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News from Renishaw

Heterodyne and homodyne interferometry

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Continuing improvements in homodyne laser interferometry have now overcome the disadvantages compared to heterodyne systems, and provide important advantages such as fibre optic beam delivery and reduced latency variation

This white paper explains the key differences between the operating principles of homodyne and heterodyne interferometer systems. It then explains the unique design features of the Renishaw laser systems, including a unique detection scheme and high-performance amplifiers, which remove the limitations associated with other homodyne systems and provide additional benefits.

Concerns with homodyne laser interferometry

It is sometimes reported that homodyne laser interferometers have the following disadvantages when compared to heterodyne systems:

- sensitivity to signal intensity and ambient light variation causing drift in position readout
- inability to measure continuously
- direction sensing only at zero crossings (quadrature points)
- ambiguous error detection
- difficult to align

ML10 calibration laser

These disadvantages were true for early homodyne systems. However, the advanced homodyne designs, pioneered by Renishaw, have **totally eliminated all of these disadvantages**. The end result is that homodyne interferometry can now provide systems with **superior performance**.

HS10 laser scale

Renishaw is the world's leading supplier of homodyne laser systems, with a 15-year track record in homodyne laser interferometry and novel, patented technology. Renishaw has supplied thousands of calibration lasers into applications ranging from machine calibration, piezo actuator and nano-motion characterisation, to fibre optic alignment, semiconductor X-Y stage mapping, servo loop tuning and sensor calibration. Customers world-wide will attest to proven and reliable operation in the most severe environments. Renishaw's ML10 calibration laser provides superb, traceable accuracy (±0.7 ppm), proven at national standards laboratories around the world.

RLE fibre optic laser encoder

Heterodyne and homodyne operating principles

Heterodyne laser systems

Figure 1 shows a heterodyne laser system. The output beam from the dual frequency laser source contains two polarisations, one with a frequency F_1 , the other with frequency F_2. The beat frequency between them is $F_2 – F_1$. A polarising beam-splitter reflects the light with frequency F_1 into the reference path. Light with frequency F_2 passes through the splitter into the measurement path where it strikes the moving reflector causing the frequency of the reflected beam to be Doppler shifted by $\pm\delta F$. This reflected beam is then combined with the F_1 frequency light at the interferometer, and returned to the laser detector unit with a new beat frequency of $F_2 – F_1 \pm\delta F$.

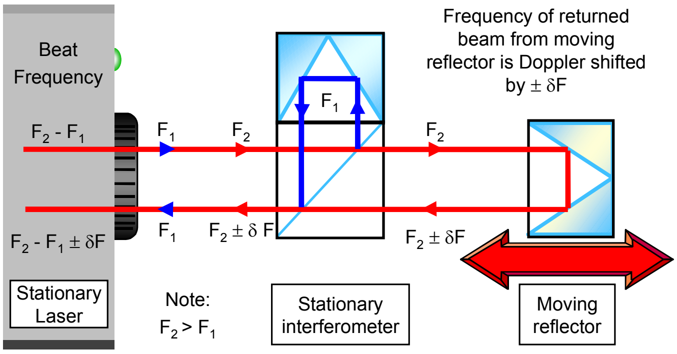


Figure 1 - heterodyne laser system operation

Figure 2 shows how the beat frequency of a heterodyne laser system varies with the velocity of the moving reflector. When the optics are stationary, the beat frequency is $F_2 - F_1$. As the optics move apart, the beat frequency rises by δF, if they move together it falls. High-resolution position sensing therefore requires stable measurement of signal phase, whilst a velocity limit occurs as the beat frequency approaches d.c.

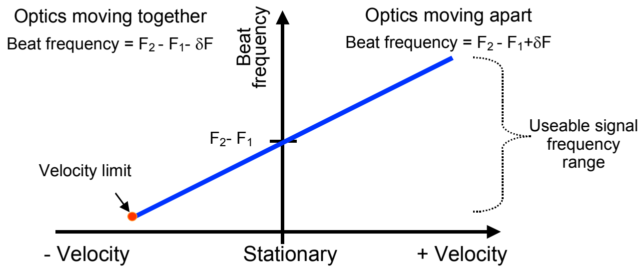


Figure 2 - heterodyne system: beat frequency vs. velocity

Homodyne laser systems

A single frequency laser source is used in homodyne systems (see Figure 3), which results in an outbound beam with a single frequency F_1. The laser beam from the stationary reference path is returned with frequency F_1 but the beam from the moving measurement path is returned with a Doppler shifted frequency of $F_1 \pm\delta F$.

