

Robust Monitoring of Rotary Motion using an Incremental Motion Encoder

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Abstract

The Incremental Motion Encoder (IME) [1] is a simple and inexpensive mechatronics instrument. It has now been commercialised and could have an enormous impact in a wide range of applications. It is a novel technique for the precise monitoring of the rotation of mechanical systems and particularly the behaviour of rotating shafts. It is well known that the angular position of a rotating shaft can be measured using an Incremental Shaft Encoder [2]. The IME is an innovative development in which two or more further read heads are added to the shaft encoder and the passing of every grating line at each read head is detected. Thus, the IME is able to resolve and measure the horizontal and vertical motion of the shaft [3], as well as improving the measurement of angular position. In addition radial and torsional vibrations, and other statistics, can be calculated. This paper describes the principle of the IME and reports on our recent developments.

1 Introduction

Unwanted vibrations are a major problem in bearings on rotating shafts and often indicate the onset of failure in the bearings. Traditionally, vibrations in rotating shafts have been monitored in two ways. Accelerometers are relatively easy to fit but they measure absolute vibration and cannot always distinguish a bearing's vibrations from background vibrations. Proximity transducers can be carefully positioned close to a precision ground shaft but they are subject to minor surface irregularities. If data on angular motion or torsional vibrations are needed, then an Incremental Shaft Encoder [2] must also be used, Figure 1(a). However, by adding two or more read heads to an incremental shaft encoder, it can be converted into an Incremental Motion Encoder (IME) [1], Figure 1(c). Figure 2 shows an example of one of our experimental rigs and Figure 3 shows the recently developed commercial device. The diagram in Figure 4 illustrates how the horizontal displacement can be calculated in the case of four equally spaced read heads.

The presence of the three (or more) read heads allows the IME to resolve and measure not only the angular position of the shaft but also the horizontal and vertical motion of the shaft in a plane perpendicular to its axis [1, 3]. These motions, including

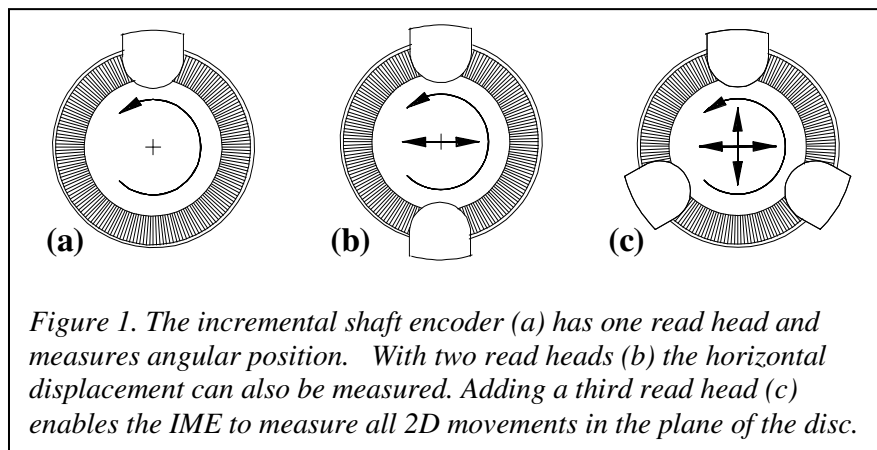


Figure 1. The incremental shaft encoder (a) has one read head and measures angular position. With two read heads (b) the horizontal displacement can also be measured. Adding a third read head (c) enables the IME to measure all 2D movements in the plane of the disc.

both radial and torsional vibrations, are difficult to measure accurately using traditional metrology. The path of the disc centre, or orbit plot, is shown in Figure 5. The IME technology is robust, versatile, broadband, digital and highly stable, and one set of readings allows all three degrees of freedom to be measured [3, 4]. Additional information can be obtained by further analysis of

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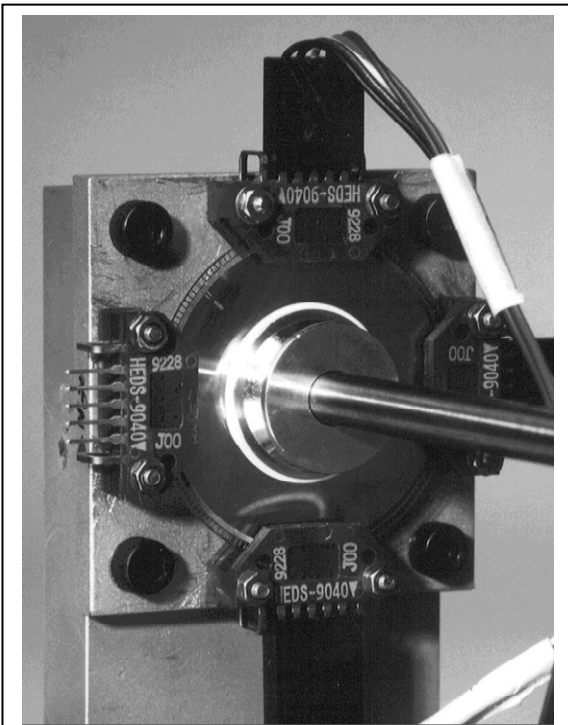


