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The compensation of large grinding machine, rotary bearing synchronous errors using a vertical axis, optimised by a non-influencing counterbalance system

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Abstract

Cranfield Precision supplies a large grinding machine, the OGM1600, that is used in the production of ultra precision freeform surfaces of up to 1.6 m diameter. This paper describes the discovery of errors that appeared in ground components after Covid lockdown restrictions began to be lifted, the interim solution to enable the machine to continue in production and the corrective action taken once Covid travel restrictions were lifted.

Keywords: Grinding, error compensation, vertical axis counterbalance, hydrostatic oil varnish.

1. Introduction

The OGM grinding tool path is an interpolated spiral using the worktable (C-Axis), synchronised with the machine's horizontal and vertical linear axes. During the Covid pandemic, the machine spent a lengthy spell with all of the machine's hydrostatic bearing axes grounded.
After lockdown was partially lifted, component measurements showed evidence of nine, equally spaced 'spokes' of around 300 nm amplitude superimposed upon the surface. The surfaces were still within specification, but as these features were new, it was essential that the source of the problem be understood and corrected. This paper describes the scale of the problem that was encountered, the interim compensation method deployed and the correction of the issue one the machine was able to be serviced.

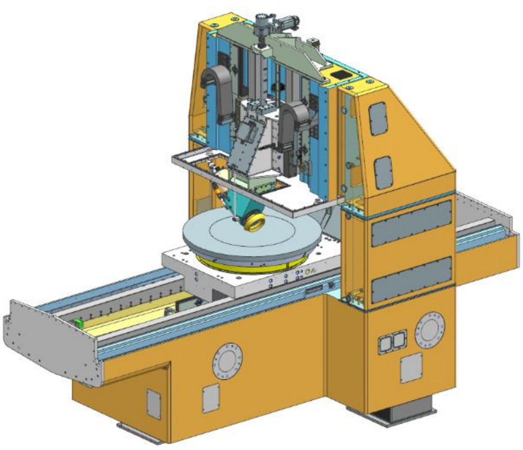
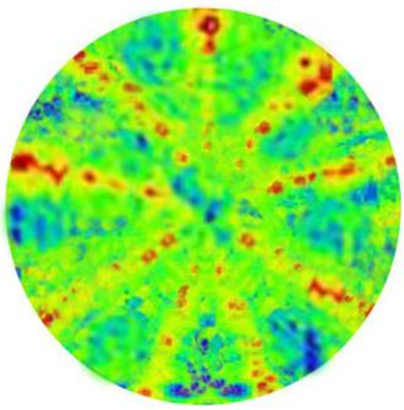


Figure 1. OGM1600 machine configuration

2. The problem encountered

By the time production re-started after the Covid lockdowns started to be lifted, the OGM machine had been powered off, with hydrostatic bearings grounded, for an extended period.

Initial components ground after lockdown, began to show evidence or regular spoke patterns superimposed upon the desired, ground surface. The regular spokes had peak to valley errors of up to 300 nm. The components were still inside specification, but this new patterning had to be understood and eliminated.



P-V error ~300 nm

Figure 2. Measured error pattern, superimposed upon the required form ground after Covid shutdown.

Once it had been confirmed that the nine spoke pattern was evident in all ground components, the next step was to identify the source of the issues.

The workhead C-Axis is an in-house manufactured hydrostatic bearing. The axial error motion of the bearing during machine pass off was measured at <100 nm asynchronous and <1 µm synchronous error motion. The synchronous axial error motion plot had a consistent two lobes per revolution over the full range of operating speeds.

To further investigate the source of the nine spoke error pattern, a spindle error analysis (SEA) was performed with Lion Precision's SEA. Measurements were taken over several revolutions and at a range of rotational speeds. The resulting measurement data was analysed and it became clear that there were now nine lobes.

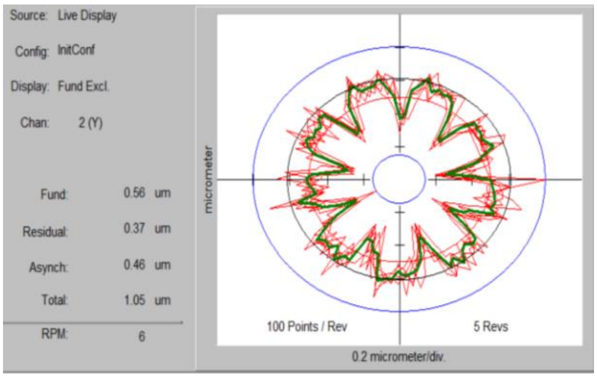


Figure 3. Axis error motion of worktable (C Axis) over five revolutions.

It is clear that there is an axial error motion, nine times per revolution of the C-Axis rotor. The spindle rotor moves downwards, which results in a local increase in the ground surface height.

