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Static and dynamic measurements of machine tools

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Abstract

Many machine tools have unwanted error motions, either due to their design or due to applied loads or thermal distortions. There are various standard methods to calibrate the machine and to compensate for some of these errors, and static measurement tests have been used for many years for machine tool acceptance. Static tests capture data at a number of target positions along the axis while dynamic tests can now capture thousands of data points while the machine is in motion.

This paper reports on dynamic calibration tests performed on machine tools and reveals some previously undetected problems with machine tool accuracy which static tests were unable to detect. The machines that were tested included a large travelling gantry universal machining centre and a travelling column machining centre located in the north of England.

Introduction

Product quality is important to both machine tool manufacturers and end users; and there is considerable pressure to shorten production cycle times and maintain a consistent and high level of product quality. This puts more pressure to achieve 'Right First Time' production. To improve product accuracy, the accuracy of the machine tools needs to be enhanced.

National and International Standards already exist for performing static measurements i.e. BS 3800: Part 2: 1991 [1] and ISO 230-2: 1988 [2]. In this paper we examine how these tests can be performed dynamically to save both time and to achieve higher accuracy, and a greater knowledge of geometric and positioning errors.

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With static measurements of positioning accuracy the machine is programmed to move to a series of target positions along the axis under test. The number of targets depends on the length of machine axis. For example, it stated that for a machine axis up to 2 metres in length, a minimum of five target positions per metre is required. Each target position is then approached by a minimum of five runs in each direction [3]. Similar tests are performed for each axis of the machine. The machine is required to stop at the target positions along the axis of each travel, making sure that both the optical component and the machine are stationary before a measurement is taken. It is also stated that for axes longer than 2 metres, one bi-directional measurement run is performed in which target positions are selected on each element on the measuring transducer, or at 250 mm intervals. Then a 2-metre length of axis in the normal working region is selected and five bi-directional runs are then performed [3]. However, these static test procedures are time-consuming and can sometimes take one or two days on a large machine, which therefore leads to expensive downtime and consequently a reduction in output.

Dynamic measurement is a new method of assessing a machine's accuracy, developed by Renishaw [4]. The dynamic software captures data rapidly, i.e. several thousand points per second along the axis of the machine, compared to the minimum of five positions per metre measured by static test procedures and is also less time consuming. However, at present, no measurement standards exist to assess a machine tool using dynamic calibration.

MACHINING CENTRES

This paper presents measurements taken using both static and dynamic tests on a large travelling gantry universal machining centre and a travelling column machining centre located in the north of England. Large machining centres were selected because this is where maximum time savings arise from dynamic tests (i.e. due to the time spent travelling along long machine axes). These are also machines where the foundations affect the straightness of the machine bed, so on-site testing is essential at the installation stage, and also at regular periods during the working life to ensure continuing accuracy.

Machine vibrations can be greater on large machines i.e. through floor-borne vibration. This will affect parts being produced whose accuracy may deteriorate in relation to the amplitude of vibration.

In the work of Postlethwaite [5], the possibility of a direct comparison between static and dynamic test procedures was considered, and these suggestions have been followed up by rigorous testing on several large machining centres.

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CALIBRATION PROCESS

A range of sampling frequencies was used depending on the length of the axis and the time taken for each measurement. Raw dynamic data recorded by the laser interferometer was then converted to positioning data for which positioning error values were generated.

Comparisons between angular errors, straightness and also positioning accuracy have been presented. It is important to note that there should be no difference between the results of linear static and dynamic measurements. However, this raised a question when analysing the static and dynamic positioning graphs.

When dynamic measurements are recorded the machine moves at a constant feedrate along the whole axis. Note must also be taken of the ramping up and down before the machine reaches its constant feedrate. In a static test the machine moves to each target position, and decelerates to a stop before each measurement is taken (Figure 1).