Figure 2. Our experimental rig showing the configuration of the encoder disc attached to the shaft (diameter 8mm.) and the four optical read heads used to detect the motion.

the data, for example velocity, acceleration and shaft loading. Analysis of these data over time can provide information about long-term degradation of a bearing and facilitate prediction of bearing life.

2 Measurement of Rotary Motion

Simple monitoring of rotary motion involves using an Incremental Shaft Encoder (ISE) [2], which can also provide some information about torsional behaviour [5]. Traditionally, monitoring vibrations traditionally requires either accelerometers or proximity sensors, both of which are analogue devices. Accelerometers are relatively easy to fit but may degrade over time. However, they are also of limited usefulness, because they suffer from cross axis sensitivity and may not distinguish between vibrations in the bearing itself and those in the whole structure. Proximity sensors, on the other hand, require precision grinding of the shaft and need very careful positioning and calibration. They are also subject to minor irregularities in the shaft surface. Both devices suffer from restrictive bandwidths and provide no information about angular motion or torsional vibrations. An IME, however, can provide digital data about both radial and torsional vibrations, as well as all the angular motion data provided by an ISE.

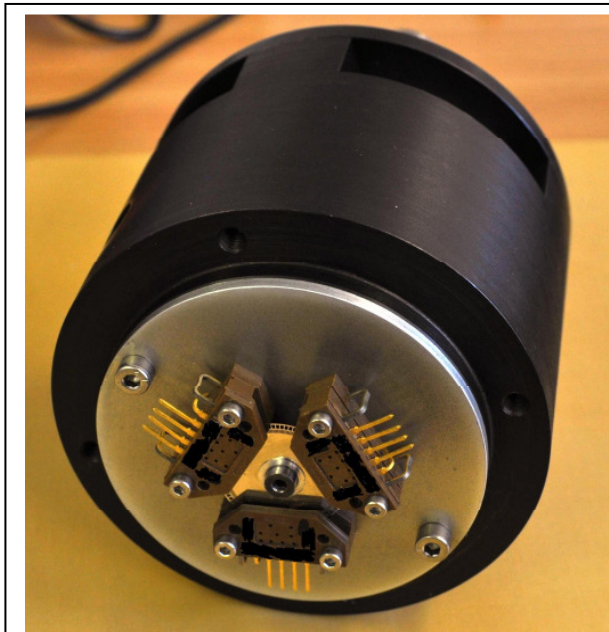
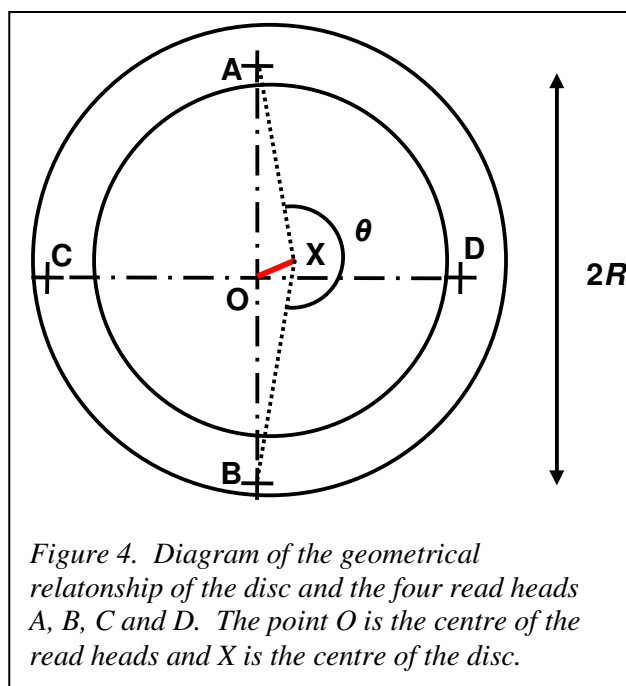


Figure 3. The commercial IME device, showing the encoder with three equally spaced optical read heads. The device has been designed with a standard attachment for testing machine tool bearings.

