High-Accuracy Small Roll Angle Measurement Method Based on Dual-Grating Diffraction Heterodyne Interferometer

Dr. Shanzhi TANG

Contributed: M. Li, H. Liang, W. Sheng, J. Yang

Beijing Synchrotron Radiation Facility (BSRF), Institute of High Energy Physics (IHEP), CAS

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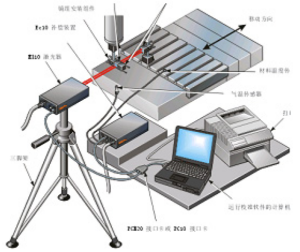
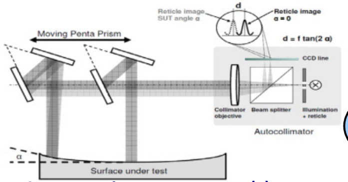
Outline

- Introduction
- Configuration & Principle
- Mathematical modeling and analysis
- Experiments and results
- Discussion & Conclusion

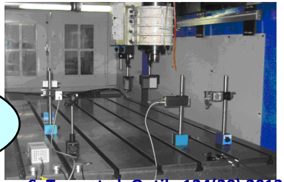


1 Introduction

- Guideway is a common technique, widely used for SR and modern industry fields, such as:

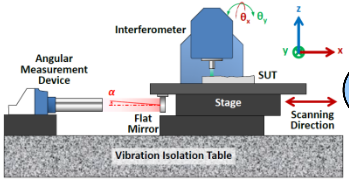


F. Siewert et al, Opt. Express, 20(4),2012

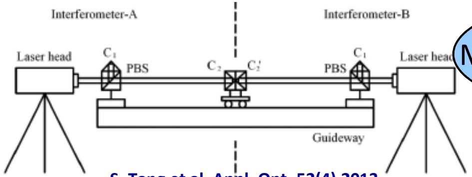


S. Tang et al, Optik. 124(20),2013

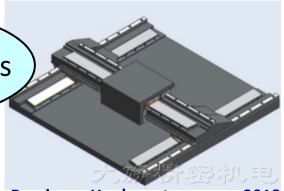
Brochure, Zeiss corp., 2018



