Inspection technology in the aero engine industry

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Abstract

Today’s advanced gas turbines such as the Rolls-Royce Trent operate in harsh conditions to levels of reliability that are unprecedented for most other complex manufactured products. Indeed Rolls-Royce holds the record for the world’s most reliable turbofan - an RB211-535 which ran for 40,500 hours and covered over 18 million miles on an Iceland Air Boeing 757 before its scheduled overhaul in March 2000. Compare that with a car engine doing 150,000 miles or ~5,000 hours before overhaul. Or machine tools, which if heavily used need an overhaul after, say 7 years or 10,000 hours of use.

In order to achieve such high levels of reliability it is clearly necessary to ensure that components are designed and manufactured to world beating levels of quality.

Since a typical engine contains over 30,000 components sourced from up to 600 suppliers world-wide, the difficulties in ensuring that these components are appropriately designed and accurately manufactured are immense. This is further complicated by the fact that, unlike most mature manufacturing industries, the materials used for aero engines, and the processes used to make them do not, today, allow the same levels of process capabilities that would be demanded by other volume goods manufacturers. Whilst the investment in modern manufacturing technology and attention to detail on the shop floor is rapidly changing this, it is still unfortunately true that for many parts, quality still has to be “inspected in” rather than automatically achieved as a result of inherently capable processes.
Measurement technology has a significant part to play in ensuring that capable processes are achieved in the manufacture of complex components. By understanding the variation manufactured into a component throughout its development and production cycles steps can be taken to control the causes of the variability and therefore process improvements can be made.

This gives serious challenges both to our industry, to suppliers of inspection equipment and to those working in academic and other research groups who are developing new equipment and technologies. I would like to outline some of these issues in this paper and leave you with some thoughts that perhaps should be considered during this conference.

2 Today’s business requirements

After the Second World War the piston engine gave way to the gas turbine as the need for faster flying speeds at greater altitudes increased. The Comet led the way in the civil aerospace market when it became the world’s first scheduled jet airliner. However competitors soon emerged and today only half a century later global air travel is commonplace and we as the ultimate customers for this technology seek ever decreasing costs for our business and holiday travel.
Today, gas turbines are mature products with the pace of evolution slowing down. The three major aero engine suppliers: General Electric, Pratt & Whitney and Rolls-Royce use their design technologies to try to gain competitive advantage by providing what the customers, the airlines, want – lowest cost of ownership. However because of the maturity of the technologies, this competitive advantage comes often from financing packages, long term service arrangements or “power by the hour” agreements.

Where does this leave the manufacturing operations? There is little need today for the breakthrough innovations of the immediate pre and post war years. For the majority of today’s components the manufacturing technology exists to allow the designer the freedom he requires to optimise engine performance. However, what is required today of the manufacturing organisation is to make components at the lowest possible cost consistent with adequate quality levels. If this is not possible within a company’s own domestic facilities then cost reduction opportunities are sought around the world.

Cost reduction in manufacture relies on the optimisation of two expensive resources – materials and labour. There is therefore firstly a continual drive to reduce manufacturing lead-times in order to minimise the cost of holding inventory. Secondly we need to be able to operate at much lower labour levels than in the past. So, today, the role of those who are engaged in developing new manufacturing technology is to firstly introduce fewer and faster operations and secondly to minimise the people overhead associated with the process.
3 The evolution of inspection technology

It is only a century and a half since Whitworth displayed his screw micrometer at the Great Exhibition at Crystal Palace in 1851. Although the micrometer was patented three years earlier by the Frenchman Laurent Palmer, Whitworth’s exhibit caused a stir of excitement. Prior to this date parts could only be measured using lines on a ruler to best accuracies of a few hundredths of an inch. Whitworth changed all that by developing a micrometer that could measure to a millionth of an inch and that acted as a catalyst to his desire for standardisation and interchangeability which today we regard as commonplace.

Another watershed for inspection technology was the introduction of the Electronic Measuring Machine by DEA in 1963. Its development together with the touch trigger probe allowed significant benefits, particularly in terms of flexibility and precision to be achieved compared with the traditional measurement regimes in use at that time.

Today we may be on the brink of a third wave of new technology. Certainly industry needs another step change in measurement and processing speed as we strive for ever more precise components and in some areas the need for knowledge of complex three dimensional surfaces. Non contact scanning and imaging systems have the potential to satisfy these needs but are not quite mature enough yet.

Prior to the invention of the jet engine the technology for manufacturing aero engines shared much in common with the motor industry since early aero engines were derivatives from this field. However the jet engine introduced the requirement for new heat resistant materials and this in turn brought about the need for new manufacturing processes such as Electro Chemical Machining, Electro Discharge Machining and Electron Beam Welding. The introduction of these and other novel processes, and the dramatically more complex components of a jet engine, bought their own demanding inspection problems. For example what inspection tools did Frank Whittle have to check aerofoil shape or measure combustion chamber temperature or assess the material integrity in a turbine disc?
In these early days, the industry pressures were more about ensuring adequate operating lives and reliability than about manufacturing at lowest cost. The ready availability of skilled tradesmen meant that there was little incentive to
automate the manufacturing and inspection functions. Indeed there was clear demarcation between those who made the parts and those who inspected them.

