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An accelerometer based-feedback technique for improving dynamic performance of a machine tool

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Abstract
A novel concept for improving machine dynamic performance was developed and realised, a virtual metrology frame, for a small size CNC machine with flexible frame. Its implementation in a simplified linear motion system shows a reduction in the magnitude of the first resonance in the plant frequency response function by 12 dB. Realising the concept required developing a real-time accelerometer-based measurement technique. It shows a low sensor noise σ=30 nm with optimal phase delay of <70 µs.

Accelerometer, mechatronic, compact machine, flexible frame, metrology frame, virtual metrology frame, genetic algorithm

1. Introduction

In recent decades numerous research efforts to develop small size machine tools have been undertaken. However, most of these machines are still at the development stage. The requirement of ultra-precision machine tools is high-dimensional precision, typically better than 1µm [1]. Thus, a compact ultra-precision machine tool must have low motion errors and high damping or dynamic stiffness. The existing solutions for these requirements are often antagonistic to a small size constraint for the overall system.

A machine frame has two main functions that work in parallel: transferring forces and position reference [2]. The reaction of servo-forces can excite machine frame resonances which influence the dynamic performance. Thus, in high-end machines a metrology frame is realised by having two frames – force and metrology. However, this concept is hard to implement in a small size machine.

The µ4 is a compact size CNC machine with 6 axes, which was developed by Cranfield University and Loxham Precision. The performance specification of the machine was set to be equivalent to that of the highest performing diamond turning and micro-milling machines. System identification techniques showed that a flexible frame phenomenon is the dominant dynamic effect influencing the machine performance [3]. Thus, improving the metrology system will enhance it dynamic performance.

This article describes the developed solution, a virtual metrology frame, allowing a high-end metrology system consistent with the compact size constraint. Realising this concept required developing a measurement technique additional to the existing physical reference system.

2. Virtual metrology frame

Dynamic rigidity is one of the most critical characteristics of machine tools, especially for ultra-precision applications. The metrology system of a machine is directly affecting it dynamic performance. Thus, in a machine with two separated frames servo-reaction forces do not influence the positioning measurement. However, it is hard to realise it due to the small size constraints. Thus, the dynamic performance of a system with one frame the can be limited by flexible frame phenomena [4], in particular the lower frequency modes. The virtual metrology frame concept solves this problem by having a metrology frame without the physical components associated with it. The concept is realised (Fig. 1) by measuring machine frame vibrational displacement (X_f) and fusing it with carriage position relative to the physical frame (X). Thus, an unperturbed position signal is obtained (X_{vmf}) and used by the controller.

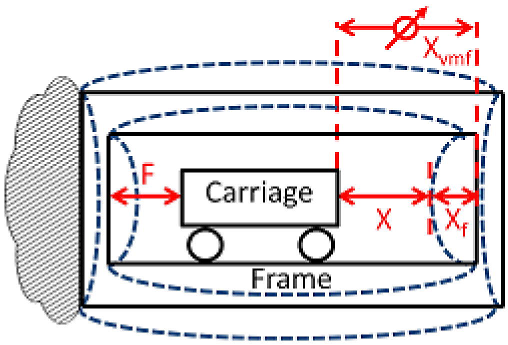

Figure 1. Virtual metrology frame concept. Frame displacement is represented by dashed lines.

3. Frame displacement measurement technique

Realising the concept of a virtual metrology frame requires first solving the problem of real-time measurement of frame displacement. Common precision displacement sensors require a fixed reference point. Thus, measuring the frame displacement will require a second frame – a metrology frame, which is not feasible. However, accelerometers measure the acceleration of a point without a fixed reference system. The displacement can be directly estimated by double integration of the acceleration signal. Hence, a frame's displacement can be estimated relative to its "unstressed" state.

