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8.1 Conclusions

The results in this thesis were developed from an archetypal mathematical model for the mechanisms of vibration generation in machining dynamics. A cutting force model was considered involving time delay effects. From this an evaluation of stability boundaries (SLDs) was made in terms of workpiece axial depth-of-cut and the cutting tool rotational frequency. The combination of the cutting force and structural dynamics leads to a linear time-delay system. A controller design for vibration suppression of this type of system is therefore challenging.

In order to improve (expand) the operating regions for stable cutting, we present novel active controller design methods based on Lyapunov-Krasovskii functionals incorporating robust stability criteria to account for model error. The control synthesis involved solving a set of linear matrix inequalities to obtain optimized controllers. Both state feedback and output feedback version were developed. The use of LKF synthesis methods allows the inclusion of time-delayed feedback components within the control laws, although the overall controllers were linear and time invariant. The controllers were also suitable for operation over all tool rotational speeds as the synthesis equations were independent of the time-delay value.

The case studies and evaluations of the controller designs were based on an experimental test system for emulating the active vibration control of real machining processes. This system was representative of a milling machine spindle with a single active magnetic bearing. The development of structural vibration models for use in the synthesis was also considered. For use in initial system design (and later for state feedback controller synthesis) a FE model of the test system was developed. This model has reasonable accuracy and supports the full information control feedback design. In order to improve the structural vibration model of the test system, and obtain a model better suited for output feedback synthesis, system identification methods were used based on frequency response data collected from the test system.

The test system was designed to exhibit two dominant vibrational modes, which are associated with rigid body motion and tool bending within the test system structure. Which for flexible mode is specify mode of the limit of the stability boundary. The test system was installed with non-contact probes to measure the spindle vibration displacements and provide observability of both the spindle motion close to the actuator and the cutting tool displacement. For implementation of the controllers, the measurement signals information was utilized. Especially, in a part of the cutting tool measurement signals, a realization signal obtain by employing a combination of the displacement signal and the strain measurements from the test system structure.

For all model-based controller designs there is a trade-off between improving cutting stability boundaries for the dominant modes and ensuring robust stability of dynamical modes that are not captured well by the system model. The synthesized controller were tuned to find the best balance in this trade-off. In all cases the controller gains (complementary sensitivity) was a high as possible without causing destabilization of unmodelled dynamics. We found that, compared with a basic PD control approach, all the model-based controllers synthesized gave significant improvements in cutting stability, in terms of the maximum rate of material removal over all possible tool rotational frequencies.

The improved stability boundaries were realized when the controllers was applied to the test system and performance compared to the local PD control. The results, in terms of increase in maximum depth-of-cut, can be summarized as follows: the increase was 46% for standard LQR state feedback controller, while the maximum increasing was 389% for a LKF state feedback design with two-step optimization of gain values (LKF-SFC3).

The state feedback control approach, although effective in improving stability boundaries was shown to have two main limitations:

1) It is harder to implement in practice, due to the large number of sensors required to obtain full state information. In particular, it would be difficult to directly measure tool displacement at the cutting location on a real system.

2) As velocity signals are obtained by discrete-time approximation of differentiation, this introduces problems with noise amplification.

Due to the aforementioned limitation of state feedback control, an output feedback control approach was considered. For implementation, this required measurement only of the spindle displacement local to the control actuator location. Hence, measurement of tool tip vibration was not required. However, the controller uses dynamic feedback and therefore is more complicated to synthesize and implement. For the developed output feedback controllers, the improvement of the stability boundary depends on the accuracy of the structure dynamics model used for controller synthesis (with low accuracy leading to conservative assumptions and limited controller gain, as imposed by the specification on the complementary sensitivity functions). The LKF output feedback controller design using high accuracy model and the most general controller structure gave the best results, as the stability boundaries were significantly improved, while problems with high controller gain and noise amplification were avoided.

Synthesis based on time-delay models appears to allow better optimization of controller properties. Although the controller dynamics are more complicated (due to extra time-delayed terms or additional states from the Padé approximation) significantly

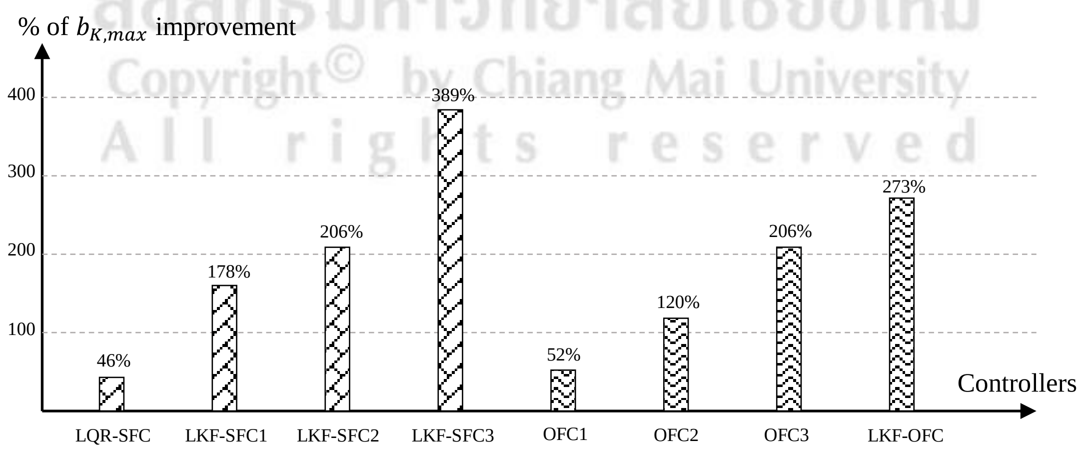

Figure 8.1 Improvement in cutting stability boundary relative to base-level PD control

improved cutting stability boundaries could be obtained. For the Padé approximation controller (OFC3) the increase was 206% compared to the PD controller, while for the LKF-OFC controller the improvement was 273%. The previously reported approach of dynamic compliance minimization (OFC1) gave an improvement of only 52% while an improvement of 120% was achieved for the norm-bound treatment of delay (OFC2). An overall comparison is shown in Figure 8.1.

Experimental tests involving emulation of the cutting process confirmed the stability boundaries established by direct testing and also showed other interesting aspects of the controller performance such as the control force, the cutting tool vibration and the noise effect. In conclusion, the controller designs that did not incorporate the time-delay effect explicitly were less effective in terms of stability and noise suppression.

8.1 Future Work

For future work following from this research, some suggestions may be given as follows:

- The dynamics models used in this research were linear, and although the structural dynamics were seen to have low error, we may be able to develop the model by considering methods that can better capture the detailed non-linear effects in the actuators or the cutting force mechanisms.
- The cutting force model in this research is a simple model suitable for the test system involving a 1D emulation of the machining process. In the future, a more realistic representation of the cutting process would better account for the properties of the tool-workpiece interaction, such as the shape of the cutting tool (helical tooth profile) or the type of cutting (up-milling, down-milling or slot milling). Furthermore, to complete the realistic model, the structure dynamics of the fixture and/or the workpiece should also be included.
- Signal noise has an important influence on vibration excitation during operation and was not considered directly in the controller design. This aspect could be included in future controller designs when it is necessary to limit noise excitation.

- Further investigations of the control methodology should involve application to a real machine, e.g. a milling spindle supported by active magnetic bearings. The dynamic model for a real spindle would be more complicated and should include gyroscopic effects (which are neglected in the current study). Furthermore, testing with material cutting could then be performed.