L. Huang et al, Opt. Express, 26(8),2018



S. Tang et al, Appl. Opt. 52(4),2013

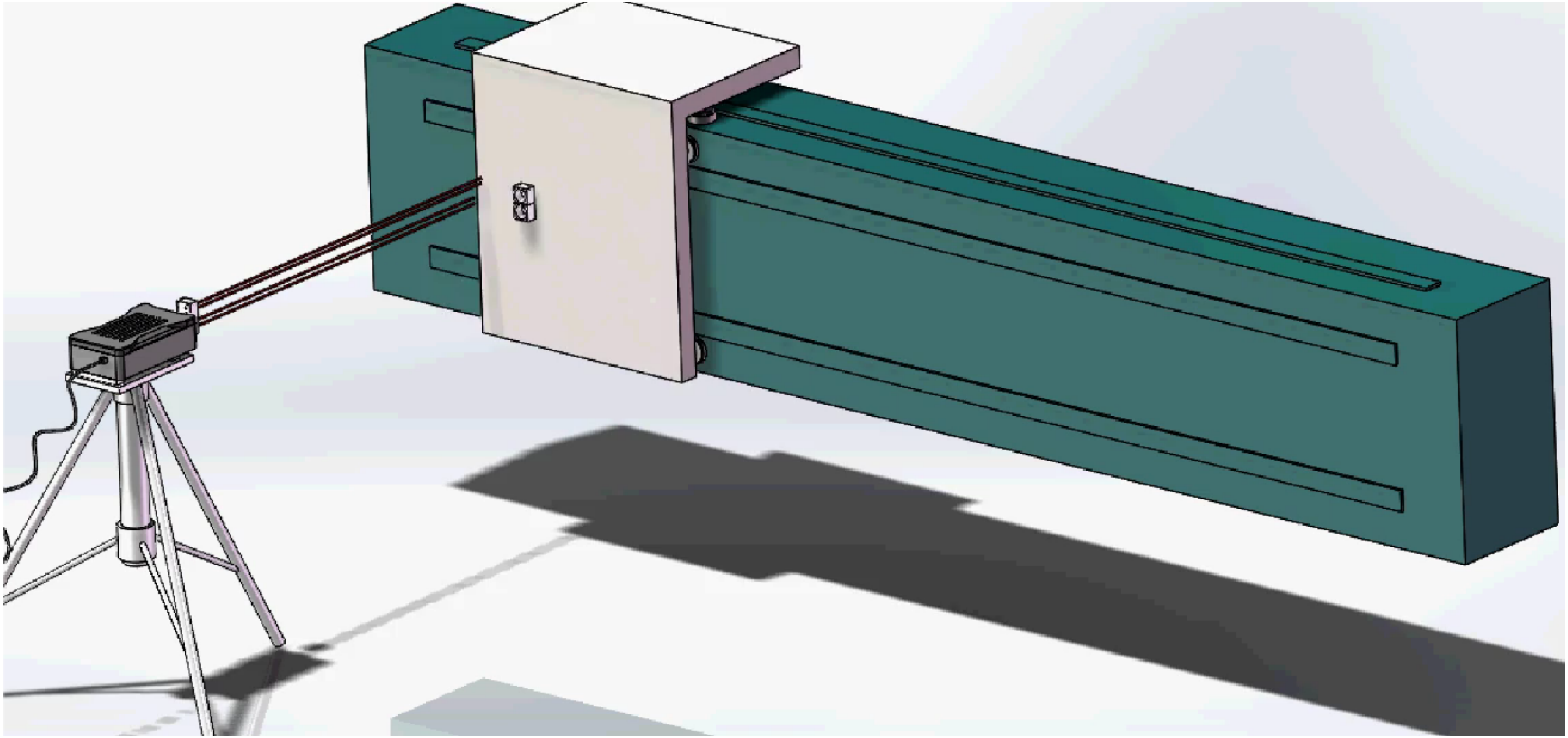


Brochure, Han's motor, corp., 2018

COMMON TECHNIQUE
Precision Guideway

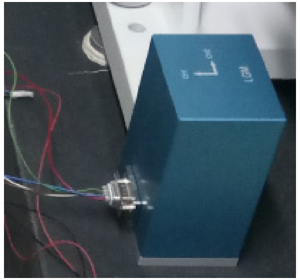
- LTP & NOM
- NC machine tool
- Stitching interferometer
- Coordinate Measuring Machine (CMM)
- Metrology calibration
- Motion mechanics

- So, they usually need a high-accuracy measurement method for the small roll angle (ROLL) of the guideway. However, it is difficult to do it.



Why?

- Different from Pitch or Yaw easy to test by using typical method as interferometer or autocollimator, etc.
- ROLL has a unique orthogonal problem { Linear motion direction (beam); Angular displacement plane }



Electronic level or inclinometer

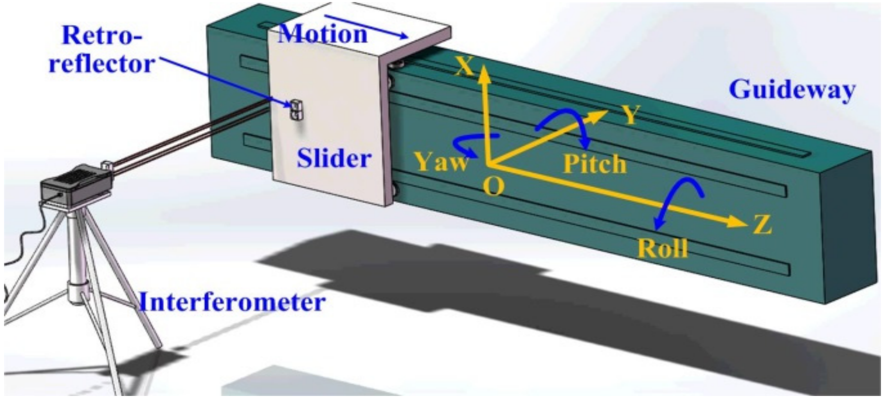


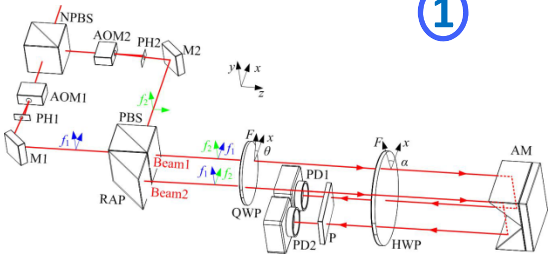
Fig. 1: The diagram of angle deviations of the guideway.

