Light Waves as Standard of Length
Light Waves

- Wave Model of Light
- Introduction to Interference
- Interferometry Applied to Flatness Testing
- Additional Interferometry Applications
- Interferometers.
History

Christiaan Huygens (1629-1695)
• First major proponent of the wave theory of light
• Considered light as a wave motion propagated in ether
Light Wave

A = Amplitude
$A^2 = \text{Intensity}$
$\lambda = \text{Wave Length}$
$V = \frac{\lambda}{T} = \text{Velocity of Transmission}$
$n = \frac{1}{T} = \text{Frequency}$
Light Waves as Standards-Benefits

• High Degree of Accuracy
  – Used by the International Committee of Weights and Measures
  – Meter is defined as: 1,650,763.73\(\lambda\)
  – \(\lambda = \) Wavelength of the orange-red isotope of Krypton 86 (605.78 nm)
  – Subdivision to 1 part per million

• Virtually Independent of Ambient Conditions
  – Temperature
  – Pressure

• Reproducible
  – No need for a physical standard artifact.
Light Sources

Krypton 86 (605.78 nm)
– Excitation takes place at very low temperatures (~68°K)
– Used as International Standard of Length

Mercury 198 (546.1 nm)
– Less expensive
– Green light easily separated with filters
– Drawback – radiates a mixture of wavelengths

Cadmium (644.85 nm)
– (Almost) symmetrical red spectral line
– Official secondary standard of length

White light (~500 nm).
Light Sources

- **Gas Lasers**
  - Helium – Neon (632.8 nm)
  - CO2 – (10600 nm)

- **Gas Lasers - advantages**
  - Produce highly monochromatic light
  - Highly intense (1000 times more intense than others)
  - Created by exciting a mixture of neon and helium in a special discharge tube

- **Gas Lasers - disadvantages**
  - High cost
  - Wavelength affected by temperature and vibration
  - Special optics required to spread the ray.
Interference- Basics

Consider Two Monochromatic Rays
When the two waves are in phase, they add:
Interference- Basics

When they are 180° out of phase, they cancel.
Interference-Basics

- The resultant wave will equal the sum of the amplitudes \( R = A_1 + A_2 \)
Fringes

• Consider rays from two point sources, A & B

• The difference in the path lengths creates light and dark bands
  – Difference of odd number of half wavelengths: destructive
  – Difference of even number of half wavelengths: constructive
Fringe Formation

In order for light interference to occur, the following conditions are necessary:

- Light from a single source must be divided into two component rays
- Before being re-combined at the receiver, the components must travel paths whose lengths differ by an odd number of wavelengths
- Note, this is a relative measure
Using Interference for Flatness Testing

• Optical Flat
  – A circular piece of stress free glass or fused quartz
  – Has two planes that are flat and parallel
  – Surfaces are finished to an optical degree of flatness

• Properties of the Optical Flat
  – Vary in size from 25 mm to 300 mm diameter
  – Minimum expansion due to heat
  – Thickness (up to 50 mm) insures freedom from distortion.
Optical Flat

- Interference in an optical flat
Using Interference for Flatness Testing

- Place an Optical Flat on the surface
  - Will lie at a small angle to the surface due to air cushion
- Illuminate with monochromatic light
- Will observe fringes like those shown below
  - Dark fringes occur for \((1/2 + n)\lambda\), \(n = 1,2,3,\ldots\)
  - Light fringes occur for \(n\lambda\), \(n = 1,2,3,\ldots\)
Using Interference for Flatness Testing

- As the angle is increased, the fringes are brought closer together
- As the angle is decreased, the fringes spacing increases
- Each adjacent fringe represents a change in elevation of $\lambda/2$
- Total change in elevation = $\lambda/2*n$
Errors

- The line of sight should be perpendicular to the reference surface of the optical flat.
- Fringe spacing will be distorted
  - A viewing error of $30^\circ$ results in an error of 15%
  - A viewing error of $45^\circ$ results in an error of 40%
Convex / Concave Surfaces

- A convex or concave surface will result in concentric fringes, as shown below.
- To determine which, apply pressure to optical flat.
Practice for Using Optical Flats

- Handle optical flats carefully
- Handle optical flats minimally
- Ensure optical flat and work surface are clean by using a lint free soft cloth
- Never wring an optical flat to a surface – do not push hard on an optical flat
- Never wring two optical flats together.
Convex / Concave Surfaces

• In the following figure, the edge is half a wavelength higher/lower than the centerline
Drawbacks of Using Optical Flats

