

TURBO-MACHINERY TIP TIMING COMES OF AGE

The complexity of a gas turbine makes its maintenance something of a black art. However, the advent of non-contact tip-timing systems has made it possible to assess turbine blade health and implement condition-based predictive maintenance routines. Currently, however, the most widely used systems are optical-based, and the sensors are susceptible to contamination from oil, dust, exhaust gases and even water. This means that data quality (and therefore reliability) degrades with time, limiting the use of optical-based systems to turbine development projects or applications where the sensors can be regularly cleaned.

During recent years research has been carried out to evaluate alternative sensor technologies, with the most promising solution proving to be eddy current probes. Ruggedized for use in the extremely harsh environment of a gas turbine and tuned to produce results on a par with industry standard optical systems, the tip-timing eddy current probe looks like a technology whose time has come.



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INTRODUCTION

Within industry there is a continuous drive towards predictive maintenance, achieved through monitoring the health of plant equipment and machinery. As explained in many technical papers, by continually monitoring the condition of equipment and machinery it is possible to receive the earliest possible warning of potential failures, and thus avoid unnecessary downtime. It is also possible to squeeze as much life as possible out of parts and components, as opposed to replacing them on a set schedule and irrespective of use. But there is one piece of equipment – an essential item in many industrial applications – that is difficult to cater for in terms of implementing maintenance based on its condition or health, viz. the turbine, be it gas or steam driven.

The majority of turbine failures occur because of blade defects, either developing over time or as a result of instantaneous damage caused by a foreign object. The earliest warning of a failure takes the form of blade vibrations, caused by dynamic loads

on the blade. These loads can be generated by various mechanisms, such as rotor imbalances, varying blade tip clearances (usually caused by non-concentric casings or orbiting of the main shaft), distortions in the inlet flow (usually caused by irregular intake geometries) and vibration of stationary vanes or struts up or downstream of the rotor blade.

VIBRATION SENSING VIA OPTICAL PROBES

During the manufacture of a turbine a common method of assessing blade vibration relies on the use of optical probes mounted in the blade casing assembly. The principle on which the optical system operates involves the focusing of a narrow laser light beam onto the passing blade tip. As the blade tip enters the path of the light beam, light is reflected back to a photo sensor. The intensity of the reflected light rises very rapidly as the blade passes and, in the absence of any structural vibration, the time for the tip of a particular blade to reach the optical probe, called the 'blade arrival time', is dependent on

the rotational speed alone. However, when a blade is vibrating its arrival times are dependent on rotational speed and any displacement due to vibration.

Such optical systems produce clear, accurate, results and for turbine development it would be fair to say they are the de facto standard. However, because a clear optical path is required between the turbine casing and the blade tips, the use of optical probes for blade vibration analysis is not a realistic proposition for the long-term, in-field, monitoring of blade health as contamination from dust and exhaust gases rapidly degrades signal quality.

There exists therefore a strong motivation to find an alternative to optical probes – one which produces optical system quality continuously. Thankfully, research conducted in the aerospace industry, where jet engine health is of paramount importance, has led to the development of such a solution. >>

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EDDY CURRENT SENSING

In addition to the use of optical systems, blade arrival times can also be measured using other non-contact methods, including the use of capacitive, high-frequency pressure, and eddy current transducers. In 2002 a series of trials was conducted, at QinetiQ's turbine test facility in Farnborough, to compare these three options against an industry-standard optical-based system.

The trials revealed that of the three technologies the eddy current sensor showed the best promise for further development. Technically, eddy current sensors have been previously used (or at least considered for use) in tip timing or tip clearance measurements by Flotow¹ and Belsterling² respectively.

Eddy current sensors are most commonly used for non-contact proximity and displacement measurements. Measurement accuracy is high and ruggedized versions are often used in contaminated environments. In a turbine application, a major advantage that the eddy current sensor has over the other probe types is that it is possible to take blade passing data through the turbine casing, as demonstrated by Roeseler and Flotow³. However, the presence of the casing does lead to significant attenuation of the target signal.

In QinetiQ's trials, bench tests were initially conducted on a standard off-the-shelf eddy current sensor. The sensor was chosen to have a reasonable range while of the sensors should be carried out by mounting the sensors in a steel pocket to evaluate how they might perform when mounted in an engine casing.