The IME is a new and potentially very important mechatronics approach to monitoring the rotation of mechanical systems. It is based on the ISE, which is already widely used. Our innovation is to use three or more read heads rather than the single head of the ISE. These three heads yield data which are more comprehensive and more precise than from a single head. In particular, the IME can provide information about the loading, vibration and motion of the shaft in the plane perpendicular to the axis of rotation. Another major aspect of the IME is that the data are sampled at much higher frequency than is conventionally used for the ISE. Rather than recording the angular position of the disc at equal intervals of time, the IME records, for each read head, the time when every grating line passes that read head. We have developed algorithms to process the large quantity of data obtained to provide information about not only radial and torsional vibrations but also the detailed motion in the plane perpendicular to the axis of motion.

The IME technology is particularly appropriate for gearbox monitoring. The high accuracy high bandwidth measurement of the input/output shaft phase relationships under differing load conditions can be used to characterise various types of wear in the transmission chain [6]. Torsional vibrations due to



gear wear can be distinguished from those caused by problems in the bearings. With appropriate digital sensors, additional encoders can be embedded inside the hostile environment of the gearbox for more detailed evaluation of bearings and gears [7].

3 How the IME Works

The IME technique involves collecting the data from three (or more) identical read heads spaced round the circumference of a rotating grating disc, Figure 1(c). Each read head senses the passing of every grating line and the time is recorded. From these timings the IME software can calculate many different measurements related to the motion.

3.1 The Principle of the IME

Three read heads are sufficient for the IME to work but the explanation is simpler in the case of four read heads evenly spaced round the grating disc. One of our experimental rigs, using four equally spaced read

heads, is shown in Figure 2. Figure 1(b) illustrates how the horizontal displacement can be found from two read heads. Figure 4 demonstrates the geometrical relationship between the disc and the read heads, with the displacement greatly exaggerated. In order to calculate the x -displacement of the centre of the disc relative to the read heads at a given time, the value of the angle θ must be found using the data from readheads A and B. Then the x -displacement is then given approximately by $x = R \tan[\frac{1}{2}(\theta - \pi)]$, which can be simplified further to $x = \frac{1}{2}R(\theta - \pi)$, provided that $|\theta - \pi| \ll 1$ (in radians). The y -displacement can be calculated in a similar way from read heads C and D. Different formulae need to be used for three read head case, as used for the commercial device shown in Figure 3, or when there are unequal angles between the read heads. After the position (x, y) has been calculated at many different times, a two-dimensional orbit plot of the centre of the disc is obtained, as shown in Figure 5 for one complete revolution of the shaft. When several revolutions of

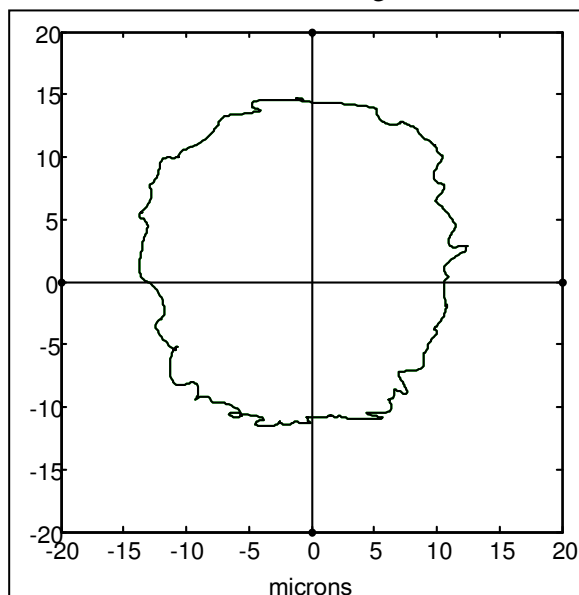
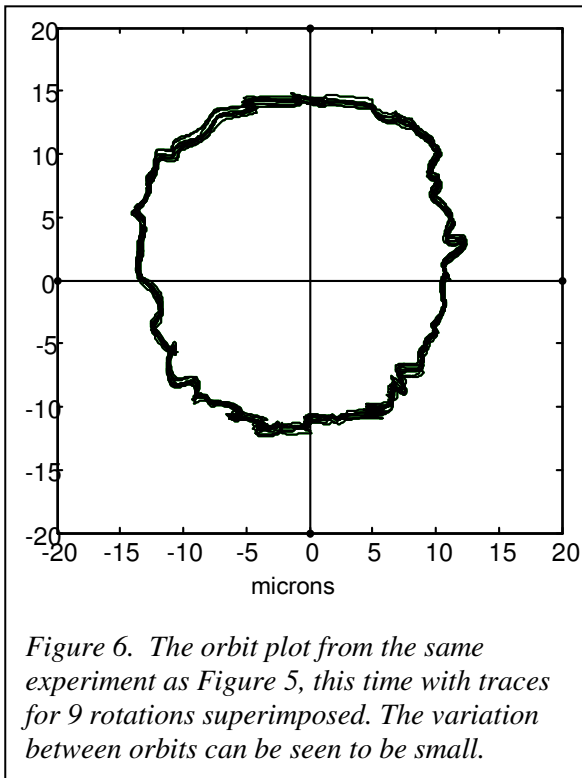


Figure 5. The 2D orbit plot showing the path of the displacement of the disc centre for one rotation of the shaft with an angular contact bearing rotating at 529 rpm using the commercial IME shown in Figure 3.