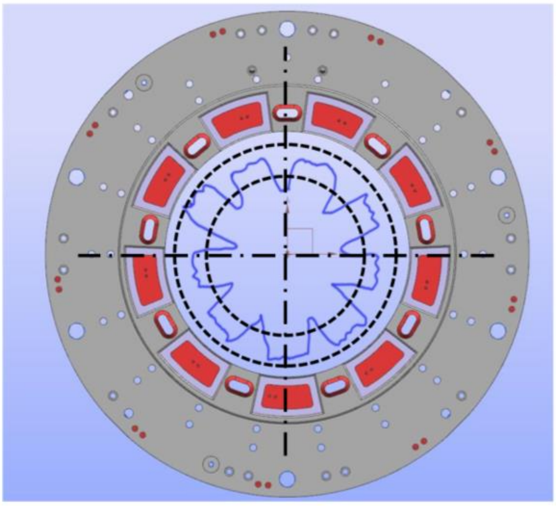


Figure 4. Alignment of vertical error motions relative to hydrostatic bearing pad positions.

The vertical error motion plot was compared to the hydrostatic bearing pad positions. Figure 4 shows the stationary housing bearing pad positions, The rotary spindle is mounted above these pads. The vertical error motions were aligned perfectly to the bearing pad positions. Thus, a mechanism whereby the spindle could be caused to drop, nine times per revolution had been identified.

There was clearly a problem with the C-Axis spindle that needed to be corrected. However, Covid travel restrictions precluded travel to the customer's site to investigate and carry out a repair.

2.1. Potential cause of the problem

It appeared that the spindle rotor was lifting up at the bearing pad positions, and lowering in between the pads. It seemed as though there was something positively imprinted onto the spindle rotor spindle that was aligned to the bearing pad, causing the bearing to lift (and drop) nine times per revolution.

A possible cause was proposed based on experience from around 10 years ago when a machine using hydrostatic linear rails was supplied to a customer in a humid location. The machine had been delivered and it was noticed that the container had been opened (probably by customs) and not re-sealed properly. When the commissioning team was sent to install the machine, it was found that where the machine's linear axis linear bearings had been sitting on the bearing rail during shipment, there were pad shaped rust patterns on the bearing rail. Machines cannot be exported with oil in situ, so must be delivered dry, making them vulnerable to rusting if exposed to humid conditions. The rust was light and superficial and easy to remove, enabling the machine to be commissioned.

The OGM machine, although unused and depressurised for an extended period, had not been exposed to humid conditions and the oil had not been drained from the machine. A theory proposed was that as the C-Axis spindle had been in contact with the bearing pads, it was possible that contamination in the oil had settled between and rotor and pads and dried/hardened, leaving imprints on the spindle rotor.

A potential mechanism for this was 'varnish' that had build up in the oil. Although the OGM oil is continuously filtered and recirculated, it is possible that over time small amounts of varnish could be produced in the oil.

2.2. Varnish in OGM oil

Varnish is commonly found in machine oils [1]. In extreme cases, varnish can be found as dark yellow/brown stains on surfaces within the oil circulation system.

Hydrostatic oil systems are highly filtered and extreme varnish stains are very rarely encountered. The OGM machine is replaced every few months, but tests indicated that very small levels of varnish are present in the oil after just a few months of use.

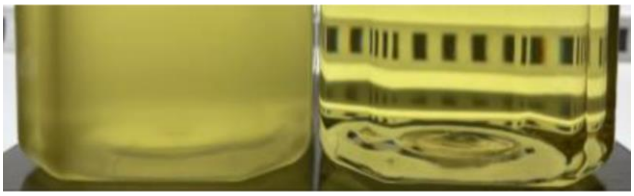


Figure 5. Oil from OGM before and after reconditioning by off-line filtration.

Figure 5 shows a sample of OGM oil, a few months old and not yet scheduled for replacement. After off-line reconditioning (and analysis) very low levels of varnish were found to be present in the oil. Potentially, the root cause of the OGM bearing issue.

However, because Covid travel restrictions had not yet been lifted, it was not possible for Cranfield Precision staff to visit the machine, so an alternative, interim solution was required.

3. Tool path generation (and compensation)

The OGM machine uses custom designed MöbiusCAM software to generate the desired machine tool path.
Figure 6 shows a typical spiral ground OGM tool path to create a freeform surface.

