Rolls-Royce Industrial Case Study: 2010

Background

To gain a better understanding of the commercial importance of measurement, Rolls-Royce has been working with Technologia Ltd (was Sagentia) and economists from the UK Department for Business, Innovation and Skills to undertake an ambitious company-wide case study. Recognising that the profile and impact of measurement practices within real companies are not well understood, the Rolls-Royce study has provided an unrivalled opportunity to look at measurement both qualitatively and quantitatively in a real industrial context.

We have looked at measurement using a multidimensional approach. We have uncovered the numerous purposes for which measurement is used, how measuring instruments are calibrated, the benefits from measurement and how measurement activities are managed within this global company.

Rolls-Royce employs over 38,000 people around the world in 50 countries and has over 100 manufacturing plants. In 2009, annual underlying revenues were £10.1 billion.

The use of measurement

We found that there are four distinct uses of measurement in Rolls-Royce:

- Within Research and Technology (R&T) to develop technologies for future programmes. This includes the development of long-term measurement capabilities themselves.
- In Research and Development (R&D) to design and test new engines and other products.
- In Manufacturing – to measure and monitor the products manufactured within the company, those made by the supply chain, those in assembly areas and then final testing of the engine before release to the customer.
- In-service by monitoring and inspecting whole engines or other products and their key components – as part of maintenance regimes.

Each has its own challenges, so each is discussed separately.

Research and Technology (R&T)

In Rolls-Royce, Research and Technology is the development of technologies ahead of their use in engines or other products. In many areas, the current state of measurement science provides little headroom over what is needed. This limits what can be achieved in design and manufacture. There are two types of measurement which Rolls-Royce regard as most challenging. The first is where the characteristics of individual components and subsystems need to be measured, but current technologies are not quite up to the challenge. This occurs with some measurements of component dimensions and material condition. The second type of measurement concerns the processes inside engines as they are running. Ideally one wants to measure the distribution of temperature, gas flows, and changes in materials and their dimensions to a high accuracy, but without disturbing the engine. Measurements may be challenging to achieve at all, or they may be challenging to apply economically. Rolls-Royce has developed techniques to do some of this – historical examples are given below.
X-Ray testing

The geometry of an operating engine is significantly different from that of a static one. The temperatures and pressures of operation cause the structures to change their shape and size. Understanding these changes is crucial to retaining effective sealing between rotating and static parts. The need to validate its design understanding in these critical areas led Rolls-Royce to invest heavily to pioneer the use of X-rays to image running engines. The technique uses high-energy linear accelerator X-ray sources. Since its inception in the 1960s this capability has been used on a wide range of engine test campaigns and has won a number of awards including the Royal Academy of Engineering McRobert award and the National Measurement Award for frontier science and measurement.

Blade Shape Measurement

While X-ray testing can track many of the changes in a running engine, sometimes more detail is needed. The development of high efficiency fan blades led to the need to predict their true running shape accurately. Again, Rolls-Royce pioneered a novel method using an indexed pulsed laser mounted upstream of the fan, and a casing-mounted camera viewing the intersection between the laser beam and the blade through a window. This system is capable of plotting the three-dimensional running shape of the blade throughout its envelope of operation. Whilst expensive to deploy, this type of technology serves to validate computational models of the components, which can then be used for future designs. Only when a major change in design is introduced, is a further detailed measurement campaign needed.

Whilst examples like these illustrate the measurement capability developed as part of the company's Research and Technology programme. The use of sophisticated measurement also underpins the whole R&T programme. The company makes extensive use of university research through its network of University Technology Centres. Many of these are pioneering measurement technology developments to support their experimental investigations and validate computational models.

We have looked at a recently approved major research programme and from the activity descriptions we have identified the metrology-related tasks within it. Improved measurement was essential to modelling and then to improved manufacturing and rig testing in which measurement was more explicitly integrated. Research on measurement techniques and methods comprised about 4% of the total programme budget. This is consistent with the other measures of the proportionate role of measurement.

