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Virtual metrology frame technique for improving dynamic performance of a small size machine tool

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ABSTRACT

This paper presents a novel concept, a virtual metrology frame, for enhancing the dynamic performance of a machine tool with a flexible structural frame. The dynamic properties of a machine are directly affected by the stiffness of its frame, and its reference system; thus, by having an unstressed metrology frame, superior dynamic capabilities can be achieved. The developed concept does not require physical components associated with metrology frame; hence it is ideal for machine tools with requirements for small footprint and ultra-precision performance. The concept relies on an accelerometer based dynamic displacement feedback technique, where the accelerometer is used as a precision frame displacement sensor. The concept does not require a complex controller, and was realized in an off-the-shelf CNC controller. The concept was demonstrated on a linear motion system, a simplified version of a compact size CNC machine, and its servo bandwidth and dynamic stiffness were improved by 36% and 70% respectively, which are the key parameters for improving the machining accuracy.

1. Introduction

Reduction of machining error enables higher dimension accuracy in Computerized Numerical Control (CNC) machines. The significant fraction (90%) of machining error is cause by dynamic positioning error in a machine tool servo [1]; this positioning error results in a contour error on the machined part. In Proportional-Integral-Derivative (PID) type servo controllers, the most common controller used in industrial CNCs [2], tracking error contributes to error in position; tracking error occurs in a closed-loop control system due to an inability to follow rapidly varying position commands [3]. This error can be reduced by increasing feedback gains and servo bandwidth [4–7]; however, the amounts by which these parameters can be increased are limited by sensitivity to measurement noise and mechanical resonance excitation, respectively [4,7,8].

There are three important types of mechanical resonances that can limit machine dynamics [9]: actuator flexibility, guiding system flexibility, and frame flexibility. 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 occurs when the driving force is not coincident with the center of gravity and stiffness is limited. Frame flexibility occurs due to servo-reaction forces causing dynamic deformation, resulting in frame resonance excitation i.e. a stressed frame. The problem of servo control limited by mechanical resonance in machine tools is well studied in literature, most references focus on actuator flexibility; few papers describe the problem of flexible frames [10–13].

Notch filtering is commonly used in industry to attenuate mechanical resonances in the control signal [14]; however this reduces the drives' bandwidths, limiting its application in improving machine tool performance [15].

Pre-filtering trajectory techniques can be used to reduce machine structure excitation [16], however their implementation is challenging [8]. Impulse/jerk decoupling technology [17,18] utilizes a mechanical low-pass filter, which adds another degree of freedom to the system. An expansion to this technology, which is often used in the lithographic industry, is a dual stage motion system [19,20]. In this concept a fine short stroke motor with ultra-precision positioning is mounted to a coarse driving mechanism; however, this concept is complex and requires additional sensors, actuators, volume, and cost.

Acceleration feedback was used for damping structural resonances [16,21,22]; by adding acceleration feedback to the position

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control loop, as an inner feedback loop, the disturbance force experiences a virtually larger mass, improving the process sensitivity [23]. Process dynamics, controller calculation delay, and accelerometer roll-off result in instability. Reducing the acceleration loop gain for higher frequencies counteract this instability; however to maintain position loop stability margins the acceleration loop requires a high bandwidth [21,24]. Controllers in industrial feed drives commonly use position feedback only, since other movement variables are not available [16,21], this limits acceleration feedback realization in commercial CNC. Acceleration can be measured directly by an accelerometer, calculated from the second derivative of position measurements, or by observer techniques. Using accelerometer provides absolute acceleration measurement; however, both rigid body and structural vibrations are mixed in the signal. Differentiation of position signal produces quantization noise [25], passing this signal through filters limits the closed loop control performance [26]. Acceleration observers offers lower noise content than differentiation, however these are limited by parameter dependence [26,27].

The position signal in a linear motion system is typically provided by a linear encoder which is generally located at the machine frame; hence, deformation in flexible elements anywhere between the encoder scale and the point to be controlled is not compensated [28]. In [29] an accelerometer located close to the Tool Center Point (TCP) is used. The TCP position is estimated by a state space observer, and used as position feedback, improving dynamic behavior; however, this implementation is non-trivial due to the non-collocated control [22]. In [8] a model-based control is used to estimate the machine frame deformation with respect to the TCP, where no additional drive is required; however, frequency and damping of structural modes may vary over time, and also as a function of machine configuration [16].

This paper addresses the problem of frame flexibility, which is often neglected in the design stage, thus leading to unexpected problems during the prototype test phase [10]. A virtual metrology frame technique was developed to achieve high dynamic performance as though the machine has a separate stiff metrology frame, by measuring machine frame displacement using an acceleration sensor. The developed technique was implemented on a commercial PID controller, while other structural resonance compensation techniques cannot be applied in commercial CNC systems [30].

