

H_∞ Control of Chatter in a Milling Machine

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Abstract

In this paper, preliminary results on the use of active chatter control in a new type of milling machine are presented. It is expected that this machine will cut metal at twice the rate of conventional machines without an appreciable increase in cost. Performance enhancements are achieved by the integration of active feedback control into an existing machine structure. To reduce computational burden, decoupled control is proposed. Extensive simulations have shown that significant performance enhancements are achievable.

1. Introduction

In milling, Metal Removal Rate (MRR) is limited by the power limit of the spindle motor and by chatter instabilities[1]. Spindle motor power can be enhanced by using larger spindle motors and chatter can be reduced by dynamically stiffening tools and machines. In many cases, conventional methods of stiffening are not feasible. In these cases, an alternative method of stiffening is by using active control. In this paper, a decoupled H_∞ active controller is used to dynamically stiffen and mitigate chatter in a milling machine.

2. Model of Milling Dynamics

A controllable and observable state space model of machine dynamics is described by

$$\begin{aligned}\dot{x} &= Ax + \bar{B}_a \bar{f}_a + B_c f_c, & \bar{d} &= \bar{C}_d x + \bar{v}, \\ y &= Cx\end{aligned}\quad (1)$$

where $x \in \mathbb{R}^{16}$ is a vector of internal states, $\bar{d} \in \mathbb{R}^4$ is a vector of displacement sensor outputs at the lower bearing, $y \in \mathbb{R}^2$ is a vector of tool tip deflections, $\bar{f}_a \in \mathbb{R}^4$ is a vector of actuator forces acting on the lower bearing, $\bar{v} \in \mathbb{R}^4$ is a vector of measurement noise, $f_c \in \mathbb{R}^2$ is a vector of cutting force at the tool tip, and A , \bar{B}_a , B_c , \bar{C}_d , and C are system matrices with appropriate dimensions. It should be emphasized that f_c is not an external disturbance. It is a nonlinear state dependent feedback force due to the tool-workpiece interaction process.

Tool-workpiece interaction is a complicated nonlinear phenomenon that depends on many machining parameters such as depth of cut, spindle speed, number of cutting inserts, workpiece material stiffness, chip loading, feed rate, etc. A specific computer program was written by researchers at Sandia Laboratories [3] which can capture the essence of this interaction. That program has been used in the simulation results presented in Section 4.

3. Active Chatter Control Using H_∞ Technique

The H_∞ control problem is illustrated in Fig. 1. Input to the H_∞ controller is measured lower bearing displacement, d_1 . Output is actuator force, f_{a1} . The H_∞ controller is used to minimize the effect of cutting force, f_c on some performance output vector, z_1 . The vector, z_1 , is a function of frequency, of tool-tip deflection, y_1 , of actuator force, f_{a1} , and of lower bearing displacement, d_1 .

Three sets of weighting functions are shown in Fig. 1. The purpose of the weighting function W_{1a} is to shape the sensitivity function such that the effects of f_c over certain frequency ranges are attenuated. For example, if tool tip deflection contains only low frequency components, W_{1a} is a low pass filter. The purpose of the weighting function W_{1b} is to deal explicitly with additive uncertainties in the system. For example, if the low frequency modes in the system contains additive uncertainties, then W_{1b} can be selected to guarantee the robustness of system against these uncertainties. And the purpose of the weighting function W_{1c} is to deal with multiplicative uncertainties in the system such as uncertainty in actuator and sensor dynamics. Although additive and multiplicative uncertainties are mathematically convertible to each other, they are left as separate quantities in this design.

Decoupled control was used to minimize computational burden. In decoupled control, two Single Input, Single Output (SISO) controllers are used to control from d_1 to f_1 and from d_2 to f_2 . This is less burdensome than controlling with one Multiple Input, Multiple Output (MIMO) controller from d_1 and d_2 to f_1 and f_2 .

4. Simulation Results

A simulation program that performs realistic efficient chatter control simulations for various cutting conditions and tools was developed. This program simultaneously simulates three interconnected dynamic models: a tool-workpiece interaction model, a machine dynamics model, and a control model. The advantage of separating the simulation into three models is to make controller design more flexible. Another advantage of the program is that it is very fast. Hence an amassment of design iterations can be assembled in a short time. The development of this program is contained in [2].

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In Fig. 2 the modeled chatter behavior of the system under no control for a depth of cut of 8 mm with a spindle speed of 3000 rpm is shown. The material is aluminum, the feed rate is 45 mm/sec, and the number of teeth on the tool is three. The magnitude of chatter is quite large. In Fig. 3 the results of completely decoupled H_∞ controllers under the same set of conditions is shown. Chatter has been suppressed. In Fig. 4, the stable regions of the controlled and uncontrolled systems are shown. Stability has been improved significantly over a wide range of conditions.

