Technical Article

(Ref: ZET06)

14th October 2010

Measuring the Rotation Angle of Large Diameter Shafts

Traditional rotary encoders can be readily fitted to shaft diameters of less than 2 inches, but what happens if your design needs a much larger diameter through shaft or bore? Mark Howard of Zettlex Ltd describes the traditional approach and a new, robust, more accurate approach using inductive sensors.

Traditional Approach – Indirect Measurement

There are many devices for measuring shaft angle. Potentiometers, resolvers and optical encoders are the most common. Potentiometers offer a simple, low cost solution but are not suitable for harsh environments or continuous rotation. Resolvers are reliable even in tough conditions but their high cost, weight and bulk mean that they are rare outside ‘high spec’ sectors such as defence, aerospace, oil & gas.

Optical encoders are not as robust as resolvers but are widely available, keenly priced and are an automatic choice for some engineers. There are many types of optical encoder; the most popular have a small (typically <1/2” diameter) input shaft with incremental pulse or absolute digital output. Through shaft versions are available but the bore is usually limited to <2”. Above this, encoder prices increase dramatically and availability dwindles.

So how do you measure the angle of a large diameter through shaft of, say, 3” or larger? Traditionally, a smaller ‘secondary’ shaft is used and its motion geared to the larger ‘primary’ shaft. In other words, the angle of the primary is measured *indirectly* from the angle of the secondary. For many years, this has been the approach in gun turrets, rotary tables, radar antennae, security cameras, large motors, medical scanners and telescopes. Large bores are often needed for slip rings, cables, hydraulic pipes or fibre optics.

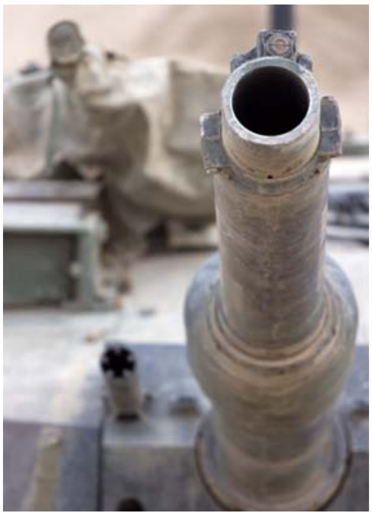

Fig. 1 – Measuring Azimuth & Elevation Angle often needs large through shafts

The motion of the secondary shaft is usually geared from the primary shaft but it could also be driven from a toothed belt or chain. A simplified schematic of this traditional approach is shown in Figure 2.

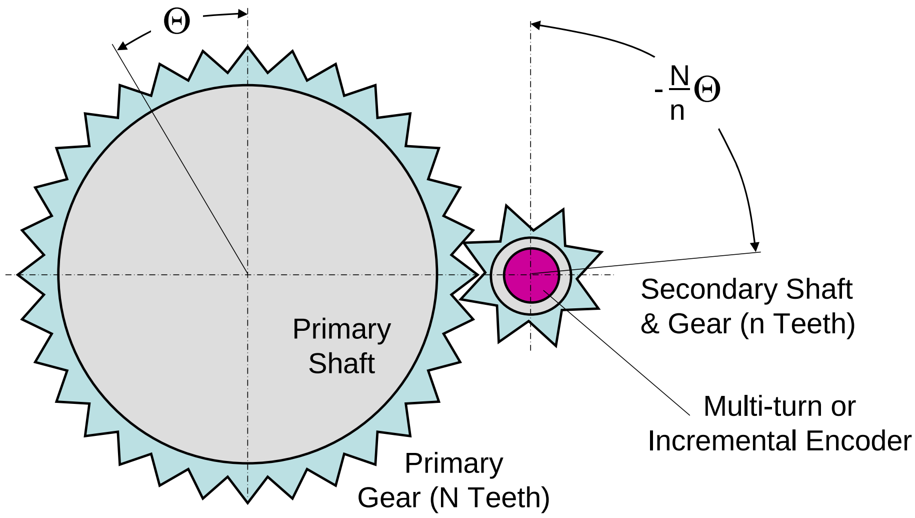

Fig. 2 - The 'Indirect' Measurement Method

Since the secondary shaft is usually small, there is a wide choice of rotary encoders and mechanical mounting is easy. If absolute (rather than incremental) angle of the primary shaft is required, then additional reduction gearing or a multi-turn encoder can be used.

Problems with the 'Indirect' Approach

The angle of the primary shaft is calculated from the angle of the secondary – assuming that the rotation of the secondary varies proportionately with the primary. Not unreasonable? As ever, the devil is in the detail and, in practice, there are problems with this assumption.

As a general rule, if the required measurement accuracy is <1 degree, indirect measurement is probably not going to work reliably – or at least not for long. There are two parts to the problem – accuracy and reliability.

Inaccuracy comes from the number of factors in the (indirect) system's tolerance stack up. For a system coupled by gears, these factors include (but are not limited to):

1. Encoder measurement accuracy.
2. Encoder thermal coefficients – *i.e. drift in encoder's output due to temperature.*
3. Differential thermal expansion in gears, shafts, bearings, mounts, etc.
4. Gear backlash.
5. Gear Wear.
6. Concentricity of gears on shafts.
7. Gear train/tooth strain versus torque.
8. Shaft concentricity.
9. Variation of gear position with shock or vibration.
10. Tolerance on gear tooth position around the pitch circles.
11. Tolerance on primary and secondary shaft centre distance.
12. Variation in shaft centre distance - due to load or bearing clearances.
13. Variations in lubrication – due to amount, type and thermal effects.
14. Mechanical friction – especially stiction at low speeds/torque.
15. Effect of foreign matter on gear teeth surfaces.
16. Twist due to torque in shafts.
17. Shaft bending due to side loading.