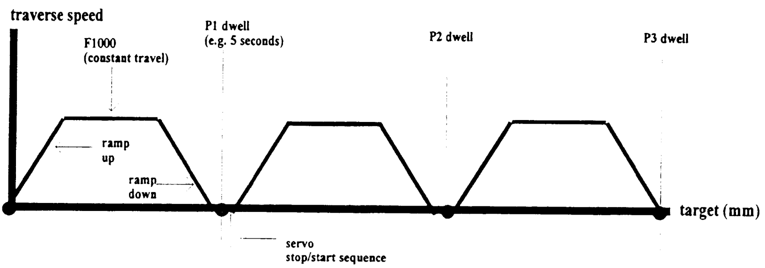

Figure 1: Acceleration and deceleration of machine axis while taking static measurements.

This is however not the case with the dynamic measurement. The ramping up and down of the machine only occurs for a few seconds at the beginning and at the end of the travel, shown in Figure 2. The dynamic test then measures the machine's position as the axis travel past the 'target position' at a constant feedrate.

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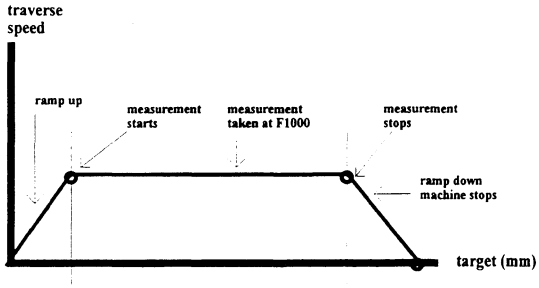

Figure 2: Machine movement while dynamic measurements was carried out.

RESULTS

Figure 3 shows results taken on the large travelling gantry universal machining centre. It is a velocity (mm/s) against time (s) graph for linear measurements taken at a feedrate of 5m/min with a capture rate of 250 Hz. A constant velocity band of between 81 to 86 mm/s can be seen. The whole length of the X axis travel is 10 metres. One bi-directional run was recorded.

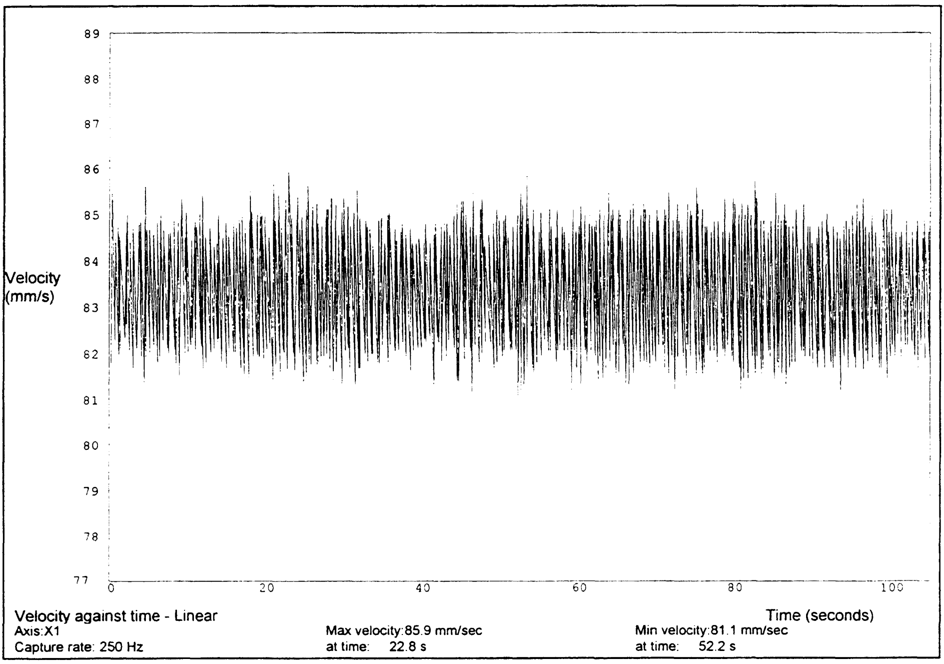

Figure 3: Dynamic linear measurements at 5 m/min.

