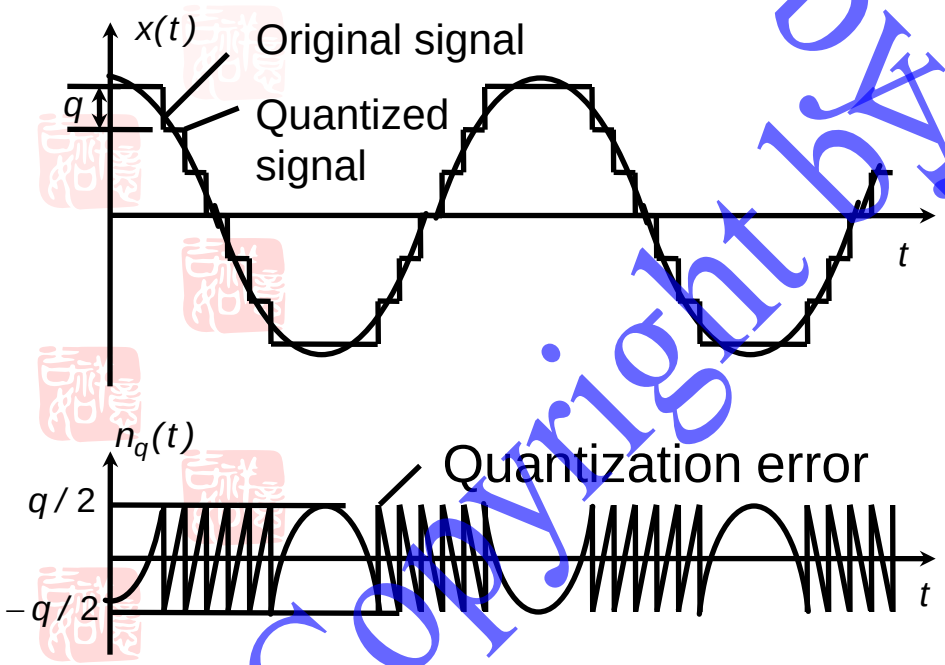
Quantization Error

- Quantization error is *sawtooth-like*. It has approximately uniform distribution between *(-q/2, q/2).*
- The form of error does not resemble the original waveform and has little to do with the global behavior.

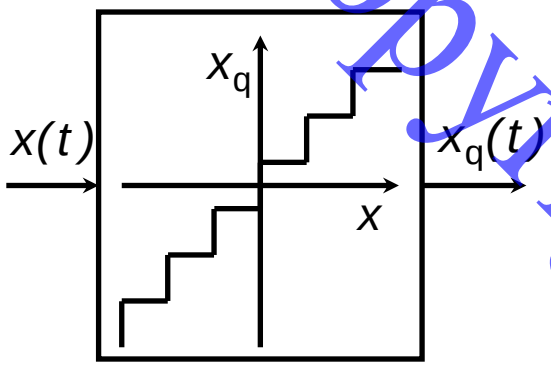


Quantization Error

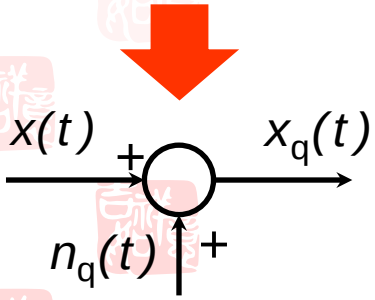
- The error contains a lot of jumps, thus, the spectral content is much wider than that of the original signal. If not sampled too densely, the error will be independent of each other.

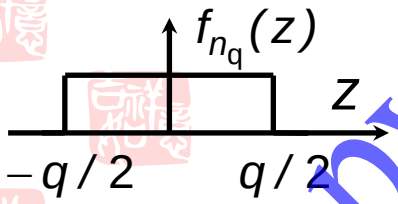


Noise Model--Statistical



Ideal Quantizer





Statistical Model

- The quantization error may be considered as an additive noise which
  - has uniform distribution
  - is uncorrelated with the input signal
  - has a white spectrum (when sampled at a sufficiently low rate)
- The model is linear, can be easily estimated and reduced.

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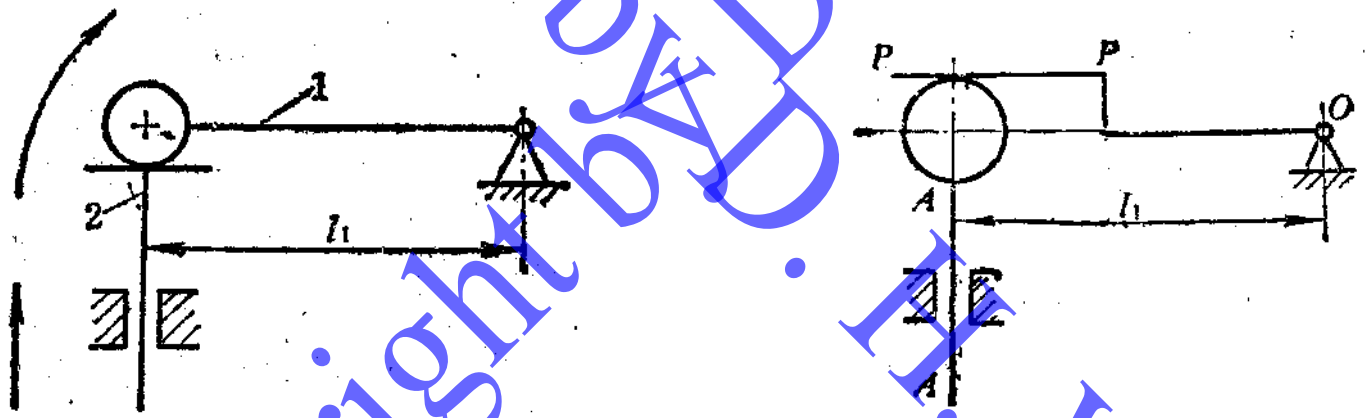
- “远望”号测量船测控神舟七号飞船入轨

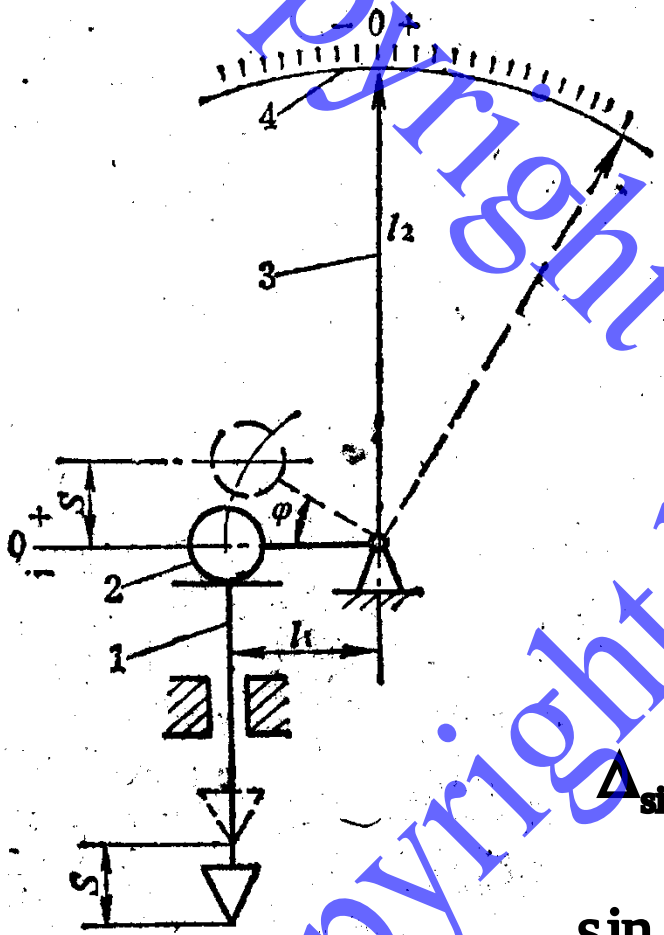
Definition

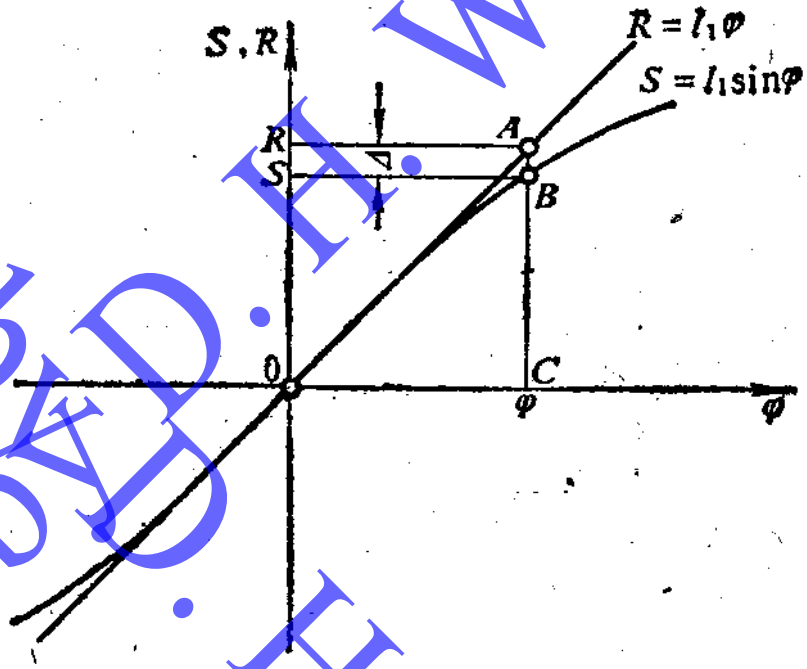
- 仪器结构有时也存在着原理误差，即实际机构的作用方程与理论作用用方程有差别，因而产生机构原理误差。
  - ***Ex.***: 正弦和正切机构，其传动方程是非线性的，当用线性方程来处理时就引起了原理误差



