Precision Metrology 8

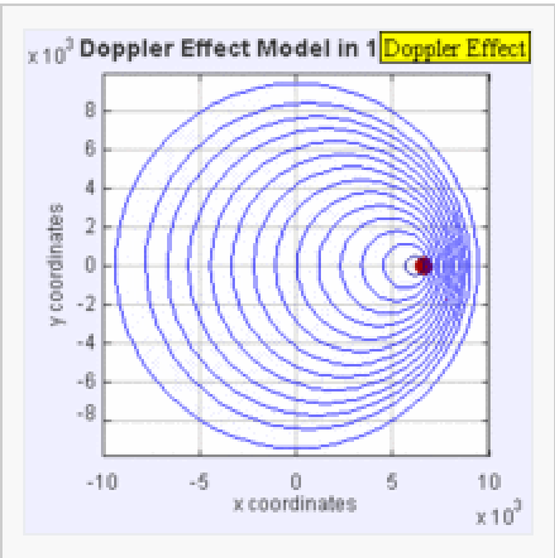
Interferometry using the Doppler effect,

or Doppler Interferometry

:Commercial Laser Interferometry is based on the Doppler Interferometry

Doppler Effect, or Doppler Shift

When there is relative motion between the source and observer, the frequency (or wavelength) of the wave observed is changed.



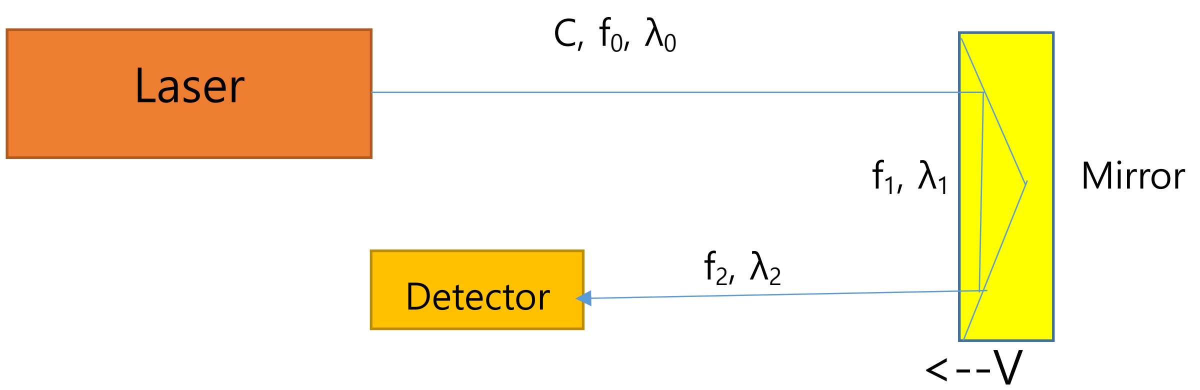
Source:wikipedia

Let C be the velocity of wave, Vs and V_o be the velocity of source and observer, respectively.

Then the observed frequency f_o and the source frequency f_s can be related as follows;

$f_O/f_S=(C\pm V_O)/(C\pm V_S)$

where the ± sign is assigned depending on the relative motion whether they are getting closer or further.



Let C be the speed of light, V be the velocity of mirror.

When f_0 is the frequency from laser source, f_1 is the frequency observed at the mirror or corner cube, and f_2 is the frequency measured at the detector.

