Practical implementation of machine tool metrology and maintenance management systems

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Abstract. Maximising asset utilisation and minimising downtime and waste are becoming increasingly important to all manufacturing facilities as competition increases and profits decrease. The tools to assist with monitoring these machining processes are becoming more and more in demand. A system designed to fulfil the needs of machine tool operators and supervisors has been developed and its impact on the precision manufacturing industry is being considered. The benefits of implementing this system, compared to traditional methods, will be discussed here.

1. Introduction

The issue of getting the best performance out of a machine tool is a constant problem that must be addressed by the maintenance and production departments of any workshop. As documented and discussed by many authors [1,4,9] there is an ever-growing need for tighter tolerances and more reliable machine tools. This increase in performance is being driven from all sides; Governments imposing regulations on industry to reduce waste and increase efficiency; customers requesting shorter production times and tighter tolerance parts; increasing globalisation raising the competition in manufacturing industries [1]. This paper will discuss the necessity for traceable, data driven system in real world environments, and the benefits it can bring to high accuracy machining.

2. Classical approaches

As machine tools become increasingly complex, they require more specialist maintenance and measurement to ensure that they remain operational and perform at the required accuracy levels. This leads to an over-abundance of data that is captured, often at great expense, and stored without being utilised to its greatest extent or much thought given to its future use.

Maintenance teams under pressures from production managers are often forced into “fire-fighting” mode when a machine tool goes out of production, as there is not the time available to develop comprehensive strategies to deliver the best possible production value for the cost of the machine repairs. This often leads to situations where the asset is corrected or compensated so that it is available to production sooner, but without addressing the root cause of the failures.

Over time these quick fixes can lead to a more unreliable asset with far greater amounts of time and money being poured into a machine than correcting the initial error would have cost. This can be down to many causes:

- Incorrect or unsuitable measurement procedures
- Poor data recording and storage methods
- Inability to correctly analyse the recorded data or select the repair actions
- Unsuitable or un-calibrated equipment
- Insufficient knowledge regarding the possible errors present in the machine tool

Any or all of these issues can mean that a machine tool is never utilised to its full potential reducing its worth to the organisation, and impacting any future maintenance plans.

One of the problems being faced by industry at present is the lack of skills regarding the suite of modern metrology equipment, the uncertainty surrounding their measurements, and the capabilities of the machine tools they are used to calibrate. This can lead to a cycle of discovering an error, attempting a correction then delving deeper if the solution does not have the desired outcome (Figure 1).

Figure 1: Fix/check cycle.

Solutions to the issue of under-utilised data has been discussed and addressed by authors such as Lee [10], and Meo [11] but the question of the uncertainty surrounding the measurements themselves still remains.

3. Measurement Uncertainty

All measurements are subject to a certain degree of uncertainty. When dealing with today's high precision machine tools, the measurement equipment is often performing close to the edge of technological limits, and consequently may be subject to an increasingly large degree of uncertainty. These limitations must be documented and stated with any calibration certificates or measurements. For example, Renishaw state that their XL-80 laser system has an uncertainty or measurement of 0.010 parts per million (ppm) k = 2. When this is combined with the environmental compensation unit and used to take positional measurements gives us an accuracy of 0.5ppm, and resolution of 0.001µm with 95% confidence[8].

Regardless of the capabilities of the equipment, it is still up to the user to attempt to minimise all the additional sources of uncertainty that may influence the readings, such as the Abbé offset error (Figure 2), poor mounting surfaces, or even the effects of gravity.

Throughout any data driven system this must be done by constantly reviewing the methods of test to reflect the most current knowledge and most up-to-date standards [5,6]. Only then can conclusive statements about the confidence in the measurements be made.