  - ***Ex.***: 凸轮机构中常需将动杆的端头设计成半径为*r*的圆球头由此引起误差。

正弦机构及其误差

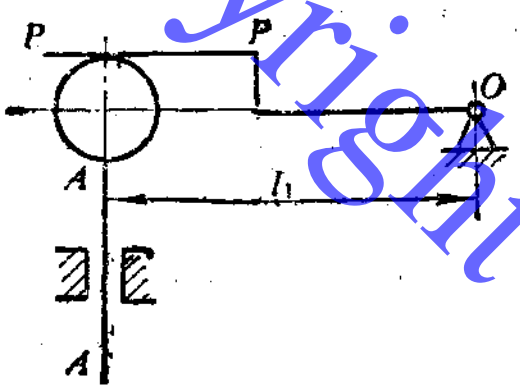


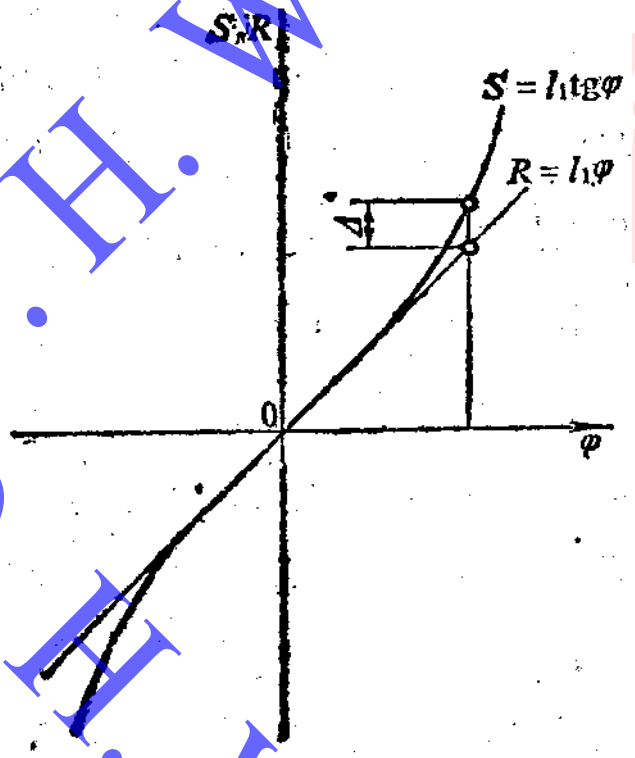


$$\Delta_{\sin} = R - S = l_1\varphi - l_1\sin\varphi$$

$$\sin\varphi = \varphi - \frac{\varphi^3}{3!} + \frac{\varphi^5}{5!} - \cdots \qquad \Delta_{\sin} \approx \frac{l_1\varphi^3}{6}$$

正切机构及其误差



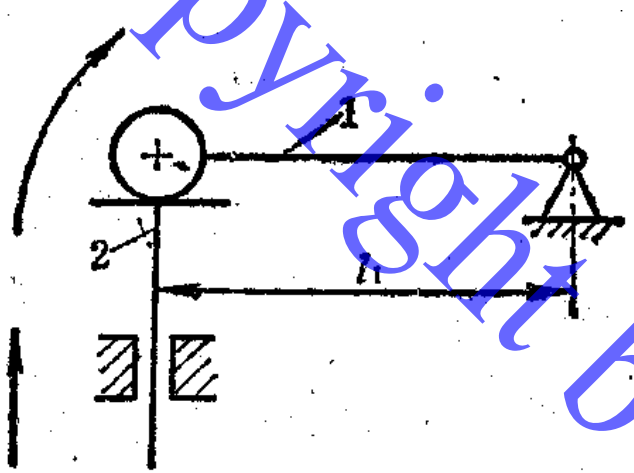


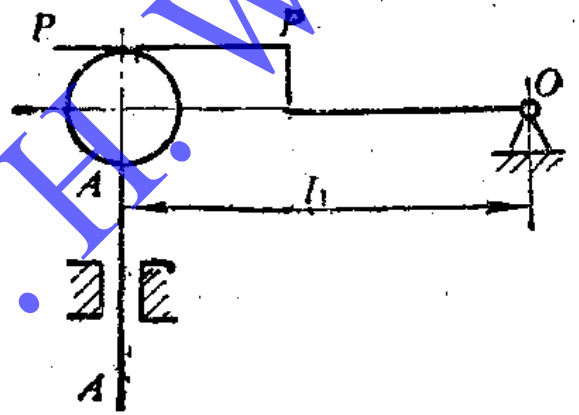
$$\Delta_{\tan} = R - S = l_1\varphi - l_1 \tan\varphi$$

$$\tan\varphi = \varphi + \frac{\varphi^3}{3} + \frac{2\varphi^5}{15} + \cdots$$

$$\Delta_{\tan} \approx -\frac{l_1\varphi^3}{3}$$

正弦机构vs正切机构

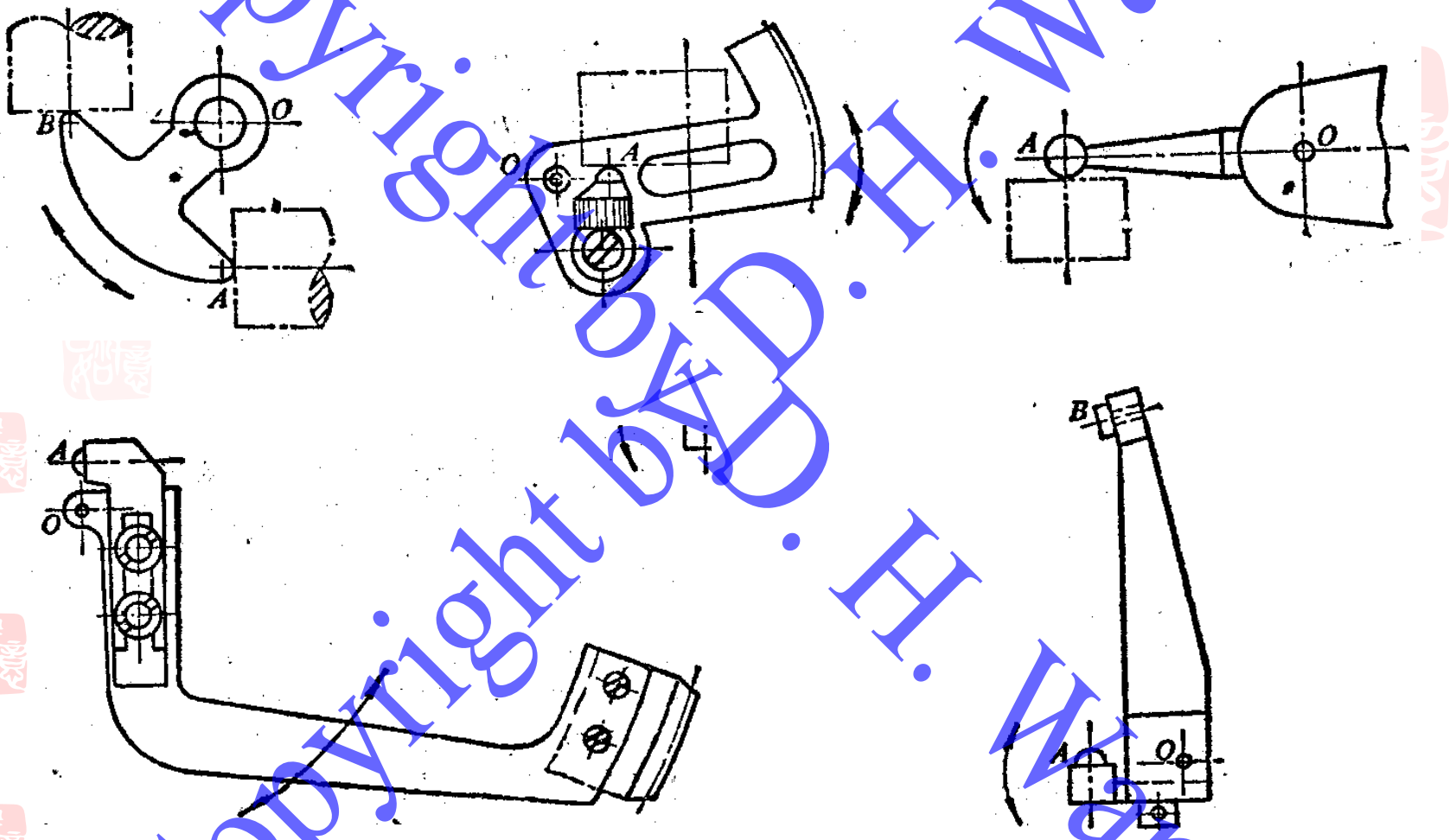




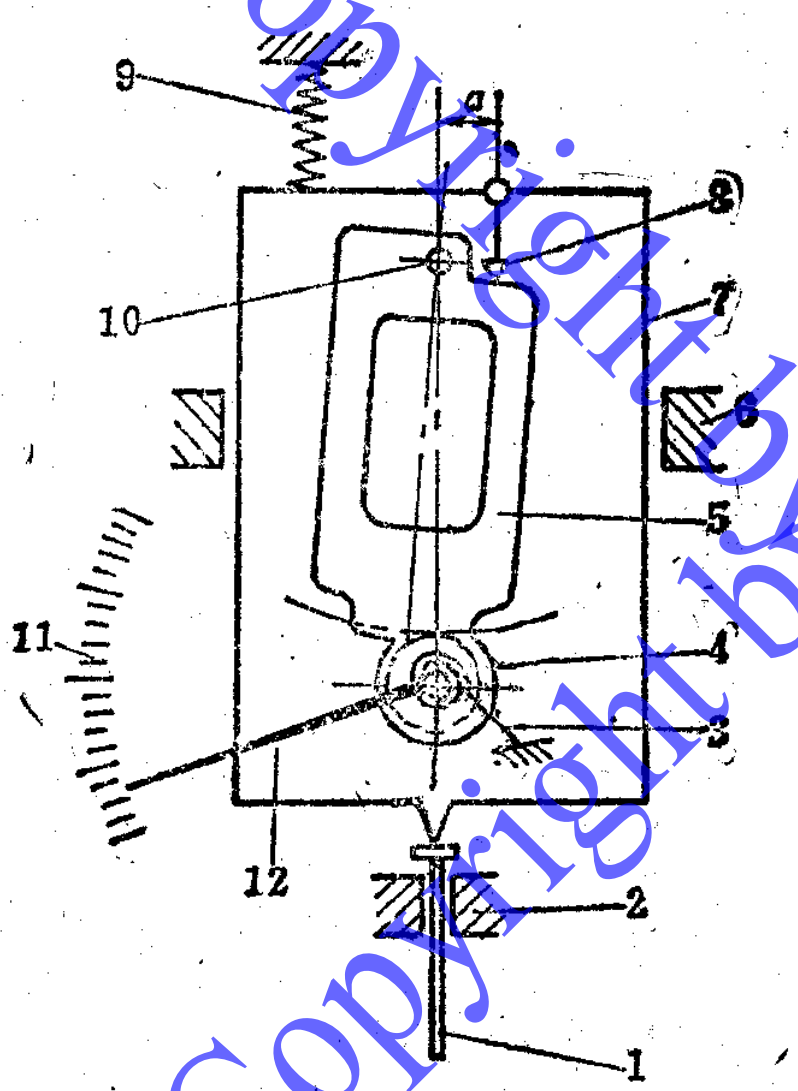
$$\Delta_{\sin} \approx \frac{l_1 \varphi^3}{6} \qquad \Delta_{\tan} \approx -\frac{l_1 \varphi^3}{3}$$