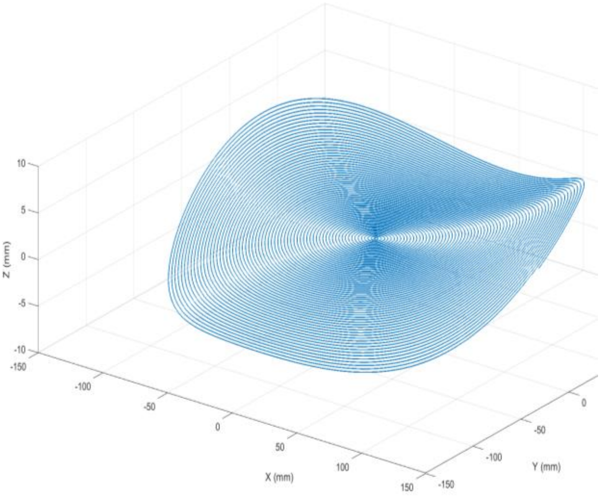


Figure 6. Desired component profile

It has been found to be possible, on machines, with low inertia linear axes and at low component rotational speeds, to compensate for ground surface ripples induced by workhead motor torque ripples. These component ripples are caused by the elastic time constant of the machine stiffness loop. As the rotational speed reduces, the grinding wheel effectively has slightly longer to cut the surface, with the infeed force being maintained by the stiffness loop spring force.

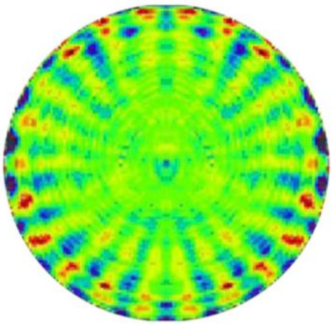


Figure 7. Component surface errors resulting from workhead torque ripple

Using MöbiusCAM, it is possible to modify the tool path in order to compensate for synchronous errors. The example shown here is a modified tool path deployed to minimise the effects of workhead motor torque ripple.

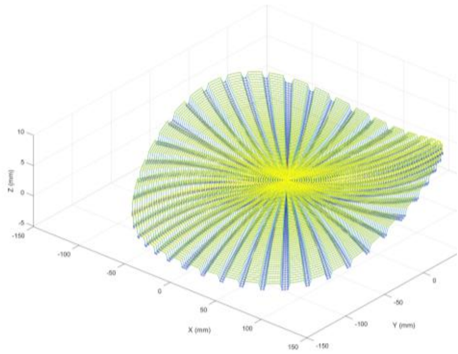


Figure 8. Modified tool path to compensate for synchronous errors

4. OGM C-Axis error compensation

The challenge was to determine whether it was possible compensate errors using the vertical axis which has a mass of around 800 kg, nine times per revolution of the C-Axis, operating at up to 60 rev per minute.

4.1. OGM Z-Axis vertical counterbalance

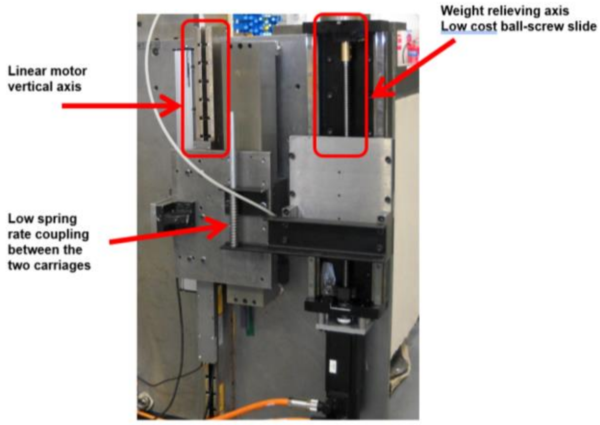


Figure 9. Basis principle of the OGM Z-Axis vertical axis counterbalance

This is the basic principle of the patented OGM vertical counterbalance [2, 3]. The primary linear axis (in the test system shown here, an air bearing) is driven by linear motor. A secondary, ball screw driven axis, takes the weight of the primary axis via a connecting spring. The secondary axis is commanded to follow the primary axis. The result is that the primary axis linear motors, are required only to respond to inertia and process forces. The mass of the primary carriage is at all times countered by the secondary axis.

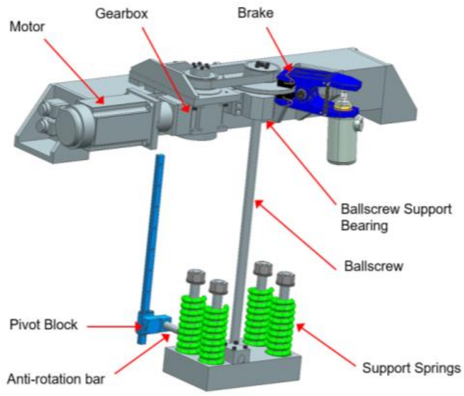


Figure 10. Counterbalance as configured on OGM

The configuration of the counterbalance in the OGM, follows the same principles as the test system. It is compact and effectively enables the vertical axis to perform as though it were a horizontal axis.