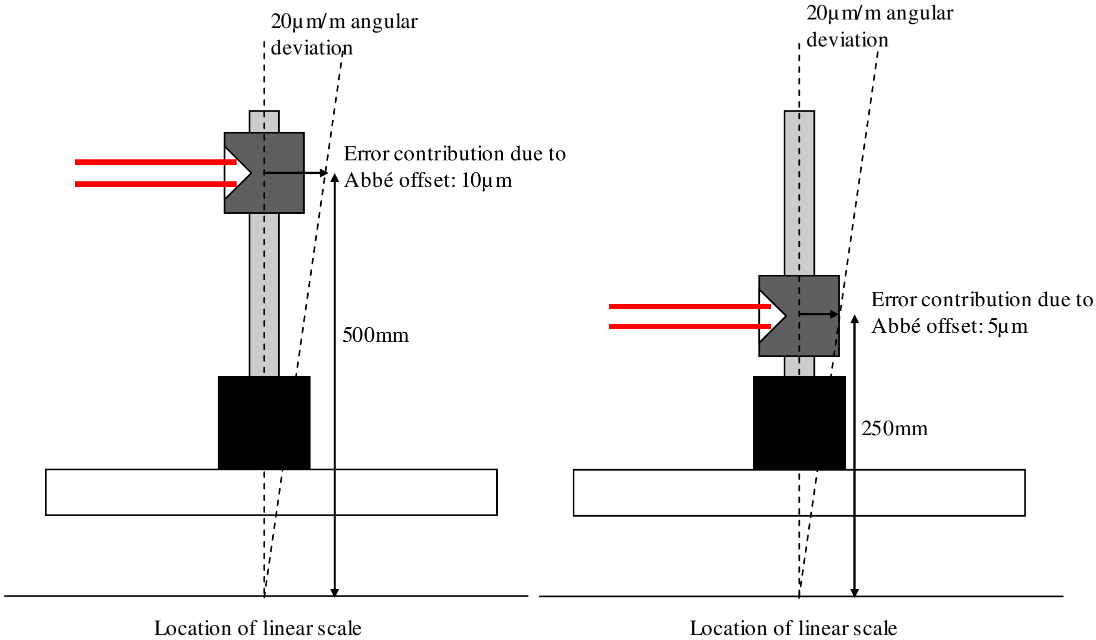

Figure 2: Abbé offset.

4. Improved System

Without proper reference to recognised standards and procedures, the reliability of captured data, and consequently the decisions based on it, can easily be brought into question. Additionally, the process of transforming measurement data from a machine tool into sensible maintenance and repair actions requires reliable data and a good understanding of machine tools and measurement to allow the most cost effective actions to be selected. Further, as more and more measurements are performed on machine tools, the need for this data to be analysed and understood as a whole by the maintenance engineers, and for it to be correctly used when deciding upon repair actions is growing fast.

The ideas introduced by Ishikawa [2] say that there are six contributing areas to consider when attempting to trace the source of a problem:

- Method(Measurement process)
- Man/operator
- Environment(temperature variation etc)
- Measurement (measurement equipment)
- Material (Information.)
- Machine

If we apply this theory to the process of measuring a machine tool in order to trace the source of an error on the machine, we can systematically eliminate sources of error until the remaining element – the machine tool itself – must be the source. The ideal data driven system must do this by specifying, controlling or recording all the other variables that could affect the measurement, leaving nothing to random chance.

4.1. *Method*

The ability of machine tools to repeatedly produce multiple parts to the same tolerances is their most desirable feature. Their continued ability to do this relies on the abilities of the calibration experts to do the same when aligning and correcting the machine tool.

Whilst measurement procedures, even those taken from international standards, may dictate what measurement is to be taken, it is rarely specified exactly where in the machine's volume the measurements must be taken, where on each machine the equipment should be placed, and numerous other setup parameters involved in designing the experiment. This is not an oversight or omission, simply a consequence of the huge number of machine tool configurations in the world, and the large number of competing measurement devices, each with their own methods, procedures and equipment.

A good example of this measurement variation due to the methods used can be seen with positional accuracy tests made with a laser interferometer. The environmental compensation is crucial to the accurate functioning of the laser and the temperature sensors are an integral part of this calculation. If the temperature sensors are not placed in the same location each time this can have a large impact on both the material and beam compensation values. If the material sensor is moved from the machine bed, to one of the axes, to one of the motor housings throughout subsequent setups (Figure 3) large temperature fluctuations will be recorded between tests. This will consequently lead to highly variable positional accuracy results and a, seemingly, highly variable machine.

To combat this, test methods and equipment setups should be both described and, ideally, photographed to ensure that as much information as possible is retained for subsequent measurements. This allows the variability of measurement setup to be reduced significantly, therefore making repeated measurements much more valuable.