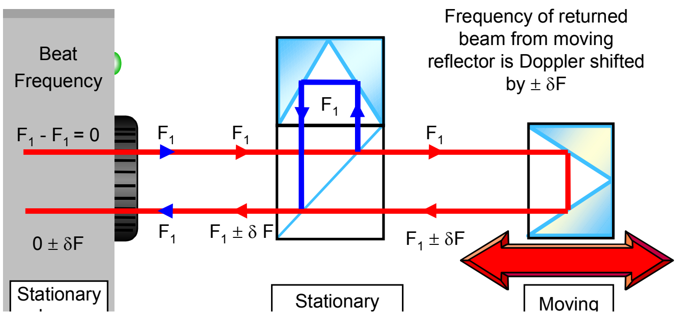


Figure 3 - homodyne laser system operation

These beams are interfered together in the detector to give a beat frequency of zero when the optics are stationary, whilst the beat frequency rises as the optics move in either direction. The direction of motion is detected from the signal phase change. Unlike heterodyne systems, high resolution position sensing requires stable measurement of signal voltage.

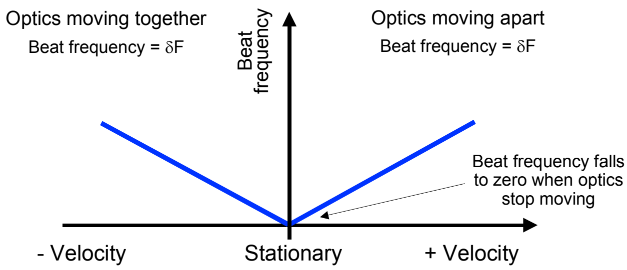


Figure 4 – homodyne system: beat frequency vs. velocity

Renishaw detection scheme

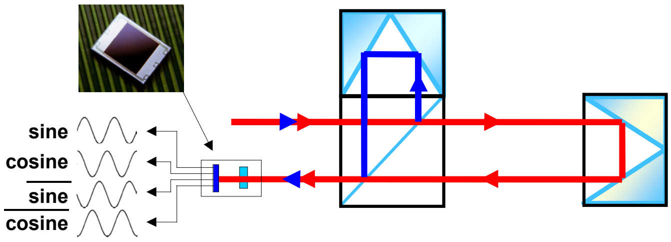
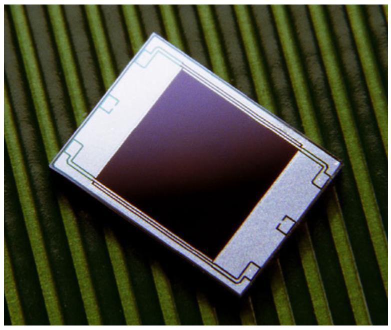


Figure 5 – Renishaw detection scheme

Renishaw's RLE10 homodyne laser system uses a special, integrated, phase sensitive photo-detector, mounted in the detector head that also includes the interferometer. The photo-detector is illuminated with the interfering reference and measurement laser beams from the interferometer, and produces four simultaneous real-time outputs of sine, /sine, cosine and /cosine. These four outputs change together, according to the phase difference between the interfering laser beams.