$$|\Delta_{\sin}| < |\Delta_{\tan}|$$

正弦机构应用实例

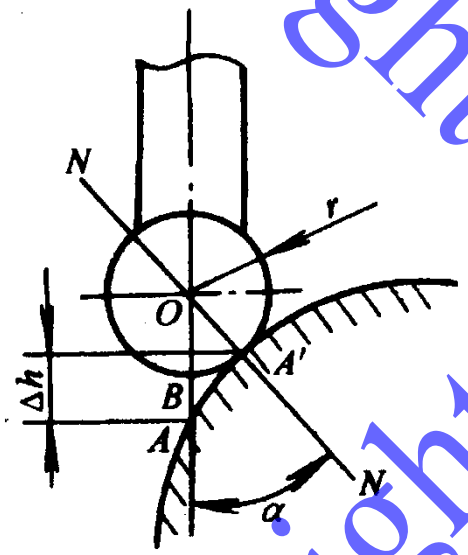


正切机构应用实例：瑞士ETALON型测微表



凸轮机构误差

- 在实现 $y=f(\varphi)$ 的运动规律的凸轮机构中，为了减小磨损，常需将动杆的端头设计成半径为 r 的圆球头，由此引起误差



$$\Delta h = OA - OB$$

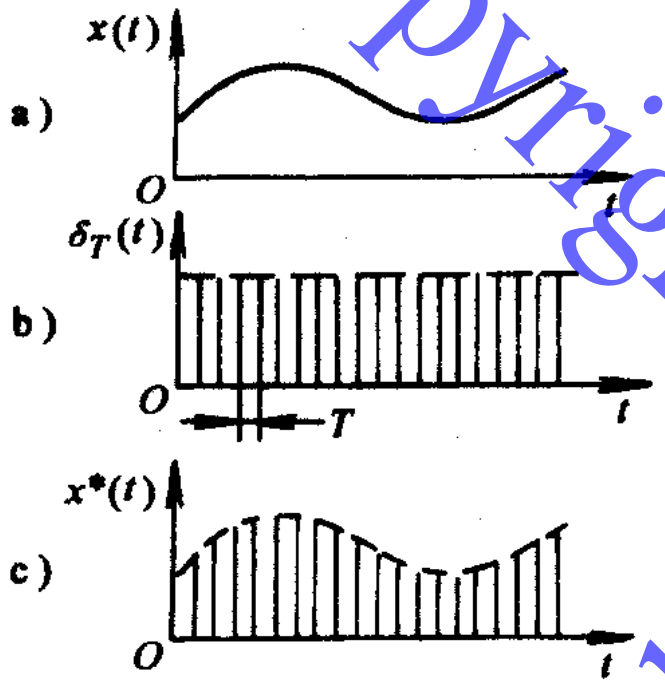
$$\approx \frac{r}{\cos\alpha} - r\cos\alpha$$

$$= \frac{r\sin^2\alpha}{\cos\alpha}$$

$$= r\tan\alpha\sin\alpha \approx r\alpha^2$$

- **How to decrease and compensate for the principle error?**

Sampling



- 在数据采集系统中，首先要进行的操作是采样 **(Sampling)**，即用一系列时间离散序列 ***x*(t)*** 来描述连续的模拟信号 ***x(t)***
- 理论上只要这种离散序列满足*香农采样定理*，则 ***x*(t)*** 将完全确定原来的连续信号，可以用理想的低通滤波器准确地恢复***x(t)***。

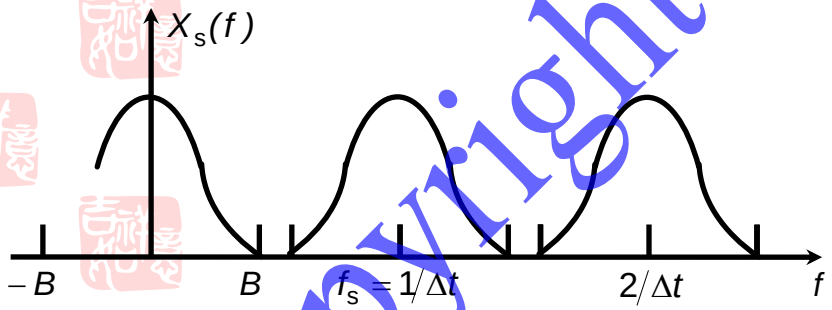
X(t) **Continuous signal**

T **Sampling interval**

X*(t) **Discrete signal**

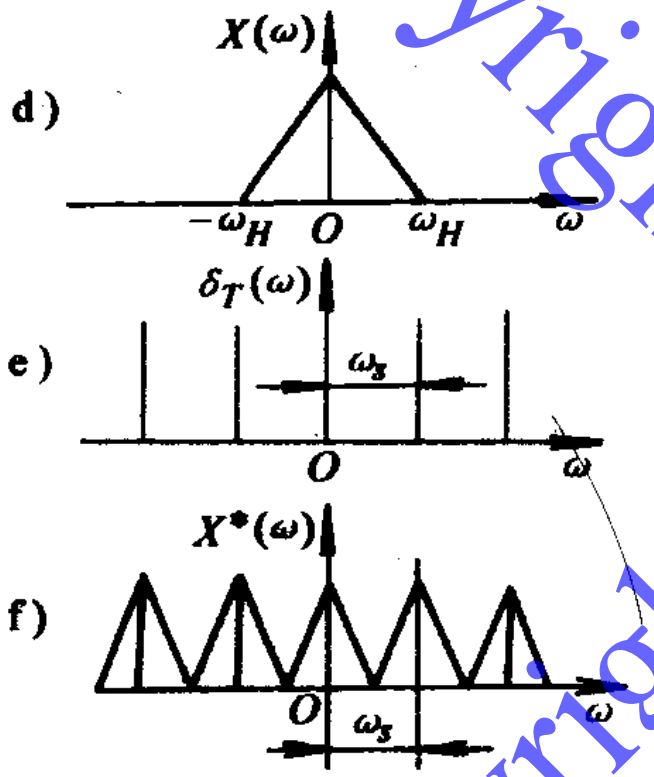
Nyquist Theorem (Nyquist 1928, Shannon 1949)

- For a band-limited time domain signal, no information is lost with sampling frequency fs >= 2B.
- This is applicable to instantaneous sampling.
- Dual slope ADC requires certain modification.
- The frequency 2B is called *Nyquist rate*.
- fs/2 is called *Nyquist frequency*.



$$x(t) = \sum_{i=-\infty}^{\infty} x_i \operatorname{sinc}\left(\pi \frac{t - i\Delta t}{\Delta t}\right)$$

Fourier Transformation

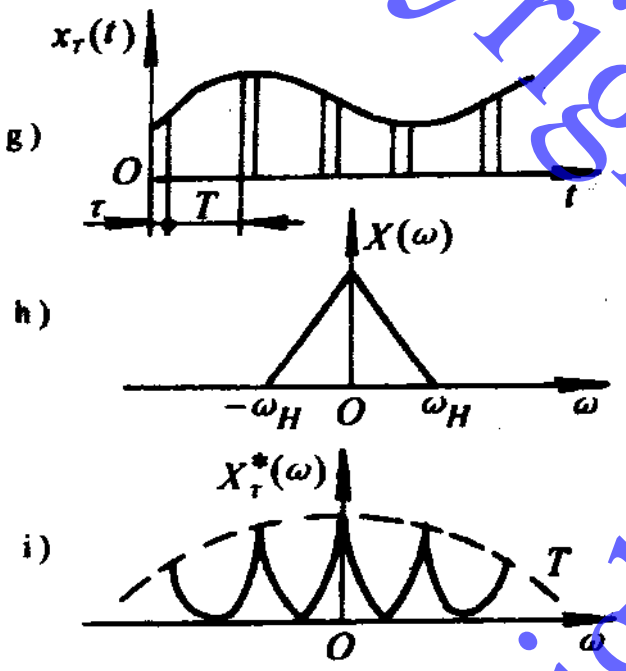


- 按照频率卷积定理，*x(t)δT (t)* 的傅里叶变换是 *X(ω)* 与*δT (ω)* 的卷积

$$X^*(\omega)=\frac{1}{T}\left[X(\omega)\sum_{n=-\infty}^{\infty}\delta_T(\omega-n\omega)\right]=\frac{1}{T}\sum_{n=-\infty}^{\infty}X(\omega-n\omega)$$

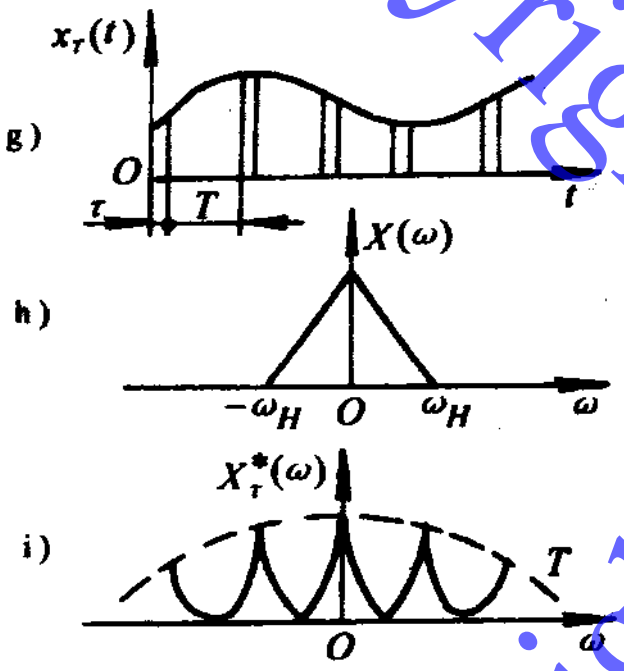
- *x*(t)*的频谱是由无穷多个相互间隔为ωs 的*X(ω)*叠加而成。由于 *X(ω)* 的频谱宽为2ωH，所以当ωs≥2ωH时，*X*(ω)*中的边带频谱互相不重叠。

Fourier Transformation



- 理想采样脉冲是不可能得到的，因为实际的采样脉冲总是有一定的宽度τ。
- 若是采用采样保持的采样方式，这一采样过程等效于理想脉冲采样后，采出的离散序列又通过一个脉冲形成电路进行保持。

Fourier Transformation



- 脉冲形成电路的脉冲宽度为τ，增益为 1，重复周期为 *T*，频率响应函数为 ***H(ω)***。
- 在脉冲保持期间τ内，采出信号***xT*(t)*** 的幅度维持不变，原信号***x(t)*** 的频谱仍为***X(ω)*** 。则 ***xT*(t)***的傅里叶变换可写成