From the Doppler effect,

$f_1/f_0=(C+V)/C$, and $f_2/f_1=C/(C-V)$

Thus $f_2/f_0=(f_1/f_0)\cdot(f_2/f_1)=(C+V)/(C-V)$

$=(1+V/C)/(1-V/C)$

$\fallingdotseq(1+V/C)(1+V/C-V^2/C^2+..)\fallingdotseq(1+V/C)^2$

$\fallingdotseq 1+2V/C$ $\quad(\because V/C\ll 1)$

$\therefore$ Frequency change, Δf, is

$\Delta f= f_2-f_0 = 2f_0.V/C = 2V/\lambda_0$ $\;(\because C = f_0\lambda_0)$

Thus velocity of mirror, V, is related to the frequency change Δf, that is,

$V= \Delta f\cdot\lambda_0/2$

When the mirror is moving at V during Δt period,

The distance change, ΔX, travelled by the mirror during Δt is,

$\Delta X = V \cdot \Delta t = \Delta f \cdot \lambda_0/2 \cdot \Delta t$; and $\Delta f = \Delta\omega/2\pi$,

where $\Delta\omega$=angular velocity change

$\therefore \Delta X=(\Delta\omega/2\pi)\cdot(\lambda_0/2)\cdot\Delta t$

$= (\lambda_0/4\pi)\cdot\Delta\omega\cdot\Delta t$

$= (\lambda_0/4\pi)\cdot\Delta\varphi$

where $\Delta\varphi$=phase change during Δt

Therefore the total distance, X, travelled during time t, is the sum of the distance change during the Δt period.

$X=\Sigma\Delta X=\Sigma(\lambda_0/4\pi)\cdot\Delta\varphi$

$=(\lambda_0/4\pi)\cdot\Sigma\Delta\varphi$,

where $\Sigma\Delta\varphi$ is the sum of the phase change that measured by the interferometry at every Δt period.

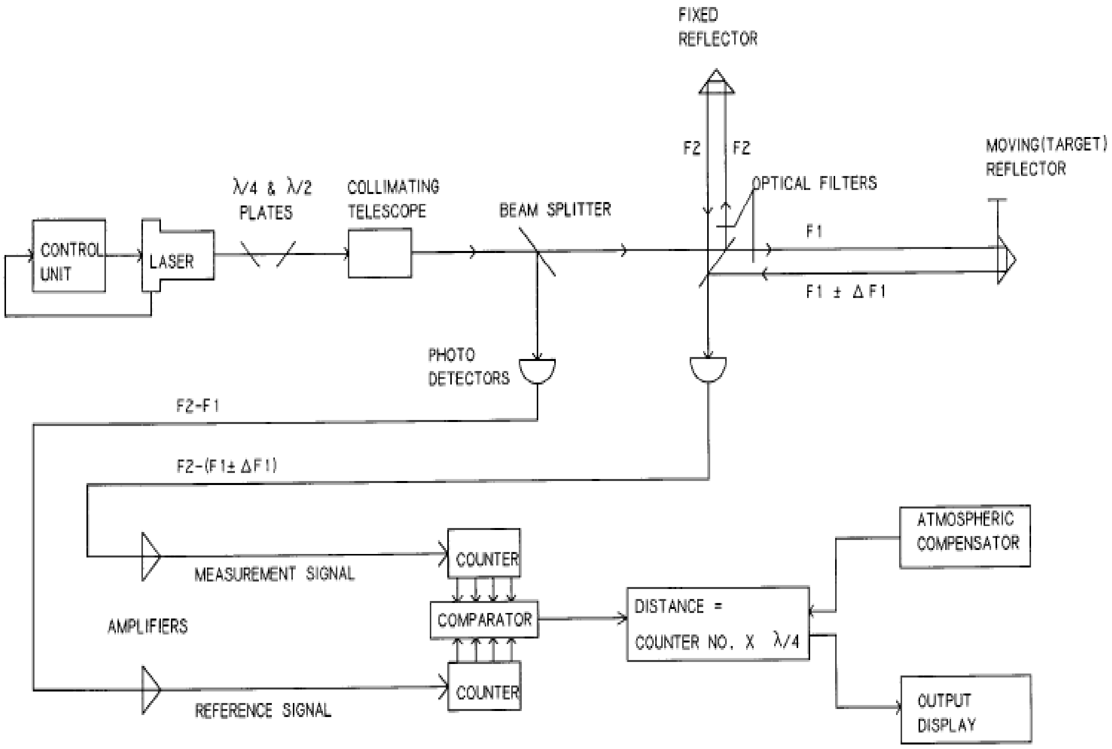
Thus, $\Delta f \rightarrow \Delta\omega \rightarrow \Delta\varphi \rightarrow \Delta X \rightarrow X$

