Self-tuning dynamic vibration absorber for machine tool chatter suppression

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Abstract

The current trend in machine tool design aims at stiffer machines with lower influence of friction, leading to faster and more precise machines. However, this is at the expense of reducing the machine damping, which is mainly produced by friction, and thus increasing the risk of suffering from a self-excited vibration named chatter, which limits the productivity of the process. Dynamic vibration absorbers (DVAs) offer a relatively simple and low cost solution to reduce chatter appearance risk by adding damping to machine tools. The proper tuning of the dynamic characteristics of the damper to the machine/process dynamics is the key for productivity improvement. A DVA which can detect its optimal tuning frequency and adapt its dynamics accordingly is proposed here. The main design and working principles of this damper, and the improvement of the machining conditions allowed by the damper will be demonstrated by real milling experiments.

1 Design of Dynamic Vibration Absorber

Dynamic vibration absorbers consist of a mass connected to the machine with a certain stiffness and damping, so that its resonance frequency is tuned to the frequency of the machine mode leading to chatter, by adding damping to it and allowing higher cutting depths [1]. Tunable DVAs are needed so that their dynamic characteristics can be adapted to a range of machine and process conditions.

The main challenges that need to be addressed are how to obtain the desired stiffness and damping values, and how to detect the frequency to which it needs to be tuned. The solution proposed here allows independent stiffness and damping tuning, with online stiffness tuning capability, with a highly repetitive and linear behaviour, compared to typical solutions based on elastomers.

In-process optimal tuning frequency detection is proposed too, based on processing an accelerometer signal, thus without need of an experimental modal analysis, which requires specialized equipment and personnel, and does not consider changes during machine operation (e.g. different workpiece mass, position dependent stiffness, etc.).

1.1 Variable stiffness spring

The stiffness of the DVA proposed here can be varied thanks to a variable stiffness spring controlled by a rotary stepper motor (see Figure 4a). Within 90º rotation, the stiffness of the spring changes between two values, easily defined at design stage through *a* and *b* parameters (see Fig. 1), providing a repetitive and linear stiffness tuning.

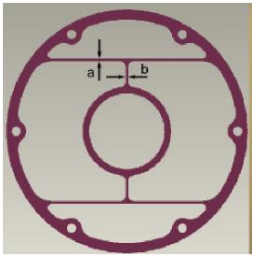

Figure 1: Rotary spring

1.2 Eddy current damping tuning

Eddy current damping is generated by the relative motion of copper plates within a magnetic field generated by magnets, and it provides a close-to-viscous damping effect. Since it generates no stiffness, and the spring presented above provides little damping to the system, the stiffness and damping of the DVA can be tuned independently, which is a great advantage over other typical solutions such as elastomers.

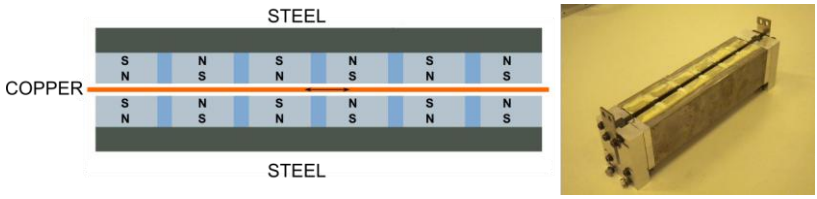

Figure 2: Magnet configuration and orientation, design and prototype

1.3 Self-tuning strategy

Optimal performance can be achieved if the tuning frequency can be calculated online during the machining process. A chatter detection algorithm is proposed here, which based on the information provided by an accelerometer placed on the DVA, detects whether chatter is being generated and at which frequency, and tunes the

damper accordingly by commanding the stepper motor to move the rotary spring according to a calibrated angular position – resonance frequency relationship.

2 Experimental setup

Machining tests have been carried out on a SORALUCE milling machine, mounting the workpiece on a flexible fixture for development and evaluation purposes. This fixture provides a dynamic response of the machine with a clear and isolated resonance mode, prone to suffer from chatter, and thus of help to avoid other disturbing effects, such us modes at similar frequencies, which would difficult evaluation of the performance of the semi-active damper presented here. Anyway, this is still a realistic test case comparable to many industrial cases.