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We then windowed-in over a one-second period time interval (Figure 4) i.e. between 18 and 19 seconds. The graph clearly shows that there are just over five distinct cyclic events in this one-second time scale.

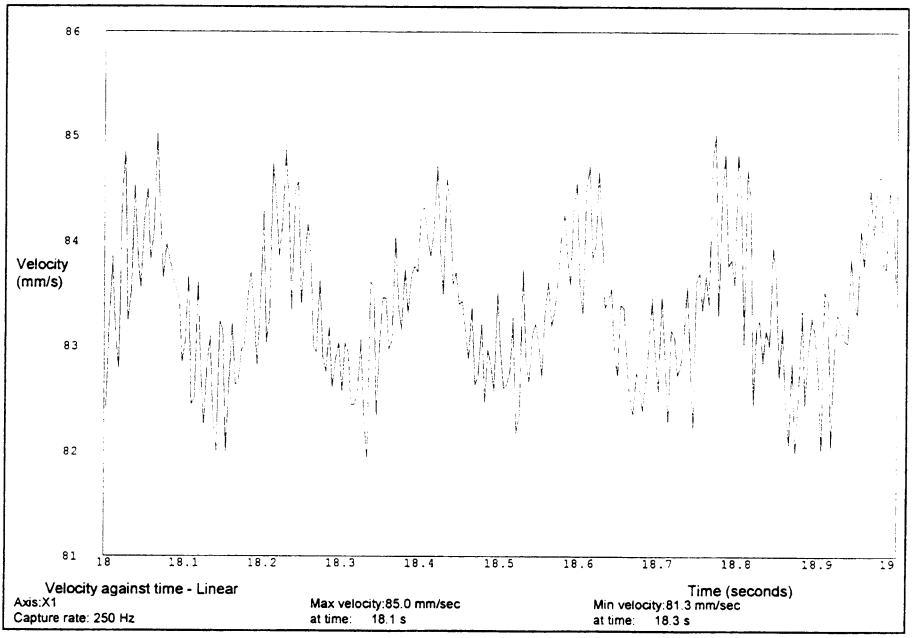

Figure 4: Dynamic linear measurements over a one second time period.

Fast Fourier Transform analysis (FFT) was carried out using the standard Renishaw software with the data obtained. In the analysis of dynamic software, FFT is a general mathematical process applied to investigate the frequency components of dynamic data captured over a period of time. Frequencies of vibrational movements of the object under test can be found using this process [4]. In this paper, FFT analysis-Hanning window is being used. The difference between Parzen, Hanning and Welch windows lies in the subtle trade-offs among the various figures of merit that can be used to describe the narrowness/peakedness of the spectral leakage functions. This may be computed as shown below [6]. The main trade-off is between trying to make central peak as narrow and the tails of the distribution fall off as rapidly as possible.

$$W(s) = \frac{1}{W_{ss}}\left|\sum_{k=0}^{N-1} e^{2\pi sk/N}\omega_k\right|$$

$$\approx \frac{1}{W}\left|\int_{-n/2}^{N/2}\cos(2\pi sk/N)\omega(k-N/2)dk\right|^2$$

The FFT analysis is performed over a frequency range between 3 Hz and 60 Hz in Figure 5. Normally, the initial few Hertz are deleted from the analysis routine, as inclusion will give a very large amplitude error solely concerned with the simple start up move. The resulting graph confirms our previous conclusion from Figure 4 showing a marked amplitude peak occurring at about 5.3 Hz.