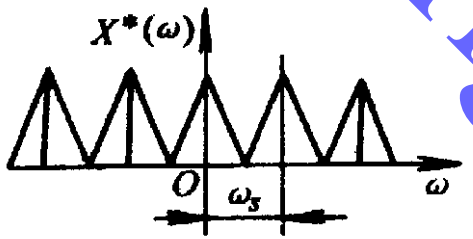
$$X_\tau^*(\omega)=\frac{1}{T}H(\omega)\sum_{n=-\infty}^{\infty}X(\omega-n\omega_s)=H(\omega)X(\omega)$$

- **Next…**

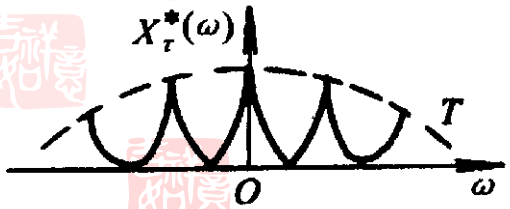
Definition

$$X_\tau^*(\omega)=\frac{1}{T}H(\omega)\sum_{n=-\infty}^{\infty}X(\omega-n\omega_s)=H(\omega)X(\omega)$$

f)



i)



- $X_T^*(\omega)$ 的频谱可看作是 $H(\omega)$ 对 $X(\omega)$ 的调制，随着信号ω的不同，其衰减幅度是不同的
- $x_T^*(t)$ 的频谱与 $x(t)$ 的频谱并不完全相同，有变形。
- 这样，即使让 $x_T^*(t)$ 通过一个截止频率为 f_H 的低通滤波器，$x_T^*(t)$ 也不能完全恢复 $x(t)$，从而产生原理误差。

Analyzing Method of Principle Errors

❒ **Analyzing method**

Principle error

=

actual relationship between the output and the input

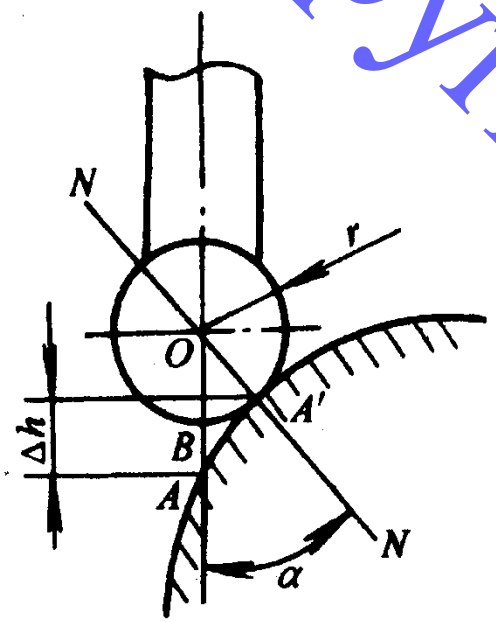
–

ideal relationship between the output and the input

Methods

- 采用更为精确的、符合实际的理论和公式进行参数设计和计算
- 研究原理误差的规律，采取技术措施避免原理误差
  - ***Ex*: 凸轮机构的原理误差减小方法**
- 采用误差补偿措施
  - 在建立原理误差数学模型的前提下，可用计算法对原理误差进行补偿
    - ***Ex* 1: 采用综合调整原理可以减小正弦和正切机构的原理误差**
    - ***Ex* 2: In-process measurement of large-scale gears' profile with a straight line basis**

凸轮机构的原理误差减小方法

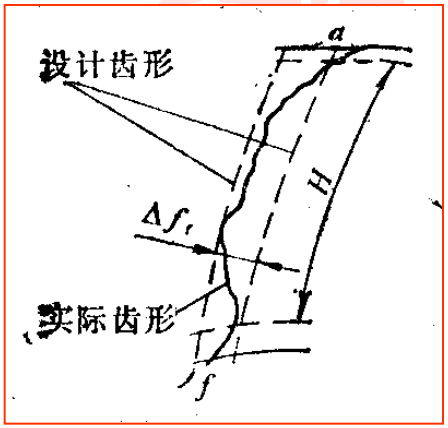


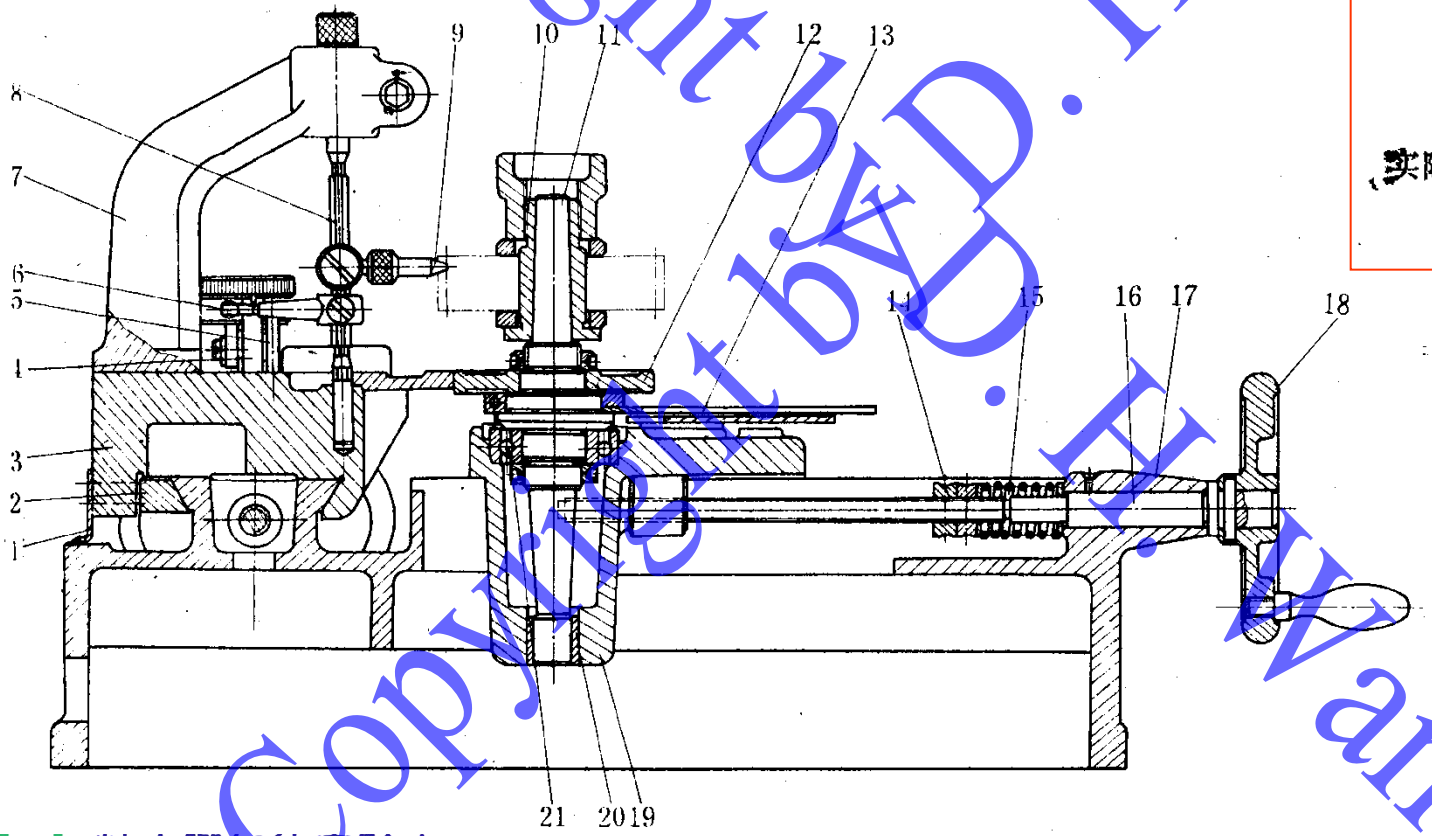
- 在实现 $y=f(\varphi)$ 的运动规律的凸轮机构中，为减小磨损，常将动杆的端头设计成半径为 r 的圆球头，由此引起误差
- 凸轮机构的原理误差产生的原因是顶杆端部不可能做成一点，实际为一球
- 加工凸轮时用半径等于顶杆球端半径的刀具加工，算出该刀具加工时的轨迹，并用端部与顶杆球端半径相同的测杆检验该凸轮，可减少该原理误差

Ideas from Hunan TV

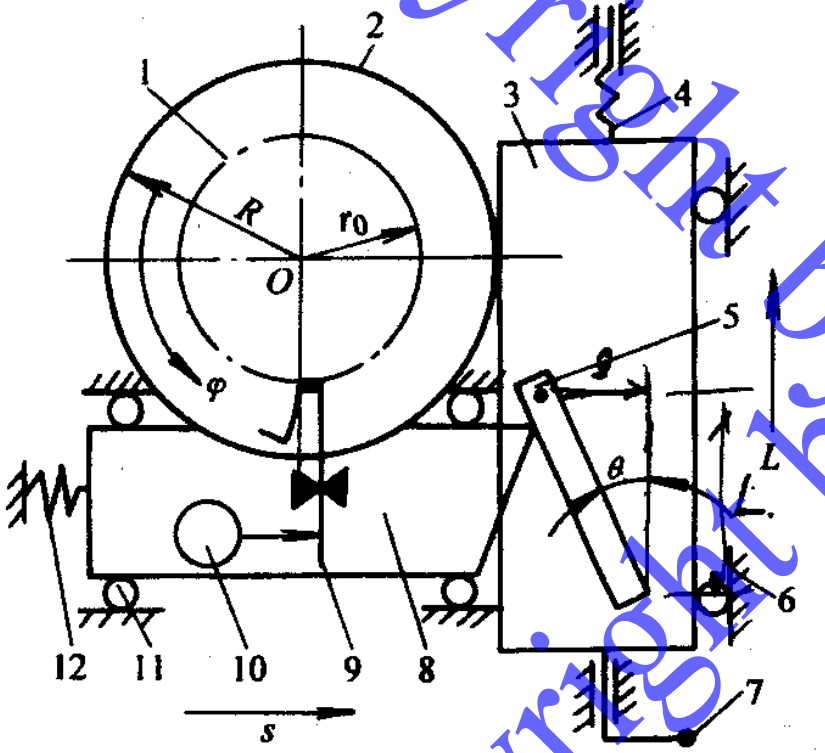
台式齿形测量仪 (1/2)

- **Involute profile error measurement with a standard involute profile basis**
  - 齿形测量仪: 固定基圆盘式