It was found that the pocket design and material had an effect on the sensor performance, and that through-casing measurements did not produce good quality signals when a shield was fitted. To overcome these problems, the pocket was re-designed with an air cavity around the sensor head. Also, the sensor coil was optimised for improved resolution, signal to noise ratio and range.



Figures 1(a) and 1(b)
The original (left) and improved (right) pockets and shields

Tests were then carried out with various tip gaps, ranging from 0.5 to 2.0mm. Although the signal was small in amplitude, it was of reasonable quality, with very well defined peaks when the blades passed by. Figures 1(a) and 1(b) show the original (left) and improved (right) pockets and shields, and Figure 2 compares the measurements from both.

ENGINE TRIALS

With a greatly improved, bench-tested, sensor it was decided to embark upon a series of engine trials⁴ and, as chance would have it, a 24-blade AE3007 engine was on test at Rolls-Royce Indianapolis.

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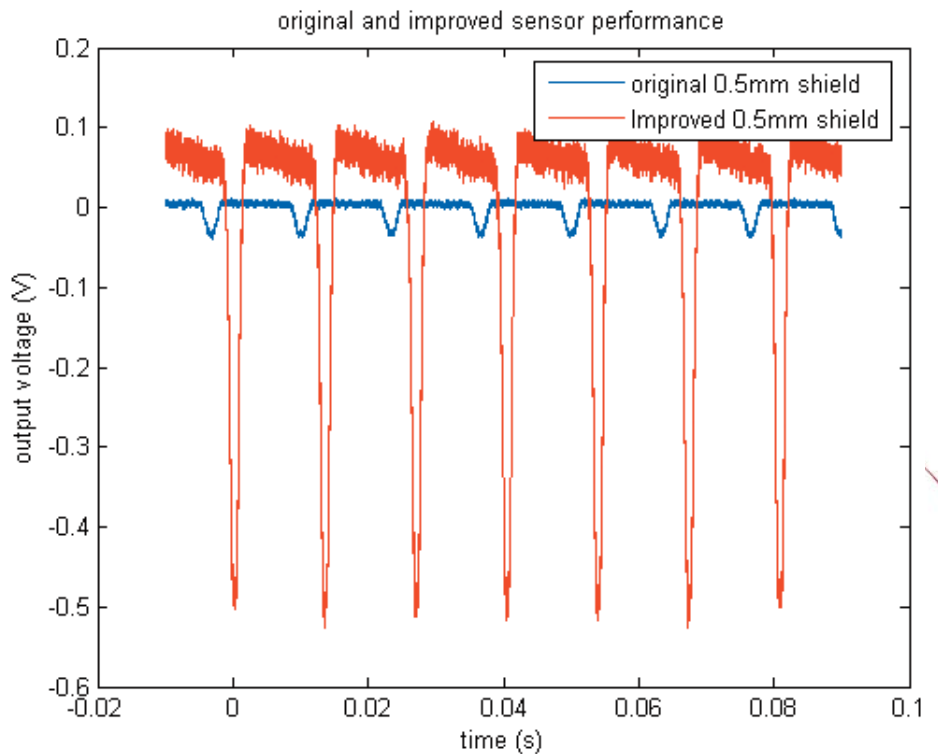


Figure 2 Measurements taken using the original and improved pockets and shields (shown in Figures 1(a) and 1(b) respectively)