Measurement research is intimately bound up with improvements in modelling. There are some areas where the ability to model an aspect of an engine has improved to such an extent that it outstrips the ability to take the measurements that drive the model. This ‘measurement frontier’ is constantly changing.

The Rolls-Royce situation is not new. A recent report¹, for example, describes of how the Wright brothers used measurement as part of their research into the aerodynamics of aircraft wings and, building on that, as part of their development effort to build the first viable aeroplane. This example illustrates a very common ‘virtuous circle’ in which measurement supports R&T and innovation.

¹ The Economics of Metrology and Measurement, G.M. Peter Swann, Innovative Economics Limited, September 2009
Research and Development (R&D)

In Rolls-Royce ‘R&D’ is dominated by the process of creating new products. For Aero engines, there is an established routine in which dozens of test engines are instrumented and tested every year. This involves calibrating, installing and leading out some 3000 individual sensors. It can take ten times more hours to assemble an instrumented engine compared to a production engine as a result of the measurement instruments and their lead-outs.

The engine is run in one of the company’s test beds with data acquisition systems to handle thousands of channels of data on each test. Up to 3000 measurement series are taken, and then the engine is stripped down. The data collected are analysed and fed into subsequent design iterations of the engine. The costs of gathering such data form a very significant proportion of those of bringing a new product to market, but are an essential part of the process.

Manufacturing

Measurements are carried out at every stage of the manufacturing process. The processes used for metal forming, machining, heat treatment, metal finishing all require many thousands of individual measurements to prove that the components comply with the design requirements. There are thousands of in process measurements, which are continuously monitored to ensure the manufacturing processes are under control. For example, control of the heat treatment and metal forming processes require careful control and measurement of the temperature gradients and profile within a furnace. Final inspection measurements are applied to thousands of key dimensions to ensure that the geometric characteristics such as roundness, form and surface finish are achieved. There are many sophisticated measurement techniques used: from contact to non contact methodologies, run charts to ensure processes are centred around the mean and NDT/NDE measurements to ensure special processes deliver the required result. Material integrity is confirmed at many stages from measurement of samples to evaluation techniques such as x ray and ultrasonic inspection on the finished components.

No process stage is ever completed without some measurement having been taken to ensure that the process is under control. The company uses adaptive machining techniques, which require continuous measurement in real time to provide closed loop control of the metal removal processes. With tens of thousands of components in an engine, each one can have many processing stages. The importance of measurement to Rolls-Royce is illustrated by the sheer number of different measurements taken, and the fundamental requirement that all measurements are traceable to National standards with many requiring retention for the life of an engine.

Besides the measurements taken within the company, there is a large supplier base and these suppliers also have to adhere to the same strict requirements of using measurement to prove conformance and measurement capability.

Finally before a production engine can leave the factory, it is mounted on a pylon then tested and the performance measurements are then used to confirm whether it meets the acceptance criteria for the particular engine type.

In-service monitoring and inspection

A growing part of Rolls-Royce’s revenues are derived from contracts with operators where the company maintains engines during use. So Rolls-Royce is faced with the need to predict when parts need to be replaced. Inspection uses measurement equipment but is time consuming and may involve stripping down parts of the engine. So there is a trend to fit modern engines with numerous sensors that provide condition monitoring data. These sensors need to be rugged, light, low cost, and reliable and the knowledge base that underpins their interpretation accumulates over many years of testing and operation. These types of measurement are a key enabler for aftermarket services.
Lifecycle analysis of a compressor blade

To further understand the uses of measurement we have looked at the lifecycle of an aero engine compressor blade – a numerous but important component. There can be around 1000 such blades in an engine. To be able to design the blade, the following are needed:

- knowledge of material properties;
- finite element models of blade stresses;
- computational fluid dynamic models of the flows around the component;
- aeroelastic models linking the first two models;
- performance and whole engine mechanical models describing the behaviour of the component as part of the whole engine system.
- Models of the manufacturing processes e.g. forging

All of the above models require thousands of exacting measurements to validate the design concept before the detail design of the component can be completed.