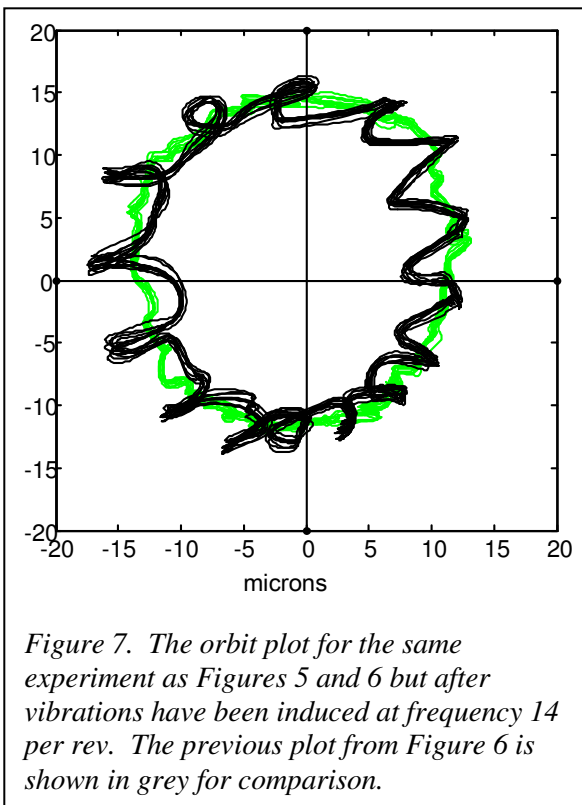
data are present, the path of the disc centre can be seen to have repeating features, as shown in Figure 6.

Thus, the orbit plot is the trace of the position of the centre of the disc relative to the read heads, which is caused by the rotation of the shaft to which the disc is attached. The radius of the orbit depends on the distance of the disc centre from the centre of rotation and is often much smaller than the separation of the grating lines. We aim to keep the distance small but we cannot control small discrepancies, because we do not have precise control over the location of the centre of rotation. The starting angle not only depends on the relative position of the two centres but also on the orientation of the disc when data collection begins. The method of collection may allow us to choose the latter but not the former. When the orbit is to be displayed, we can control the radius and starting angle, by using a Fourier Transform to remove this “natural” orbit and replace it with a circle of known radius and starting angle. (The “natural” radius and the “natural” starting angle contain mainly arbitrary information about the motion; what is useful is to be able to relate particular events to a known orientation of the shaft.) When the index pulse for each channel is also detected, it is possible



produced are expected to be very small. However, we have investigated the error likely to be caused by this method of interpolation and made an estimate of an upper bound for its magnitude.

We have found that the maximum size of the error can be related to the size of the variation in length of time between the passing of one grating line and the next, provided that the variation in speed is very small. Therefore we require that any vibrations present have a frequency much lower than the frequency of the passing of the grating lines, which is given by $N\omega$, where N is the number of grating lines on the disc



to determine the orbit relative to the centre of the read heads. This is useful when comparing data collected on different occasions, if the change in position is to be calculated. Without the index pulse data, the starting position is unknown for each new set of contiguous data, so the orbit plot can only be found relative to the starting position for that set of data.