Renishaw's proprietary integrated phase sensitive photo-detector

The benefits of the single integrated photo-detector are:

- compact size
- easy alignment
- high stability output
- balanced differential sine and cosine outputs
- immunity to effects of ambient light variation, beam intensity variation and laser alignment changes
- high purity sine and cosine signals allow high accuracy interpolation

High performance amplifiers

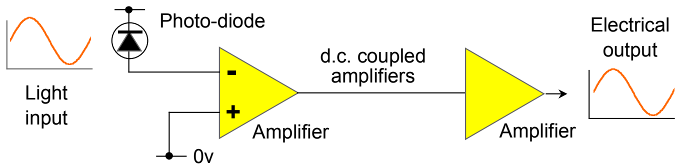


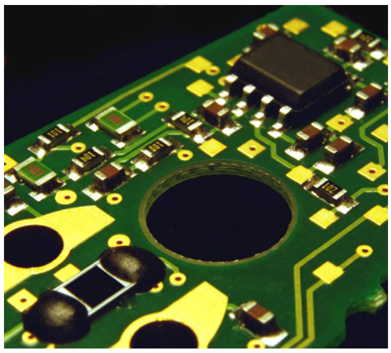
Figure 6 – amplification of detected signals

As explained above, homodyne laser systems require stable measurement of signal levels. Rapid advances in electronics have have produced very high bandwidth amplifiers which also have excellent d.c. performance. These amplifiers have allowed significant improvements in the performance of homodyne systems.

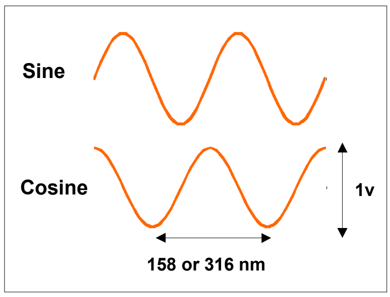
When used in a homodyne interferometer, these high performance amplifiers provide **differential**, real-time, 1V pk-pk sine and cosine output signals with:

- 316 or 158 nm period *
- low noise (~0.1 nm)
- high stability
- minimal distortion
- minimal latency (<100 nS) and minimal latency variation

* 316nm with single pass interferometer, 158 nm with double pass



Renishaw's detector unit circuit (above) and differential outputs (below)



Differential analogue sine and cosine signals are the industry standard feedback signal format supported by most motion control systems. Furthermore, they offer good noise rejection whilst allowing for transmission of high resolution data with a minimal number of wires. These factors, combined with their suitability for interpolation to sub-nanometre resolutions, makes them ideal for real time motion control of precision stages.

The balanced differential sine and cosine outputs from the photo-detector make it easy to reject the effects of electrical noise and ambient light pick-up, as well as the impact of variations in laser beam intensity and alignment. This is done using high quality differential amplifiers.

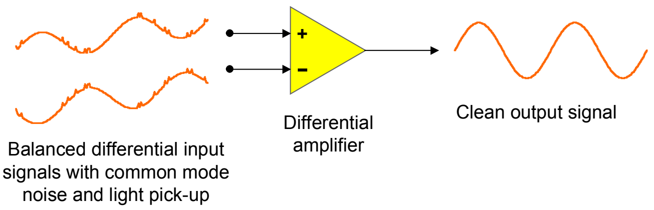


Figure 7 – noise rejection using differential amplification

Interpolation and counting

Renishaw use high speed flash A/D (analogue to digital) convertors and digital signal processing to simultaneously measure movement and signal strength. They provide a continuous readout of position, and direction, as well as unambiguous error detection.

If the sine and cosine signals are plotted on the X and Y axes of a graph they produce a circular "Lissajous" figure. When the optics are moving, the sine and cosine signals vary and sweep out a circular arc. When the optics are stationary the signals stop changing at a stationary point on the arc. The distance moved is measured by counting revolutions.

- 1 revolution = ~316 nm (single pass interferometer)
- 1 revolution = ~158 nm (double pass interferometer).

Higher resolution measurement is obtained by interpolation of the instantaneous phase angle, θ (refer to figure 8).

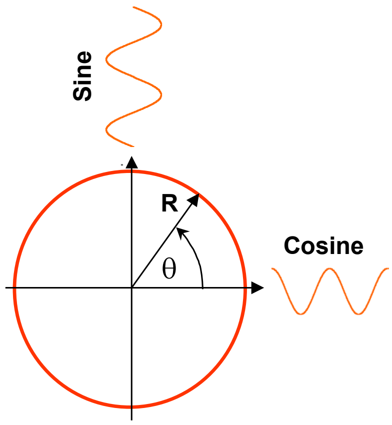


Figure 8 – 'Lissajous' figure

Counting

The sine and cosine signals are digitised by very high speed (Flash) analogue to digital (A/D) convertors. The most significant bit (MSB) outputs follow the zero crossings of the sine and cosine signals. These are the A.Quad.B digital quadrature signals that can be used drive a digital counter. The counting circuit is shown in figure 9.