Each of these effects alone is probably not a major influence on accuracy. The problem arises because all these effects stack together. Experience shows that factors #1, 2, 3, 5 and 10 are larger than most engineers expect.

A common misconception in #1 is that an encoder with 1,000 counts per revolution is accurate to 1/1000th of a rev. If you read the small print in the encoder specification, it soon becomes clear that resolution is not the same as accuracy. Also, any accuracy calculations should account for thermal coefficients (#2) and thermal expansion/contraction (#3) at the temperature extremes.

Factor 4 is not normally an issue in geared systems because most engineers know about anti-backlash gears and will use them if required. Unfortunately, truly anti-backlash belts or chains are yet to be invented.

Factor 9 is notable, as this is often overlooked. A typical design approach is that if the primary gear has 100 teeth and the secondary gear has 10 teeth, then – because the gears are coupled (i.e. cannot jump a tooth) – when the primary rotates once the secondary gear rotates 10 times. This part is true, but when the primary gear rotates 0.37125 times, the secondary will not have rotated exactly 3.7125 times. This is because there is a tolerance on gear teeth position around the gear's pitch circle. This will cause a periodic non-linearity. In other words, inaccuracy. Depending on how good the gears are, the secondary will have rotated 3.7125 +/- 0.1000 times.

As regards reliability, most engineers know that the reliability of any mechanical system is proportional to the number of parts in it – especially moving parts.

Gear, pulley or chain systems are susceptible to foreign matter – especially in a large reduction gear train. This can often be overlooked by engineers who expect their equipment will always be operated within the specified envelope and all servicing will be done by diligent, skilled personnel who always replace baffles and seals.

Experience shows this is wishful thinking. Foreign matter often arises from unexpected, sometimes bizarre, conditions. Examples of foreign matter to consider are dust, sand, mud, rain, snow, ice, hail, condensation, insects, rodents, rodent waste, mould, fungus, rogue mechanical tools, rogue mechanical fasteners, swarf *(from original production),* particles (*from wear*), coffee *(from accidental spillage*), cola, pollen, air-borne seeds, vegetation, water residue, smoke/cordite residue, insect faeces/secretions, snails, worms, brake/clutch dust, hair, textile fibres. Far fetched? In my experience, unexpected foreign matter is to be expected. Recently, a CCTV had a major product recall after their housings became the ideal place for wasps to build their nests. Dead bees, bits of honeycomb, larvae, honey, pollen and bee waste will defeat a gear and optical encoder system.

A New Approach – Direct Measurement

As a general rule, if the position of an object is to be measured accurately then the measurement should be made at, or close to, the object. Measuring shaft angle directly simplifies the system and reduces the tolerance stack up. The result: improved accuracy and reliability.

So why doesn’t everyone use direct measurement? The reason is that, until recently, large bore rotary encoders were disproportionately expensive, delicate and difficult to fit.

Ring style optical encoders have been around for years but are expensive, bulky, need careful installation and are prone to failure with foreign matter. Similarly, large bore or ‘pancake’ resolvers have been around for many years but their price, complex electrical supply/signal processing and bulk make them unsuitable for most mainstream applications.

Zettlex IncOders enable a simple, effective and accurate way to measure the angle of large diameter shafts. These devices work on similar principles to contactless resolvers and are just as reliable in harsh conditions. Rather than wire spools or windings they use printed, laminar windings. This enables a low profile, annular encoder ideally suited to large diameter shafts. The electrical interface is simple due to on-board electronics – DC voltage in; absolute digital data out. The mechanical arrangement of these new generation devices is simple and eradicates all gearing. The result: a simple, compact, lightweight, low inertia, accurate and reliable solution.

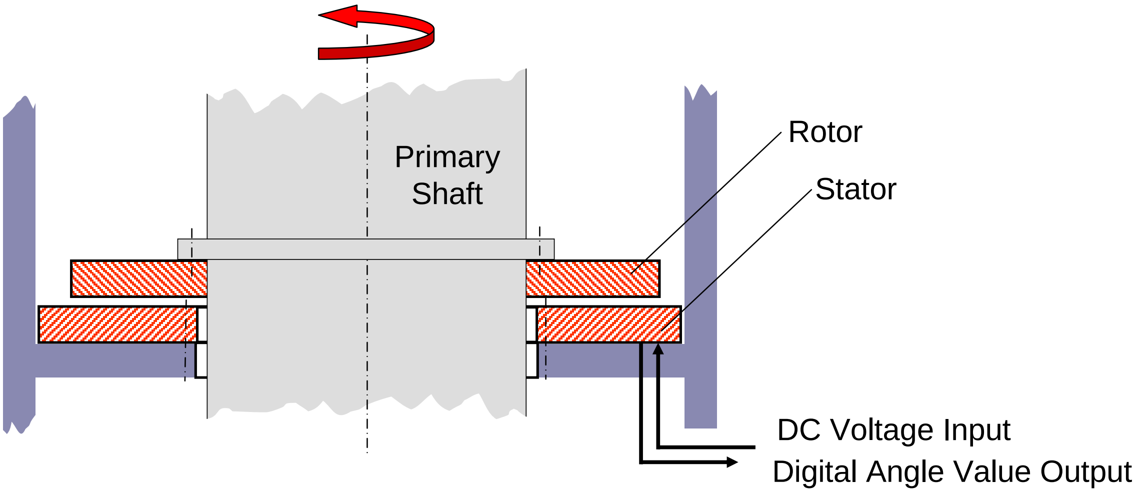

Fig. 3 - The 'Direct' Measurement Method with a New Generation Inductive Device

Fig 4 - Example of the New Generation of Inductive Rotary Encoder - rugged, flat, light & accurate with a big hole in the middle.