3.2 Processing of the Read Head Data

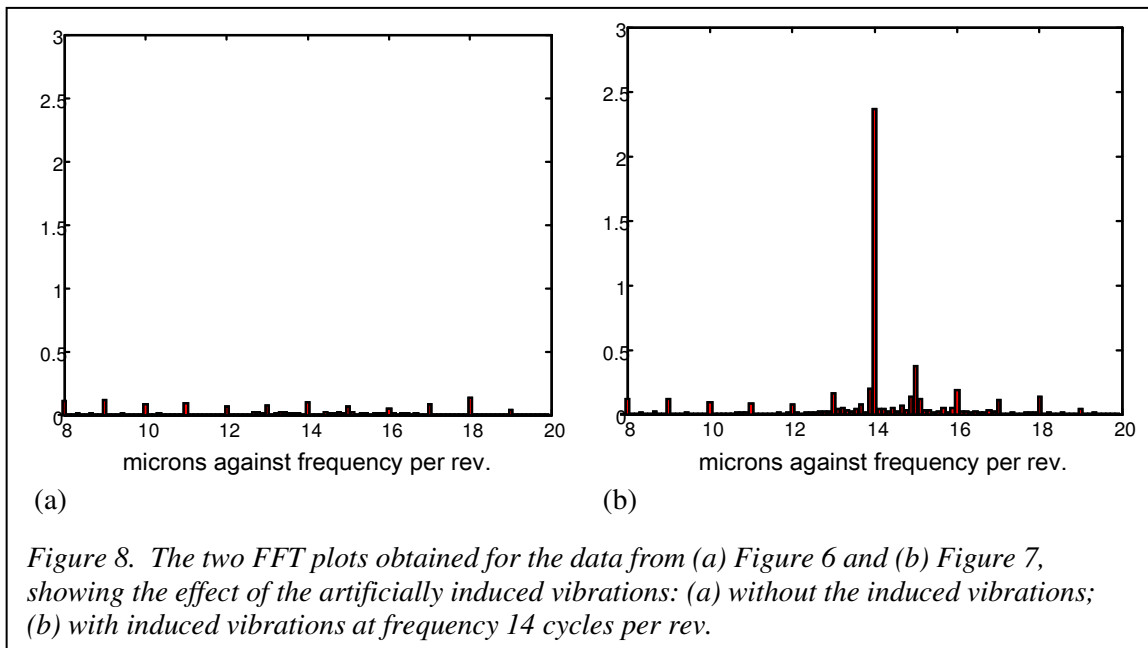
The approximate formulae given in Section 3.1 for calculating the x and y -displacements can be replaced by exact versions of the formulae that have been derived. In order to calculate, for a given time, the value of the angle θ , and the corresponding one for y , it is necessary to interpolate the data, since the timings obtained from the read heads are not only unequally spaced in time but vary for the different read heads. Early work used linear interpolation between the data points from a given read head, which has the advantage of being simple and very quick to calculate, so that the large number of points for the orbit plots can be produced in real time. More recently we have investigated whether cubic spline interpolation can be used. Usually the data points from one read head are very close to linear, so the errors

(resolution of the disc) and ω is the rotational speed of the disc. This will usually be the case when the disc resolution is large (typically 512 or 1024). The requirement that the frequency of any vibrations must be much lower than the grating line frequency (i.e. sampling frequency) can be seen to agree with Shannon's Sampling Theorem [8].

3.3 Detecting Vibrations

The IME can detect the presence of vibrations at different frequencies by calculating the FFT from the calculated orbit. Figure 7 shows an example of data from the same experiment as Figure 6, but after vibrations of a known frequency have been introduced artificially. The two FFTs for the data from Figures 6 and 7 are shown in Figure 8, where a large increase in the magnitude can be seen in the latter at frequency 14 cycles per rev.

Because of the method of collection of the IME data, we normally use frequency measured in cycles per revolution. This means that we can exploit the result that the frequency of vibrations due to a defect does not depend on the speed [9]. However, since the speed is known, the frequency can always be converted into Hz.



4 Data Collection

An encoder disc has typically a large number of radial grating lines equally spaced around the circumference. Instead of merely counting the number of lines that pass in a fixed time, as is normally done with the ISE, the IME records the timing data for each read head, i.e. the time when every grating line passes it, using a crystal clock with, typically, a speed 100 MHz. It can collect the time stamps at rates up to 500 kHz and thus, for each revolution of the shaft, a large number of high resolution time stamps are collected. We have developed systems to collect and transmit the data as well as algorithms to process the data to calculate many different measurements, as required. Since the data arrive asynchronously on separate channels, special hardware is required, which is similar in architecture to what would be found in a logic analyser.

