euspen's 15th International Conference & Exhibition, Leuven, Belgium, June 2015
www.euspen.eu

Position errors due to structural flexible modes

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Abstract
This research aims at improving dynamic performance of a compact size machine tool. A simple method for system identification was used to identify the main dynamic effect influencing the machine performance – flexible frame. The method is based on comparing operational modal analysis measurements and position error frequency content, using servo impulse acceleration commands. It was found that the linear encoder scale, which is fixed to the lightweight structure, is subject to vibration and causes positional errors; These frame flexible modes are the principal cause of the servo response dynamic signature.

Keywords: Compact machine, modal analysis, system identification, linear motion

1. Introduction

Many consumer products have seen significant miniaturisation while production machine tools have not seen significant size reduction. Numerous research efforts to develop so-called small size machines have been undertaken in the past two decades. However, most of the machines are still at the development level. The µ4 CNC machine with 6 axes was developed by Cranfield University and Loxham Precision [1]. The machine motion axes were split into two near identical modules. Each module consists of two 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 dynamic to static mass, which affects the dynamic performance. 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. This article focuses on identifying what is the main dynamic effect influencing the machine dynamics using a simple technique for system identification. In this initial work, investigation and analysis of mechatronic designs were made as well as experimental work on a simplified motion module.

2. Linear motion system

A simplified linear motion module consists of: frame, air-bearings and guideways, linear motor, encoder and carriage (figure 1a). The frame is designed with four aluminium plates bolted together. The module is designed with a master-slave air 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 dynamic effects influence the machine dynamics of a positioning device: actuator flexibility, guiding system flexibility and flexible "frame" [2].

In a servo system a force (F) is applied in order to achieve required displacement of the carriage (X). Due to the limited mass of the frame, it will exhibit resonances that are excited by the reaction of the servo force (figure 1b). Thus, at the end of a set-point motion the frame is not static, that is a cause of position error.

Due to design constrains, the driving force (and the sensor) is not applied at the centre of gravity but on the "master side". The carriage movement has to rely on the guiding system to supress motion in an undesired direction. Thus, carriage rigid body modes may be excited. These modes governed by the guiding system stiffness (figure 1b). Since that the guiding system is based on air bearings, its stiffness is nonlinear.

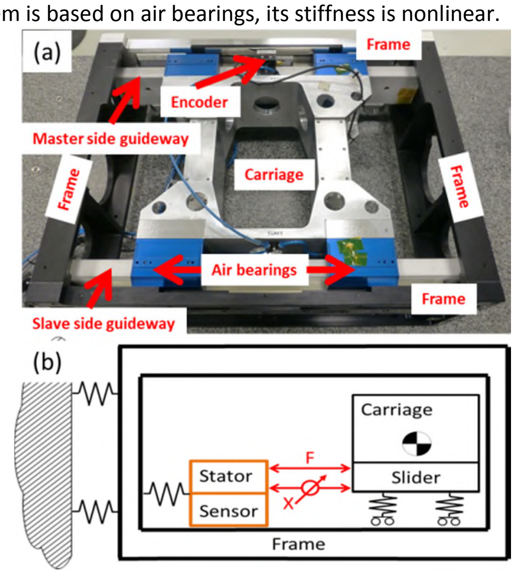

Figure 1. Linear motion module (a), motion system 2D model with (b).

3. System identification

Frequency Response Function (FRF) can be measured by injecting noise at a certain point in the control loop. Then, by measuring the signal at two points in the control loop and by applying a Fast Fourier Transform (FFT) the FRF is calculated.

The plant transfer function was measured from the input force (F) to the position measurement (X) using the servo system. It main characteristic was found to be of type

Antiresonance-Resonance (AR) which corresponds to both flexible frame and flexible guidance dynamic effects [3]. Based on plant FRF, one can't identify the main dynamic effect.

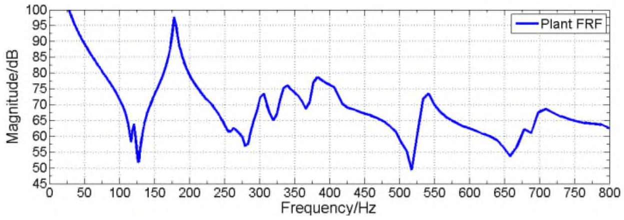

Figure 2. Plant FRF.

Therefore a simple Operational Modal Analysis (OMA) was used. OMA of the motion system was measured by 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 (figure 3). As opposed to using hammer excitation and noise injection, this simple position command allows exciting the system with the motor always at the same place. Furthermore, this excitation simulates the working conditions. The accelerance FRF response was measured by three axis accelerometers at various locations.

An animation movie was made for each mode and then used to analyse the mode shape of the motion system.

