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Position errors due to structural flexible mode

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1.Introduction

The µ4 compact size CNC machine with 6 axes was developed by Cranfield University and Loxham Precision (Fig. 1). The machine motion axes were split into two near identical modules. Each module consists of at least one rotary and one linear motions made by direct drive motors. Due to the compact and lightweight design of the machine there is a high ratio of moving to static mass, which affects the dynamic performance.

This project is focused on improving the dynamic performance of a compact size machine tool. The apparently antagonistic requirements of compact size on one hand and high dynamic performance on the other, demand finding new techniques to allow ultra-precision motion control. A simplified linear motion module of the µ4 machine (Fig. 2) was used during this research to develop a new technique.

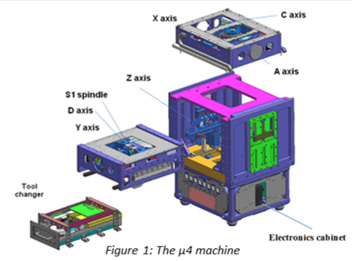

Figure 1: The µ4 machine

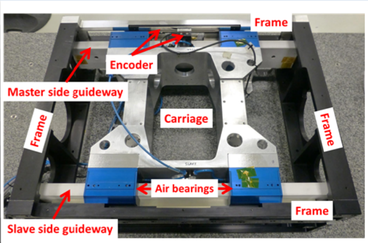

Figure 2: Simplified motion module

2.Linear motion system

A simplified linear motion module consists of: frame, air-bearings, linear motor, encoder and carriage. The module is designed with master-slave bearing configuration. The master side consists of the linear motor and encoder. The encoder measures the position of the carriage with respect to the frame.

Three important effects influence the machine dynamics (Fig. 3): (a) actuator flexibility, (b) guiding system flexibility and (c) flexible frame.

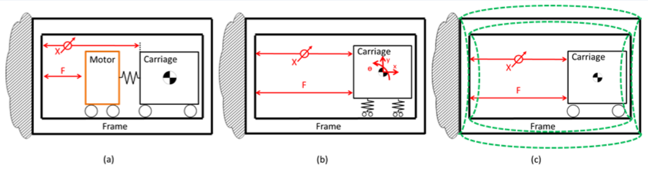

Figure 3: Three important dynamic effects

3.System identification

By injecting noise in the control loop the plant Frequency Response Function (FRF) was measured (Fig. 4). Its main characteristic was found to be of the type Antiresonance-Resonance (AR) which corresponds to both guiding system flexibility and flexible frame [1]. In the plant FRF one cannot distinguish between guiding system flexibility and flexible frame. Therefore, a simple Operational Modal Analysis (OMA) was used.

OMA of the motion system was measured using the acceleration command signal of the servo control as the excitation signal. A step position command – impulse acceleration command was measured as for an impact excitation, using modal measurement equipment (Fig. 6&7). Then, a comparison was made between the measured acceleration error and the measured accelerance FRF (Fig. 5). The acceleration error was calculated by double differentiation of the encoder signal from the servo system.

The comparison allows identifying that the important dynamic effect which influences the machine dynamics is the flexible frame. It was concluded that the static part of the linear encoder vibrates at the natural frequencies of the frame, causing positional errors.

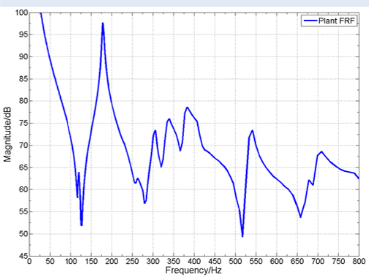

Figure 4: Plant FRF

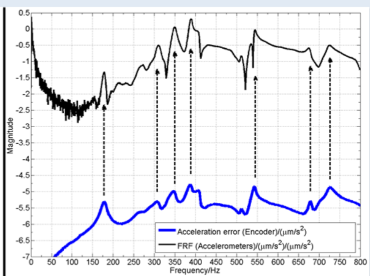

Figure 5: Comparison between acceleration error FFT and accelerance FRF in the motion direction

In a "flexible frame" system the servo forces act on the frame and cause it to vibrate. Closed loop control causes the carriage to tend to follow the vibrating frame. Thus, the machine performance, e.g., settling time, position error and bandwidth, is affected .