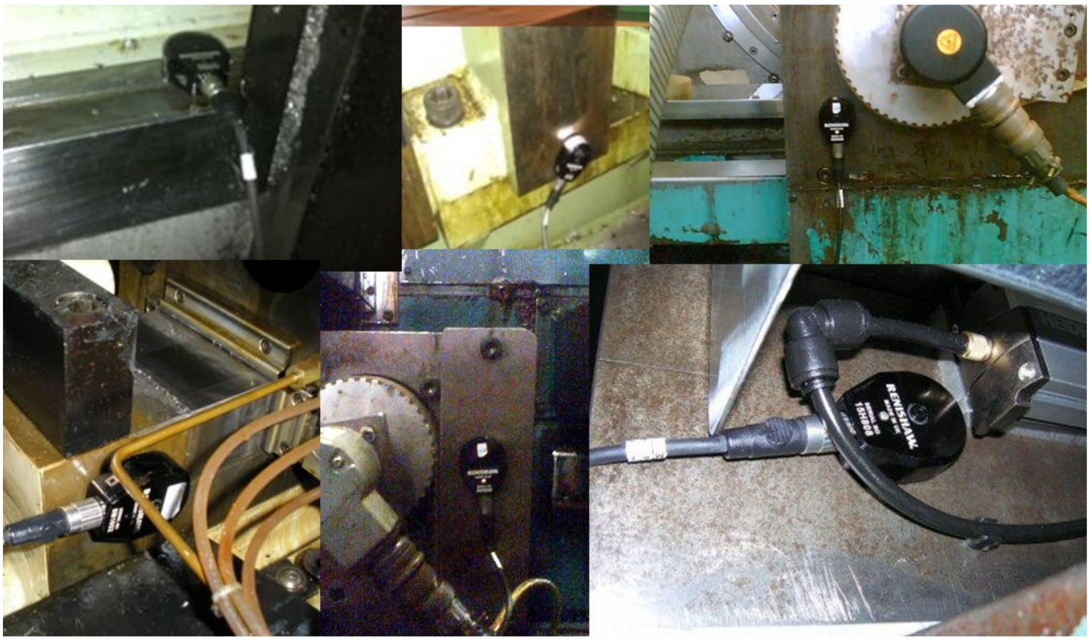

Figure 3: Temperature sensor placement.

Traceability standards must also apply to the methods and techniques used to take the measurements in order to ensure that they are being used in the correct manner. To this end, the methods and processes used in a successful data driven system must be referred back to the relevant national or international standards wherever possible.

4.2. *Operator*

Almost all measurement equipment is designed to be utilised by a human operator. This allows equipment to be as flexible as the operator can make it, but also allows the introduction of further variation through the human operator. To combat this, individuals using the equipment should have the necessary knowledge and understanding to competently use the required equipment, and also follow the procedures and diagrams that may be required to complete the required measurement. Again, to satisfy traceability standards, the appropriate documentation and certificates should be available to prove that the required training has been undertaken.

Adequate training in these areas can allow maintenance engineers to make far better, evidence based decisions, and to understand the strengths and weaknesses of different equipment in different environments. It will also reduce the chances of operator induced error due to a mistake such as recording a sign incorrectly. This is displayed in Figure 4, where a 2μm variation in leads to a large recorded variation if the sign is incorrectly noted.