It is then necessary to confirm, through measurement, that the concept design satisfies the intended purpose:

- vibration testing of the prototype enables the vibratory response in each of 20+ modes to be measured;
- blades are installed in a compressor test rig and thousands of measurements made on the air flows and the power absorbed over a range of conditions (to avoid potential damage to the rig, hundreds of additional indirect measurements may be needed);
- the final validation of performance will be through a range of tests in a full engine, where, again, thousands of measurements of the performance, thermal, and mechanical behaviour will be made.

After the design validation process, the manufacturing processes must be defined. The manufacturing process for a blade is as follows:- (raw material entering the factory to finished blade leaving it):

Raw material is pre-inspected for composition and properties. The forging process involves measuring 31 features at each of three process stages (93 features in total). Machining involves the dimensional measurement of between 50 and 171 features on the most complex blades. All finished features are 100% inspected (i.e. not inspected through sampling)

Visual inspection is carried out at six stages through the process (including final inspection) and surface finish measurements are made on sample blades after finishing.

In total there are between 150 and 300 feature measurements on each blade, and on average over 1 million such items are produced each year.

Measurement does not stop once the blade has been manufactured. Once in service, measurements of vibration are monitored for evidence of blade damage and the blades are inspected at intervals using flexible endoscopes.
Finally, even disposal involves measurements of material composition to confirm the composition of the recycled material.

This lifecycle analysis has demonstrated the sheer volume of measurement data that accompanies each blade, and also the extent to which gathering this data is an integral part of the company’s operations.

**Findings from the calibration database**

Rolls-Royce maintains databases of all the measuring equipment used in manufacturing, development and test. This information includes the location, type and calibration history of each item. Analysis of one such database gives an insight into the calibration practices within a major engineering firm. There are over 200,000 pieces of measuring equipment listed on this database. Of these, some 133,000 items are in active use. To maintain the active items, there were approximately 170,000 calibrations undertaken in 2008. Thus, on average each instrument is calibrated every 10 months with calibration frequencies ranging from 3 months to 5 years.

This data enabled us to scale the amount of measurement equipment and activity relative to turnover. There is approximately one item of measuring equipment listed per £70,000 of turnover and one calibration per every £50,000 of turnover.

**Types of measuring equipment**

The database of gauges and measuring equipment we studied primarily supports the manufacturing operations with the majority of measurement equipment being used for dimensional measurement. Some 70% of the equipment is used for dimensional measurement whereas just under 30% comprises instrumentation used for non-dimensional measurements.

A breakdown of the top ten types of measuring equipment is shown in the graph below.
The scope of equipment used by the company is very large. There is dimensional measuring equipment both contact and non contact, engine testing instrumentation, laboratory test equipment (e.g. hardness testers, extensometers, electron microscopes) and process instrumentation for furnaces, hot presses and autoclaves. The physical size and scale of the measurements ranges from sub micron for surface roughness and roundness to large volume measurements such as the engine/wing interfaces on large civil Trent engines.

The most numerous pieces of measuring equipment are 'special to product gauging'. These are unique and are used for measurement of a particular feature within a component or sub-assembly. Typically these are bespoke items and need special measurement techniques such as measuring the feature from first principles or use of a co-ordinate measuring machine (CMM). Rolls-Royce as a global company also has around 450 coordinate measuring machines.

The figures above do not include measurement sensors such as thermocouples, which are fitted to test engines. The number of these used has been estimated at 50,000 pa with many of these having individually assigned calibrations.

Calibration

All measurement equipment is calibrated according to set procedures with traceability to the NPL or other national standards laboratories. Using data from 2008 (again, not comprehensive but indicative) it can be seen that the average interval between calibrations is less than a year. Instrumentation tends to be calibrated more frequently than dimensional equipment. This may be because it is difficult to know what is happening inside an electronic instrument so it is better to calibrate it as a matter of course. By contrast, it is easier to ascertain visually whether a mechanical item has suffered damage or high usage.