The inspection "tools of the trade" were general purpose measuring equipment and special purpose gauges which complimented "hand inspection" methods on the bench.

The increasing volumes of the late 60's and early 70's brought a need to increase the speed of inspection and as engine design technology matured, more gauge points were required to be "in specification". This led to the introduction of "multi-probe gauges", almost universally for complex components such as turbine blades and nozzle guide vanes. Although these were quick to operate — typically a few tens of seconds per part - they had high initial costs and a high ongoing maintenance cost to ensure they were kept in calibration. Their inflexibility meant that when component designs changed there was a need for a new suite of multi probe gauging equipment and the cost cycle started over again.

Figure 5: Multiprobe gauge for inspecting compressor blades

The advent of the co-ordinate-measuring machine started to bring about a solution to some of these problems, although it in turn brought problems of its own. Flexibility was certainly improved but speed of response was poor, cost was high and the debate about survivability on the shop floor continues to this day. Early machines were installed in "standards rooms" where only the highly skilled inspector would use them and whilst they gradually emerged onto the general machine shop floor the time they took to program and the speed of
taking measurements still meant that they were only used for “special” inspection tasks.

The breakthrough came when CMM’s were linked to automated cells dedicated to the manufacture of a family of parts. Here the programming time penalty was carried during the cell design phase and the inspection cycle time could be carried out in parallel with the remainder of the cells processing cycle. As the cost in real terms of CMM’s decreases this is becoming a preferred operating regime in many areas of our industry.

4 Inspection Technology

As previously explained, the CMM with the touch trigger probe has significantly reduced the need for special to product tooling. This trend has been accelerated by the introduction of CNC machine tools incorporating inspection probing which can be used within the machining cycle. Whilst these are used predominantly for measuring tool and cut offset’s they have significantly contributed to higher levels of process capabilities and hence the need for reduced inspection levels. Nevertheless the drive is on to achieve process capability levels which match those in other “consumer goods” industries and this is why the GE “6 Sigma” and the RR “Better Performance Faster” initiatives are so important.

So inspection suppliers should consider these issues in the development of their equipment:

4.1 Faster inspection cycles

CMM cycle times have improved significantly over the last 10 years as improvements to bearings, reduced weight structure, drives and control systems have been achieved. The introduction of scanning probes has also brought great benefit for the measurement of complex surfaces such as aerofoils. However it can still take several hours to inspect and analyse the data for a complex component. As designers want to know more and more information about the shape of complex surfaces this time penalty becomes unacceptable.
4.2 Programming

Again the introduction of off-line programming languages has brought real advantages in reducing the need for either skilled NC programmers or the time penalty of "teach and learn" routines. CAD data can be imported, an inspection program generated and the measured results can be formatted to suit the needs of the individual user. Nevertheless there is still need for improvement in this area. The provision of "inspection templates", better version control, and simulation packages would be helpful. Although these are available from many suppliers, improvements in user friendliness and versatility are still required.

Areas for improvement centre on the use of parametric CADs where tolerances can be added to the model and user configurable inspection software for complex aerofoil shapes. It would also be useful for "best practice" routines to be generated – for example "how many ways are there to inspect a non round hole?"

Other useful features would include:

- Separate operator interfaces to allow different inspectors to create their own tailored inspection routines.
- Easier integration with robots, machine tools, conveyors, etc in a cell environment.
- Combined touch-probe and scanning programs.

Again the ability of the user to format the results of an inspection operation has improved significantly in the last 10 years. Nevertheless this is still an area that I would like to encourage further improvements. Easier access to a results database, the ability to have good graphical presentations and real time SPC reporting are areas of specific need.

4.3 Non contact measurement systems

Laser scanning systems have been on the market for over 20 years and in some areas such as the auto industry there is a significant number of applications. However resolution and hence speed and accuracy have not generally matched the touch trigger or analogue probe CMM and these need to be improved before we will get serious applications in measuring gas turbine parts. However their promise is immense. The ability to collect hundreds of data points quickly, to interpret these for comparison to the CAD's model and to align surfaces in space without the need for complex tooling is a considerable advantage. I must encourage more work in this area and the specific areas that need work are in post processing the raw data and in off line programming.
4.4 Vision Systems

The belief that linking a camera to a computer would automate many manual vision inspection operations has been a dream for at least the last 20 years. Unfortunately, although there are a few industrial applications (e.g., hole area measurement), the dream is still largely unfulfilled. Perhaps today's faster, more powerful computers and high-resolution digital cameras will soon turn the dream into reality but I fear not. We lack the real champions for this technology.