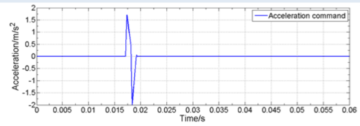

Figure 6: Acceleration command

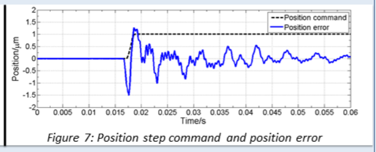

Figure 7: Position step command and position error

4.Machine frame concepts

The machine frame has two main functions that work in parallel:

- Transfer of forces – acceleration forces to the floor and machining forces between the tool and fixture
- Position reference to sub-systems and maintain geometrical accuracy

There are three main concepts meeting the two required functions [2] (Fig. 8): (a) the traditional concept, (b) using an additional moving balance mass (BM) to balance the servo forces concept and (c) separating the two functions by having an unstressed metrology frame. Concepts (b) and (c) can be combined to achieve superior performance. However, realising concepts other than the traditional one is difficult due to the compact size design constraint. Thus, a novel positioning technique is proposed with expected performance equivalent to an unstressed metrology frame.

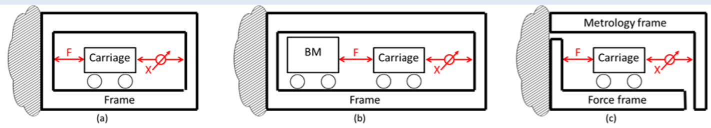

Figure 8: Three machine frame concepts

5.Novel positioning technique

The main idea of the proposed solution is to distinguish between carriage position in respect to the stressed frame - x and the frame displacement due to flexible modes – x_f. Thus, unperturbed real time position measurements - x_{mf} can be obtained in the presence of frame flexible modes (Fig. 9). The unperturbed position signal will be then used to control the motion of the system using the machine controller – C (Fig. 10).

The technique implementation is:

- Measuring frame vibration - a_f using low noise accelerometers [3]
- Applying high pass filter to a_f that passes signals with frequencies higher than the frame antiresonance
- Generating real time frame displacement signal based on accelerometer signals - x_f using a DSP
- Fusing frame displacement (accelerometer) signal – x_f with the carriage position (encoder) signal - x

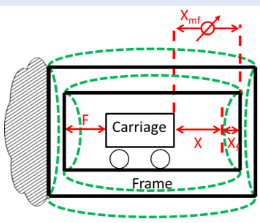

Figure 9: Proposed positioning technique

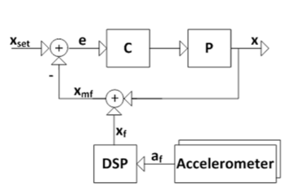

Figure 10: Proposed control structure

Based on the proposed technique of fusing the frame displacement signal (using accelerometers) and carriage positon signal (using encoder), the expected machine performance is the same as "frame concept c". Thus, the constraints of the machine size and dynamic performance will be mitigated.

6.Future work

Future work will be focused on the following aspects:

- Noise analysis of the position based acceleration signal
- Validation of the novel position technique using external position measurements of the frame
- Real time implementation of the proposed solution
- Expanding the solution to multiple axes

References

[1] Coelingh E, de Vries T.J, and Koster R. "Assessment of mechatronic system performance at an early design stage". 2002, Mechatronics, IEEE/ASME Transaction on, 7(3), 269-279.

[2] Somers H. "Design principles: for precision mechanisms". 2010, T-Point print, 222-224.

[3] Levinzon F. "Piezoelectric accelerometers with integral electronics". 2015, Springer International Publishing, 107-116.

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