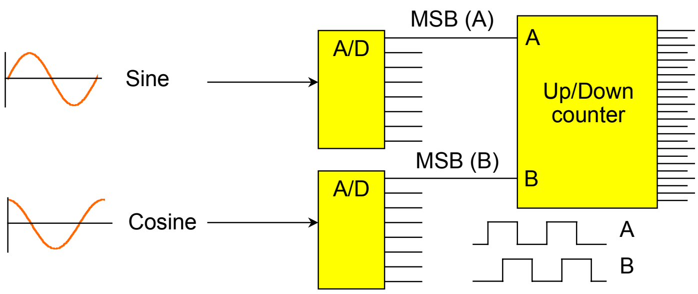


Figure 9 – counting circuit produces quadrature output

Error detection

Interpolation and signal strength monitoring

The outputs from the A/D convertors are also connected to the address inputs of a memory chip, the data cells of which have been pre-loaded with the interpolated angle (θ) and the signal strength (R) results, using the equations below:

- The instantaneous **signal strength** R, is calculated by: **R = SQRT (X^2 + Y^2)**

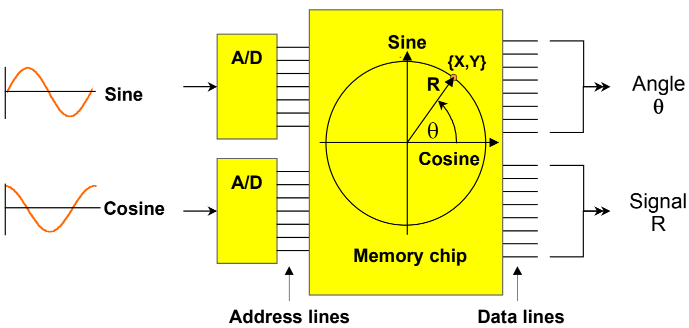


Figure 10 – interpolation and signal strength monitoring circuit

- The instantaneous interpolated **phase angle** θ, is calculated by: **θ = ATAN2(X,Y)**

Note: equations are quoted in Excel format

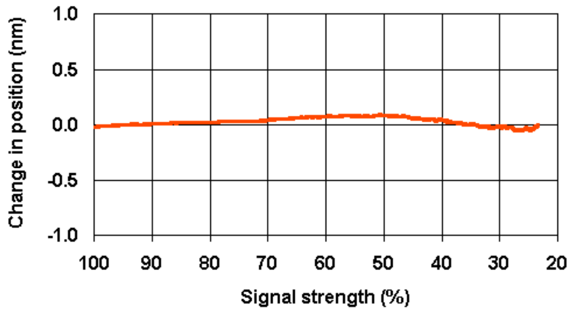


Figure 11 – Graph shows the stability of the interpolated sine and cosine output signals from a plane mirror Renishaw RLE10 laser system as the signal strength was reduced from 100% to 20 %

High stability position sensing

The use of both X and Y values to calculate the interpolated angle θ ensures the result is unaffected by variations in R, the signal strength (see figure 11 for more details). This, combined with the balanced outputs from the interference detector, provides a very high stability position readout, even if laser alignment, beam intensity or ambient light changes.

Continuous update and unambiguous error detection

Flash A/Ds can sample at frequencies of 100 MHz or more with 12 bit resolution. RAM and EPROM memories are available with similar access times. These components provide homodyne systems with sub-nanometre resolution data at update rates over 100 MHz.

The availability of synchronous digital A quad B signals and interpolated phase data from a single source allows the construction of extremely robust synchronous counting, interpolating and signal strength monitoring circuitry. Every reading is checked for signal strength loss and over-speed giving totally unambiguous error detection of the highest integrity. Figure 12 shows an example of this counting and error detection circuitry.