4.5 Applications Engineering

In truth our industry is a relatively minor customer for inspection technology. Because of this, the overhead costs for maintaining the application engineering expertise tends to rest with the user. This resource is getting harder and harder to attract and I would like to create an environment where the equipment supplier knows as much about operating the system for the customers applications as he does about building the equipment. There are some companies who excel at this but there are improvements to be had by improved relationships here. The input of user feedback into software user groups can lead to better exposure of our industry's needs to the CMM industry.
5 Non destructive testing

Unlike conventional, shop floor inspection, NDT is used to detect anomalies within or on the surface of parts covered either during the manufacturing process or subsequently in service. The aim is to ensure that harmful anomalies are eliminated but that benign anomalies are permitted such that expensive parts are not unnecessarily rejected.

There are five processes that are routinely used in our industry:

Magnetic Particle
Penetrant
Radiography
Ultrasonic
Eddy current

The technological status and future requirements of these are as follows:

5.1 Magnetic Particle

The problem with this technology is that the traditional way of validating the technique is to conduct practical trials on real parts. This is too late in the component definition process and what is required is the ability to model the magnetising process from the engineering model and generate the technique instructions well before a part has been made. I recognise that this is a long-term undertaking and some work is underway at Ohio State University in this area.

5.2 Penetrant

Automated penetrant processing lines are now readily available for the majority of our components. However the supply industry is fragmented and our reliance on a few, small companies is a concern.

Despite considerable research, spanning more than 20 years it has not been possible to reliably automate the inspection of defects shown up by penetrant processing and therefore this is still a labour intensive operation. Whilst the vision system employed in the human eye and brain combination is unsurpassed for its versatility and pattern recognition ability it is extremely unreliable. The danger of failing to detect defective parts is significant and so automated inspection systems are desperately needed.

5.3 Radiography

Here, filmless systems are slowly taking over from the traditional x-ray process. Clearly these bring cost advantages compared to the use of photographic film
but again inspection and interpretation of results is mainly down to trained inspectors and the risks inherent with their fallibility.

5.4 Ultrasonics

Cost reduction activities have focused on minimising the amount of material used in many of our parts and so forgers are being encouraged to provide closer to finish form material. This makes the ultrasonic inspection task difficult as traditionally we are used to inspecting rectilinear shapes with automated scanning equipment. A large amount of manual intervention is required when shapes move away from simple two-dimensional surfaces and this obviously increases inspection costs.

5.5 Eddy current

Eddy current testing is becoming almost mandatory for engine certification and life determination of high-energy rotors. It is the only practical method of providing reliable inspection data for features such as bolt hole integrity. Automated scanning systems are required that are capable of traversing complex shapes to high degrees of repeatability often in areas that are difficult to access. Perhaps lessons could be learnt from the microelectronics industries.

Figure 7: Eddy current inspection of holes in a turbine disc
6 Customer – Supplier relationships

There are two issues that should be considered under this heading. The first is that regrettably, too often, suppliers promise what is not achievable. We have had recent instances of hardware not functioning to specification and software needing several upgrades before it is acceptable. Whilst in these instances the suppliers carry the costs for correcting the problem it is always the customer that pays the highest cost in terms of lost output, scraped parts or missed deliveries. We have got to get better in this area.

The second issue is machine reliability. As we reduce lead times to save the cost of inventory, the buffers around us and the available time to fix problems reduces. If we are not to hazard deliveries to our customers we need machine tools and equipment that are an order of magnitude more reliable than they are today. I acknowledge that the customer is not always good at carrying out the planned maintenance tasks but this is an area that we are addressing. The challenge to suppliers is to make your equipment as reliable as our engines – after all you have many fewer parts!

7 Academic – Industry Partnerships

Rolls-Royce has established 19 “University Technology Centres” in order to harness and focus our research effort in key areas. One of the latest of these is the “Manufacturing Technology” UTC at Nottingham University under the direction of Professor Nabil Gindy. We are very keen to turn the ebbing tide of “hard” manufacturing research in the UK and are supporting this initiation with a grant of £300k per year for the next 5 years. In addition we are providing machine tools and other equipment to the centre. I am very keen to encourage other UK companies to participate in this for mutual benefit and for the benefit of the UK as a whole. Only by focusing our research efforts into areas where there is a real industry need will we make the breakthroughs to remain a viable and competitive manufacturing industry.

8 Conclusions

The development of inspection technology has been crucial for the growing success of Rolls-Royce plc. There are many areas that I have not covered including vibration and test equipment, in service condition monitoring and the numerous special techniques that are used in our rig and engine development programmes. However the messages that I would wish to leave you with are:

- Inspection technology development needs to concentrate on user interface issues and how we can reduce the manual overheads.
Key areas for the future are automated data processing for NDT and visual inspection.

Faster, more accurate non-contact methods are needed for complex geometry parts.

Improved reliability of equipment is essential for modern manufacturing facilities.

Research should be focused and carried out in partnership for the benefit of supplier, customers and the whole of the UK.