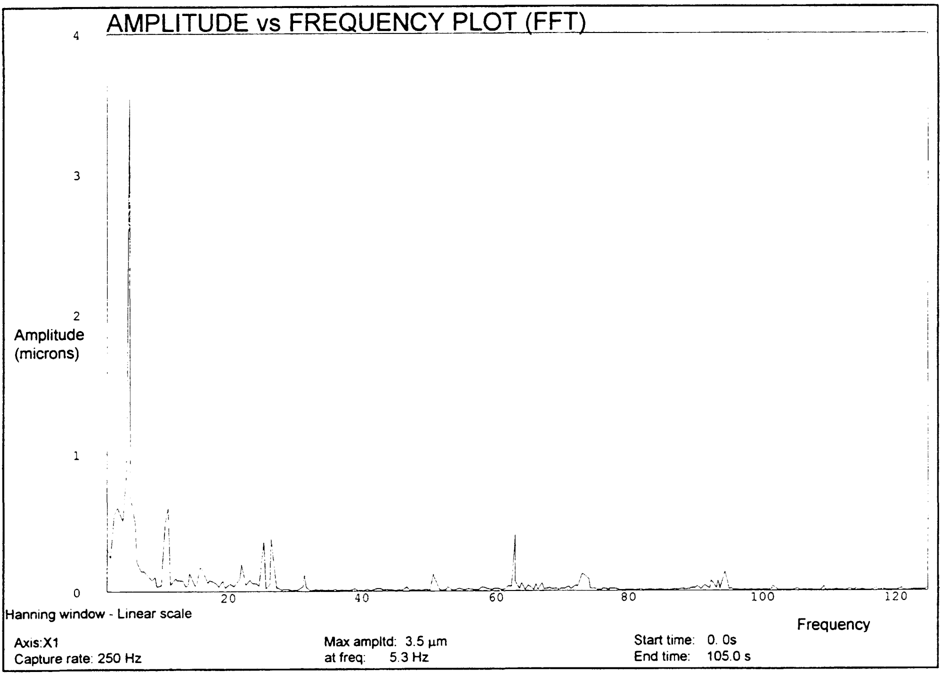

Figure 5: Fast Fourier Transform analysis.

In accordance with British Standards [1], only a 2-metre length of axis in the normal working region was selected for static measurements and five bi-directional runs were performed. Figure 6 presents static and dynamic positioning errors along the same X axis. The same data were being used and the distance against time data was then converted to dynamic error against distance travelled.

While one unidirectional dynamic measurement run was being observed, five unidirectional runs were selected for this static measurement. A mean of the five static measurements was calculated and superimposed onto the dynamic measurement graph along the axis. Over this 2-metre axis, 6014 points were taken dynamically, compared to only 55 points statically. The length of time required for dynamic test was 24.1 seconds while approximately 370 seconds were required for the static test. The graph in Figure 6 shows that static test results remain almost constant while large amplitudes are observed on the dynamic plots. Cyclic error could be seen on dynamic plots, which was not observed on the static measurement results. The graph exhibits an average change in positioning error of about 30 μm.

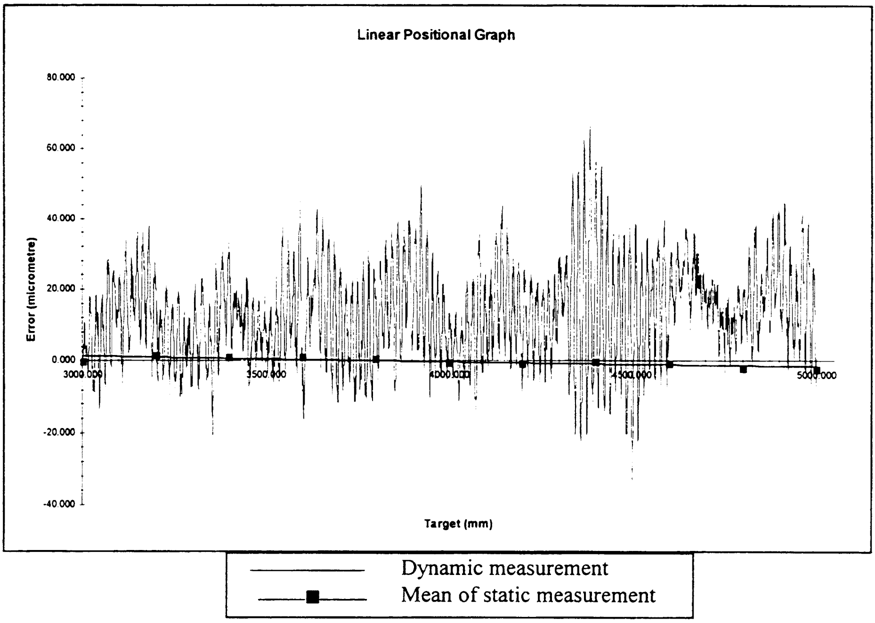

Figure 6: Static and dynamic linear positional graph.