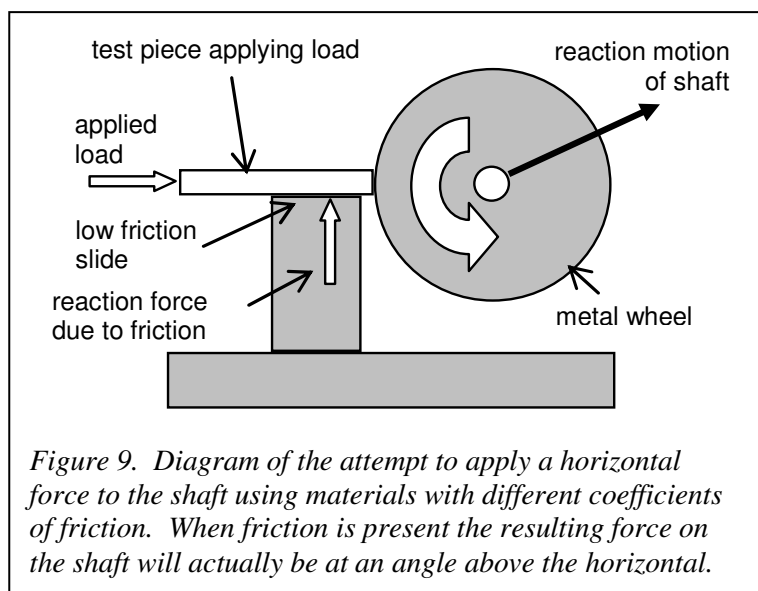
5 Robustness

Traditional methods of condition monitoring, such as proximity sensors and accelerometers, are able to provide some of the measurements that the IME can provide. However, apart from the problems of positioning and calibration, such sensors also have a high level of false alarms. These false alarms can be caused by faulty sensors, poor calibration or other errors in the data, which are difficult to detect. If, for example, three sensors are used, some redundancy checking is possible, and then readings can be disregarded as faulty unless two of the sensors agree within a small margin of error. The IME is able to avoid such problems much more effectively, because the highly characterised nature of the data allows our algorithms to perform consistency checks before deriving the measurements. Even when the data are poor, it may be possible to investigate further to detect the cause of the problems.

The problem of faulty signals causing false positives when diagnosing problems can be avoided by using the IME, because it is possible to have a high degree of certainty whether the data received are valid or not. A considerable number of tests using hardware and software can be used to ensure the reliability of the results obtained. The IME system is digital, so we have installed special hardware to test each channel for any of the following: transmission line faults, open-circuit, short circuit, low differential voltage and common-mode range violation. If none of these faults are detected, then the IME software can test for inconsistencies within the data it has received. These include testing *on each channel* that:

1. the rate of change of pulse time stamps is below a given limit*;
2. the pulse mark-space ratio lies within given limits*;
3. the phase and duration of the index pulse lie within given limits;
4. the number of pulses between any pair of index pulses is equal to the disc resolution.

The complete set of data *from all channels* can also be tested for:

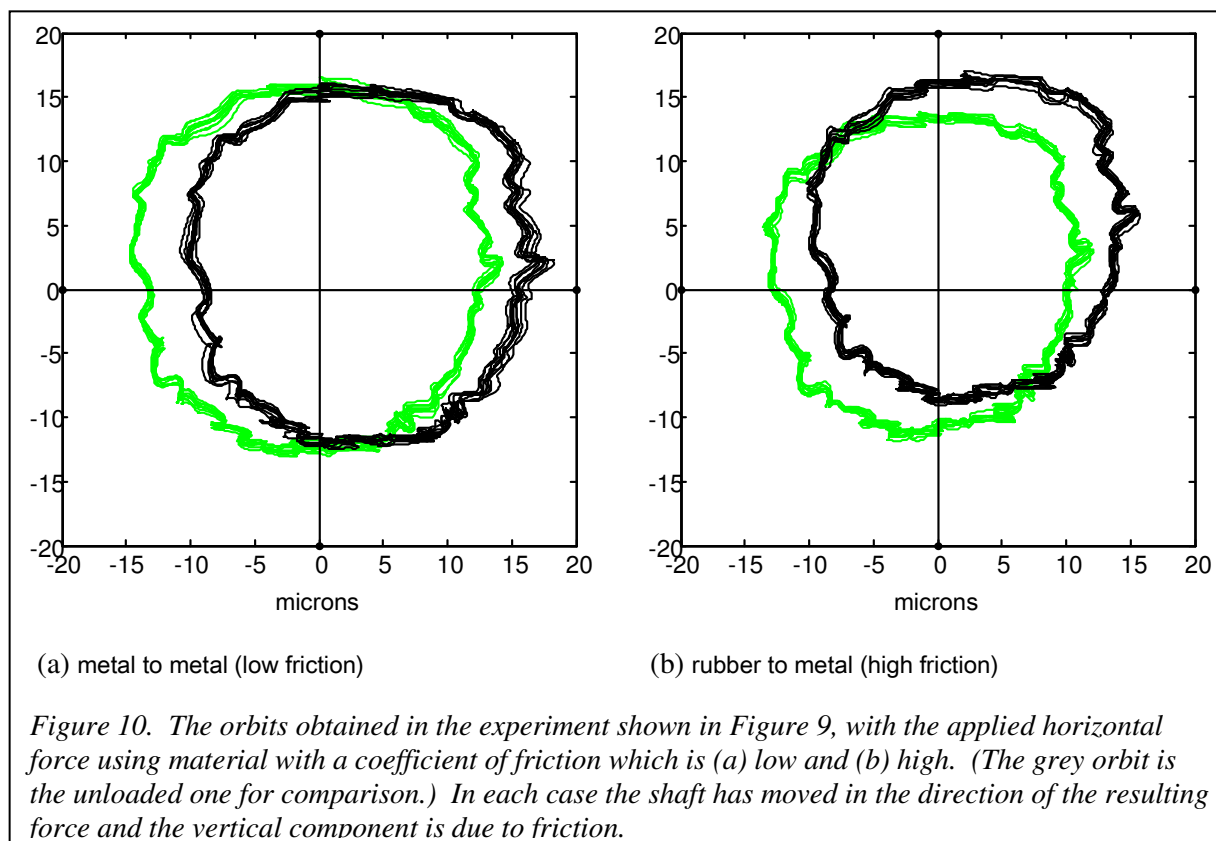


5. the pulse counts on all channels for any number of revs. differ by less than a given limit*;
6. the times on all channels for any number of revs. differ by less than a given limit*;
7. the number of pulses between the index pulses on different channels correspond approximately to angular separation of the read heads.

Those marked with a * are possible even when the index pulse is not available (provided the resolution of the disc is used to determine the duration of 1 revolution). Even when some failures occur, it may be possible to obtain some information from the data that is known to be reliable.

Regular estimation of disc errors (see Section 6.2) also allows damage to the grating lines to be detected and compensated. Thus, the IME is effectively a monitoring instrument which can also seriously monitor itself. When four read heads are present, the further redundancy can be exploited to allow operation even when one of the read heads is faulty.

An industrial version of the IME has been manufactured and installed by our company. It has been able to remotely monitor a machine used for processing food and record the data over many months. Fast Fourier Transform analysis has allowed the frequencies of vibrations relative to the rotational motion to be found independently of any changes in speed; the ball-passing frequencies of the bearings have been detected accurately.



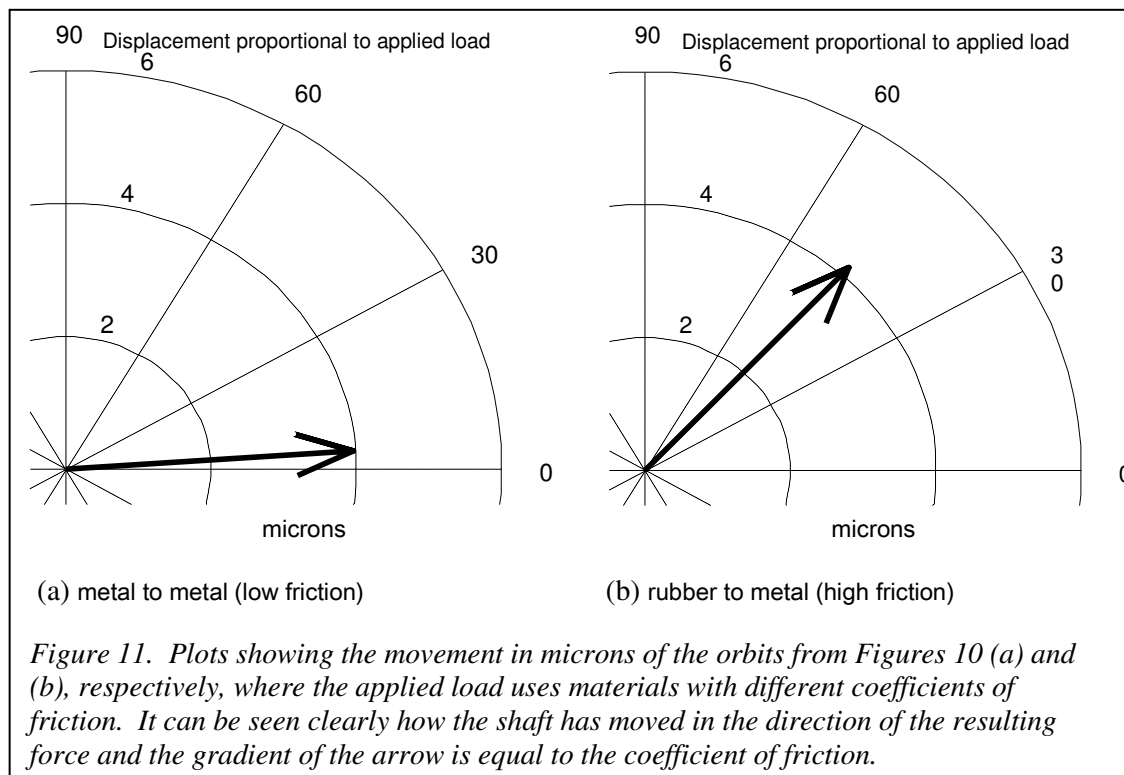


Figure 11. Plots showing the movement in microns of the orbits from Figures 10 (a) and (b), respectively, where the applied load uses materials with different coefficients of friction. It can be seen clearly how the shaft has moved in the direction of the resulting force and the gradient of the arrow is equal to the coefficient of friction.