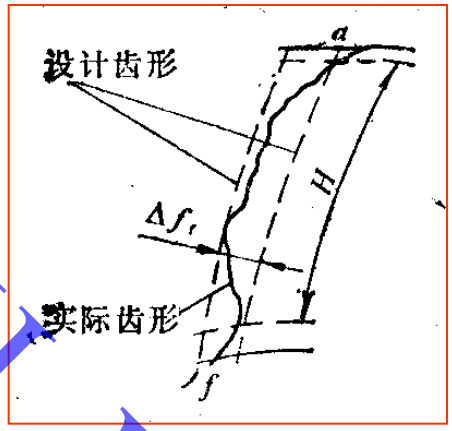
台式齿形测量仪 (2/2)



- Involute profile error measurement with a standard involute profile basis
  - 齿形测量仪: 基圆盘+直尺
- 适用范围?
  - 中小模数齿轮的齐形测量

台式齿形测量仪器的实质

- 产生标准渐开线齿形
  - 产生标准渐开线齿形的方法？？
    - 固定基圆盘式
    - 基圆盘+直尺
- 与实际渐开线齿形进行比较！！！
  - 台式
  - 其它方式：有？没有？？

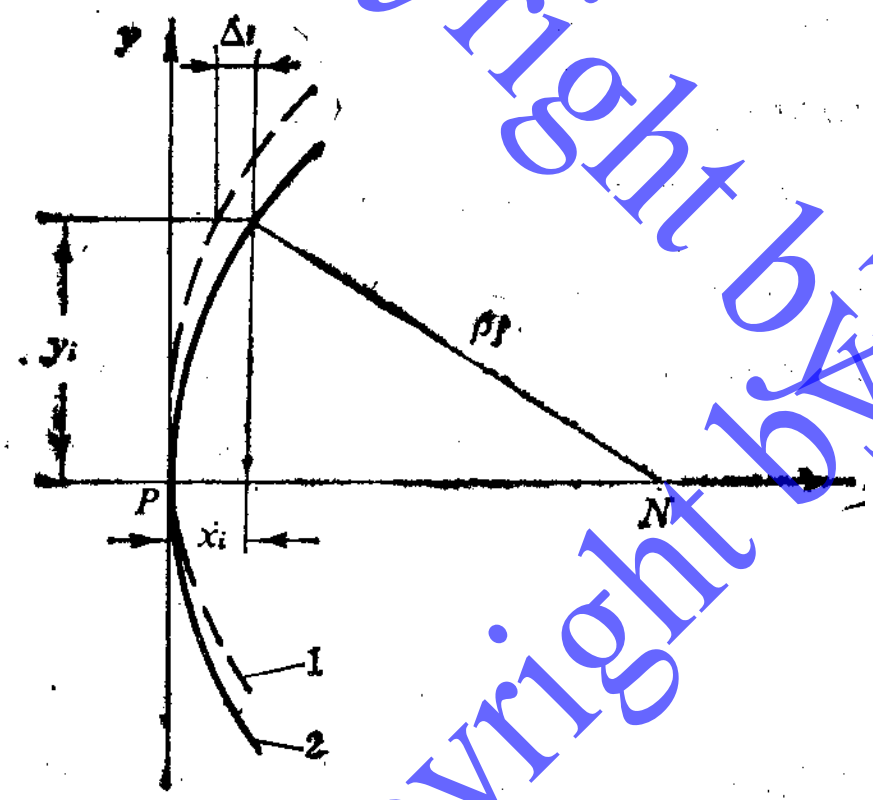


Questions?

- How to measure the large-scale gears when its weights are more than 1000 kg and its diameters are more than 1000 mm?
  - In-process measurement
  - On-line measurement
  - In-situ measurement

圆弧基准 (1/2)

❒ **Involute profile error measurement with a circular basis**



$$\left(\rho_f - x_i\right)^2 + y_i^2 = \rho_f^2$$

$$x_i = \rho_f - \sqrt{\rho_f^2 - y_i^2}$$

$$\Delta f_i = \Delta_i' - \Delta_i$$

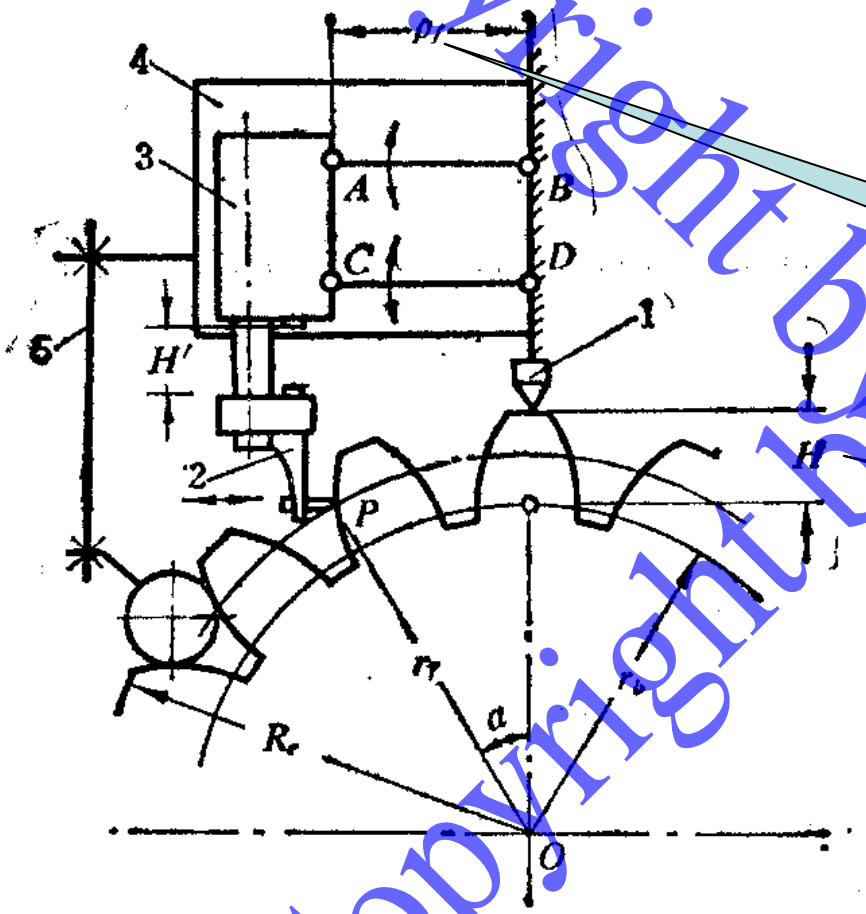
Principle Error

Measured Data

1 - Involute; 2 - Circular

圆弧基准 (2/2)

❒ **Involute profile error measurement with a circular basis**

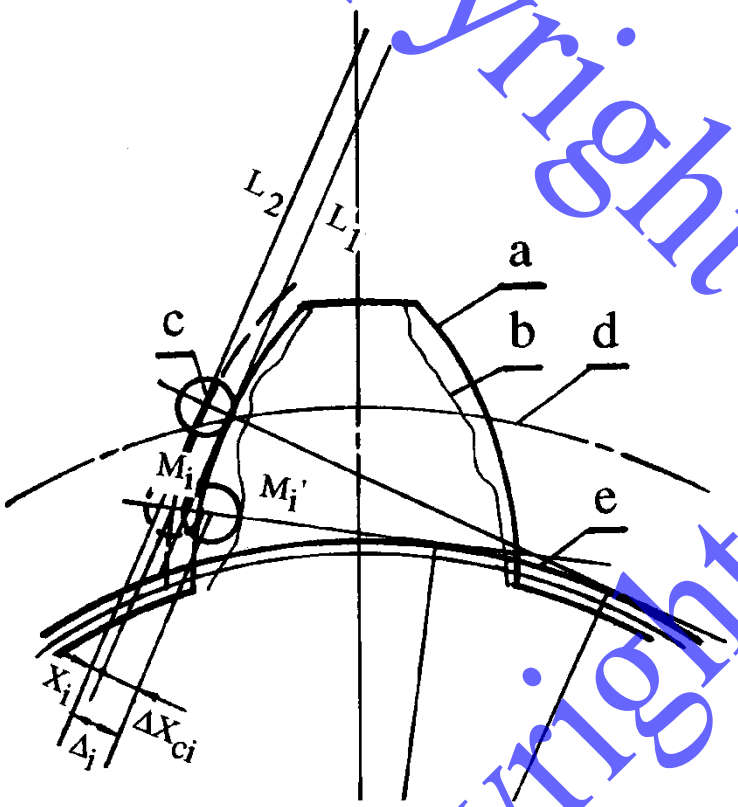


$$\rho_f = r_f \sin\alpha$$

$$H = R_e - r_b$$

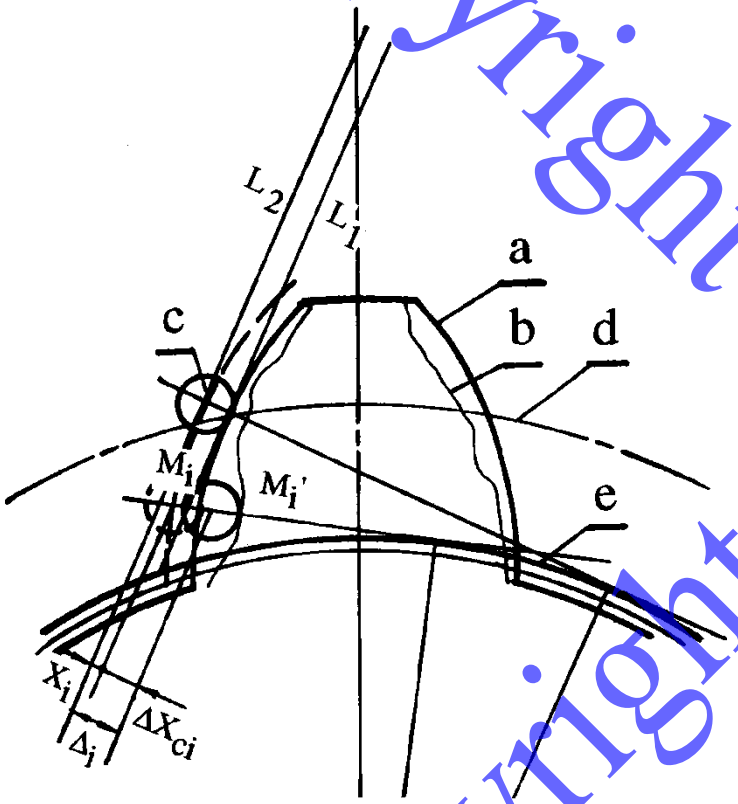
$$\Delta f_i = \Delta_i' - \Delta_i$$

Involute Profile Error Measurement with A Straight Line Basis



- In the measure range of the tooth flank, a tangent line in the involute profile can be obtained through optimization to which the maximum perpendicular distance from any point Mi in the involute profile is minimum.