- Tiltmeter? Not enough.

So, there are exploration researches, such as:

1. **Polarization method**:
   polarization detecting based on interferometry, including intensity [6, 7] and phase sensing [8-15].
2. **Wedge prism method**:
   using special shape component based on interferometry, such as using wedge prism and its derivative [16, 17].
3. **PSD method**:
   Geometrical transfer test using position sensitive detector (PSD) [18-20].
4. **Synthesization method**:
   combined other optical methods [21-24], such as grating interferometer.

1



J.Qi et al, Opt. express, 26(8), 2018

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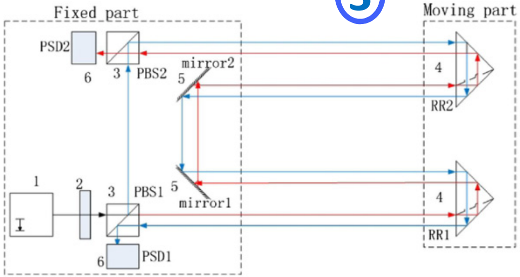

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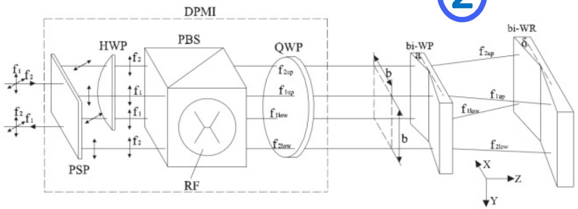
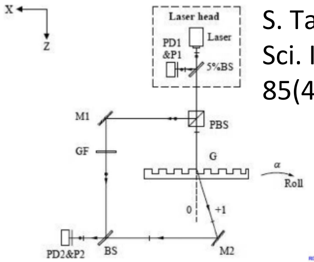


T. Jin et al, Rev. Sci. Instrum, 88(2), 2017



S. Tang et al, Rev. Sci. Instrum. 85(4), 2014

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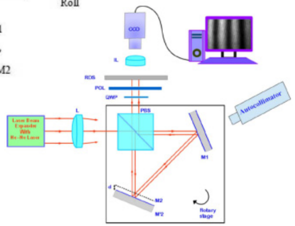


Y.P. Kumaar et al, Appl. Opt. 55(5), 2016

These achievements indicate progress of ROLL test in laboratory, but there is a little way for practical application, especially for LTP, CNC, and CMM.

2 Configuration & Principle

- Method based on DGD-HI
  - Laser head
  - PBS, RAP or mirror
  - Sensor: Dual-Grating (1&2)
  - Retro-reflector (RAP 1&2)

Grating equation:

$$d\sin\theta = \lambda$$

Doppler effect:

$$\Delta f_M = \frac{2V_M}{\lambda}\cos\left(\frac{\pi}{2}-\theta\right)$$

$$\Delta f_M = \frac{2V_M}{d}$$

$$\Delta f_R = \frac{2V_R}{d}$$

$$\boxed{V = \frac{d}{2}\Delta f}$$

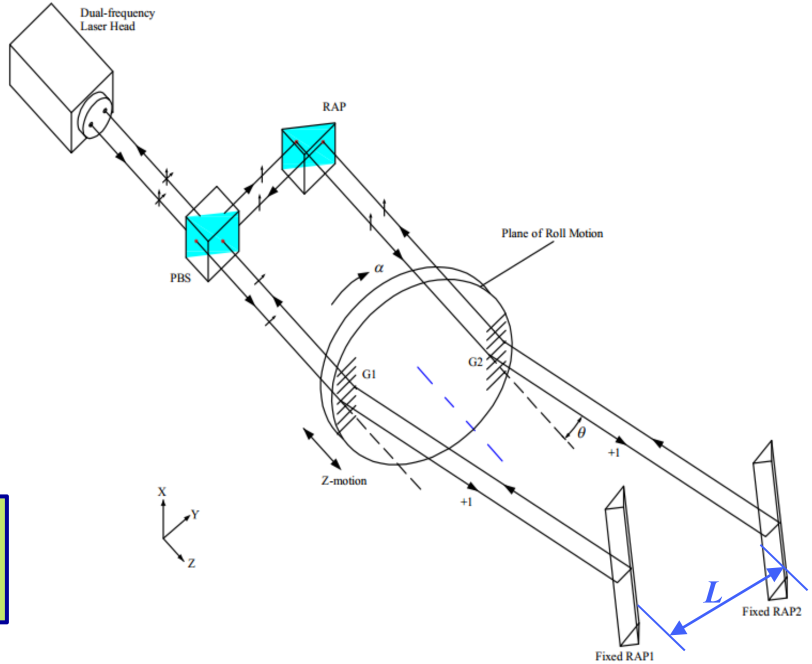


Fig. 2: The principal diagram of the proposal method.

3 Mathematical modeling and analysis

So, the angular displacement:

$$s = \int_0^T V \cdot dt = \frac{d}{2} \cdot \int_0^T \Delta f \cdot dt$$

And, the ROLL test modeling:

$$\boxed{a = \frac{s}{L} = \frac{d}{2L} \cdot \int_0^T \Delta f \cdot dt}$$

d* vs *λ

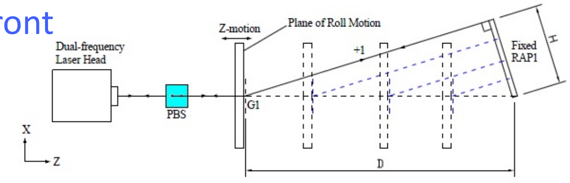
Similar to

Length standard

$$s' = \int_0^T V \cdot dt = \frac{\lambda}{2} \cdot \int_0^T \Delta f \cdot dt$$

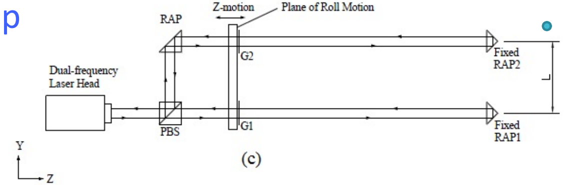
$$a' = \frac{s}{L} = \frac{\lambda}{2L} \cdot \int_0^T \Delta f \cdot dt$$

Front



(b)

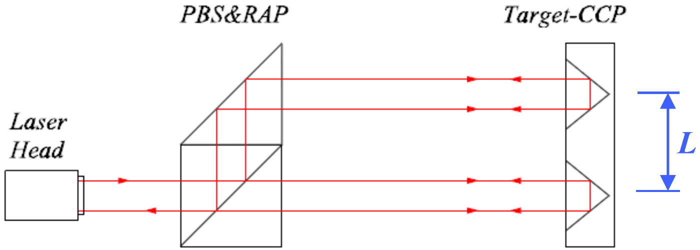
Top



(c)

If using same subdivision and *L* like HI, the Res. as

C=d/λ



Typical heterodyne interferometer for angle

Parameters and errors:

- *d(D,H): restricted by geometry sizes*
- *L: differential distance*
- *Height error of surfaces of RAP: mapping to eliminated*

$$a_r = \frac{d}{\lambda L} = \frac{D}{HL} \ nrad \begin{cases} a_r = \dfrac{s_r}{L} = \dfrac{d}{\lambda L} \\ \sin\theta = \dfrac{H}{D} = \dfrac{\lambda}{d} \end{cases}$$