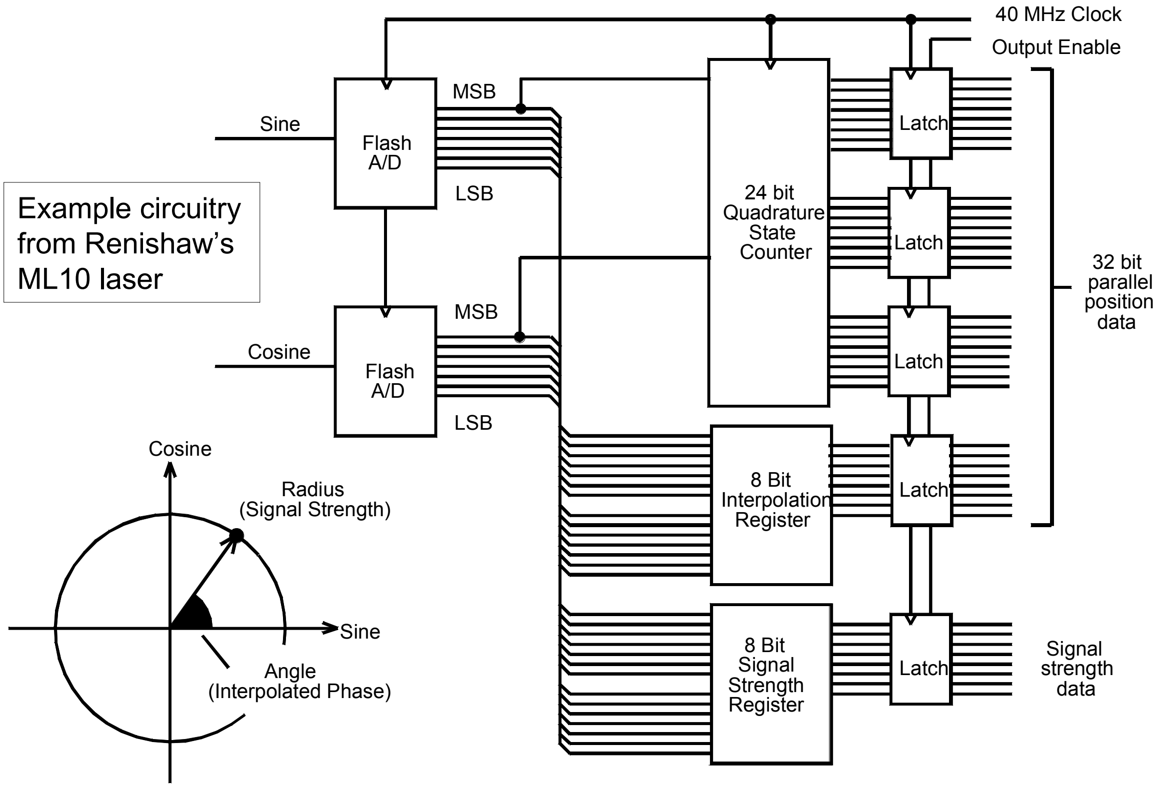
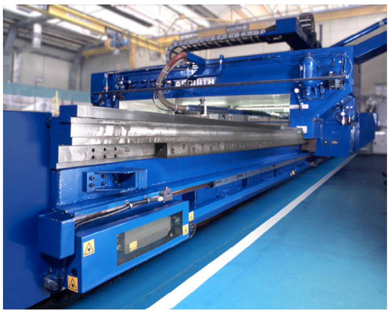


Figure 12 – every data bit is checked for signal strength loss and overspeed

Robust high integrity feedback
In addition to use for calibration and position feedback on small motion systems, Renishaw homodyne laser systems are frequently used for motion control of very large high speed milling machines. These machines operate 24 hours a day with axes from 5 to 50 metres long in dirty, noisy environments.

Even under these severe conditions the Renishaw HS10 homodyne laser interferometer provides reliable, continuous position feedback.