Involute Profile Error Measurement with A Straight Line Basis



❒ **Principle error**

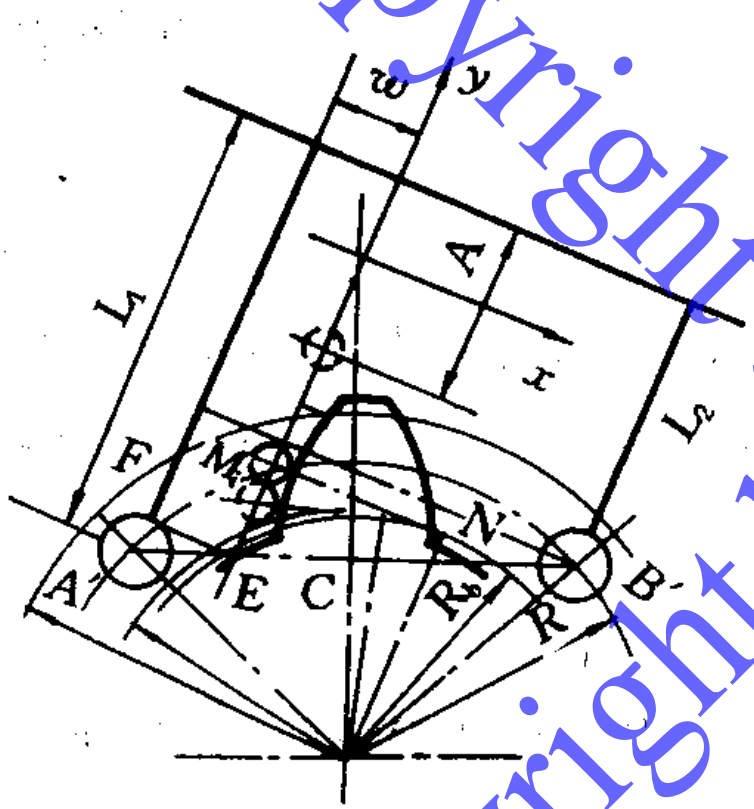
Difference between straight line and involute tooth profile

$$\Delta_i = x_i + \Delta x_i$$

Measured signal

Tooth profile error

Involute Profile Error Measurement with A Straight Line Basis



❒ Principle error

The measured signal

The tooth profile error

$$\Delta_i = x_i + \Delta x_i$$

The difference between the straight line and the involute tooth profile

Involute Profile Error Measurement with A Straight Line Basis

$$\begin{cases} x_i = R_1\cos\varphi_t - R_2\sin\varphi_t + R\sin\alpha_t + (D\sec\beta_b)/2 \\ y_i = R_1\sin\varphi_t + R_2\cos\varphi_t - R\cos\alpha_t - \dfrac{R\sin(\pi/2z) + [D\sec\beta_b\cos(\alpha_t - \pi/2z)]/2}{\sin(\alpha_t - \pi/2z)} \end{cases}$$

❒ **where** $\varphi_t = \tan\alpha_t$

$$R_1 = R_b(\sin\varphi_{ti} - \varphi_{ti}\cos\varphi_{ti}) \qquad R_2 = R_b(\cos\varphi_{ti} + \varphi_{ti}\sin\varphi_{ti})$$

β_b **- the helix angle of the base circle**

α_t **- the pitch circular press angle in the rotation plane**

D **- the pick-up's diameter**

❒ **Orientation position of the pick-up in XOY coordinate**

$$\begin{cases} -x_{\lim} \le x_c \le +x_{\lim} \\ y_c = -(OE + A'F - L + A) \end{cases}$$

❒ **where**

$$\overline{OE} = \frac{\frac{1}{2}D\sec\beta_b \csc(\alpha_t - \frac{\pi}{2z}) + R\sin\frac{\pi}{2z}ctg(\alpha_t - \frac{\pi}{2z}) + R\cos\frac{\pi}{2z} - \overline{AO_1}\cdot\cos\frac{\pi N_c}{z}}{\cos(\alpha_t - \pi/2z)}$$

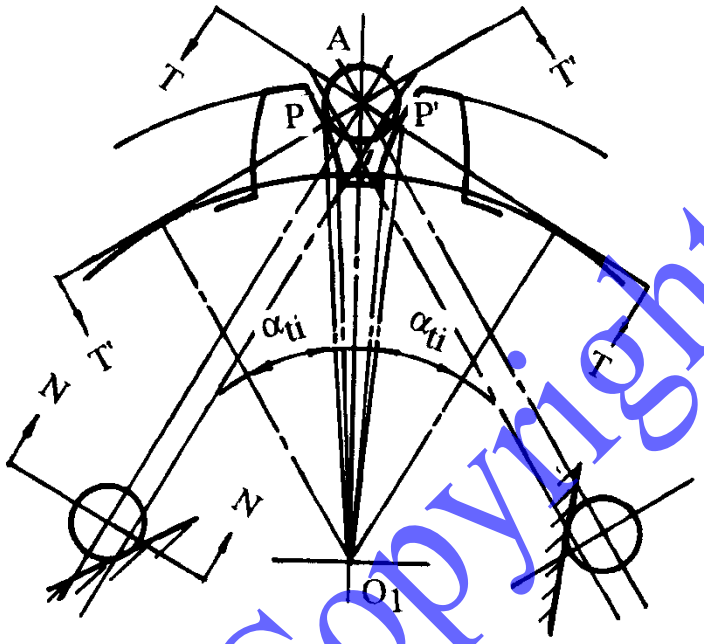
$$- \frac{[D\sec\beta_b ctg(\alpha_t - \pi/2z)]}{2}$$

$$W = \overline{A'O_1}(\sin\frac{\pi N_c}{z} + \cos\frac{\pi N_c}{z})\cos(\alpha_t - \frac{\pi}{2z}) - \frac{1}{2}D\sec\beta_b - 2R\sin\frac{\pi}{2z}\cos(\alpha_t - \frac{\pi}{2z})$$

$$\overline{A'F} = W \cdot tg(\alpha_t - \pi/2z)$$

❒ Mathematical model of orientation relation

- The orientation relationship between the instrument and the gear to be measured is determined by two orientation balls in two teeth spaces.



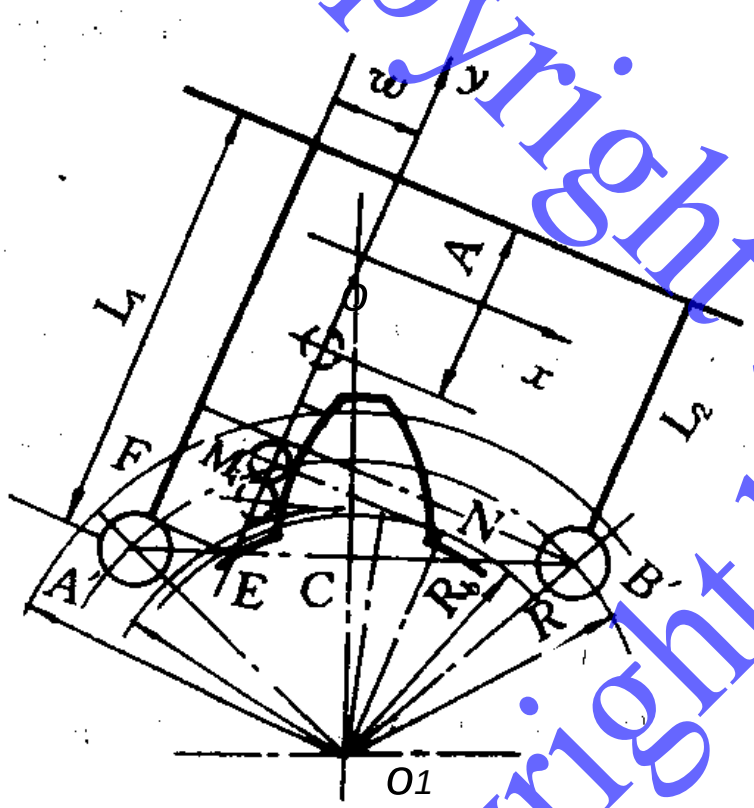
$$\frac{D\sec\beta_b\cos\alpha_{ti}}{2\sin\left(tg\alpha_{ti}-\alpha_{ti}+\frac{\pi}{z}-\frac{S_t\cos\alpha_t}{2r_b}-inv\alpha_t\right)}$$

$$=\frac{R_b}{\cos\left(tg\alpha_{ti}+\frac{\pi}{z}-\frac{S_t\cos\alpha_t}{2r_b}-inv\alpha_t\right)}$$

***D* – Orientation balls' diameter**

***St* – the circular tooth thickness in the rotation plane**

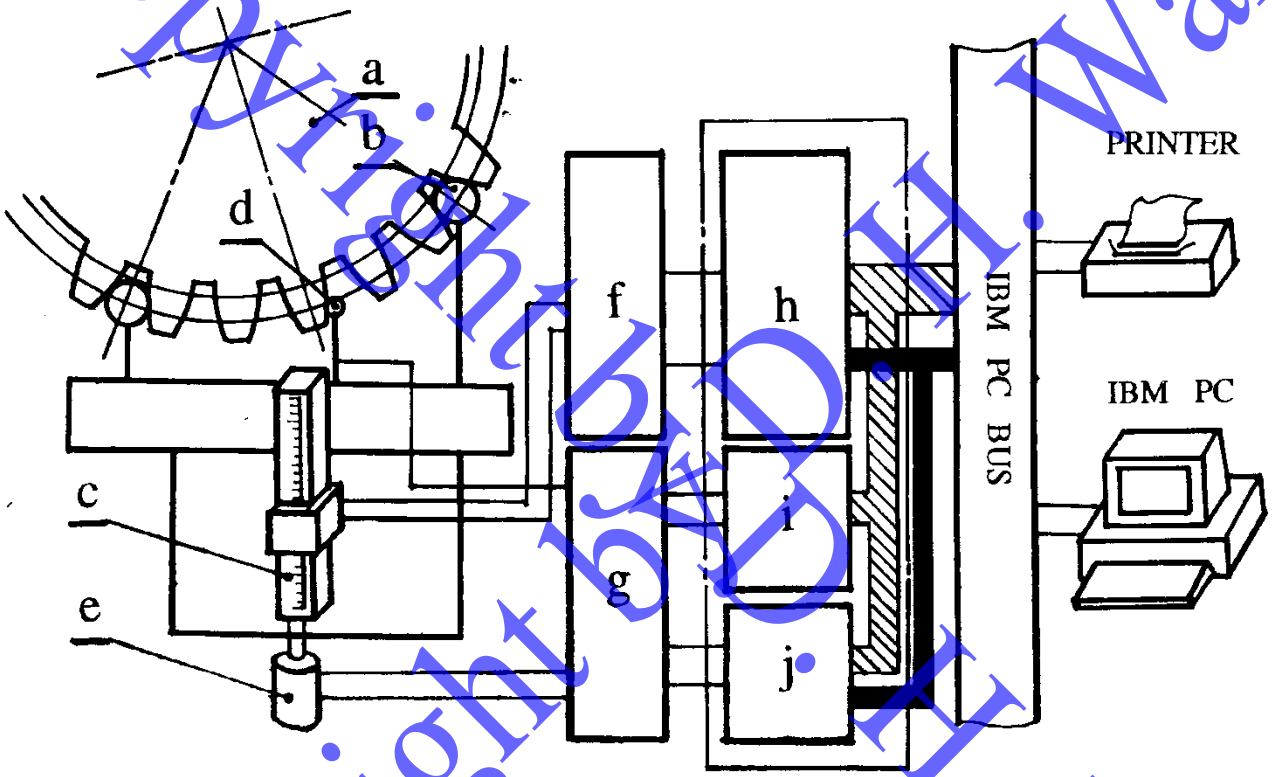
Involute Profile Error Measurement with A Straight Line Basis



