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Two Predictive Control Methods for Suppressing Vibrations of Thin Plates

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Abstract. This paper investigates the mechanical vibration suppression problems for thin-walled workpieces in high-speed milling process and uses two different predictive control methods: General Predictive Control (GPC) and Laguerre Model Predictive Control (LMPC), where laser displacement detectors and high-frequency voice coil motors are utilized as sensors and actuators, respectively. The proposed control algorithm is validated in a vibration control system with a rectangular cantilever aluminium-alloy plate, which is used for simulating the thin-workpiece's vibrations in the milling process. The experiment results demonstrate that LMPC is superior to GPC in active vibration control systems with flexible plates.

Key words: General Predictive Control(GPC); Laguerre Model Predictive Control (LMPC); Vibration suppression

1 Introduction

Thin-walled plates, such as aeroplane's wings and screw's vanes, are widely used in a number of industries due to their light and strong properties. However, their strengths decreases when there are long-time vibrations. Hence, many researchers have been concerned with suppressing the vibrations of thin plates for decades since 1990s. They found that there usually exist two kinds of methods to reduce damages from vibrations, i.e., passive and active control approaches. The passive method is to change the structural inertia, for example, mounting many materials together to increase damping. As to active control, most researchers focus on the applications of smart materials such as piezoelectric ceramics [1], which has remarkable gains as well.

In the manufacturing industries, structural vibrations degrade the production rates as well as the qualities of the end products [2]. However, the present available scientific research achievement still can not be applied directly in the mechanical process especially with harsh environment or complex dynamics between flexible plates and rigid tools. Most academics hence focus on spindles

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which could hold cutter tools. For example, to avoid chattering, we only need to regulate spindles' speed [3]. In 2004, Dohner *et al.* [4] developed an active control system, where a Smart Spindle Unit is attached with actuators and sensors for suppressing the vibrations between cutters and workpieces. However, the equipment, using mere Linear Quadratic Gaussian (LQG) control, has limited effectiveness because of the difficulties and complexities that actuators and sensors are located in two separated coordinate systems, one rotating and the other stationary.

In machining operations, cutters and workpieces indeed interact with each other. As a whole, it is a rigid-flexible coupling system. Hence restraining the vibrations from the workpieces has the same influence on the whole system compared with cutters' active control methods. In 2010, Brecher *et al.* [5] designed an active workpiece holder to diminish the chatter vibrations with two high-dynamic axes controlled by piezoelectric actuators, which led to 50% increasing in productivity. So far, it is still an urgent yet challenging task to develop some advanced control methods to reduce the vibrations in manufacturing process.

General Predictive Control (GPC), as a kind of MPC methods, shows good performance and a certain degree of robustness. It can handle many different control problems for a wide range of plants with a reasonable number of design variables, which have to be specified by the user depending on prior knowledge of the plant and control objectives [7]. Eure [6] used GPC for an aluminum plate, with its clamped boundaries mounted on the top of a plexi-glass box and a loud speaker mounted at the bottom of the box to provide noise for plate vibrations. It was proved that GPC as an adaptive control method can regulate structural vibrations over a large bandwidth with a piezoelectric transducer mounted under the plate as an actuator. By contrast, Laguerre Model Predictive Control (LMPC) is easy to use since little prior knowledge of the system is required and time delays can be very well represented as part of the plant dynamics due to its resemblance to the Pade approximants [8]. Motivated from the above mentioned literatures, in this paper, we'd like to show that GPC and LMPC both can suppress the vibrations of the plate effectively.

The rest of the paper is organized as follows. In Section 2, the controller design is introduced. The vibration model is described in Section 3. In Section 4, the effectiveness of the control algorithms will be verified on a thin-walled aluminium-alloy workpiece. Finally, conclusions will be drawn in Section 5.

2 Controller Design

Just as other MPC methods, GPC and LMPC have the three core principles: model prediction, receding horizon and feedback rectification.