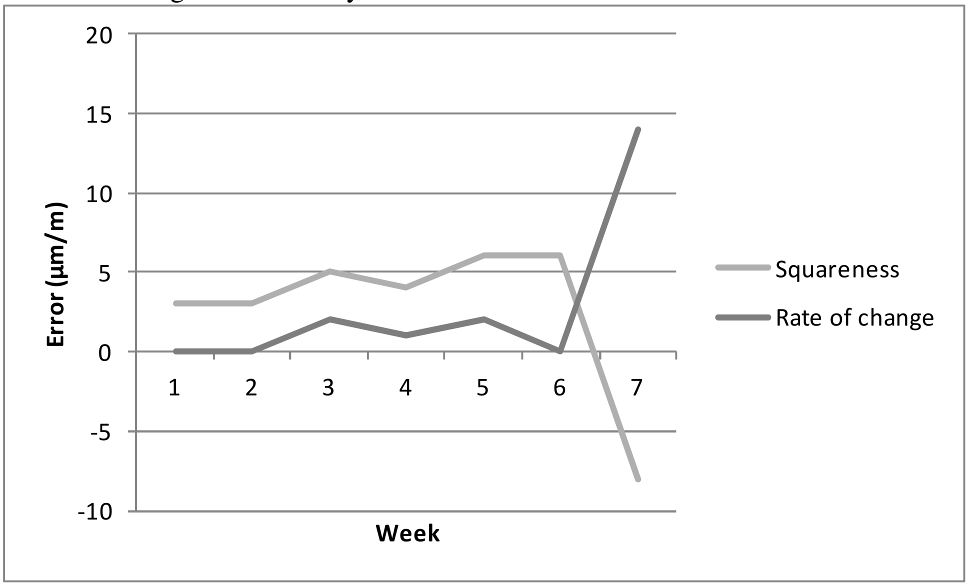

Figure 4: Incorrect sign recording.

4.3. *Environment*

As tolerances become tighter, and the accuracy that machines are designed to achieve are driven ever higher, the effects of environmental variation become more and more problematic. As modern, high accuracy machine tools are being produced with stated accuracies of 10 microns, and repeatability figures of 6 microns (or better), new methods of excluding environmental effects from the process are having to be explored. Steel (still by far the most common material used in machine tool construction) has a coefficient of thermal expansion of 11 to 13 μm/m/^{o}C dependent on the specific type or composition used. A temperature change of just 1 ^{o}C could therefore introduce a positional error of 13 microns in an axis of 1 metre, putting the machine outside tolerance unless this temperature variation is taken into account. This has led to a range of solutions ranging from temperature controlled machine shops to advanced thermal control systems within the machines themselves to extract excess heat [7]. However, the commercial implications of such systems usual means that control is seldom better than ±1 ^{o}C, resulting in a band of 26 μm\m.

To address this issue, any measurements that could be affected by temperature variation must be accompanied by temperature readings in order to account for any variance in readings. If this is not correctly addressed then a change in measurement could lead the engineer to suspect mechanical change, whereas the machine is really mechanically stable.

4.4. *Measurement equipment*

Measurement equipment traceability is an issue for any organisation where guaranteed accuracy is a concern as measurements are only as good as the equipment used to take them. Simply trusting that equipment performs as well as it has been claimed can lead to serious problems for many reasons. Equipment may have been damaged, may never have been able to perform to the stated levels or may need recalibrating or resetting.

Using the procedures set out for a robust system, all equipment used in the measurements must be in good working order and must have a valid calibration certificate. Without this, large amounts of time may be wasted attempting to track down the source of erroneous measurements that may not have existed in the first place. Worse than this, a correctly aligned machine may be adjusted using incorrect data from unreliable equipment leading to a situation where the machine is worse than when the work began.

4.5. *Material - Data*

The ability to store and retrieve the relevant data relating to a machine tool and its errors in a way that will retain the full meaning of the measurements is of almost as much importance as the reliability of the measurements themselves. The format presented and used in any system must allow all the relevant data relating to the machine error in question to be quickly and concisely accessed. Without this record of the machines status, the asset owner may be left exposed if errors come to light in future that affects delivery or reliability of parts.

4.6. *Machine*

After all the previous sources of variation are accounted for, the remaining deviation can be attributed to the degradation of the machine – within the bounds of measurement uncertainty – or incorrect adjustments within the CNC control. This is where comprehensive understanding of machine tool construction, geometry and control is essential in allowing the correct sequence of tests and measurements to be conducted. Without this, measurements may be omitted – leading to incomplete data regarding a machine, or duplicated – leading to additional unnecessary machine downtime.

5. Standards

Multiple standards exist for verification of a machine tools capability. They range from specifying the elements of the asset that should be measured [3] to the procedures and tolerances that should be used to take these measurements [8]. The authors of these reference standards can be the original equipment manufacturers (OEMs), various standard bodies (BSI, ISO, VDI), calibration houses, or even the machine tool owners themselves. Attempting to combine all these procedures into a concise manual for the present machine and process can be a tricky endeavour, which can lead to mistakes if there is not sufficient knowledge of measurement and uncertainty.