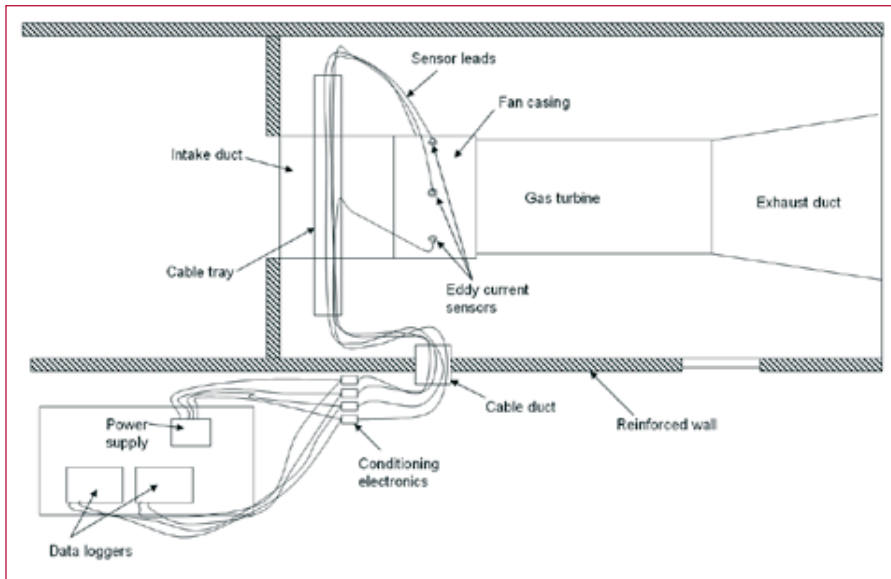


Figure 3 A diagram of the arrangement for the fan tests

A number of tests were carried out, with the engine running at 8700rpm, on the first stage fan rotor of the engine. **Figure 3** shows a schematic of the test cell and the instrumentation configuration.

Four sensors, in pockets, were mounted into the fan casing. **Figure 4** shows one of these mounting holes from the underside with the sensor pocket fitted. The outside of the casing was spot-faced to allow the pocket to sit squarely on the

casing and the sensor was positioned with its centreline at approximately 0.3 axial chord. While this reduced the signal strength, placing the sensor head nearer the leading or trailing edge resulted in a better measurement of the blade vibrations.

The pockets were manufactured in stainless steel with different base thicknesses in order to test the sensor's ability to measure blade passing data through thicker shields and to allow

comparison of the different results. **Figure 5** shows an example of the sensor outputs with the engine at full speed. The red trace is a once per rev. signal measuring the engine low pressure shaft speed using a speed encoder.

Through the (blue) 0.75mm shield the sensor is clearly able to pick up the blade passing, with 24 clearly defined peaks per revolution. The peaks are not all the same height, indicating the variation in blade tip clearance from the casing. For the 1.0mm shield the sensor captured some blade data, but it was not of sufficient quality for tip timing purposes.

The same proved to be true for measurements taken using 1.25 and 1.5mm shields. It is worth noting that during the initial running very poor signals were obtained until the engine was at full speed. On inspection it was found that the static clearance between the blade tips and the casing was larger than that for which the sensors had been configured. In addition, the shield of the sensor pockets was sitting below the surface of the casing. This meant that the sensors had to pick up the blade passing across a larger tip gap than had been envisaged. The results only improved when the tip clearance reduced as the turbine approached full speed and the blades untwisted and stretched under the centrifugal loading. >>



Figure 4 The sensor pocket fitted in the fan casing

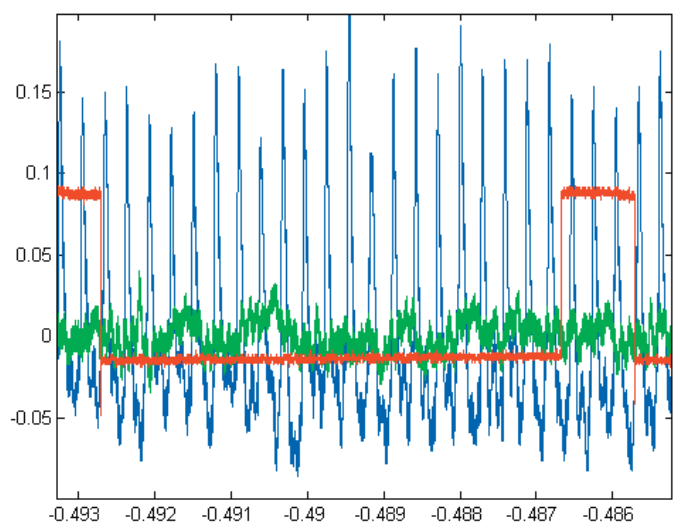


Figure 5 The initial sensor's output through casings of thickness 0.75mm (blue) and 1.0mm (green)