As for the accuracy of the laser interferometer is,

accuracy= 0.1ppm for commercial interferometer

= 1 part in 10^{11} for I_2 stabilized laser

where I_2 (Iodine) stabilised laser is to separate the light generation unit from the rest of laser tube such that a cell of I_2 is inserted into the cavity; “Length Standard”



Source: Dr. H. J. Pahk’s PhD Thesis, University of Manchester

Length measurement using the Laser Interferometer

Two frequency laser, F1, F2, from the Zeeman laser source is divided into two direction by the beam splitter, one for the measurement beam, the other for the reference beam. The beam splitter is a kind of half mirror such that half of beam is reflected and the other half is transmitted. The ratio of reflection and transmission can be adjusted by the material coated. The reference beam of dual frequency, F1, F2 is detected by the photodetector, measuring the F2-F1 signal for reference beam. The measurement beam meets the second beam splitter, then divided into the two beam path, one toward the fixed mirror (reflector, corner-cube) and the other toward the moving mirror(reflector, corner-cube). After the second beam splitter, the light becomes the laser beam of single frequency, F1, F2, via passing through the narrow bandwidth optical filters, respectively.

The beam of F2 frequency is reflected from the fixed mirror, then arrives at the beam splitter, and waiting the beam from the moving mirror for the interference. The F1 frequency beam is reflected from the moving mirror, and arrives at the beam splitter, with the changed frequency F1±ΔF1 by the Doppler effect. The two beams are interfered, and measured by the photo detector, giving the F2-(F1±ΔF1) signal for the measurement beam. The two signals are compared and accumulated at every time interval. Therefore the distance can be calculated as the product of accumulated number and quarter wavelength of light.

Wavelength compensation for the Laser Interferometer

Laser wavelength is always changing, thus it needs to be compensated for higher accuracy , according to the condition of media beam travelling.

The wavelength, λ, is the function of temperature, atmospheric pressure, and humidity, and the wavelength increase when the entropy increase for the beam travelling media.

For small change of ΔT, ΔP, ΔV;

$\lambda(T,P,V) \fallingdotseq \lambda_0(T_0,P_0,V_0) + \partial\lambda/\partial T \cdot \Delta T + \partial\lambda/\partial P \cdot \Delta P + \partial\lambda/\partial V \cdot \Delta V$

$\fallingdotseq \lambda_0[1 + K_T(T_m-20) - K_p(P_m-760) + K_H(V-10)]$

$= \lambda_0 + \Delta\lambda$

Thus $\Delta\lambda/\lambda_0 = K_T(T_m-20) - K_p(P_m-760) + K_H(V_m-10)$ [ppm]

where K_T=0.93ppm/K, K_P=0.36ppm/mmHg, K_H=0.05ppm/mmHg;

Tm=mean air temperature of media, reference=20°C

Pm=mean air pressure of media, reference=760mmHg

V_m=partial pressure of water vapor in the media, reference=10mmHg,

and V_m=R.H/100 · P_s, where R.H=Relative Humidity[%],

P_s= saturated vapor pressure of water vapor at the media temperature

In practice, at least 3 sensors are closely located to the beam path, and measurement for temperature, pressure, and humidity are performed for the media during the whole measurement sequence. It also should be noted that the sensor measurement results have to be checked prior to the real measurement whether they perform proper measurement.

Ex) For an environmental condition, T=23°C, P=758mHg, and R.H.(Relative Humidity)=50%, predict the wavelength change.

T_m=23, P_m=758, V_m=0.5*Ps, and P_s=17.6 mmHg from the Dew point table, thus V_m=8.8mmHg.