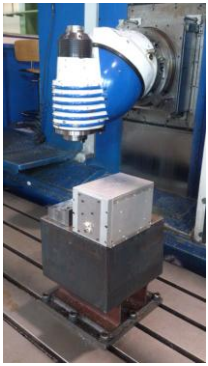

Figure 3: Machine tool and DVA setup

A DVA prototype has been built to meet the requirements of this test bench, which shows a critical mode at 94 Hz and 150 kg modal mass. With a moving mass of 7 kg, the DVA can change its main resonance frequency between 65 Hz and 105 Hz, providing an estimated 800 Ns/m damping, values which are in range with the optimal [1]. As it can be seen on Figure 4, the moving mass is formed by the four magnet racks, with the copper plates fixed to the frame, providing thus a very compact system. An accelerometer is placed on the frame to measure machine vibration.

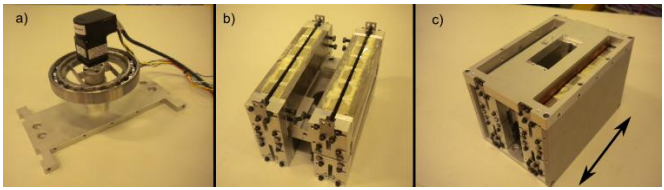

Figure 4: DVA component a) rotary spring and motor b) magnets c) assembly

3 Machining results

By performing an experimental modal analysis of the machine, the stability lobes of the cutting process have been calculated, in order to show the maximum cutting depth that can be achieved without the damper. A number of machining tests show the

validity of this prediction. The DVA was placed on the machine next, and it was tuned automatically during the cutting process, without using the information from the modal analysis. The process was found to be stable up to the maximum cutting depth defined by the tool (5 mm), compared to the unstable conditions with 1 mm depth without damper. A time simulation of the cutting and tuning process predicts much higher stable cutting depths, but they cannot be reached due to tool limitations.

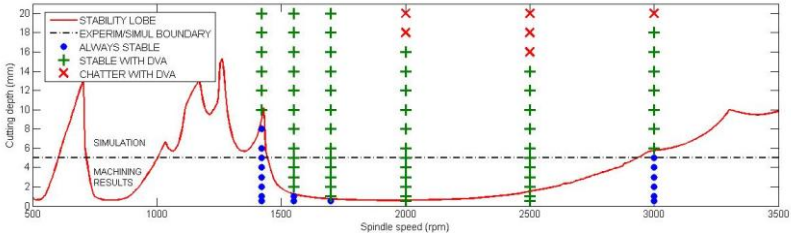

Figure 5: Machining test and simulation results, with and without DVA.

In Figure 6, the part that was used for the machining tests is shown. Clear chatter vibration marks can be seen without damper and 3mm depth, while a smooth surface is produced using the DVA with 5 mm depth, for several spindle speeds.

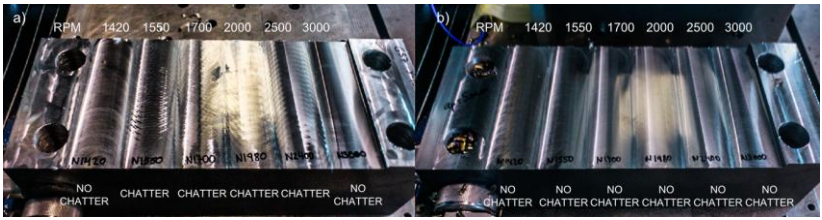

Figure 6: Workpiece surface: a) no DVA, 3 mm depth b) with DVA, 5 mm depth

4 Conclusions

These results demonstrate the effectiveness of the self-tuning DVA principle presented here. In real applications, productivity improvement will not be so high, but it will outperform existing DVAs by providing a low cost solution that does not require a previous experimental modal analysis and that works in close-to-optimal conditions even when process dynamics change during operation.

References:

[1] N. D. Sims, “Vibration absorbers for chatter suppression: A new analytical tuning methodology,” Journal of Sound and Vibration, vol. 301, no. 3–5, pp. 592–607, April 2007.