$$\overline{A'O_1} = \frac{R_b}{\cos(\alpha_{ti} + \theta_{ti} + \theta_{etb})}$$

$$W = \overline{A'O_1}\left(\sin\frac{\pi N_c}{z} + \cos\frac{\pi N_c}{z}\right)\cos\left(\alpha_t - \frac{\pi}{2z}\right) - \frac{1}{2}D\sec\beta_b - 2R\sin\frac{\pi}{2z}\cos\left(\alpha_t - \frac{\pi}{2z}\right)$$

Involute Profile Error Measurement with A Straight Line Basis



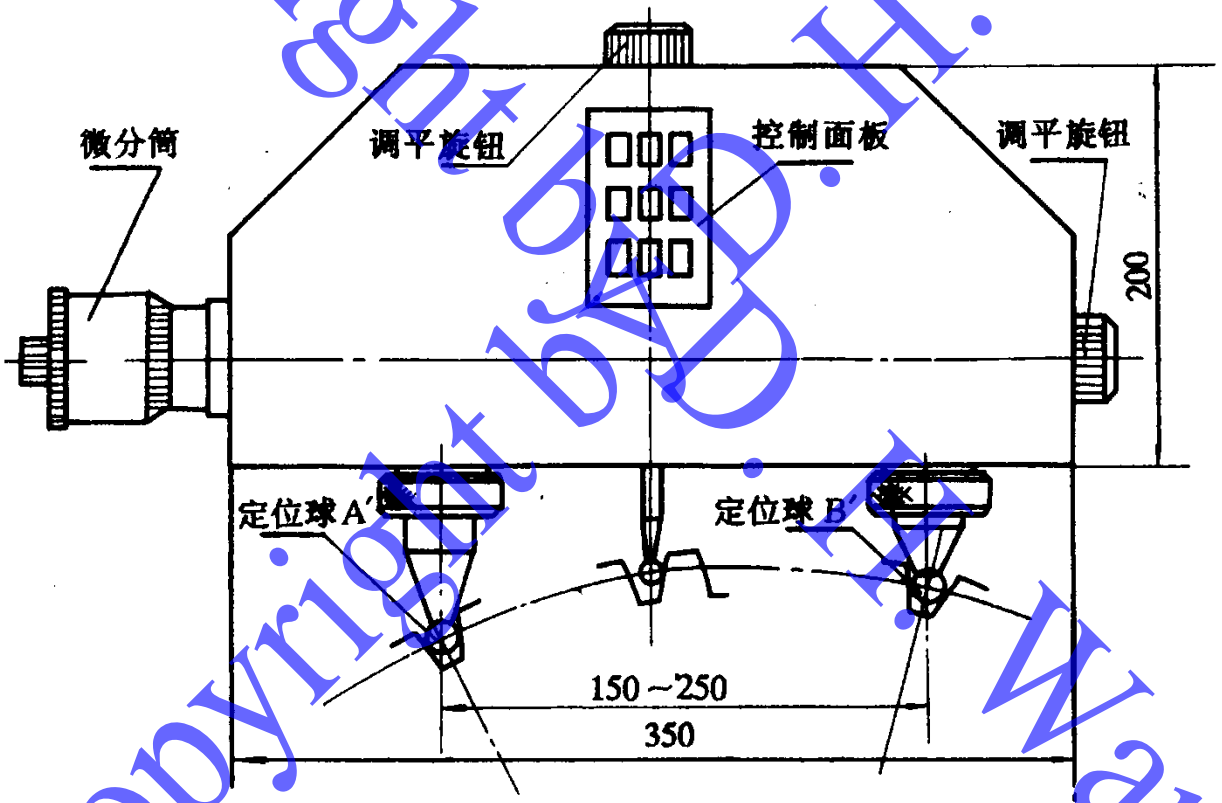
Schematic of the system: D. H. Wang and etal, "Experimental research on in-process measurement of large-scale gears' profile with a straight-line basis", In: *Proceedings of the Second International Symposium on Measurement and Intelligent Instruments*, 1993, SPIE Vol. 2101, pp. 458-491

Involute Profile Error Measurement with A Straight Line Basis

Modeling test of the in-situ measurement of tooth involute profile: D. H. Wang and etal, "Experimental research on in-process measurement of large-scale gears' profile with a straight-line basis", In: *Proceedings of the Second International Symposium on Measurement and Intelligent Instruments*, 1993, SPIE Vol. 2101, pp. 458-491

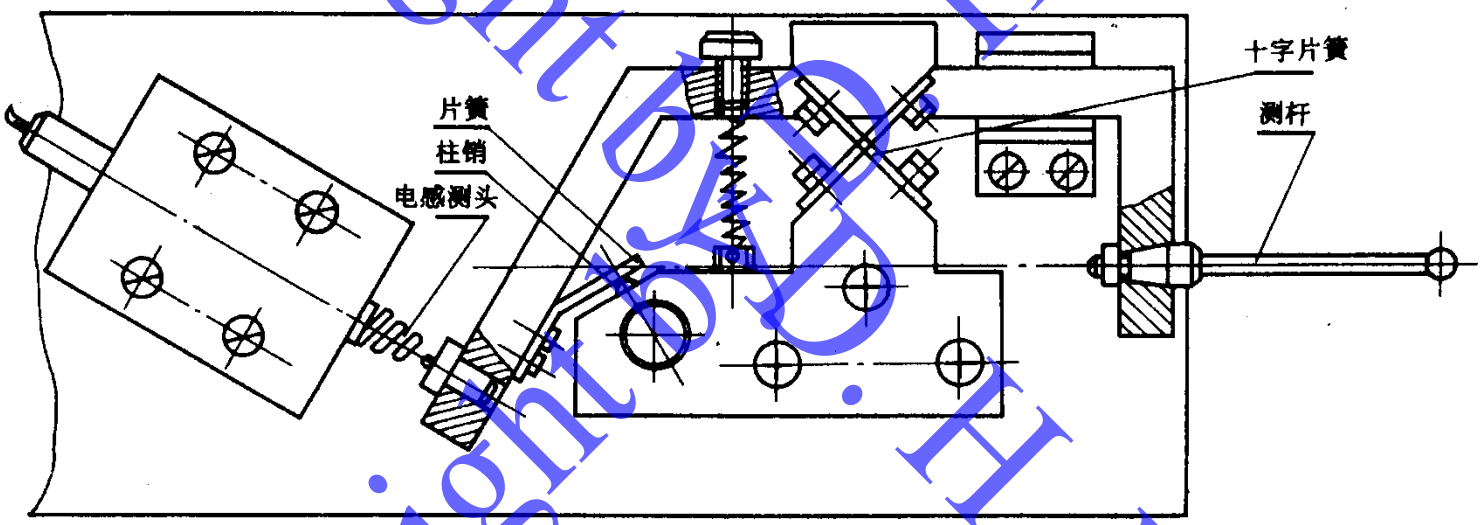
Involute Profile Error Measurement with A Straight Line Basis

- The in-situ measuring system for the large-scale gears' involute profile



Involute Profile Error Measurement with A Straight Line Basis

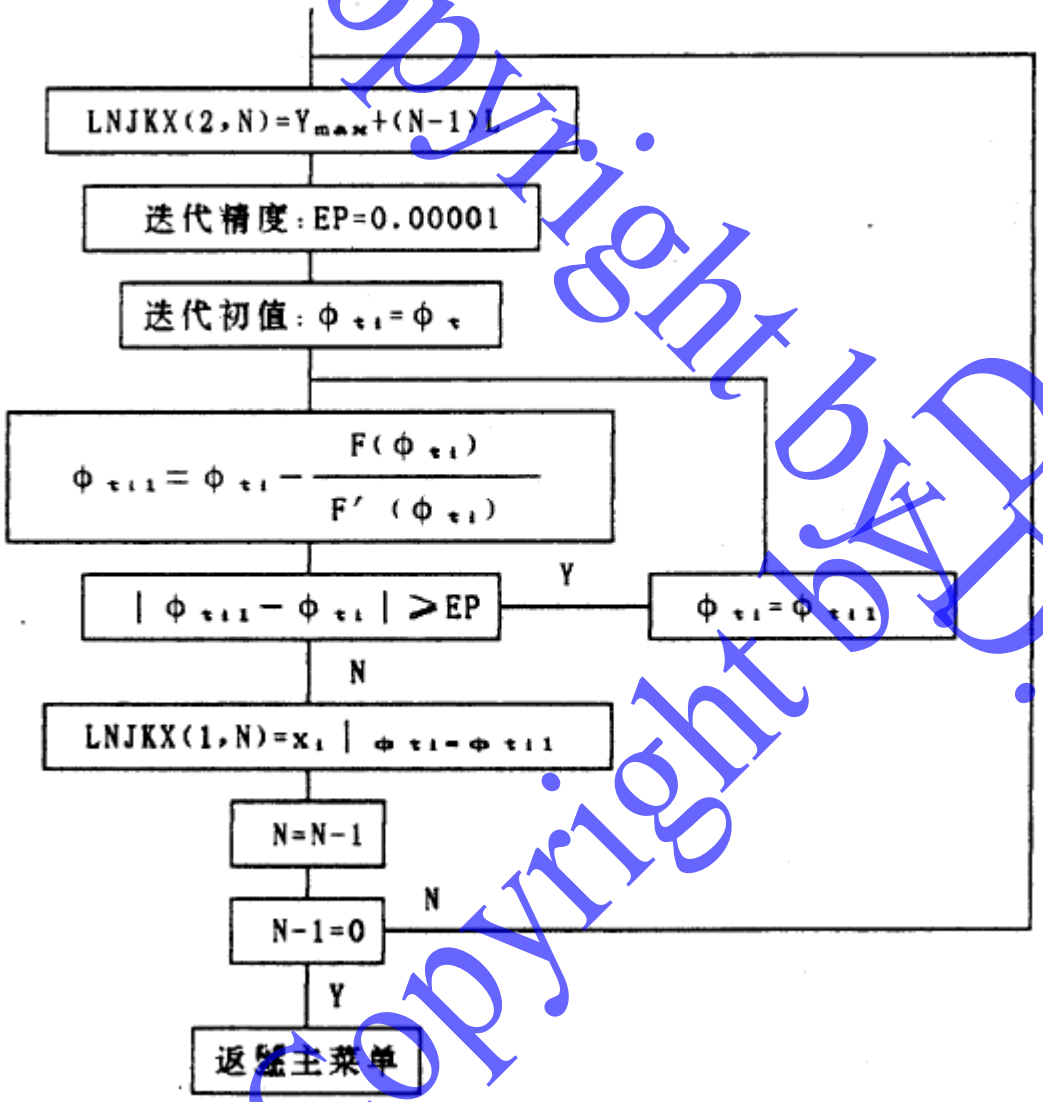
❒ **Involute profile error of the gears sensor system**