Static positioning errors are relatively small due to linear error compensation being inserted into the machine controller over the complete axis travel. Short term averaging has already been carried out on the static measurement data above, whilst the dynamic raw data has not been averaged. The magnitude of the dynamic error is greater than static error. The rack and pinion error of 5 Hz detected in dynamic analysis could have been transferred to positioning errors because the machine moves at a constant feedrate when dynamic measurement is taken. Examination of the machine confirmed that the rack and pinion used to drive the machine had a 15 mm pitch. A mean traverse velocity of 83 mm/sec gives 5.5 tooth engagements per second which matches the FFT analysis of the dominant frequency of this cyclic error.

Figure 7 shows the change in positioning error as measured dynamically over a one second period of time. This change is a result of the varying velocity as seen in Figure 3. With an axis travel of 86 mm this again shows just over five cyclic events. This change in positioning error seems to mirror the change in velocity as shown in Figure 4. The 5 Hz frequency could also be related to the rack and pinion positioning system employed on the machine.

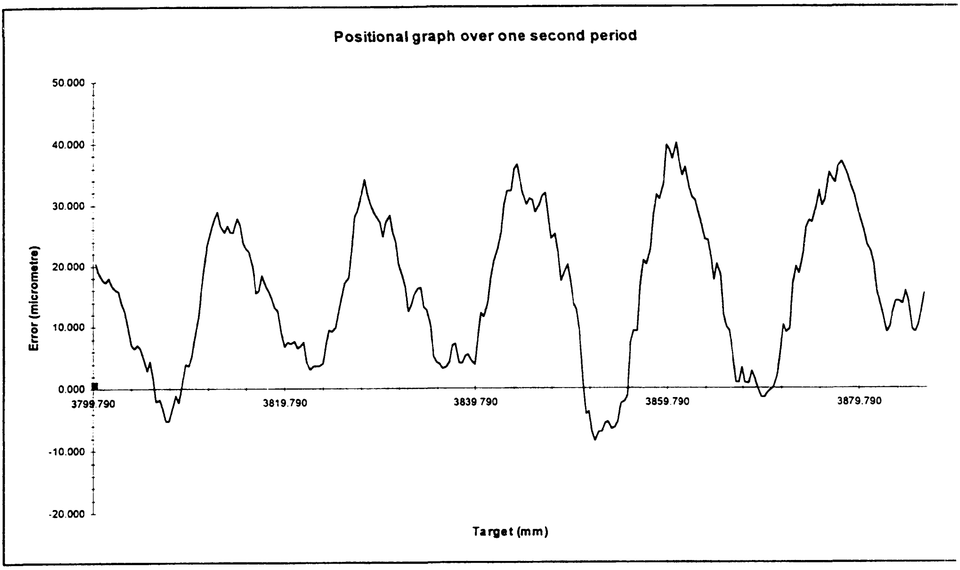

Figure 7: Dynamic error against distance travelled of one second time period.