<table>
<thead>
<tr>
<th>Type of measurement equipment</th>
<th>Number in active use</th>
<th>Calibrations in 2008</th>
<th>Calibrations per item</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensional</td>
<td>91296</td>
<td>113419</td>
<td>1.24</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>38115</td>
<td>57025</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Traceability

All calibrations must be traceable to international standards. The table below shows the proportion of gauges or instruments which are directly calibrated by the NPL.

<table>
<thead>
<tr>
<th>Source of traceability</th>
<th>Number of items</th>
</tr>
</thead>
<tbody>
<tr>
<td>On site within Rolls-Royce</td>
<td>132,932</td>
</tr>
<tr>
<td>National standard</td>
<td>52</td>
</tr>
<tr>
<td>TOTAL</td>
<td>132,984</td>
</tr>
</tbody>
</table>

Only a tiny fraction of traceability is directly taken from national measurement organisations or standards bodies. These are either reference standards or relate to parameters where there is no in-house calibration capability, e.g. magnetic field strength or ionising radiation measurements.
Not all national standards are UK ones. For example, Rolls-Royce uses other European labs for certain types of calibration.

However, the importance of the UK National Measurement System to large companies such as Rolls-Royce cannot be underestimated as these standards underpin all the UK calibrations. It has long been known that the cost of these calibrations would at least double in the absence of the UK NMS\(^2\).

**Fan-out**

As an example of how calibrations ‘fan out’ across the organisation, Rolls-Royce in the UK uses 4 sets of reference slip gauges (the standard building blocks of dimensional measurement) to calibrate 670 boxes of slip gauges. This gives a fan out of roughly 150. If any one of the reference slip gauges were sized incorrectly the consequences could be dire, as any error would be transferred to around 150 boxes of slip gauges used in the factories. This in turn would mean that aero engine parts could have been measured incorrectly with incorrect parts finding their way into engine assembly and taking considerable time to identify and correct. This type of error might not be found until the box is re-calibrated the following year and by then, many parts could have been built into engines causing widespread disruption to manufacturing.

**Organisation of measurement activities**

Measurement at Rolls-Royce is not always a full-time job. Sometimes it can be a major part of someone’s work (e.g. in manufacturing engineering, test instrumentation) but mostly it is embedded in a business activity concerned with a particular component’s lifecycle stage (design validation, for example). Three categories of people are involved:

- technicians carrying out measurements as part of the production, test, or maintenance processes.
- engineers developing new products and needing to make associated measurements; or developing new manufacturing processes; or designing components and needing to understand the production measurement capability;
- engineers working specifically on measurement techniques.

The measurement skills deployed range from carrying out physical measurements, to designing measurement systems. While any measurement task requires some understanding of the principles of measurement, the necessary depth of understanding differs according to how routine or challenging the activity is.

Of the 38,000 staff, several hundreds of employees are engaged directly in measurement engineering activities (including design and validation) with many more using measurement, and tens of thousands more in the supply chain.

**NMS interaction**

The company’s measurement specialists interact with the NMS in numerous ways - accessing standards, technical support, project work, services, and relying on the traceability of all of its measurements to the National standards held by the NPL. A number of NPL guides are referenced on the company’s intranet and the NPL dimensional metrology training courses have been widely adopted as the basis for building and developing metrology skills in the business.