❒ 软件系统

✎ 系统软件主模块框图

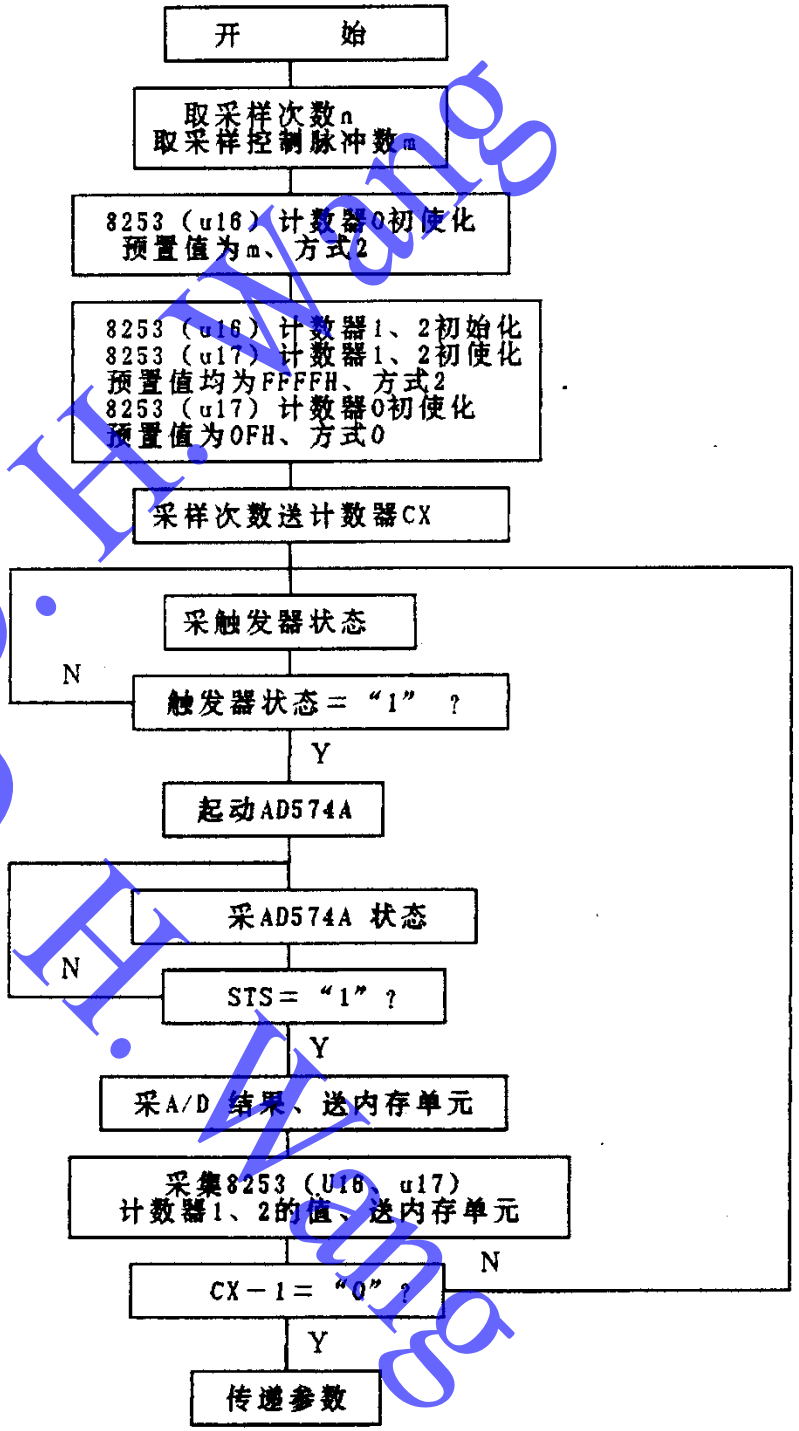
Involute Profile Error Measurement with A Straight Line Basis



- 软件系统
  - 原理误差求解

Involute Profile Error Measurement

- 软件系统
  - 采样控制程序



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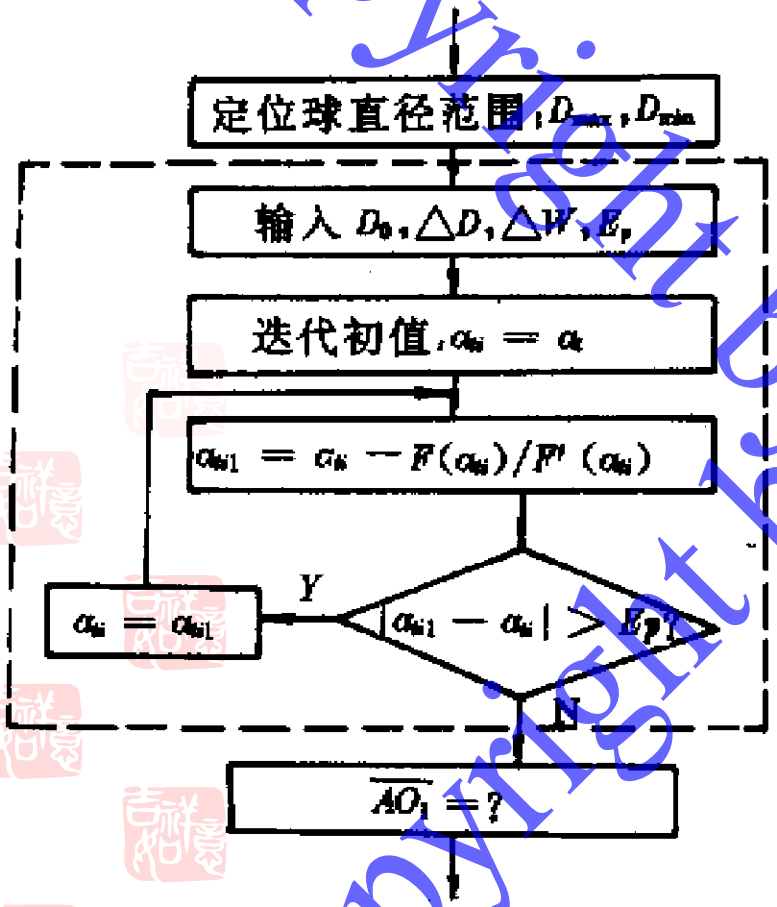
Precision and Intelligence Laboratory
E-mail: dhwang@cqu.edu
URL: http://www.pilab.coe.cqu

Involute Profile Error Measurement with A Straight Line Basis



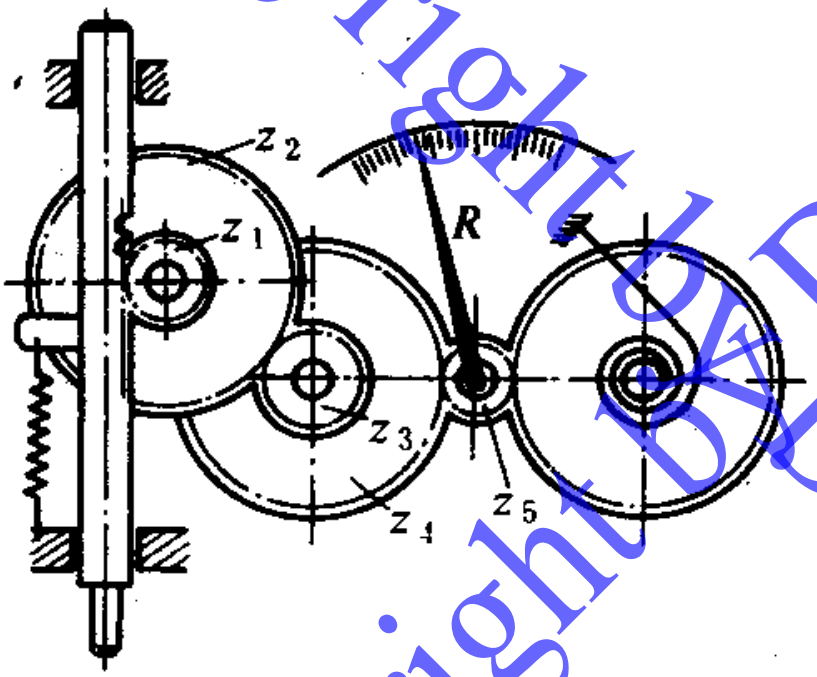
❒ 软件系统

✐ 定位球直径求解

$$\frac{D\sec\beta_b\cos\alpha_{ti}}{2\sin\left(tg\alpha_{ti}-\alpha_{ti}+\frac{\pi}{z}-\frac{S_t\cos\alpha_t}{2r_b}-inv\alpha_t\right)}=\frac{R_b}{\cos\left(tg\alpha_{ti}+\frac{\pi}{z}-\frac{S_t\cos\alpha_t}{2r_b}-inv\alpha_t\right)}$$

Questions?

❒ Does any principle error exist in *0.001 mm dial indicator* ?



The 0.001 mm dial indicators are a high accuracy length measuring tool. They are widely used for measuring the geometric deviation and position deviation of workpieces.

The End

Thank you very much for your attention!

E-mail: dhwang@cqu.edu.cn
URL: http://www.pilab.coe.cqu.edu.cn/