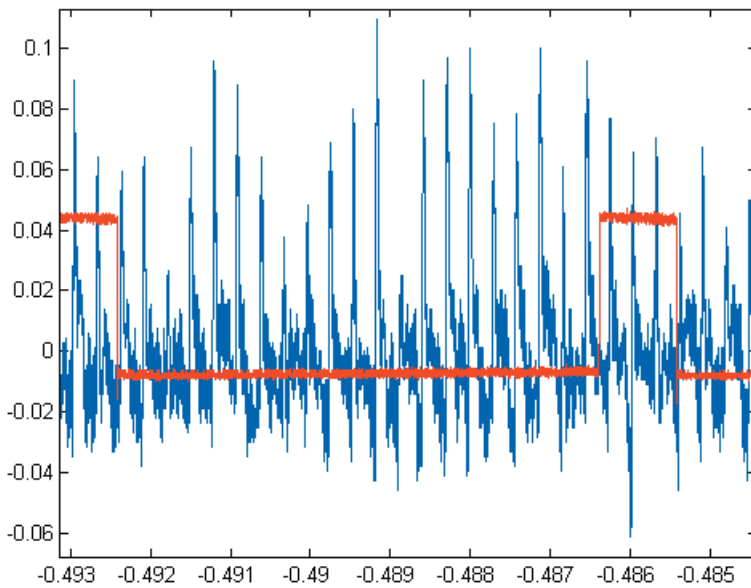


Figure 6 The sensor's output through a 1.0mm thickness casing following reduction of the tip clearance

Having addressed the 'static clearance' issue a number of tests were then conducted to compare shield thicknesses under more realistic operating conditions. **Figure 6** shows the sensor output through the 1.0mm shield, and it can be seen that there are significant differences in peak values [blue trace]. Similar results were obtained using 1.25 and 1.5mm shields, except that all peaks were slightly lower. It was still possible to count all the blade passings, despite the extra thickness of shield.

After the acquisition, through a shield, of blade passing data, the ends of the pockets were machined off to allow such data to be taken without any intervening material between the sensor head and the blade tips. **Figure 7** shows one of the modified pockets prior to being fitted back on to the engine, and **Figure 8** shows data from one sensor taken at full speed.

Not surprisingly, the output is much larger with no shield present and the blade passing is clearly visible. In addition, the base noise level is much reduced in comparison to the 'through case' data. In order to be of use in a blade tip timing system, data from sensors must be adequately monitored

and conditioned so that the outputs to any turbine health monitoring system would be both reliable and repeatable.

Although four sensors were fitted into the engine fan casing, each was tested in a slightly different configuration. All the sensors successfully survived the engine running throughout the testing

with no degradation of the signals becoming apparent. This shows evidence of the high mechanical integrity and immunity from contamination displayed by the sensors. It also indicates that for fan blade applications the sensors are sufficiently robust to be used without any form of metallic shielding. >>



Figure 7 The sensor pocket machined to allow direct line of sight from the sensor to the blade tip

