Available online at www.sciencedirect.com

ScienceDirect

IFAC Papers Online
CONFERENCE PAPER ARCHIVE

IFAC-PapersOnLine 49-21 (2016) 553–558

A novel accelerometer based feedback concept for improving machine dynamic performance

Jonathan Abir* Paul Morantz* Stefano Longo Paul Shore*****

**Precision Engineering Institute, Cranfield University, Cranfield, MK43 0AL, UK, (j.h.abir@cranfield.ac.uk)*
***Centre for Automotive Engineering and Technology, Cranfield University, Cranfield, MK43 0AL, UK*
**** National Physical Laboratory, Teddington, TW11 0LW, UK*

Abstract: Small size ultra-precision Computer Numerical Control (CNC) machines require high dynamic performance. Flexible frame phenomena can limit the machine dynamic performance, particularly in small size machines. A novel accelerometer based feedback concept for improving machine dynamic performance was developed and realised, a virtual metrology frame. It expends the limited techniques for improving dynamic performance of a small size machine by measuring the flexible frame displacement, and feeding it into the controller. The concept was implemented in a simplified linear motion system, and showed a 12dB reduction in the magnitude of the first resonance in the plant frequency response function. This allowed improving the servo bandwidth by 58% based on a PID controller. A new technique for real-time dynamic displacement measurements using accelerometer was developed. It shows a low sensor noise σ<30 nm; thus, accelerometers are used as a displacement sensor in a control system.

Keywords: Accelerometers, CNC, digital filter, flexible frame, noise, ultra-precision, virtual metrology frame.

1. INTRODUCTION

In recent decades, numerous research efforts to develop machine tools with positioning performances at the nanometre level or better have been undertaken (Eijk 2008). Achieving such performance creates challenges for the metrology systems (sensors systems), with semiconductor patterning and inspection machines setting these high demands. Most breakthroughs have been achieved by separating metrology from the moving elements.

Many consumer products have seen significant miniaturization, especially in the IT industry, which brings higher demands for ultra-precision manufacturing capabilities. In contrast, many ultra-precision production machines have not seen a significant size reduction although numerous research efforts have been made. An ultra-precision production machine requires high machine accuracy, low motion errors, and high damping or dynamic stiffness. The existing solution for these requirements, as were developed in the semiconductor industry, is often antagonistic to the compact size constraint.

The µ4 is a small size Computer Numerical Control (CNC) machine with 6 motion axes (Shore et al. 2013). It was developed by Cranfield University and Loxham Precision. It specification in terms of machining accuracy was set around feature tolerance capability of < 1 µm and form accuracy of <0.1 µm, which requires position accuracy in the nanometre scale and servo bandwidth of > 50 Hz.

There are four important dynamic effects which influence machine dynamics (Coelingh et al. 2002): actuator flexibility, guiding system flexibility, flexible frame, and backlash and friction. In a direct drive system with air-bearings the backlash and friction effect is negligible, even though there is (a small value of) friction due to cables. Actuator flexibility occurs when there is compliance between the motor and the load, typically where there is a gear in the system. Guiding system flexibility is a dynamic phenomenon where there is a limited stiffness of the guiding system combined with a driving force applied not at the centre of gravity. Flexible frame occur when the reaction forces effect on the machine dynamic, due to servo driving forces, are not negligible. It stimulates the machine frame resonances due to low stiffness of the frame.

A small size machine, equipped with high stiffness air-bearings, was identified as having flexible frame phenomena (Abir, Morantz, et al. 2015). Thus, the limiting dynamic effect to the machine performance is flexible frame, and not guiding system flexibility.

This article presents an accelerometer based feedback concept, a virtual metrology frame, allowing high-end metrology system consistent with the compact size constraint. The developed concept was demonstrated on a simplified linear motion system; a module of a small size CNC machine - µ4. In Section 2, various concepts of machine frame are introduced, and the effect of reaction force on a machine performance is analysed. In Section 3, the virtual metrology frame concept is presented. In Section 4, the acceleration based dynamic displacement measurement technique is described. The experimental setup and experimental results

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.660

are presented in Section 5 and Section 6 respectively. Finally, on Section 7 the paper is concluded.

2. MACHINE FRAME

A machine frame has two main functions (Soemers 2011): transfer of forces and position reference. Acceleration forces to the floor and process forces between the tool and fixture are transferred via the machine frame. The geometrical accuracy of the machine is maintained using the frame as a position reference to machine sub-systems.

In a servo system, a force F is applied to achieve the required position X of the carriage relative to the frame. There are three main concepts meeting the two required functions (Fig. 1). In the traditional concept (a), one frame structure is used for both functions. Reaction of the servo forces can excite the machine frame which will affect its performance. Thus, two concepts can be realised: Balancing Mass (BM) and metrology frame. The balancing mass compensates for the servo forces (b). Metrology frame is realised by separating the two functions, and having two frames – force frame and an unstressed metrology frame. The BM and metrology frame concepts can be combined to achieve superior performance (d), which is implemented in semiconductor lithography tools (Butler 2011). The metrology frame has its own vibration isolation system to prevent floor vibrations and servo reaction forces. However, the implementation of concepts other than the traditional one in a small size machine is difficult.