Implementing a displacement-based acceleration sensor in a control system requires solving practical problems such as small phase delay and sensor noise. Removing 0g-offset and low frequency noise of the acceleration signal is critical for reducing drift of the displacement signal, especially for long term (>10 seconds) and accurate (<1 µm) measurements [5]. Due to these requirements real-time implementation in a control system has been rarely demonstrated [6]. Low noise Integrated Electronics PiezoElectric (IEPE) accelerometers were used due to their low noise, wide dynamic bandwidth and high sensitivity [8].

Using a multi-objective genetic algorithm and dynamic-error-budgeting an optimal estimator was designed. The estimator (heave filter) of the frame displacement is based on a combination of High Pass Filter (HPF) for reducing low frequency noise, and double integrator [7]. A pole-zero placement filter was added for correcting the phase delay error due to the HPF, as if it is an ideal double integrator. An optimised estimator was achieved by constraining the measurement bandwidth (>60Hz) to include dynamic displacements which occur at the flexible frame resonances.

4. Results

The displacement-based acceleration technique was validated by long term measurements at 0g-motion, which showed a noise level of σ=30 nm (dashed lines, Fig. 2(b)). Due to the nature of the double integrator, the noise in 0g-motion is higher than in dynamic measurement. The developed frame displacement measurement technique, based on accelerometers (PCB 356A025), was validated against low noise high sensitivity capacitance sensors (Lion precision PX405HC). It showed a disagreement of <3dB and phase delay <70 µs in the critical bandwidth (low frequency modes).

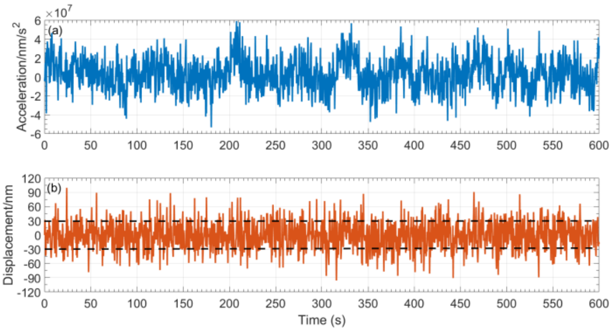

Figure 2. Long term displacement estimation noise measurement. Acceleration signal for t=600 seconds at 0g-motion (a). Displacement estimation signal for t=600 seconds at 0g-motion (b).

A simplified linear motion system [3] was used to validate the virtual metrology frame concept. The initial result shows a reduction of 12dB in the magnitude of the machine first resonance (flexible frame mode) appearing in the plant transfer function (Fig. 3). This reduction potentially improves the servo bandwidth from 40Hz to 60Hz based on a PID controller.

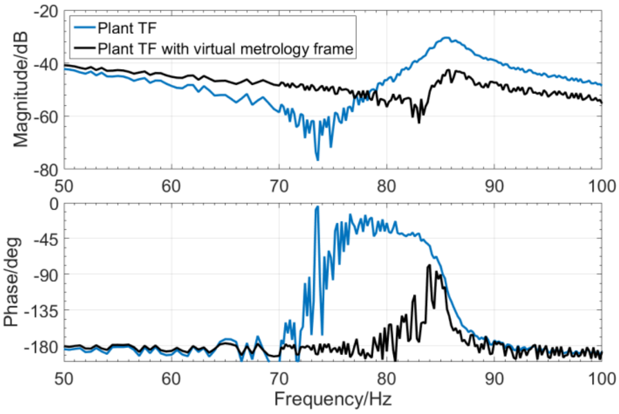

Figure 3. Comparison of the plant Transfer Function (TF) measurements with and without the virtual metrology frame.

5. Conclusions

The virtual metrology frame is a novel mechatronic concept for improving machine dynamic performance, especially in the case of a flexible frame. In a control system, displacement-based acceleration measurement is rarely used due to the practical problems of phase delay and noise removal. However, a new technique was developed which allows significant noise reduction by measuring only in the machine frame resonances bandwidth.

Further research is being carried out by assessing the improvement to the servo bandwidth and improvements to the developed technique.

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