The ISO standards (ISO 230 series in this case) attempt to provide an impartial reference for the measurement and calibration of the various functions of a machine tool. Various methods and equipment are proposed and the most suitable for the users budget and expertise can be selected. As the standards are released periodically, and do not favour any particular manufacturer, they cannot contain full operational manuals for the operation of all the possible measurement methods and equipment – only general procedural guidelines. The particular equipment used for a measurement must be supported by its own documentation and usage instructions. This can introduce a further level of uncertainty to the measurement procedure depending on the complexity of the equipment and how difficult it is to operate.

As the manufacturer of a machine, the OEM is best placed to understand the strengths and shortcoming of any particular machine, and to supply the procedures and documentation to monitor them. In some cases when dealing with exotic configurations of machine, these procedures may be the only way to measure a certain aspect of the machine's geometry. These procedures should not necessarily be trusted completely, as the manufacturer may not want to highlight a shortcoming of the machine they have produced.

To address all these different techniques and procedures the documents and methods of test within the system must combine the most appropriate guidelines from the ISO standards, whilst at the same time incorporating the tolerances and any specialist knowledge and tolerances from the OEM's specification. This will allow the largest amount of data to be captured from the machine to aid in the later analysis

6. Analysis

Once the credibility of the data acquired from the machine has been assured, analysis can take place without the threat of time being wasted, or incorrect compensations applied. The process of analysing the machine's freedoms of movement from the foundations up, rather than the tool downwards, allows the errors reported by the asset owner to be traced to the source, rather than attempting to correct a symptom without isolating the cause. Importantly, as the measurements are being analysed with the machine's current process in mind, any repair actions that may be required can be targeted to allow the production of the current parts. This combination of metrology and maintenance is what allows great savings to be made. Instead of a maintenance team attempting to correct a machine, followed by a metrology team measuring the results and cycling between the two until the goal is reached (Figure 1), the measurements are now directly utilised to create the most effective repair plan to achieve the desired levels of accuracy and repeatability (Figure 5).

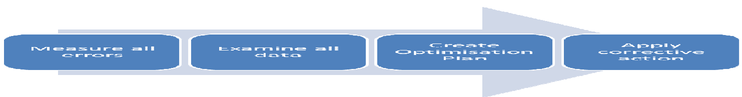

Figure 5: Optimisation flow.

7. Examples

A simple linear positioning error can serve as a good example; If the positional accuracy of a linear axis is not performing to the required levels, the maintenance department may be called to investigate. If the equipment and procedures used are not certified and traceable back to recognized standards, results may be produced, but the measurements can be called into question at a later date. If the results are not recorded with reference to all the relevant coordinates, environmental conditions and setup parameters, everything from the result of the test to the repeatability of the test and competence of the operator can be called into question. Even if all these elements are in place, if the operator of the equipment is not sufficiently skilled the process may still fail to produce conclusive results.

A common choice for taking these readings is a laser interferometer system as it can provide highly accurate information when used correctly. If the measurements highlight that there is a backlash issue this may result in the replacement of a ballscrew – often a costly and time-expensive procedure.

Mistakes that lead to this costly, unnecessary repair can occur at any stage and lead to serious consequences:

- Incorrect procedures used – the error is not identified at all, leading to scrapped/reworked parts

- The equipment is used incorrectly or is not performing correctly (out of calibration) – a larger error is recorded than is actually present leading to a costly ballscrew replacement.
- Environmental variables are not taken into account – the error may appear and disappear leading to inconsistent part production and large amounts of downtime attempting to trace a transient error.
- Results not recorded/incompletely recorded – the error has been seen with the equipment but has not been documented correctly leading to loss of data and repeated measurements.
- Limitations of equipment not completely understood – comparing angular readings from a laser and those from a level over large distances may create confusion if the curvature of the earth is not taken into consideration.

If all the errors on the machine that can contribute to this reported machine symptom had been examined it would have been found that the ballscrew was in fact performing within its specified tolerances. This would have led to a closer inspection of the measurement system where it would have been found that the scale reader head was slightly loose.

Even if the error was in fact being produced by the ballscrew, using a comprehensive examination system, with the additional knowledge of the process the machine is tasked with, it could have been suggested that the machining area be moved to a different part of the machine's working volume. This could allow the machine to produce parts to the required tolerances with no repairs or further downtime on the machine.