• Difficult to control the lay of the flat
  – difficult to orient the fringes to their best advantage

• Fringe pattern not viewed from directly above can cause distortion and generate errors.
Optical Flat with Fringes

8 inch Zerodur, J/10
Two Flats

Difference in heights is 0.0001 (±2μin WRT calibration)
Flat’s in Operation

Pushing on a Flat

Pivot Points
Interferometers for Flatness Testing
Interferometers for Flatness Testing

Surface flat & parallel

Surface flat but not parallel from left to right

Surface convex or concave

Surface flat but not parallel from top to bottom
Interferometers

• Michelson Interferometer

• Wyko NT9100 3-D Surface Profiler

• Laser Interferometer
Michelson Interferometer

- Compares the path lengths of light traveling two different directions
Michelson Interferometer

- Used for examining minute details of surfaces
- Used by Michelson to disprove the theory of ether
WYKO NT9100

Z- Resolution – 0.01 nm

Scan length – 10 mm

Lateral resolution – 1 μm
Interferometry-Basics
Plots from Whitelight Interferometer

Periodic and/or random deviations of a real surface from the nominal surface (texture)

Isotropic Surface: random

Turned Surface: Periodic
Surface morphology of groove bottom surface

3D groove height (other fresh groove)

Reference surface

Machined surface

Top surface
Laser Interferometer

• Counts the number of wavelengths that the laser traverses between the two points to determine distances
  – Measures only relative displacements
• Can be used to measure:
  – Linear Displacement
  – Angular Displacement
  – Straightness
  – Squareness
  – Parallelism
Laser Interferometer

\[ \Delta x = \Delta \phi \frac{\lambda}{4\pi} \]

- \( v_L \): Wave Velocity
- \( v_R \): Reflector Velocity
- \( f_0 \): Wave frequency
- \( \lambda_0 \): Wavelength
- \( \Delta \phi \): Position Shift
- \( \Delta x \): Position shift

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Instructor: Ramesh Singh; Notes: Profs. Singh/Kurfess
Laser Interferometer

- Typical laser path

- The accuracy of the interferometer is determined by the laser wave length, which is known to better than 0.05 parts per million.
Improvements

- Phase Detection
  - Michelson interferometer 1/8 resolution, easily
  - Can take half the signal and retard it by 90 phase
  - Using a quarter wave plate
  - First detector and second detector generate sine and cosine components.
Improvements

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Subdividing – Expanding Resolution

- Sine and cosine detector output follow a predictable sinusoidal curve
- Common resolution interpolators 16X to 256X
Improvements-Hetrodyne lasers

- As target moves faster, fringes occur faster and Doppler effects become significant
- Using a dual frequency laser with a slight variation in frequencies (20 MHz) one can generate a beat frequency.

\[
\begin{align*}
Y_1 &= A \cos(2\pi f_1 t) \\
Y_2 &= A \cos(2\pi f_2 t) \\
Y_1 + Y_2 &= A \cos\left(\frac{2\pi}{2} \left(\frac{f_2 - f_1}{2}\right) t\right) \cos\left(\frac{2\pi}{2} \left(\frac{f_1 + f_2}{2}\right) t\right) \\
\omega_{\text{waveform}} &= \frac{f_1 + f_2}{2} \\
\omega_{\text{amplitude}} &= \frac{f_2 - f_1}{2}
\end{align*}
\]
Laser Interferometry - Cosine Error

- **Definition**
  - the measurement error in the motion direction caused by angular misalignment between a linear displacement measuring system and the gate of displacement being measured
  - cosine errors are present when comparing any 2 displacement measuring systems

- **Assuming perfect laser (or artifact) and machine**
  - a laser angular misalignment causes the laser to always display a smaller or shorter value that the machine’s display
  - an angular misalignment of an artifact of length standard causes the machine’s display to always be longer than the artifact’s length
Laser Interferometry - Cosine Error

- Misalignment of the laser beam path to the axis of motion of the machine tool with results in an error between the measured distance and the actual distance traveled
Environmental Conditions

• In making linear measurements, it is necessary to compensate for:
  – the change in wave length of the laser light due to the ambient conditions of the air (VOL)
  – The change in length of the machine’s scales due to thermal expansion or contraction
Laser Dead Path

- The compensation for velocity-of-light (VOL) error is applied only to the portion of the path where displacement is measured
Summary

• Interferometry
• Laser Interferometer
• White Light Interferometer
• Errors