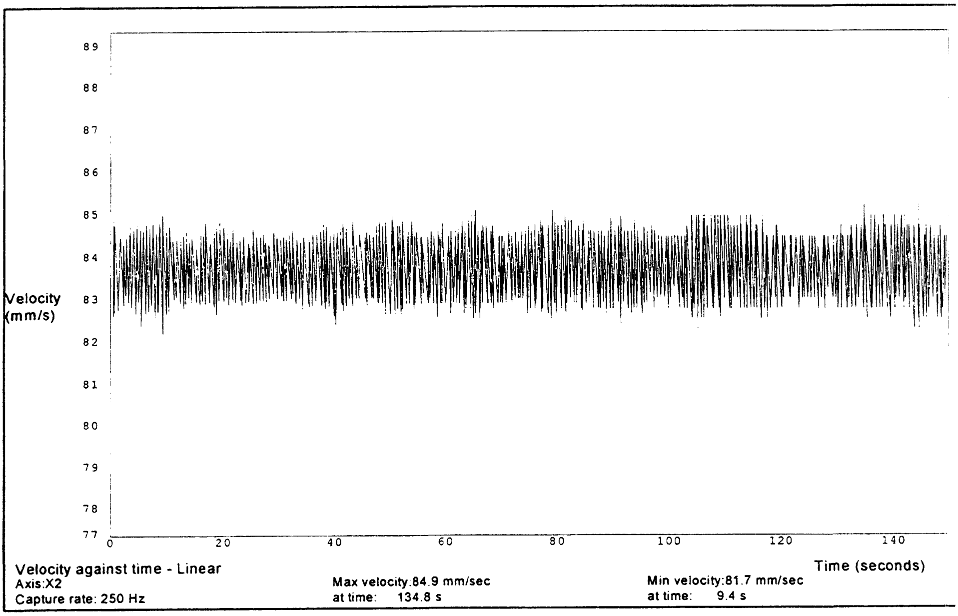

Figure 8: Dynamic linear measurements on travelling column machining centre

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Further investigation was carried out on a travelling column machining centre. Figure 8 shows a velocity against time graph taken on the same feedrate as the machine above i.e. 5 m/min. The whole length of the X axis travel is 13 metres and time taken to carry out the dynamic measurements is 150 seconds. A constant velocity band of between 82 - 85 mm/s can also be observed. This again shows that a considerable amount of time could be saved via the dynamic test and the whole measurement process could also be completed within a few seconds.

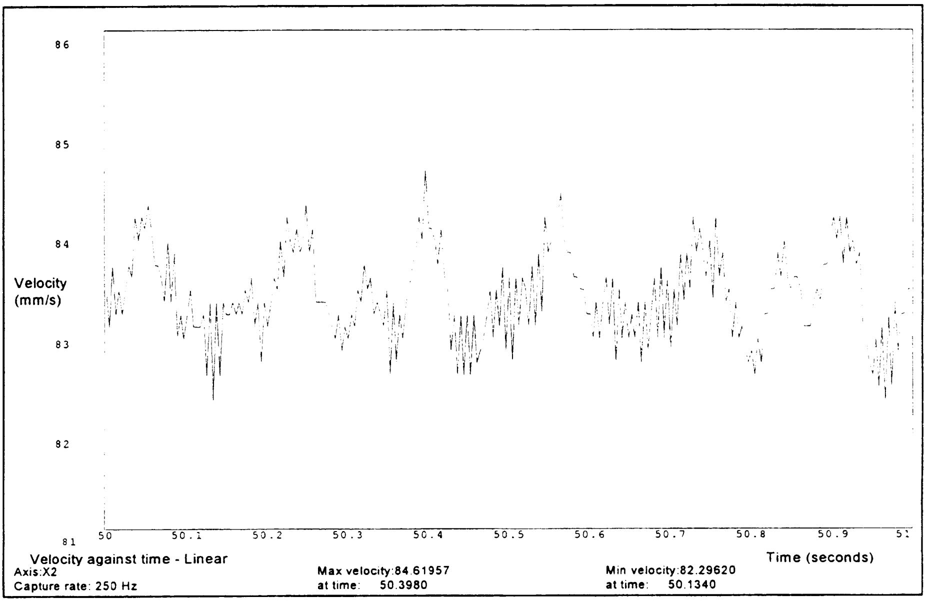

Figure 9: Measurement over a one second time period.