Thus $\Delta\lambda/\lambda_0 = K_T(T_m-20) - K_p(P_m-760) + K_H(V_m-10)$

=0.98(3)-36(-2)+0.05(-1.2)=3.45 [ppm], ant it will give

-3.45 um error for 1m length measurement.

(Why the minus sign?)

Procedures for Length measurement by the laser interferometer

Optics Setup

Laser tube, Interferometer optics togethe with fixed reflector, moving retroflector optics, wavelength compensation unit together with the sensors for P_m, T_m, V_m The beam should be aligned parallel to the length of measurement, and the dead path should be minimized as possible. The Abbe offset also should be minimized.

Warm-Up Sequence

A warm-up sequence of at least several forward/backward cycles is recommended for the measurement travel of each linear axis, using the same program or manual operation to measure

Measurement Step, Number of repeat measurement

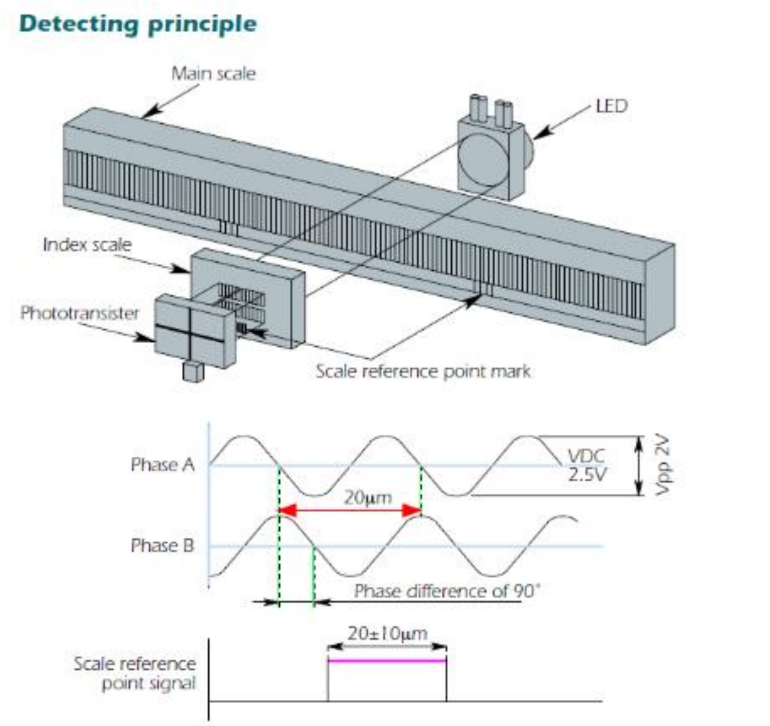
Small measurement steps are recommended if possible, and minimum 10 measurement steps are strongly recommended for the whole machine travel.

At least 3~5 sets of bi-directional (forward and backward) measurements are strongly recommended for each axis.

All scales or lead screws may have periodic error caused by the pitch error in lead screw, mis-mounted nuts; error in line spacing for optical scale; and error in coil spacing for inductive scale. Some form of interpolation error may occur during the electronic interpolation between scale divisions.

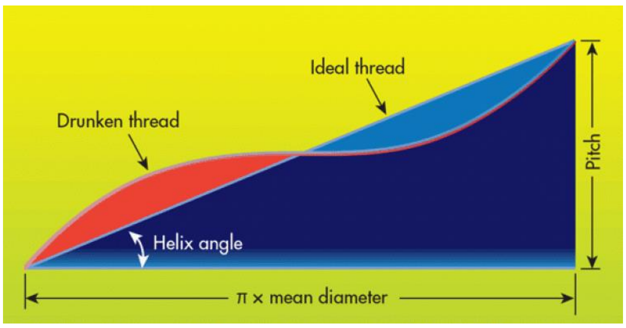
When any periodic error of linear scale/lead screw is to be measured, the positioning error measurement is performed for about 20 points uni-directionally over the two periods of the expected pitch.