The plant model is a central part of predictive control, which greatly determine the validity of the control system.As is well known, GPC algorithm is usually designed based on CARMA (Controlled Auto-Regressive Moving Average) model and utilizes Diophantine Equation to ascertain the relationship among input sequence, future predictive output and the past output. Compared with GPC, LMPC is based on Laguerre functions whose continuous pattern is a complete orthonormal set, which can be represented in a stable, observable and controllable state-space form [9].

Receding horizon means that the control law will be implemented in a finite future time based on calculating the minimum of the cost function, and control vectors can be achieved from the cost function. Feedback rectification is designed to adjust the plant parameters with the information of inputs and outputs. Because of the uncertainty from the identified model and the nonlinear factors from the real system, we consider using Recursive Least Squares (RLS) model to estimate system parameters on line.

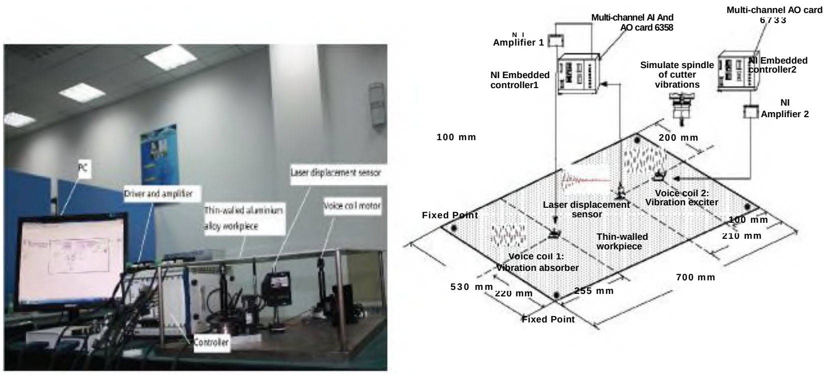


Fig. 1. Active control platform.

3 Vibration System Model

It is necessary to derive the motion equations of the plate structure to achieve better control effect, therefore, we perform some experiments to test the plate dynamics in this section, i.e., detecting the variation of plate displacement when absorber motor starts to push and pull the plate while activation motor is forcing the board with sinusoid signals.

The experiment equipment, as shown in Fig. 1, consists of an aluminium alloy plate (750mm × 540mm × 3mm) as the thin walled workpiece, a laser displacement detector as sensors, and two voice coil motors (one as the activation source which can produce a number of wave form vibrations to the plate, the other as the control actuator). The embedded controller1 (see Fig. 1), PXI-6358 from National Instrument Incorporation (NI for short) which can detect and output analog voltage, is used to control the first voice coil motor to absorb vibrations. The embedded controller2 (see Fig. 1), PXI-6733 from NI which can output analog voltage, is used to produce varied sinusoidal signals excite plate. The sensor is laser displacement measurement equipment LK-GD500 from KEYENCE. This whole equipment could be used to verify whether active control methods are valid and convenient to suppress the plate vibrations.

Test results demonstrate that the plate structure's first order natural frequency is between 16 and 17Hz. The plate oscillation engenders larger fluctuations in low eigenfrequency than that in high eigenfrequency due to its low pass filtering property. While it causes larger deviations from equilibrium position of the plate in high eigenfrequency than that in low eigenfrequency. Accordingly, to measure the control effect, we choose some discrete frequencies (5Hz to 25Hz), which are around the aluminium alloy plate's first eigenfrequency. Then we choose five different frequencies and calculate the parameters using CARMA model and Least Square Estimate (LSE) methods. The results are shown in Table 1.

Table 1. CARMA Model coefficient identified at different frequencies

	$y(k-2)$		[illegible]		$u(k-1)$	$u(k)$	d
5Hz	0.9613	-1.903	1	-0.02109	-0.01274	0	1
10Hz	0.9706	-1.918	1	-0.01504	-0.01599	0	1
15Hz	0.9617	-1.91	1	-0.02657	-0.0034	0	1
20Hz	0.927	-1.88	1	-0.03748	0.004395	0	1
25Hz	0.9365	-1.873	1	-0.02613	-0.003405	0	1

Put the same control variable input sequence to the real system at 5Hz and four models identified at 10, 15, 20 and 25 Hz. The results (see Fig. 2) show the displacements of the plate.The responses with real system and models have the same variant tendency, although the biggest difference is about 25% at wave crests and valleys, produced by the plate model at 25Hz.