Figure 9 shows the windowing-in over a one second-time period i.e. between 50 and 51 seconds and shows just over 6 cyclic events.

FFT-Hanning window was then carried out (Figure 10) over the maximum time domain which shows a marked amplitude peak of around 6 Hz. This corresponds with the number of cyclic events found within a one second time period.

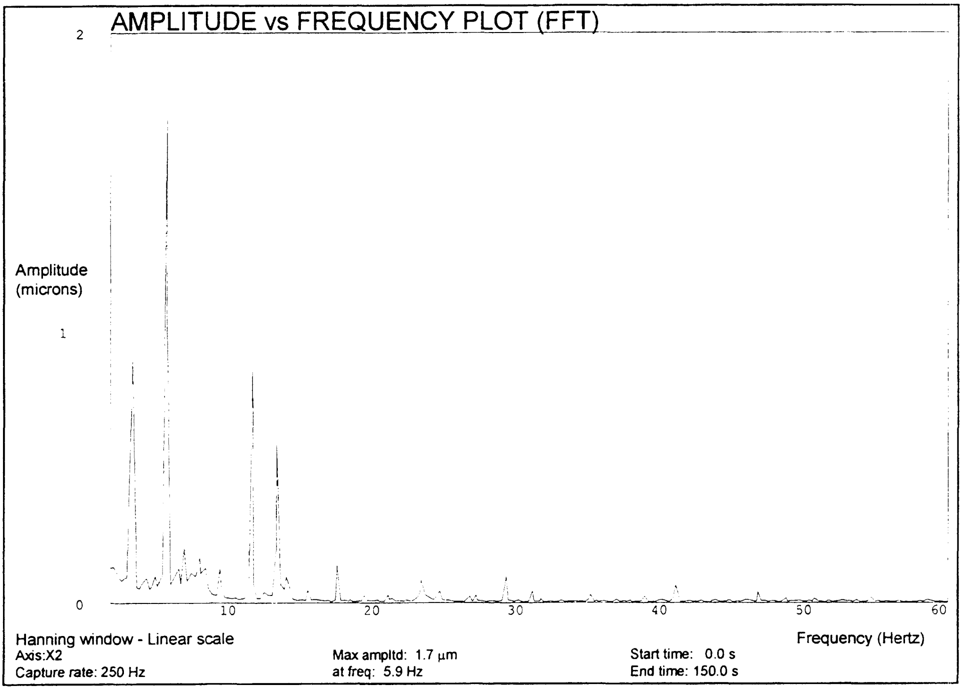

Figure 10: Fast Fourier Transform analysis

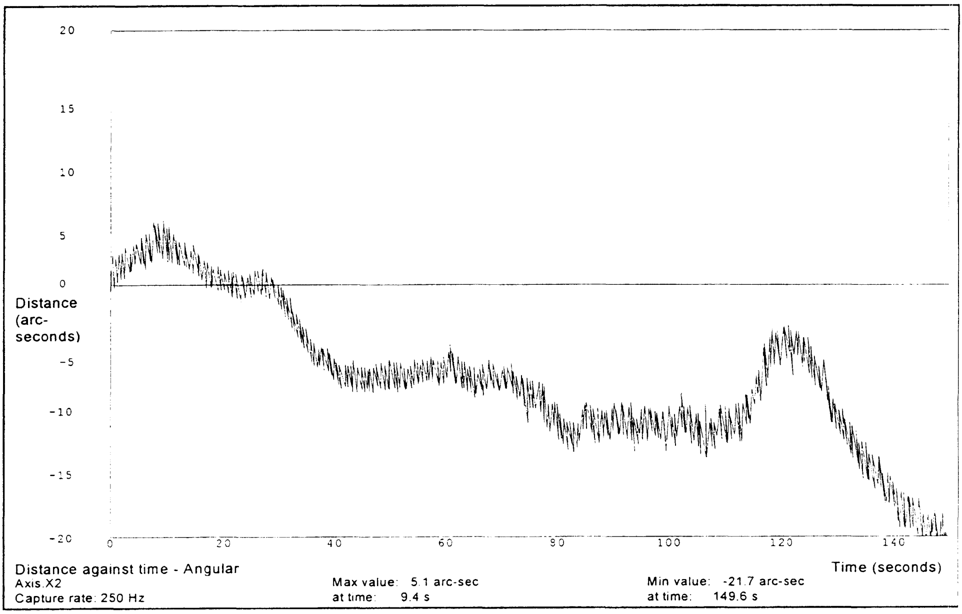

Figure 11: Angular (pitch) dynamic measurements.