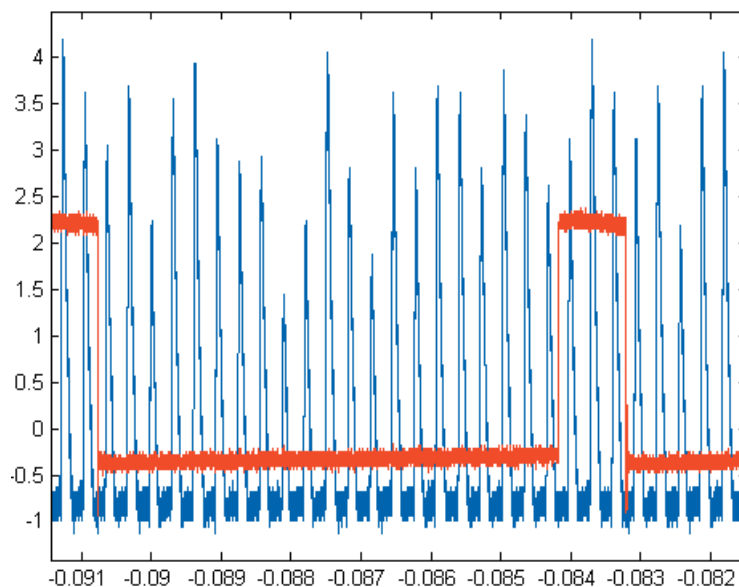


Figure 8 The output from the casing sensor during engine operation at full speed



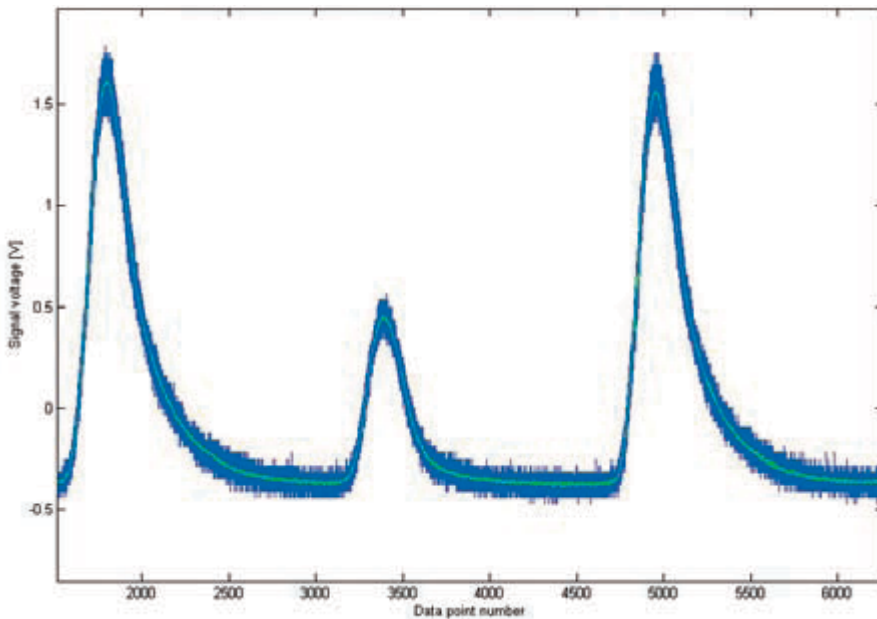


Figure 9 Sensor output data rev-to-rev and averaged (the white, inner trace)

increases the signal amplitude increases, causing a shift in the triggering position which shows up as a change in arrival time. This results in the output for some blades shifting in relation to the adjacent blades. In both plots, a large blade vibration is detected during the engine acceleration at around 6200 RPM.

The preferred option for correction of this latter problem would be to develop an alternative triggering technique more suited to the output signal from the eddy current sensor. However, it may be desirable to input signals into existing acquisition systems that use a threshold triggering system. In order to overcome the uncertainties, which occur due to amplitude variations, the signal would need to be conditioned to remove these variations.

USEFUL DATA

The eddy current sensors used in the tests proved sensitive to the tip clearance. However, the pulse shape generated by each blade was not significantly altered, suggesting that a repeatable amplitude-independent triggering technique would be possible. **Figure 9** is a plot of data rev-on-rev from a single data file containing 26 revolutions. Three blade passings are plotted, with the ensemble averaged data over-plotted. The plot demonstrates that the sensor output is repeatable where the tip clearance is maintained at a near constant value.

and the signals generally have a very sharp rising edge, with the result that threshold triggering systems work well with these probes. This can be seen in **Figure 10**, which shows data from optical and eddy current probes which were input to a standard technology system for the acquisition and analysis of tip timing probe data⁵. For the optical probe data on the left, the arrival time essentially remains flat, except for the fluctuations caused by blade flutter. On the right, the eddy current sensor data shows that as the engine speed

Blade arrival times calculated from an amplitude-corrected signal showed promise and it was decided to embed the correction into the signal-conditioning hardware, so it could be performed in real time. The signal conditioning system produced a square wave output, which was fed into an acquisition system that used a threshold triggering system. **Figure 11** shows the raw and output signals from the signal conditioning system, with the output pulse occurring on the falling edge of the raw signal. The conditioning was performed using analogue electronics. >>

Although the sensitivity to clearance of the eddy current sensor offers useful additional information that is not provided by optical probes, amplitude variations lead to increased uncertainty in the determination of blade arrival times when using simple threshold triggering.

The amplitudes of the output signals from optical probes are not clearance dependant

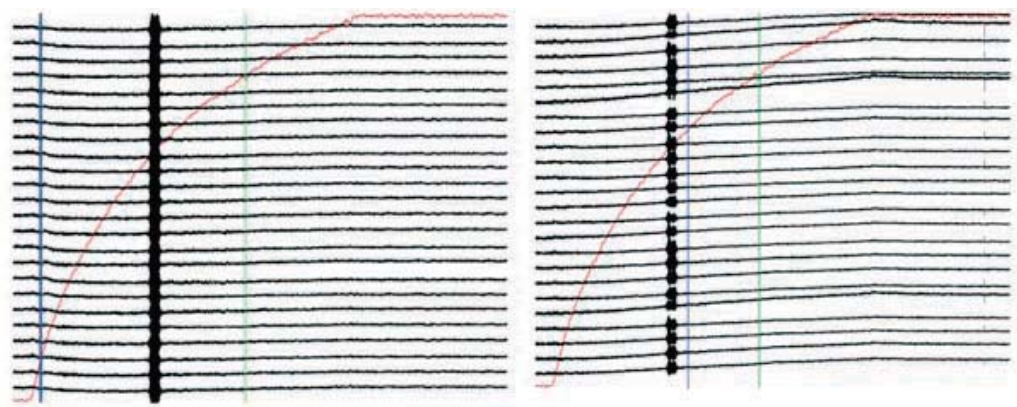


Figure 10 Individual blade waterfall plots – data obtained using a leading optical probe (left) compared against data obtained by the eddy current sensor (right)



