Design and Validation of an Active Damping Device for Chatter Suppression on Flexible Workpieces
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To cite this version:
Iker Mancisidor, Iñaki Laka, Xavier Beudaert, Jokin Munoa. Design and Validation of an Active Damping Device for Chatter Suppression on Flexible Workpieces. 5th International Conference on Virtual Machining Process Technology (VMPT 2016), May 2016, Taipei, Taiwan. hal-01509569

HAL Id: hal-01509569
https://hal.archives-ouvertes.fr/hal-01509569
Submitted on 18 Apr 2017

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Abstract: The apparition of self-excited vibrations known as chatter limits the productivity and accuracy of many industrial machining processes since they cause a reduction in the surface quality and in the lifetime of mechanical elements and tools. When large welded parts are machined, chatter vibrations are usually related to the flexibility of their relatively thin walls and special fixtures have to be designed in order to get a chatter free cutting process. The present paper proposes the design and validation of a novel active damping device attached directly to the workpiece surface by means of magnet and able to suppress chatter vibrations. The actuator introduces a force depending on the measured vibration to increase the damping of the flexible workpiece modes and hence increase the stability limit. The results obtained with this active device are demonstrated in industrial conditions.

Keywords: Chatter, Active Control, Stability, Thin Walls.

1. INTRODUCTION

Nowadays, chatter vibrations are one of the most important limits of machining processes in productivity terms as they prevent from obtaining required surface finishes and decrease the life of cutting tools and involved mechanical components. The first investigations of machine tool vibrations and instabilities appeared at the beginning of the 20th century. The regenerative effect was reported as the principal reason of chatter vibrations. After that, several studies proposed stability models to predict the behaviour of chatter vibrations [Altintas et al., 1995; Insperger et al., 2002; Zatarain et al., 2004].

Chatter suppression methods have been investigated for many years with solutions focusing on different aspects of the problem [Munoa et al., 2016]. The distortion of the regenerative effect has been achieved using special tool geometries [Slavicek, 1965] or continuous variation of the spindle speed [Sexton et al., 1978; Bediaga et al., 2006]. The improvement of the system dynamics using tuned mass dampers attached to the structure has also been largely employed [Sims, 2007]. However, the passive dampers are generally too bulky and not robust enough to handle system dynamic variations.

Active dampers can overcome this limitation, due to their adaptability to changing conditions. Generally, such actuators are based on the introduction of a controlled force, associated to the measurement of a parameter related to the vibration. In this way, a dynamically correlated external energy is applied into the flexible structure. In 1970, the
employment of an electromagnetic inertial drive with an accelerometer was proposed to introduce active damping into the machine tool structure [Cowley et al., 1970].

For inertial actuators, electromagnetic technology is usually employed, although some electrohydraulic actuators have been proposed in the literature to take advantage of their large strokes and forces [Brecher et al., 2005]. However, their main disadvantages are the time delay that is required for the actuators to reach the required pressure and the control quality. Among electromagnetic devices, magnetic attraction actuators offer large forces, but their nonlinearity makes them hardly controllable. Lorentz force actuators can generate less force, but they are very useful in vibration control due to their high linearity. Several authors have applied inertial actuators based on Lorentz forces for avoiding chatter on machining processes [Munoa et al., 2013].

When the workpiece flexibility is at the origin of chatter vibrations, the employment of special fixtures to stiffen the part has been proposed in the literature [Zeng et al., 2012]. However, this solution is costly when only few quantity of the same part reference is required. Other authors have proposed the addition of external dampers for improving the workpiece dynamics. [Bolsunovsky et al., 2013] attached small tuned mass dampers to the surface while [Yang et al., 2015] used small eddy current dampers. Active solutions have also been proposed by [Zhang et al., 2005] who used a piezoelectric patch bonded to the surface. All these solutions have been applied in small parts with thin walls, but they also could be scaled to large welded workpieces.

This paper presents the design and validation of an active electromagnetic damping device for the dynamics improvement on large flexible workpieces. This actuator permits to increase the stability in different points of flexible parts without necessity to tune control parameters or modify the fixture clamping, and hence, it is proposed as a confortable and accurate solution for this kind of vibrations problem.

2. DESIGN OF THE ACTUATOR

The main goal of the active damper is to suppress chatter and increase the process stability by locating an electromagnetic actuator in a flexible workpiece. In order to size correctly the actuator, a mechatronic model [Mancisidor et al., 2015] has been employed. For large welded parts, simulations have shown that a force capability of 300N is sufficient to increase significantly the stability limit. For this kind of workpieces, the frequency of the problematic vibration modes vary from 50Hz to 200Hz. Thus, it is important to design an actuator able to provide a linear behaviour in this frequency range.