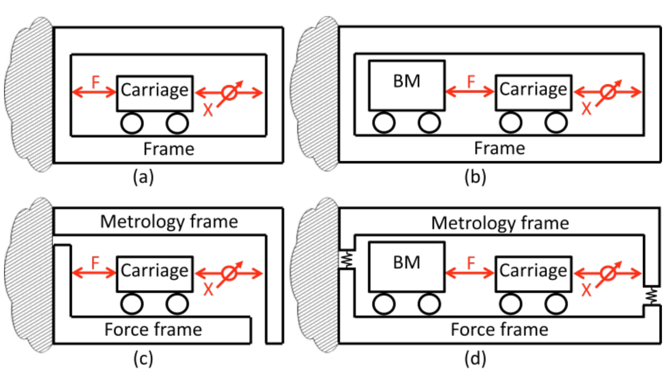

Fig. 1. Machine frame concepts. Traditional (a), balancing mass (b), metrology frame (c), and combined concept (d).

Based on the traditional design, the effect of reaction force on the machine performance can be analysed. Consider a linear direct drive machine with limited mass and stiffness (Fig. 2). There are two possible Transfer Functions (TFs) for the system depending on the reference system used to measure carriage position (Rankers & van Eijk 1994): TF_{fw} (1) the carriage position relative to a "fixed world", and TF_c (2) the carriage position relative to the machine frame. The TFs are given below.

$$TF_{fw}(s) = \frac{x_{fw}(s)}{F(s)} = \frac{1}{m_c s^2} \quad (1)$$

$$TF_c(s) = \frac{x(s)}{F(s)} = \frac{1}{m_c s^2} + \frac{1}{m_f s^2 + k_f} \quad (2)$$

TF_{fw} is an "ideal" TF, while TF_c is the practical TF which can be observed in any system.

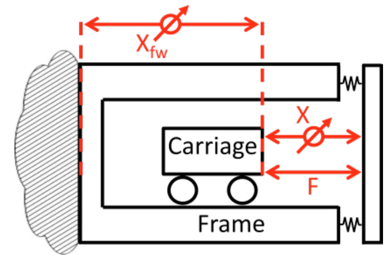

Fig. 2. Machine with linear direct drive and limited frame stiffness.

The TF_c consist of two modes: carriage rigid body mode and flexible frame mode. In the TF_{fw}, there is only carriage rigid body mode. In case of infinite frame stiffness (or mass) or in the case of separate metrology system, the flexible frame mode is negligible and $TF_c \approx TF_{fw}$. The Bode diagram of the TFs is shown in Fig. 3. The TF_{fw} is a double integrator type while TF_c is Antiresonance-Resonance (AR) type.

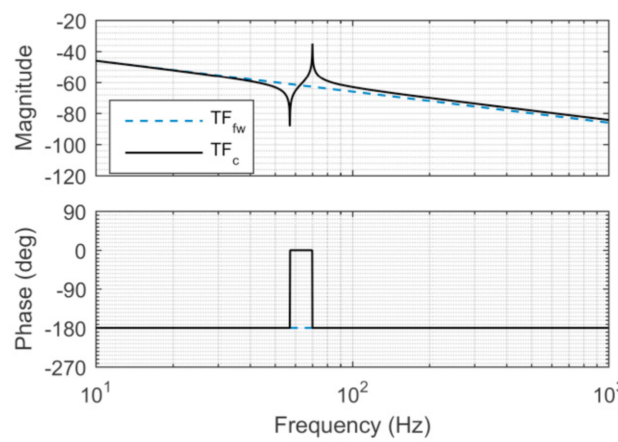

Fig. 3. Theoretical plant transfer function of a direct drive system with limited frame stiffness.

The dynamic properties of the machine are directly affected by the stiffness of the frame, and its reference system (Abir et al. 2016). Thus, by having an unstressed metrology frame the machine TF is as if it is TF_{fw}. Hence, superior dynamic capabilities can be achieved. Thus, a novel concept is required for allowing small size machine the capability of metrology frame without conflicting with it size constraint.

3. VIRTUAL METROLOGY FRAME

The *Virtual Metrology Frame* (VMF) concept solves the problem of the antagonistic requirements of small size machine and a metrology frame. The concept does not require the need of physical components associated with metrology frame, while the expected performance as if the machine has a separate metrology frame. The concept is realised (Fig. 4a) by distinguishing between the carriage position in respect to the stressed frame X_c and the frame displacement due to flexible modes X_f. Thus, unperturbed