\(^2\) See for example, Review of the NMS, Part 1, Scientific Generics, 1992
Cost-benefit analysis

Using data from Rolls-Royce we have been able to make several estimates of the resource utilisation and proportionate cost of measurement and metrology within the company.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Calculated value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workforce ratio</td>
<td>5%</td>
<td>Roughly 5% of engineers are engaged directly in measurement, or make use of measured data. A similar proportion of employees in total are directly engaged in measurement. The process of inspecting a complex component can take longer than the process used to produce the component.</td>
</tr>
<tr>
<td>R&amp;T ratio</td>
<td>2%</td>
<td>At least 2% of the company’s technology budget is devoted to improving measurement capability.</td>
</tr>
<tr>
<td>R&amp;D ratio</td>
<td>3%</td>
<td>This is the proportion of R&amp;D budget spent on measurement and metrology</td>
</tr>
<tr>
<td>Inventions disclosed by RR employees</td>
<td>6%</td>
<td>6.3% of inventions disclosed by RR employees relate directly to measurement capability when searched using the words ‘measurement’, ‘sense’, ‘inspect’ or ‘monitor’ in the title. This could be an underestimate as it excludes those that involved innovation in measurement but didn’t use one of the specified words in the title.</td>
</tr>
</tbody>
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The proportion of the workforce involved in measurement, and also the various proportions in this table, are in accord with estimates from the USA in 1984. At that time, a report from NIST estimated that the average value added from measurement was 3.5% of contribution to GNP. This was based on calculations of the labour hours expended on measurement in each sector.

The benefits of measurement are impossible to quantify overall because measurement is an inherent and embedded part of manufacturing. Indeed, manufacturing would simply be impossible without measurement.

However it is possible to estimate the benefits of individual metrology projects in which better measurement has helped solve a problem or improve an engine.

Economic analysis

This case study has illuminated several aspects of the economics of measurement in Rolls-Royce.

Firstly, measurement and metrology are largely indivisible from the production and product development processes on which the company depends. Rather than trying to estimate the value they add, it is more instructive to consider what would happen if the different types of measurement and calibration were dispensed with.

- Within Research and Technology (R&T), if long term measurement capabilities were frozen as they are now, then the company would not be able to develop the next but one generation of engines. Since each generation has a lifespan of ~10 years, this would limit the company’s ability to survive beyond this timescale.
- Within Research and Development (R&D), if measurement and calibration were stopped, then there would be no next generation of engines.
- Within manufacturing, measurement is essential for day-to-day operations to ensure that components, subsystems and systems fit together. Without measurement there would be no
parts. Without calibration the ability to produce parts to specification would rapidly diminish, causing production to cease.

- Within In-service monitoring and inspection, without measurement, this part of the business would not be able to exist and flight operations would rapidly cease.

The study has therefore demonstrated that Rolls-Royce is dependent on measurement, calibration and metrology for its short term and long term viability, as well as for the development of new business areas.

Secondly, national measurement systems (principally the UK NMS, given the company’s UK engineering base) are essential to underpin and supplement in-house capabilities and to enable the company to effectively interact with its supply chain.

Thirdly, measurement activity seems to account for between 2% and 6% of input measures (e.g. numbers of engineers) and output measures (e.g. patents). This accords with other published research.

Conclusions

There has been very little published on the detail of how measurement is used within large engineering firms. In this case we have seen that Rolls-Royce uses measurement intensively:

- in the innovation of new products, design models, materials and manufacturing processes;
- at each and every stage of manufacturing;
- to support trade with suppliers and end customers;
- as part of the product, using sensors to monitor and control engines;
- as part of the service offering, using data from monitoring and inspection to manage product throughout its operating life.

Accurate and timely measurement is therefore crucial to delivering the company’s leading-edge engine products and services. This is supported by a sophisticated appreciation of the importance of metrology. Metrology is an actively managed function within the company. There is senior management accountability, and there are internal processes to allow best practice to be shared. The company has a long established measurement training programme. Rolls-Royce maintains an engagement with the UK NMS through advisory bodies that enables it to guide and to some extent shape the NMS agenda in relevant fields of measurement.

With measurement being so extensive and embedded, it is impossible to isolate the benefits of measurement overall. But it is possible to say with certainty that there have been a number of research projects that have delivered better measurement, and these have had benefits far in excess of their costs.