HS10 closed loop laser position feedback on an Asquith machine

Noise in heterodyne and homodyne systems

Effects of noise in homodyne and heterodyne systems
In order to measure to high resolution, both homodyne and heterodyne systems need to precisely determine the phase of the returned interference signal.

Homodyne systems measure phase by comparing the intensities of two sinusoidal signals (sine and cosine). By contrast, modern heterodyne systems measure phase by timing the arrival of zero crossings on a sinusoidal signal (see figure 13).

Because the signal slope at the zero crossings is nominally 45º, phase noise ≈ intensity noise. **Therefore the influence of noise on both systems is effectively the same**.

The charts in figures 14a and 14b illustrate this point. The graphs show the effect of 5% pk-pk noise on heterodyne and homodyne systems in a plane mirror interferometer.

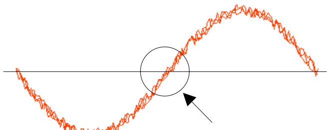


Figure 13 – heterodyne systems measure phase by timing zero crossings

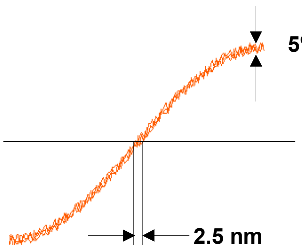


Figure 14a – impact of noise in heterodyne systems

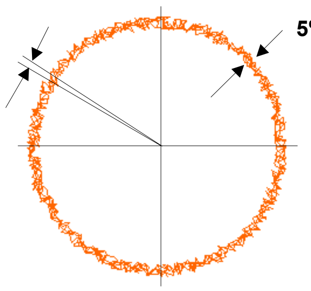


Figure 14b – impact of noise in homodyne systems

Heterodyne
- the zero crossing point shifts by ±1.25 nm

Homodyne
- the Arctangent result shifts ±1.25 nm

Note: The noise level on both systems has been exaggerated for visual clarity

High frequency noise reduction
Early heterodyne systems used phase locked loop circuits to detect the phase of the returned interference signal. These loops could average thousands of cycles of the sinusoidal signal to reduce the effects of high frequency noise. However, this severely reduced the dynamic response and increased the latency of the system. Modern high resolution, high speed motion systems cannot tolerate this reduction.

Therefore, many modern heterodyne systems directly time individual zero-crossings to reduce latency. But this gives them a similar noise sensitivity to homodyne systems. Downstream digital filtering can be used by homodyne and heterodyne systems alike, in order to trade response time against noise to a similar degree.

Low frequency noise reduction

Heterodyne laser systems eliminate low frequency noise by a.c. coupling the signal. This acts as a high pass filter, eliminating low frequency noise. Renishaw's homodyne systems use balanced signals and differential amplifiers with high common mode noise rejection to eliminate low frequency noise.

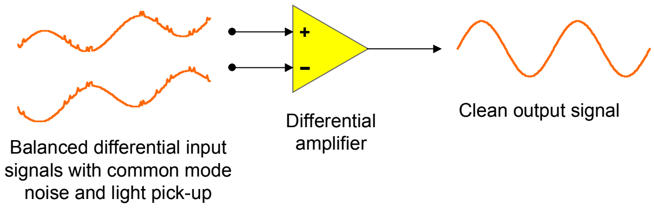


Figure 15 – common mode noise rejection

Low noise homodyne laser technology

Figure 16 shows the positional noise content of Renishaw's RLE10 laser encoder system at various bandwidths for correctly aligned plane mirror and retro-reflector configurations at short range in a vacuum.