![Figure 1; Magnetic design of the actuator.](image-url)
2.1. Magnetic design

The magnetic design of the actuator is based on a common voice coil (Figure 1). The 4 coils are located on the static exterior part and will carry the sinusoidal current with the desired frequency. The permanent magnets are on the moving iron mass and due to the Lorentz theory, a perpendicular linear force is generated on the mass when a current is introduced in the coils. The proposed configuration offers a great ratio between the force capability and the occupied space, which is very important for such devices.

Once neodymium permanent magnets are selected, the current value and the air gap between the fixed part (coils) and the moving mass (permanent magnets) have to be defined in order to achieve a certain force. A magnetic finite element commercial software package (FLUX®) has been employed for sizing these variables, calculating the theoretical force capability of the defined design. In this way, 300N force capability has been predicted when 5A current is passed through the coils with 1mm airgap.

2.2. Guiding system design

Apart from the magnetic design, a correct guiding system is necessary in order to endure the magnetic forces. In this work, the two complex shape flexures located on both ends of the moving mass have been designed to guide the mass and provide the required stiffness. The implementation of flexures is interesting in this kind of design, due to their linearity. In this case, the flexures provide a completely linear displacement over the axial axis and avoid radial movements of the mass. In this way, the gap between the magnets and coils remains constant and the possibility of a collision between them is avoided. Therefore, the airgap can be considerably reduced and hence, the magnetic flux is increased, providing a higher force density on the actuator.

In order to size the flexure, two simulations have been performed by finite element method (FEM) (Figure 2-a). First, a fatigue simulation has been performed to check the reliability of the flexure. Besides, enduring the maximum possible stress, it has to be sufficiently stiff so that the moving part displacement is not too large. Second, the dynamic behaviour of the flexure has been analysed. Indeed, the suspension mode of the actuator must be at low frequency not to affect the operating range of the active control. Hence, a low stiffness is required as long as it does not induce fatigue problems.

The simulated stiffness for each flexure is around 90 kN/m, so the total stiffness is 180 kN/m. In this way, after the commented simulations, the final design of the flexures will be capable of enduring theoretical forces and will have a 24 Hz suspension mode, considering 8 kg moving mass.

![Figure 2; a) flexures finite element model; b) circular magnetic chuck; c) actuator.](image)
2.3. Clamping system
In order to locate the actuator on the workpiece, an effective clamping system has to be selected. The system cannot depend on the workpiece shape and has to be non-destructive, since it is attached to the final part. This work proposes the employment of a circular magnetic chuck (Figure 2-b) which provides the possibility to attach the actuator on all ferromagnetic materials.

2.4. Controller and power electronics
Energy has to be provided to the coils to generate the required force by means of the introduction of sinusoidal current signals. The controller commands a voltage which can be converted into proportional current by a servo amplifier.

The selection of electronics is an important issue since some delays or electric noise problems can appear depending on the selected hardware. Ingeteam IC3 real time controller has been selected due to its good behaviour in relation to the electrical noise and processing time. For the current conversion, Xenus XTL digital servo drive is employed. It permits to introduce up to 20A continuous and 40A peak currents in the coils, working in current loop depending on an analogic voltage set point. All the power electronics can be integrated on a mobile platform to easily carry all the system.

3. CHARACTERIZATION OF THE ACTUATOR
After the design and the assembly, the actuator (Figure 2-c) is characterized regarding the suspension mode frequency, the force capability and linearity.

In order to analyse the ratio between the input voltage and the obtained force, a chirp excitation signal with constant amplitude is commanded to the servo amplifier and force is measured by means of a dynamometric plate. In this way, the frequency response function (FRF) between the generated force and the applied voltage input is obtained (Figure 3-left).

![Figure 3; Left: Force/voltage ratio; Right: Measured forces.](image)

The frequency of the suspension mode of the actuator is around 24.2 Hz, as shown in Figure 3. In this way, the finite element model is validated. Moreover, it can be observed that the behavior does not change too much depending on the input force level in the desired frequency range and, hence, a linear behavior can be considered for the actuator. In this way, the correct performance of the guiding system is proved.
The force exerted by the actuator with different input amplitudes has been also measured. A sinusoidal excitation is introduced and, as in the precious test, the force is measured by the dynamometric plate. In such analysis, 3 different frequencies have been tested. As shown in Figure 3-right, the actuator allows exceeding the minimum force established in the design requirements. Moreover, experimental force is higher than the results obtained by magnetic FEM software.

4. CONTROL LAWS

When active control systems are employed, one of the most important factors is the control law applied to calculate the force that the actuator should perform. Generally, feedback controls are applied for chatter suppression, since feedforward controllers require a reference disturbance signal which is very difficult to obtain.

Among feedback control strategies proposed in the literature, some authors have proposed model based algorithms [Bilbao-Guillerna et al., 2010; Kleinwort et al., 2014]. These strategies can benefit the control since efforts of actuators can be focused on the frequencies of interest, not wasting energy over all vibrations. However, the model should be modified for each working position in systems where the dynamics change during the process. Moreover, the elaboration of a model can be a complicated task, which, at best, can only be a low-dimensional approach of the actual system.