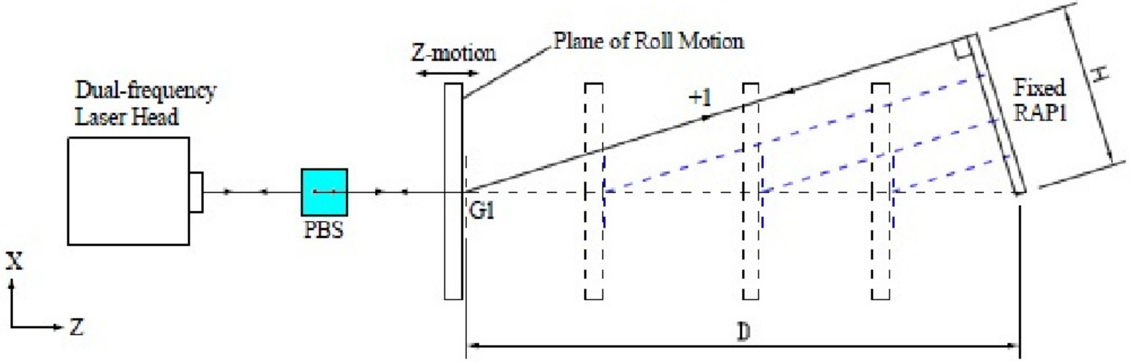
if d=1000/300um

L=250mm

Res. HI=0.1nm

If D=1m, then H=~200mm

Theoretical res. 2nrad



Geometric relationships of several parameters

4 Experiments and results

Specification:

- Laser head: 5519A(Agilent,633nm)
- Grating: 300lines (*d*=3.333um)
- *L*: 96.2mm
- *H*: 200mm, *D*=1000mm
- Res. 55nrad (0.01 arcsec)

Experiments and tests:

- *Test values using the proposal*
- *Nominal values: tilt stage*

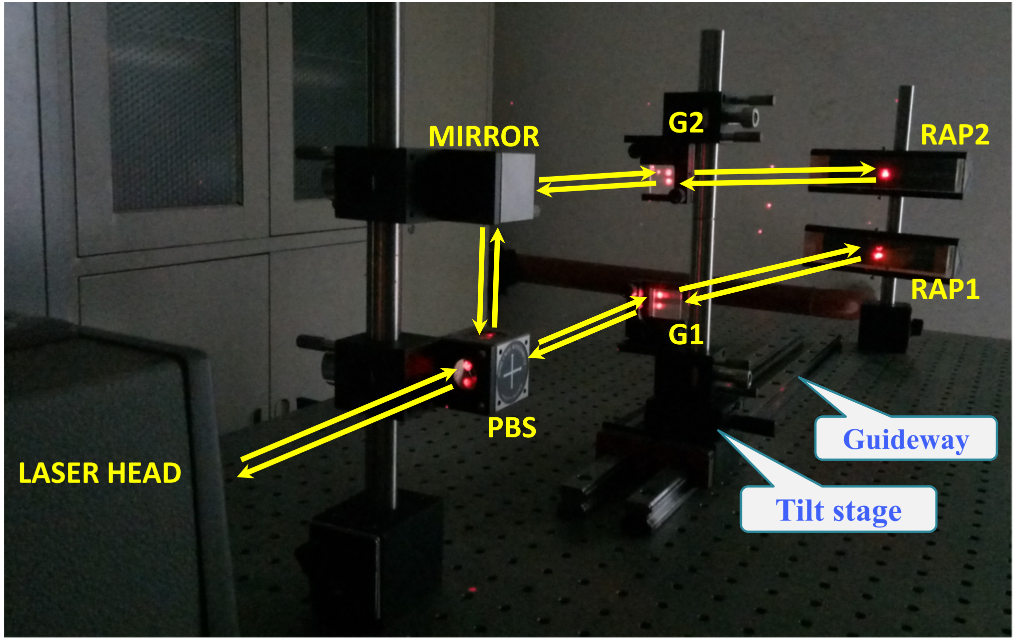


Fig. 3 The prototype of test setup based on the proposal method.

Results-1

- Std. deviation: 94.96 arcsec
- Relative deviation: 0.052% (aver.)
- Std. Relative deviation: 0.069%

- Due to restriction of tilt stage, So, the test accuracy can be improved by better nominal ROLL.
- Results still validate the feasibility.