Then, a comparison was made between the measured acceleration error Fast Fourier Transform (FFT) and the measured accelerance FRF. The acceleration error was calculated by double differentiation of the encoder signal from the servo system. The accelerance FRF was analysed in the motion direction only (Y axis).

3. Results

The AR type plant FRF showed the main antiresonance and resonance frequencies of 126Hz and 178Hz respectively. There are shown clearly in the accelerance FRF (figure 4). The plant FRF and the accelerance FRF show similar resonances, however in the accelerance FRF the magnitude of the resonances is increasing with frequency.

Analysing the OMA animation movies allowed identifying flexible frame as the main dynamic effect of the system. A comparison between the accelerance FRF and the acceleration error is shown in figure 4. It should be noted that this heuristic graph compares values with different units. The acceleration error FFT and the accelerance FRF units are µm/s^2 and unitless ((µm/s^2)/(µm/s^2)) respectively. This confirms that frame flexible modes are the principal cause of the servo dynamic response signature.

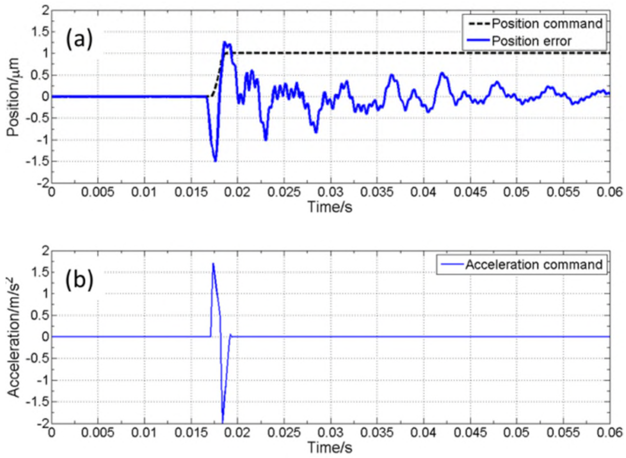

Figure 3. Position step command and position error (a), acceleration command (b).

4. Conclusions and summary

Plant FRF is an in adequate tool to identify the main dynamic effect. Thus, a simple method of applying a servo command as an excitation signal for OMA was used as a system identification technique. A clear heuristic correlation between the acceleration (position) frequency content and the frame natural frequencies was made. Thus, one can identify what are the important structural resonances affecting the machine performance. The accelerance FRF and the plant FRF showed similar resonances.

It was concluded that the "static" part of the linear encoder vibrates at the natural frequencies of the "frame" causing positional errors. Due to limited mass and stiffness of the machine frame, reaction of the servo-force is exciting the machine frame natural frequencies.

The next step of this research will be developing a new compensating technique for the flexible frame effect. So that relatively unperturbed real time position measurements can be obtained in the presence of frame flexible modes. The new technique performance will be compared to "frame acceleration" technique [2].

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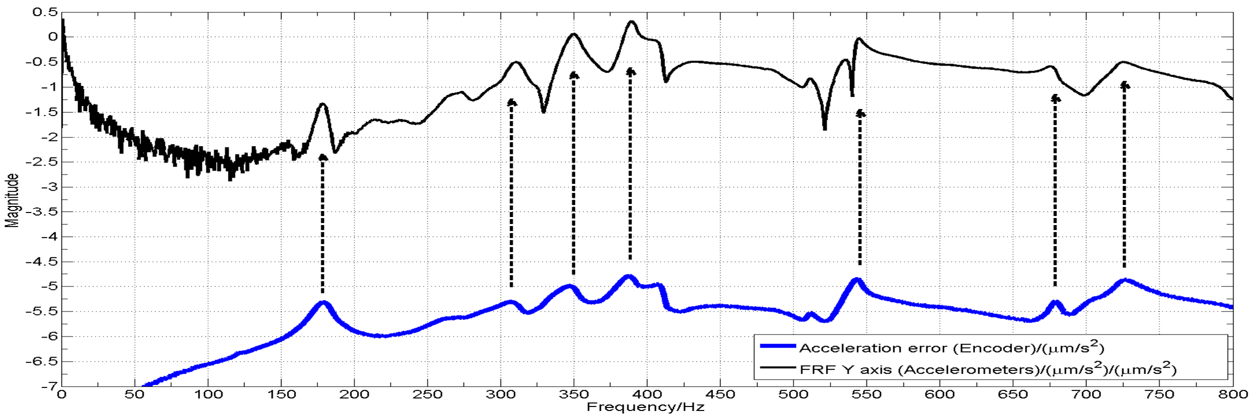

Figure 4. Comparison between acceleration error FFT and accelerance FRF in the motion direction.