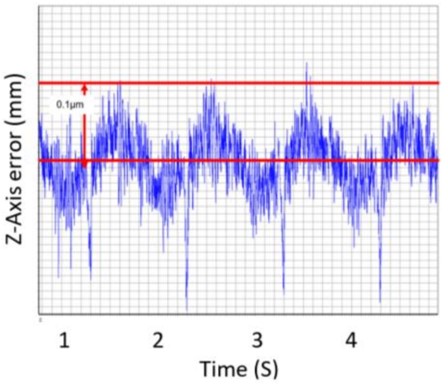


Figure 11. Vertical axis error: +/- 1 mm, 1 Hz

Tests using the OGM counterbalance had demonstrated that it is possible for the primary vertical axis to reciprocate at +/- 1mm, 1 Hz with a following error of 100 nm.

To compensate for the measured C-Axis errors of, compensations of around 300 nm at up 9 Hz (at C axis speed of 60 rev/min)

In order to determine the shape and amplitude of the compensation values to be superimposed upon the tool path, a sensor was mounted upon the grinding spindle housing and a reference flat mounted upon the C-Axis.

The errors were measures over a number of rotations of the C-Axis.

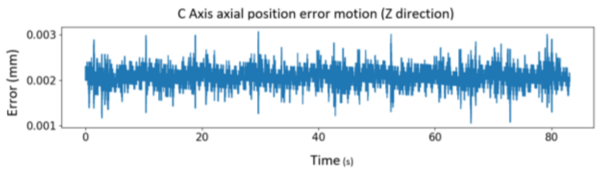


Figure 12. C-Axis axial position error (Z direction), with thermal drift removed

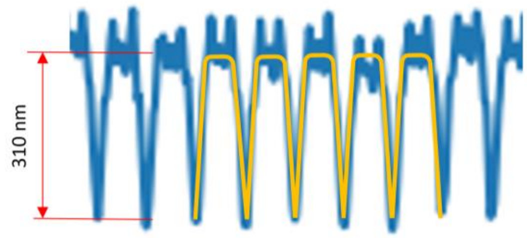


Figure 13. C-Axis axial position error motion signature, per revolution with simplified error plot superimposed.

From the raw axil position error, the signature of the nine cycles per revolution C-Axis axial position motion was established.

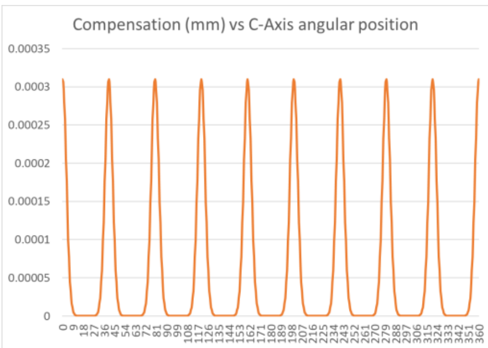
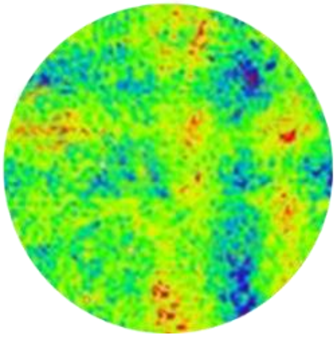


Figure 14. C-Axis error compensation applied to Z-Axis

The compensation profile in figure 14 was applied to the Z-Axis and synchronised to C-Axis angular position. Effectively, the inverse of the simplified error plot in figure **13**.

5. Results

After the Z-Axis compensation was deployed, the measured axis error motions reduced by over 80%. But the real test was the effect on grinding results. Fig 15 shows a typical post-compensation component error plot.



P-V error ~20 nm

Figure 15. C-Axis error compensation applied to Z-Axis

6. OGM machine corrective action

Once Covid travel restrictions were lifted, it was possible to visit the OGM machine and test the theory that the source of the problem was indeed, bearing pad imprints of oil varnish on the spindle rotor.

The procedure was simple and low risk. The bearing pressure was reduced until it only just floated. The pressure was reduced a little more and the spindle turned over around 90 degree by hand.

The C-Axis was re-calibrated and the vertical compensation values were now present in the error plot. The compensation values were then removed and the C-Axis error plots returned to the levels measured before the Covid shut down.

Although the levels of varnish in the OGM hydrostatic oil remains very low between each change cycle, it is now proposed to retrofit machines (not only OGMs) with stand-alone oil reconditioning systems to virtually eliminate the build-up of varnish in oil systems.

7. Conclusions

The vertical axis counterbalance system deployed in OGM machine, was originally designed to enable Z-Axis following errors of <1 µm. However, it has been demonstrated to enable error compensations to down to around 20 nm.

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