4 Experiment

The common initial steady offset voltage $0.8V$ is added to both control and activating motor, which can tightly touch the plate and supply original displacement upward, for the sake of providing effective pulling force to make the structure produce downward displacement while the actuator can naturally bring thrust force to the plate for upward movement. Carry out zeroing operation and the laser sensor would produce $0V$ voltage on the corresponding initial position.Then a series of sinusoidal signals from 5Hz to 29Hz with the same amplitude, $u_d(t) = 0.15\sin(2\pi f t)V$, are successively loaded to activating point for generating disturbance.Then, apply the GPC and LMPC control methods to suppress the vibrations.

Fig. 3 illustrates the results with GPC algorithm. Indeed, the plate system vibrations got worse since onerous computations for solving the Diophantine Polynomials and matrix inversions, which spent about 10 milliseconds, while the

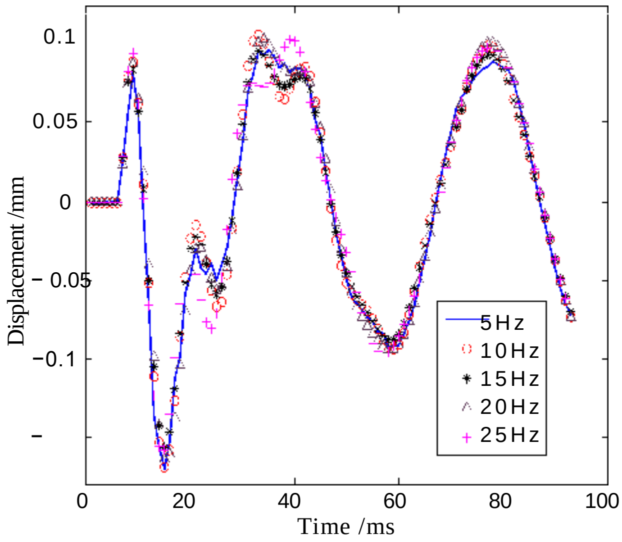


Fig. 2. Displacements of the plate at different frequencies.