A system that puts into practice these guidelines has been developed and utilized by Machine Tool Technologies Ltd. (MTT) – this system is called machine performance evaluation, optimization and monitoring (MPEOM™) [4].

7.1. *Case study 1:Data capture errors*

A seemingly simple process of recording the direction of the recorded error in relation to the relevant axis and the rest of the machine can cause extreme problems if overlooked or omitted. To illustrate this, the straightness measurement of a linear axis can be used.

A straightness measurement was being performed on a 5 axis gantry machine. Due to time pressures the direction of the measurement was not recorded correctly. The compensation table was generated and inputted into the machine and the axis re-tested. During the re-test it was found that the error had doubled in magnitude and changed direction (when the direction was confirmed). The compensation values were re-entered and the correction re-checked to confirm that the adjustment had been made correctly this time.

If this instance, the only consequence was a minimal loss of time (approx. 30 mins), however if the adjustment had been made to the guide rails of the axis much greater amounts of time would have been lost and the machine may not have been returned to its previous state correctly.

7.2. *Case study 2: Root cause analysis*

MTT was asked to investigate surface finish errors on a high accuracy lathe. The client had previously spent many hundreds of man hours attempting to trace suspected vibration, positioning and alignment issues. After a full machine examination (according to ISO 230 – part 1[3]) to eliminate the static errors on the machine the machine was found to be within tolerance. With this area excluded from the investigation the problem was traced to the drive optimization setting and the following errors in the axis drives. Before and after plots of the dynamic response of the machine's axis are shown Figure 6.

7.3. *Case study 3: Retrofit and Rebuild*

A proposal was put forward from a customer for a Retrofit and Rebuild (R&R) of a machine that was reaching its end of life period, but who's process was still required. Traditionally there are two options available at this point: Replace the machine with a new one, or Strip down, retrofit, and rebuild the machine to provide a new lease of life. Both of these options were highly expensive, costing £580,000 and £270,000 respectively. Additionally, the R&R of the machine would require 12 weeks downtime, with the construction, delivery, installation and commissioning of a brand new machine taking even longer.

The third option provided was that of passing the machine over to MPEOM™ control. This involved thorough analysis of the machine itself and the process it is being asked to carry out, followed by targeted repairs to allow production to continue. It was calculated that the cost of completing this targeted repair was £30,000, and required only 3 weeks production downtime. The only caveat is that as this system does not significantly upgrade the machine or its ancillary equipment beyond its original scope, it can only provide an additional 3 years of production in the current state.

The third option was selected and completed, and the machine is currently still in production, and producing satisfactory parts over 12 months later.