6 Recent Developments

The IME is an original patented invention [1], which allows accurate digital data to be collected from rotating shafts using inexpensive components. This paper has explained how the level of redundancy in the data means that this is a highly robust measurement system, which provides many different measurements when this single instrument is used to monitor the rotary motion.

6.1 Measuring the Force on the Shaft

The IME is able to measure the force on a shaft, once a simple calibration has been performed. The distance moved by the shaft is proportional to the applied load, as shown in the experiment illustrated in Figure 9, where a horizontal load is to be applied to the shaft. In the presence of friction there will also be a vertical force required to maintain the vertical position of the slider applying the load. This is typical of what happens when the shaft is part of a grinding machine. Figure 10 shows examples of orbits obtained under both low and high friction using a metal or rubber surface, respectively, against the shaft and Figure 11 shows the average change in shaft position from the two sets of data used for Figure 10.

6.2 Compensating for Errors in the Disc

When the encoder disc has errors in the grating lines, the results will be distorted, as can be seen in Figure 12 when we used an optical disc with small imperfections in our experimental rig. This problem is typical of what happens when a magnetic disc is used; even when the motion is smooth, the orbit plot is liable to be very poor, because the disc is not built in one piece and the joins create magnetic differences. Several ideas have been proposed for detecting errors in the grating lines on an encoder disc and compensating for them [5, 10]. We have used our algorithm [10] on the data from Figure 12 and the resulting orbit plot is shown in Figure 13.

7 Conclusions

The IME is a commercially available mechatronics instrument with great potential. It is able to monitor reliably many aspects of rotary motion using a grating disc and three or more read heads. When the data streams from the three read heads are valid, they exhibit synchronicity within narrow limits. This feature makes it easy to check the validity of the data and ensures robustness of the collected data from the instrument, thus avoiding the false alarms which normally plague condition monitoring.

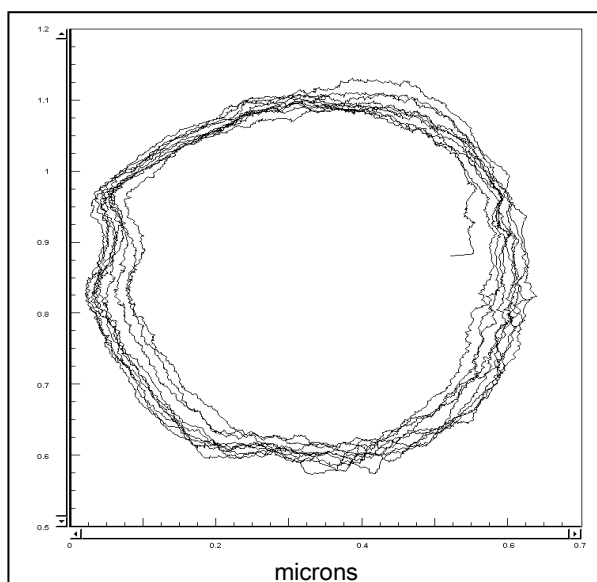


Figure 12. A poor quality orbit plot obtained using the experimental IME (shown in Figure 2) when the optical disc used has small imperfections in the grating lines.

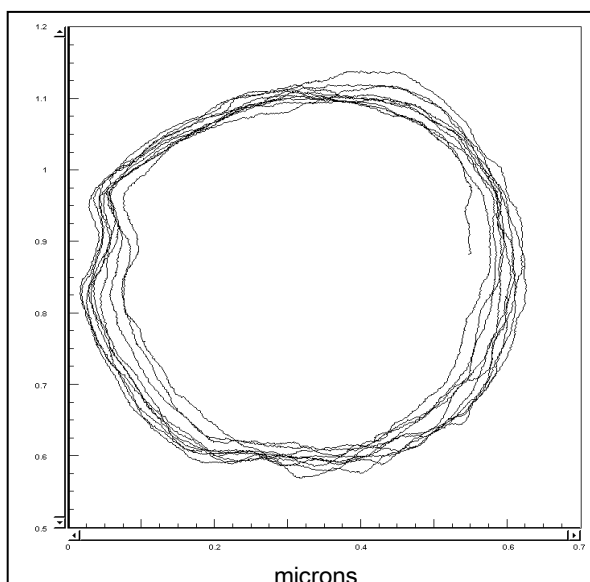


Figure 13. The orbit plot for the same data as Figure 12 after applying compensation for the disc errors [8], showing the improvement in the quality of the orbit.

Acknowledgments

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