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Because all degrees of freedom (positioning accuracy, pitch and yaw errors and straightness errors in both measurement planes) are of equal importance, these must be measured also along the linear axis [7]. Because of this, dynamic angular and straightness tests were also carried out on this machine. Figure 11 shows angular pitch dynamic measurements taken over the same travel length. There are about 15 arc-seconds of pitch error over the whole travel of the machine.

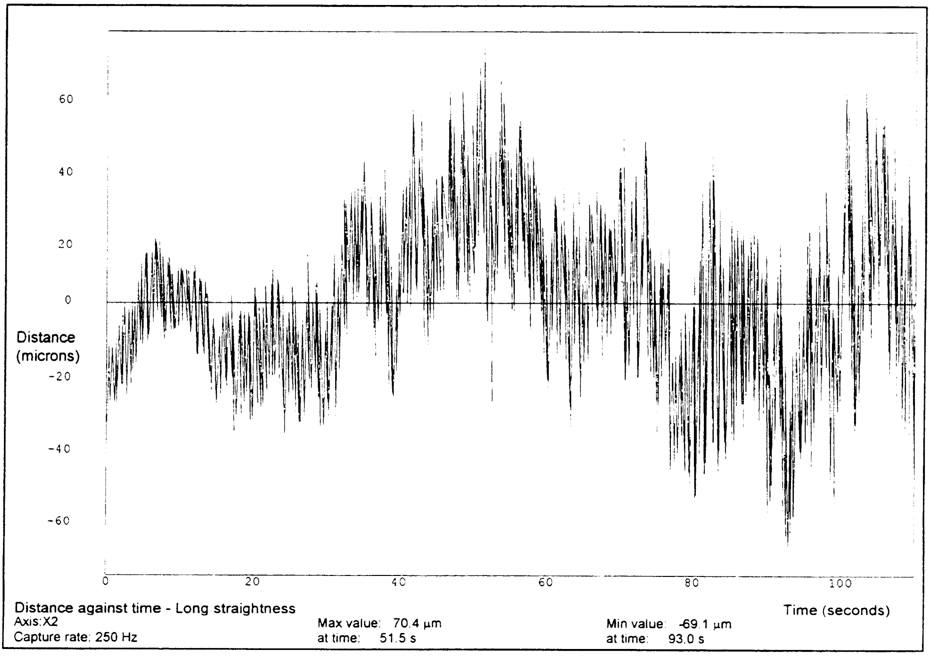

Figure 12: Vertical Straightness dynamic measurements.

Straightness and angular plots for motion along an axis pose a different problem since we are now measuring the degree of linearity of the table motion. However, it should also be noted that straightness tests are more sensitive to air turbulence. The uncertainty of measurement is affected by the resolution attainable with the measuring system and random fluctuation [3]. Figure 12 shows vertical straightness measurement results taken on the same machine. Angular and straightness errors can arise from the positioning of an axis, but in different directions [7].

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CONCLUSION

Based on these observations, it can be concluded that:

- Dynamic measurements are able to detect errors previously undetected in static tests.
- A considerable amount of time can be saved when dynamic measurements are carried out.
- The existence of 5 cyclic events over a one-second period on the large travelling gantry universal machining centre was verified by the FFT analysis which revealed a major amplitude peak of 5.3 Hz.
- The 5.3 Hz cyclic error could be due to the rack and pinion positioning system employed on the machine.

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