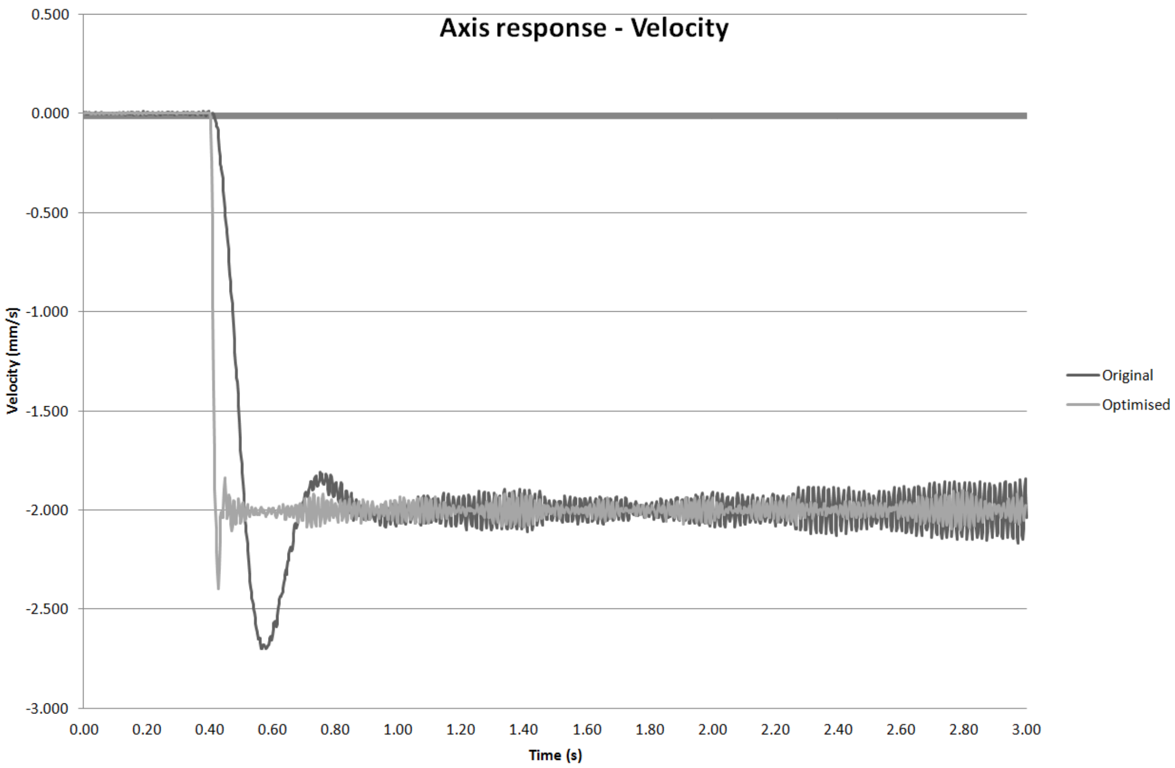

Figure 6: Axis drive response.

8. Conclusions

As demonstrated here, utilizing a data driven analysis process provides a robust and traceable framework through which a machine tool can be repeatably assessed, measured and optimised for its current process. Many of the recognised shortcomings of general measurement practices are addressed and wherever possible minimised or eliminated by the equipment or procedures used in order to minimise measurement variation. This allows evidence based conclusions to be drawn from the data, and the most cost effective repairs to be made.

As the data is stored and presented in a standardised format, mistakes and misinterpretations are minimised, and analysis of the data is greatly accelerated.

9. Further work

One of the outcomes of the research conducted here has been the development of a software project to bring together the lower level analysis functions of the MPEOM™ system and a selection of the features of a Total Productive Maintenance (TPM) scheme. This has allowed the creation of a machine condition and maintenance monitoring system that can be used by machine tool operators, maintenance engineers and management personnel. It aims to both reduce the time spent completing and transcribing paper based records and allows instant access to full details of a machines metrological and breakdown history making both day to day monitoring and in depth analysis faster and easier.

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References
[1] Ahuja I.P.S and Khamba J.J 2006 *Total productive maintenance: literature review and directions* International Journal of Quality & Reliability Management, Vol25, No. 7 (Emerald Group Publishing)
[2] Ishikawa, K. 1990 (Translator: J. H. Loftus) *Introduction to Quality Control* (Productivity Press)
[3] ISO 230-1:1996 , *Test code for machine tools -- Part 1: Geometric accuracy of machines operating under no-load or finishing conditions*
[4] Willoughby P, Verma M, Longstaff A P. and Fletcher S, *2010 A Holistic Approach to Quantifying and Controlling the Accuracy, Performance and Availability of Machine Tools* Proceedings of the 36th International MATADOR Conference p 313-316 (Springer: London)
[5] JCGM 100:2008 *Evaluation of measurement data – Guide to the expression of uncertainty in measurement*
[6] Stephanie Bell 2001 *Measurement Good practice Guide No. 11(Issue 2)* (NPL: Teddington)
[7] Tasi K 2008 *A novel control scheme for temperature control of Machine Tool Coolers* Journal of Applied Sciences 8 (13)
[8] *Renishaw XL-80 Software*, Version 20.01.02 2012 (Renishaw)
[9] Wang C, Thomas R 1997 *Predictive maintenance and machine tool calibration techniques* Modern Machine Shop Volume 69, Issue 11 p 102-109. (Gardner Publications)
[10] Lee J, Ni J, Djurdjanovic D, Qiu H, Liao H 2006 *Intelligent prognostics tools and e-maintenance* Computers in Industry, No 57, p476-489 (Elsevier)
[11] F. Meo, M. Foursa, S. Kopàcsi, T. Schlegel 2009 *Predictive Maintenance and Diagnostics of Machine Tools* IPROMS procedings 2009