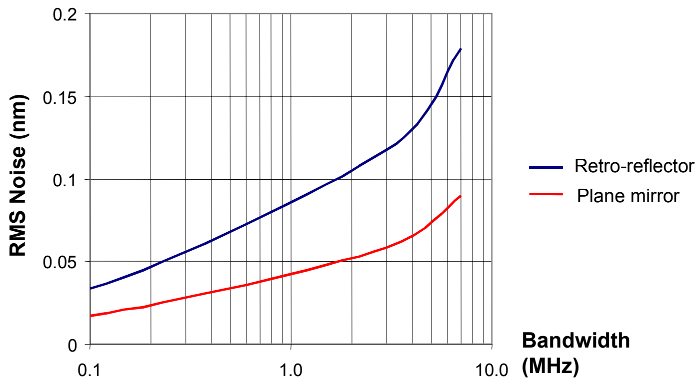


Figure 16 – positional noise vs bandwidth

Advantages of homodyne systems

Heterodyne systems need to produce two laser output frequencies. There are three basic methods, each with its own disadvantages:

- **Zeman split** - this requires large powerful magnets in the laser head making it bulky. Also the split frequency is typically limited to a few MHz which can limit the maximum speed of travel to 500 mm/sec (plane mirror).
- **Acousto-optic (AO) modulator** - causes misalignment between measurement and reference beams that must be corrected. AO modulator temperature changes can cause reading drift (unless an additional photo-detector is used to resample the reference beat signal after the AO modulator).
- **Dual mode laser** - has a very high beat frequency (~1 GHz) requiring very specialised electronics.

In a homodyne system the reference beam and measurement beams are split at the interferometer. The measurement is based on the optical path length changes after that point. By contrast, in a heterodyne system the reference and measurement beams are either split inside the laser (Zeman split or dual mode systems) or at the AO modulator.

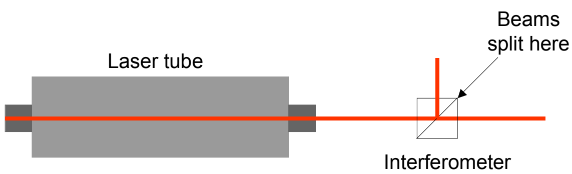


Figure 17a – homodyne systems split beams at the interferometer

Heterodyne systems are therefore sensitive to the nature of the medium through which the laser beams pass before the interferometer. This sensitivity means that it is difficult to deliver a heterodyne laser beam through an optical fibre. In order to preserve the

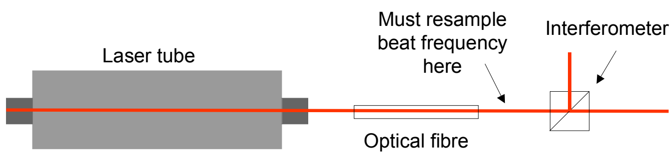


Figure 17b – heterodyne systems require resampling of the beat frequency external to the laser

polarisation state of the laser it is necessary to use polarisation preserving optical fibre (PPF), which is birefringent. Therefore, fibre temperature or stress changes alter the relative path lengths of the laser's measurement and reference beams causing laser measurement drift (unless an additional photo-detector is used to resample the reference beat signal after the optical fibre).

Homodyne systems allow easy alignment

The Renishaw RLE10 system is able to use fibre optics to deliver the beam directly to the point of measurement, avoiding the need for beam benders and splitters. The Renishaw RLD10 detector units incorporate Renishaw's integrated photo-detector and a laser beam steering optic for simple alignment.

Laser beam delivery and alignment is a simple, quick "bolt down and dial in" process, unmatched by any other system.

Renishaw's RLE10 laser encoder provides simple 'bolt down and dial in' installation thanks to fibre optic laser delivery and an integral beam steerer in the RLD detector head

Minimal latency variation

The readily available analogue sine/cosine outputs from the Renishaw's homodyne systems are effectively real time as they avoid any digital signal processing delays. In addition, the delay (latency) between sampling these signals with the A/D convertors and producing a valid digital output of position (see figure 10) is entirley stable and predictable. In contrast, the zero-crossing detection method employed by some heterodyne systems suffers from a variable and unpredictable delay as the system must wait for the next zero-crossing to occur before it can produce a measurement. Whilst it is possible to overcome this problem, the circuitry required is far more complex than that required by a homodyne system.

Conclusion

Renishaw have eliminated the performance problems previously associated with homodyne interferometers to produce robust systems with a world-wide reputation for accuracy and reliability.

The latest Renishaw laser encoder provides the additional benefits of fibre optic beam delivery, integrated beam steering technology, minimal latency variation and real time sine/cosine outputs.