2. Virtual metrology frame concept

The Virtual Metrology Frame (VMF) concept was designed to improve the performance of a machine with flexible frame phenomena that limit performance. The dynamic properties of the machine are directly affected by the stiffness of the frame and its reference system. By utilizing an unstressed metrology frame, superior dynamic capabilities can be achieved [10,19,31,32].

The VMF concept is realized (Fig. 1a) by distinguishing between the carriage position, with respect to the stressed frame X_c, and the frame displacement due to flexible modes X_f; hence, an unperturbed position signal X_{vmf} can be obtained in the presence of these frame flexible modes. A typical PID controller structure C can be applied using the VMF (Fig. 1b). A reference position signal X_{set} is fed into the controller C, with output u, the control signal. The plant P is the system to be controlled, it has input u, and output X_c measured by a position sensor, typically a linear encoder; however, in the VMF concept a second output to the plant X_f, the frame displacement, is added to X_c within the controller; thus, the controlled position signal X_{vmf} is the sum of the position measurement signals, enabling attenuation of the machine frame resonance.

In a system with a flexible frame, there are two possible plant Transfer Functions (TFs): P_c (1) and P_{vmf} (2) depending on the carriage position signal X_c and X_{vmf} respectively, where m_c and m_f are the carriage and the frame mass respectively and k_f is the frame stiffness. The P_c consists of two modes: a carriage rigid body mode and a flexible frame mode. In the P_{vmf}, there is only carriage rigid body mode. In a system with an infinite frame stiffness, the flexible frame mode is negligible and $P_c \approx P_{vmf}$. The Bode diagram of the plant TFs is shown in Fig. 2; the P_{vmf} is a double integrator type while P_c is Antiresonance-Resonance type [9]. In practice, P_c may con-

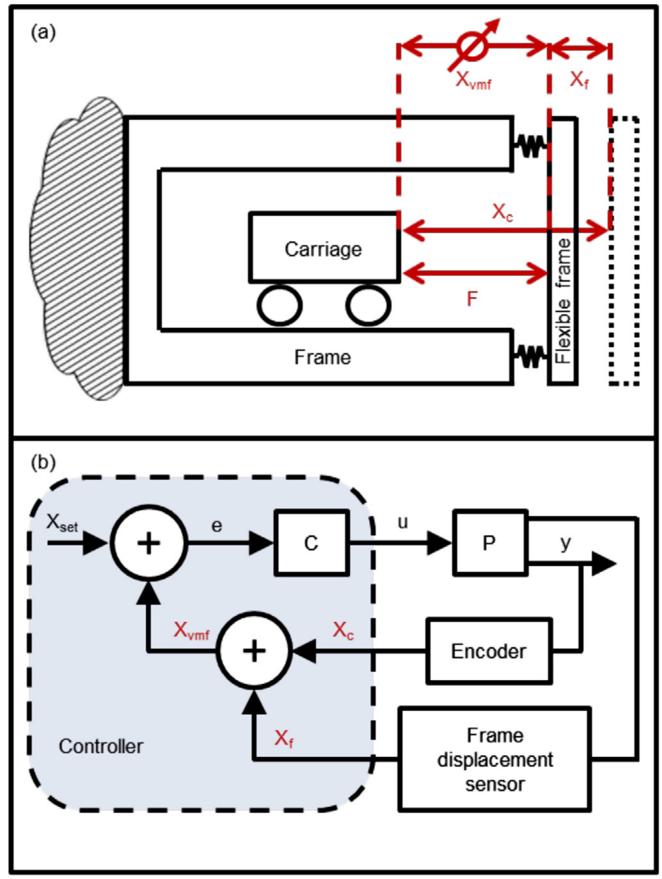

Fig. 1. The Virtual Metrology Frame (VMF) concept.

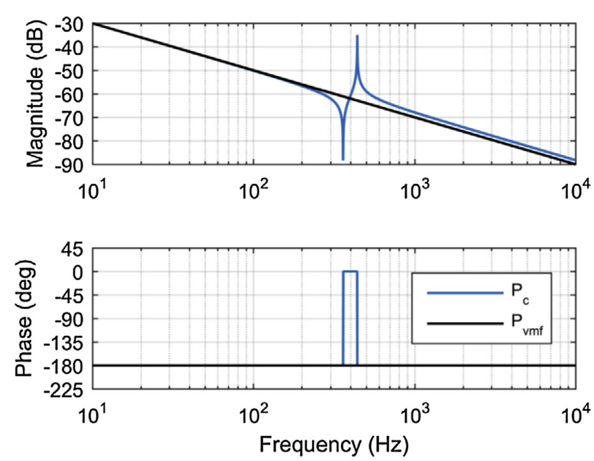

Fig. 2. Plant Transfer Functions (TFs). P_c and P_{vmf} are the plant TFs where the position signal is X_c and X_{vmf} respectively.