Linear Optical Scale



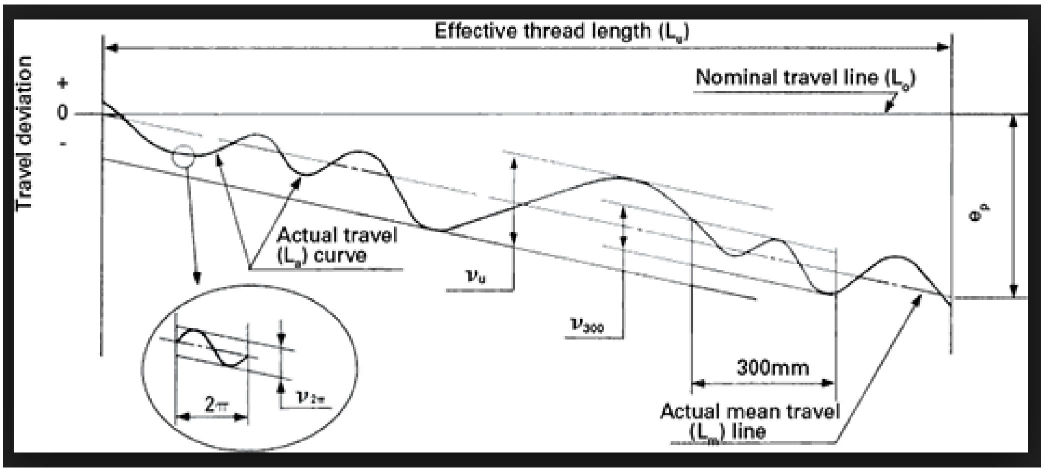
The detector of each scale unit consists of a light source (LED) and a photoelectric device (phototransistor) which face each other with the main scale and index scale between them. When the main scale moves, relative to the index scale, the quantity of light that is transmitted through the gratings on the index scale varies with the same period as the grating pitch. This variation of light intensity is converted into electrical signals and output as two-phase (A and B) waves with a phase difference of 90°. The display unit divides these signals to determine the direction of the scale movement, and digitally displays the displacement of the scale.

Source: Mitutoyo catalog for optical scale, and interpolation electronics such as the quadrature decoding gives the finer resolution; Pitch/2^N ≒ 0.1 um for Pitch=20um, N=8 (bit)



'Screw Drunkenness', source: machine design

Lead Accuracy of Precision Ball Screws



Source: Nook Industries

Lead Screw Grade

Tolerance on specified travel (+/- *ep*) and travel variation (v_u) of positioning (C type) ball screws

Accuracy grade		C0		C1		C2		C3		C5	
over	or less	+/- *ep*	v_u	+/- *ep*	v_u	+/- *ep*	v_u	+/- *ep*	v_u	+/- *ep*	v_u
–	100	3	3	3.5	5	5	7	8	8	18	18
100	200	3.5	3	4.5	5	7	7	10	8	20	18
200	315	4	3.5	6	5	8	7	12	8	23	18
315	400	5	3.5	7	5	9	7	13	10	25	20
400	500	6	4	8	5	10	7	15	10	27	20
500	630	6	4	9	6	11	8	16	12	30	23
630	800	7	5	10	7	13	9	18	13	35	25
800	1000	8	6	11	8	15	10	21	15	40	27
1000	1250	9	6	13	9	18	11	24	16	46	30
1250	1600	11	7	15	10	21	13	29	18	54	35
1600	2000			18	11	25	15	35	21	65	40
2000	2500			22	13	30	18	41	24	77	46
2500	3150			26	15	36	21	50	29	93	54
3150	4000			30	18	44	25	60	35	115	65
4000	5000					52	30	72	41	140	77
5000	6300					65	36	90	50	170	93
6300	8000							110	60	210	115
8000	10000									260	140
10000	12500									320	170
Effective thread length (mm)		Units (μm)									

Source: Design World