Model free algorithms have the advantage that the reduction of vibrations can be achieved without a model of the structure and, hence, they can adapt their behaviour to changing condition [Mancisidor et al., 2014]. Direct velocity feedback (DVF) is the most common control strategy for chatter problems when an external actuator is employed. It is based on the measurement of vibration velocity and its negative feedback multiplied by a gain \( G \).

\[
m \cdot \ddot{x}(t) + c \cdot \dot{x}(t) + k \cdot x(t) = F_c + F_{\text{act}}(t)
\]

Where the \( m \), \( c \) and \( k \) are the mass, damping and stiffness matrices respectively and \( F_c \) and \( F_{\text{act}} \) are the cutting and actuator forces. Applying the DVF for the actuator force:

\[
F_{\text{act}}(t) = -G \cdot \dot{x}(t)
\]

\[
m \cdot \ddot{x}(t) + (c + G) \cdot \dot{x}(t) + k \cdot x(t) = F_c
\]

The equation demonstrates that the actuator force provides an increase of damping when DVF control strategy is used. The present work employs this control algorithm. However, since an accelerometers is employed as measurement sensor, an integration has to be introduced in the control algorithm and consequently, signal has to be conditioned by means of different filters.

5. INDUSTRIAL APPLICATION

This chapter shows the application of the designed actuator on a real industrial application, where the active device is employed for improving the dynamic behaviour of a large welded frame.
5.1. Initial tests
The selected industrial case is a large welded iron (F-1140) frame in which some hubs are machined (red zones in Figure 4). A 100mm diameter tool with 7 teeth is employed for that purpose, cutting at 1100rpm spindle speed. Due to the large dimensions of the frame, the face to be machined tends to vibrate and no more than 0.1mm depth of cut could be cut without huge chatter problems (Figure 4).

![Figure 4: Chatter marks and frequency at the studied welded frame.](image)

5.2. Analysis of the flexible workpiece
The workpiece has been modeled by FEM in order to know the vibration modes (Figure 5). Taking into account the most critical modes, the best location for the actuator has been determined. For the machining process studied in this paper, the actuator is located close to the larger hub and on the machining opposite face (Figure 6).

![Figure 5: Improvement on the dynamic response carried out on the most critical modes.](image)

5.3. Final cutting tests
Before the cutting tests, the structure has been excited by an impact hammer and an accelerometer has measured the response of the machine for different control gains and filters. Figure 5 and Figure 6 show the improvement carried out by the actuator in the main three vibration modes and in the cutting time domain signal respectively, in which the amplitudes are reduced considerably. The employment of the actuator permits to increase the depth of cut from 0.1mm to 1mm, increasing significantly the productivity.
6. CONCLUSIONS

The work presents a new inertial actuator with high linearity for active damping of flexible workpieces. The actuator can be easily handled and clamped magnetically in different points of the flexible part, without necessity to be tuned for each position. In this way, it permits to increase the stability of the machining process and hence to improve the productivity.

The magnetic design, based on Lorentz force theory is showed, which finally provides more than 300N. Two complex flexures guide the moving mass along the desired direction and avoid radial movements which could generate friction problems. In this way, the airgap is constantly maintained, offering a balanced force. The validation tests show that the suspension mode is out of the targeted frequency range. Moreover, the linearity of the actuator has been proven.

The actuator has been applied in a real industrial case, where chatter problems appear on a large welded frame machining process. The optimal locations for the actuator and the accelerometer have been defined by means of a FEM modal analysis. In this work, direct velocity feedback (DVF) control algorithm has been applied to damp the workpiece vibration modes. The implementation of the designed active damping device provides huge productivity increase, demonstrating the improvement carried out by the system.

ACKNOWLEDGEMENT

This work was partially supported by the European Community under the MC-Suite project (H2020-FoF-2015-680478) and the Basque Government under CPS4SME ETORGAI project (ER-2015/00039).

REFERENCES


[Bediaga et al., 2006] Bediaga, I.; Egaña, I.; Munoa, J.; "Reducción de la inestabilidad en cortes interrumpidos en fresado de alta velocidad mediante variación de la
velocidad del husillo"; In: XVI Congreso de Máquinas-Herramienta y Tecnologías de Fabricación; San Sebastian, Spain, 1995.


[Zatarain et al., 2004] Zatarain, M.; Munoa, J.; Villasante, C.; Sedano, A.; "Estudio comparativo de los modelos matemáticos de chatter en fresado: monofrecuencia,
multifrecuencia y simulación en el tiempo”; In: *XV Congreso de Máquinas-Herramienta y Tecnologías de Fabricación*; San Sebastian, Spain, 2004.