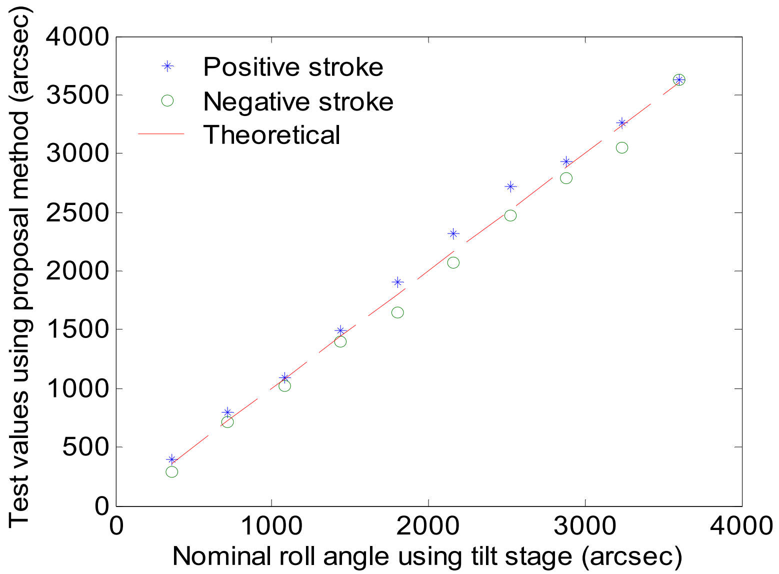


Fig. 4: The results of the ROLL test.

Results-2

Real-time test and monitor for steps:

- Sampling rate: 100Hz (Max.50kHz)
- Period: 500s (Possible longer)

Working as same as typical Michelson interferometer

It is proved high-performances and good operation.

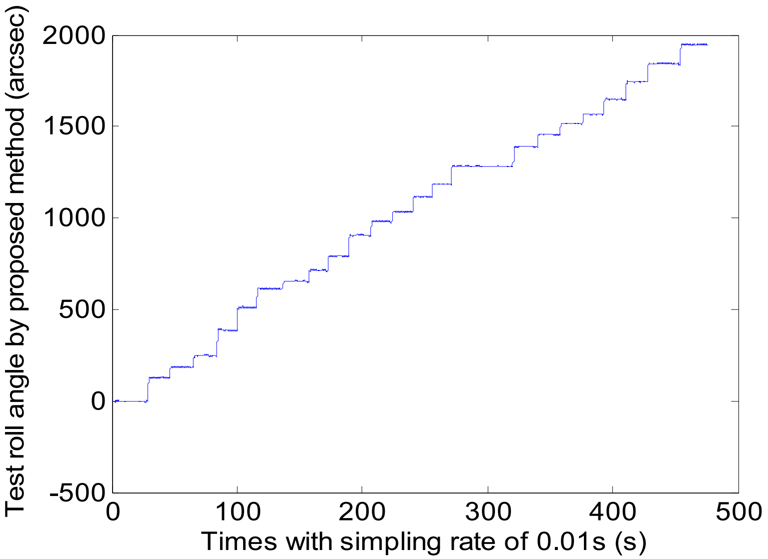


Fig. 5: The test curve of step-manual ROLLs using the proposal with simpling rate of 100Hz.

5 Discussion & Conclusion

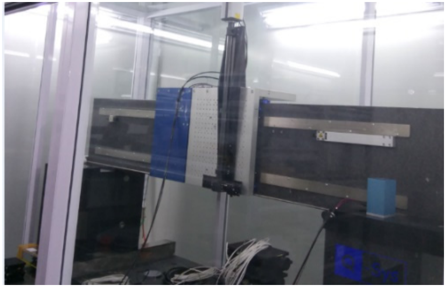
A novel method for ROLL measurement based on dual-grating diffraction heterodyne interferometer proved by:

- Theoretical analysis
- Experimental verification

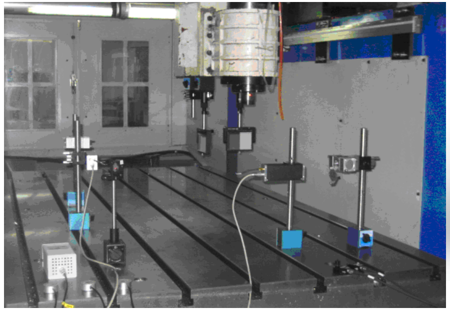
Many merits inherit from the typical HI as:

- High-accuracy/resolution
- High sampling rate
- Contactless
- Good operation

Application: ROLL monitoring and compensation for R & D of advanced LTP, advanced manufacturing technology, other relative fields.



LTP



CNC

CMM

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