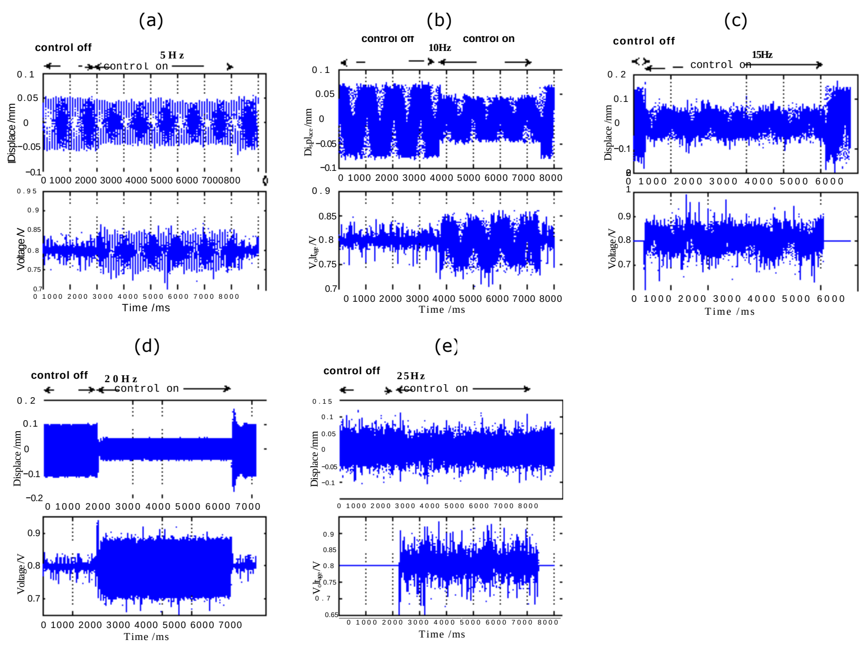
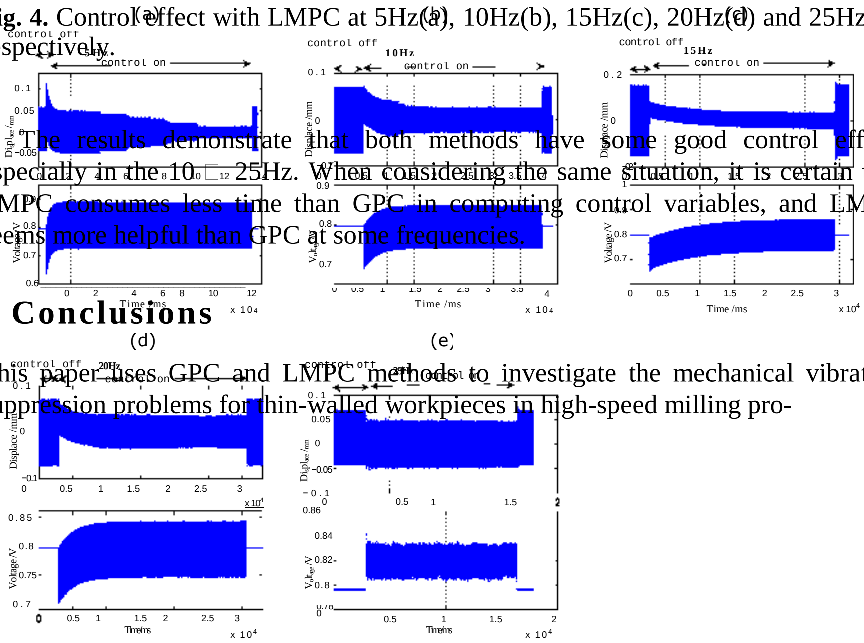


Fig. 3. Control effect with GPC at 5Hz(a), 10Hz(b), 15Hz(c), 20Hz(d) and 25Hz(e), respectively.

sampling time is set to be only 2 milliseconds in order to avoid feedback signal distortion based on Shannon's law. According to the slight differences of the model at different frequencies described in Section 3, we use fixed and identified model at 15Hz in open-loop circumstance to compute Diophantine Polynomials instead of on-line model parameter identification, then future control variable sequence could be figured out in less than 1 millisecond, which can be performed successfully.The suppression results as Fig. 3 are acceptable in 10, 15, 20Hz, while the control effect is poor at 5 and 25Hz. Fig. 4 illustrates the results with LMPC algorithm. As we can see, the effect is improved greatly, especially at 5Hz and 25Hz.

Fig. 4. Control effect with LMPC at 5Hz(a), 10Hz(b), 15Hz(c), 20Hz(d) and 25Hz(e), respectively.



The results demonstrate that both methods have some good control effect, especially in the 10□25Hz. When considering the same situation, it is certain that LMPC consumes less time than GPC in computing control variables, and LMPC seems more helpful than GPC at some frequencies.

5 Conclusions

This paper uses GPC and LMPC methods to investigate the mechanical vibration suppression problems for thin-walled workpieces in high-speed milling process. Experimental results illustrates that LMPC has more higher performance than GPC especially considering consuming time for calculations. Furthermore, LMPC can be conveniently utilized in the high speed machining process, which shows its great potential applications in future manufacturing industries. In fact, we can reduce the amount of computations in solving Diophantine Equations with GPC algorithm as well, for example, using explicit expression instead of system model to avoid calculating Diophantine Polynomials, or replacing the hardware with higher-performance chips such as Digital Signal Processor (DSP) and Field Programmable Gate Array (FPGA). This will be our future work.

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