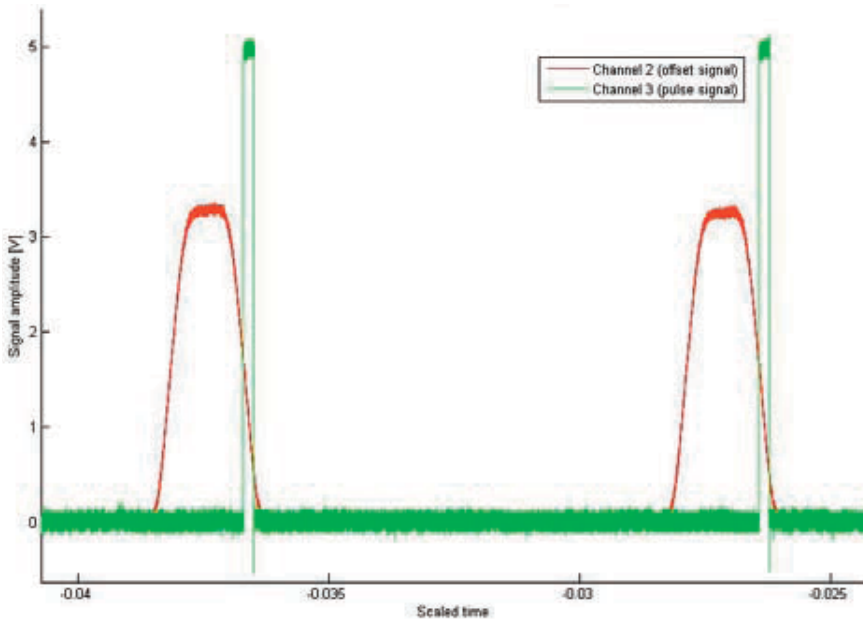


Figure 11 Falling-edge triggering technique, producing an output with a relatively square wave

A DSP-based system will remove the need for traditional tip timing acquisition and analysis systems, which are very expensive.

Figure 12 shows two of the eddy current sensors developed by QinetiQ and Monitran for turbo machinery blade tip-timing. ■

signal processor (DSP) is currently under development that will improve the accuracy of the timing pulse.

Also, with tip timing systems generating terabytes of data, even for just a few hours worth of recording, a DSP will be able to autonomously process in real time what would otherwise require several days of analysis. Accordingly, a DSP-based system will be able take the (blades') time-of-arrival data and process it into blade deflection information, and output (real time) blade health in a typical traffic light format: with green indicating that all blades are fine; amber indicating that at least one blade has exceeded a predetermined limit of deflection or vibration; and red indicating imminent failure - and that the turbine should be shutdown.

CONCLUSION

During the trials the eddy current sensors demonstrated their effectiveness for tip-timing applications. They also proved to be extremely robust and suitable for through-casing applications.

Further development of the signal conditioning electronics, specifically in terms of allowing the triggering correction to be carried out in real time, will deliver acquisition and analysis of tip timing data derived from eddy-current probes, which will be on a par with that derived from optical systems - but with the benefit of contamination tolerance in long-term use. The user (the maintenance engineer) need not be an expert in the field of tip timing.

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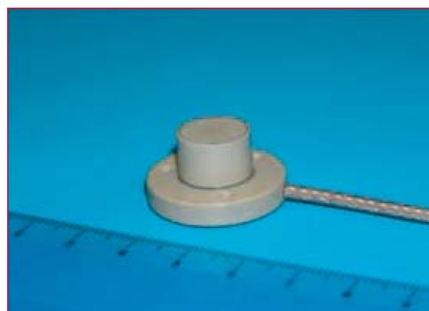


Figure 12 Examples of the eddy current sensors developed by QinetiQ and Monitran Technology