5. Conclusions

Future work includes the implementation of the developed decoupled H_∞ controllers in a real milling machine. Results will be presented in the near future.

References

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Acknowledgments

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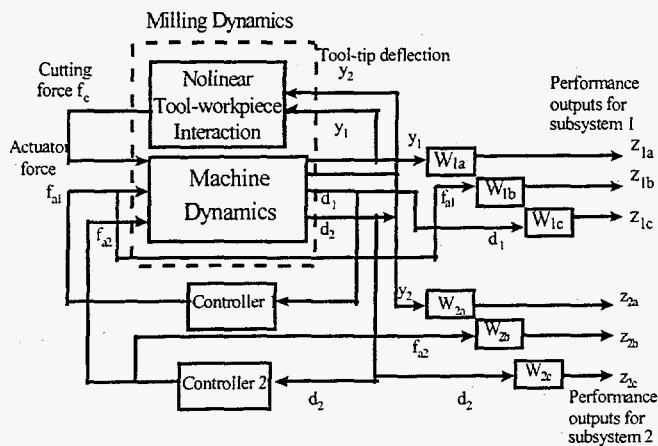


Fig. 1 Completely decoupled H_∞ controller structure.

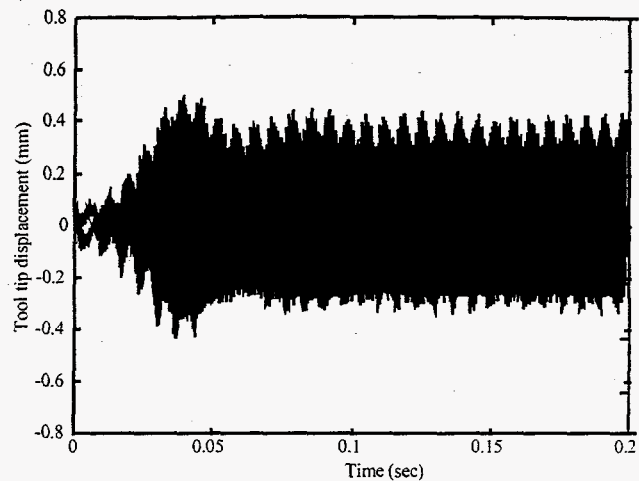


Fig. 2 Uncontrolled chatter behavior ($n = 3000$ rpm, $b = 8$ mm)

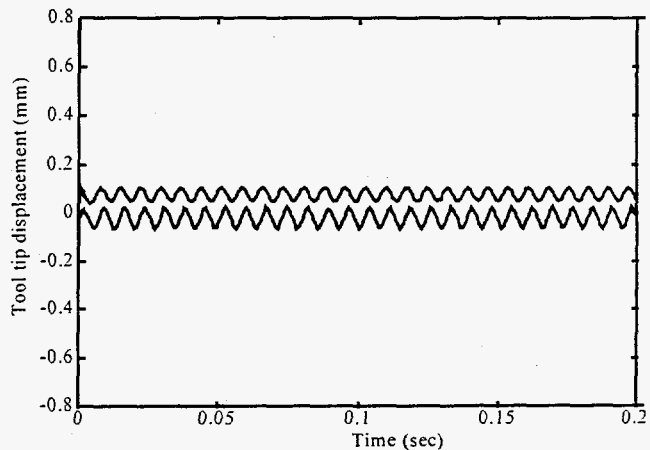


Fig. 3 Controlled behavior ($n=3000$ rpm, $b=8$ mm)

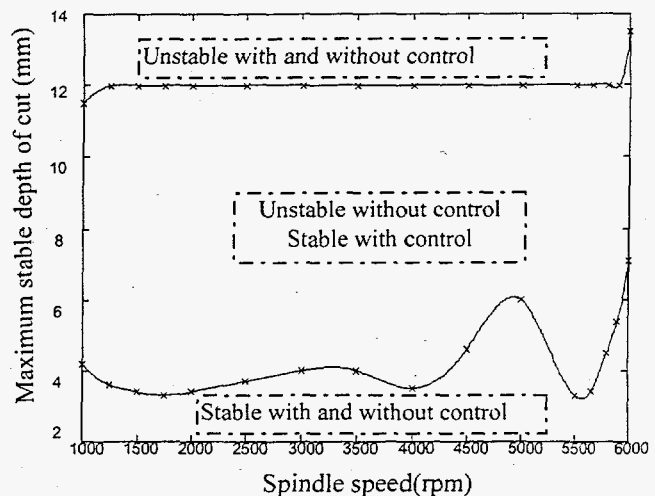


Fig. 4 Open-loop and closed-loop stability diagrams