G Model
CIRP-1826; No. of Pages 4
ARTICLE IN PRESS
CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx
Contents lists available at ScienceDirect
CIRP Annals - Manufacturing Technology
journal homepage: http://ees.elsevier.com/cirp/default.asp

Increased productivity in centerless grinding using inertial active dampers

D. Barrenetxea (2)*, I. Mancisidor, X. Beudaert (3), J. Munoa (2)

IK4-Ideko, Elgoibar, Basque Country, Spain

ARTICLE INFO

Keywords:
Centerless Grinding
Chatter
Active damping

ABSTRACT

Regenerative chatter during centerless grinding processes is one of the main factors limiting the productivity. This paper presents a novel chatter suppression technique for centerless grinding using an active damping system based on inertial actuators. Dynamic characterisation of the machine with and without active damping is used first to compute theoretical stability maps. The active nature of the system allows stabilising a wide working range of infeed operations. Finally, experimental results validate the predicted increase of stable grinding area and verify that the technology is very effective for avoiding chatter, ensuring workpiece quality and increasing process productivity.

1. Introduction

Regenerative chatter is known to be one of the most critical factors limiting the productivity in centerless grinding. Although chatter is common in all kind of grinding processes, the wide grinding wheels used in centerless grinding make it more prone to suffer from dynamical instabilities. The research community thoroughly studied the origin and suppression of grinding chatter [1]. Particularly in centerless grinding, a large number of publications have been focused on the suppression of the geometric and dynamic instabilities [2].

Chatter suppression techniques can be classified into three main categories: model-based process parameter optimisation, regenerative effect disturbance and machine dynamics improvement. Model-based process optimisation is a well-studied approach which can help finding the best process parameters [3]. However, it requires a detailed process characterisation that should be updated every time the process conditions are changed. Moreover, the stable working area is not changed, so the productivity increase is limited. The continuous workpiece speed variation is effective to disturb the regenerative effect and does not require any dynamic characterisation or stability model [4]. However, the speed variations needed in areas of low lobe number might be technically infeasible when heavy wheels are used. Finally, various attempts have been made to improve the machine dynamic stiffness to increase the process stability limit. It is known that the friction in the guideways can increase the machine damping, but a compromise should be found with the machine accuracy. Finite element simulations have been widely used for machine's structure design improvement [5,6]. Spindles, guiding systems and feed drives have also been optimised [5,6] letting little room for further improvements in state-of-the-art centerless grinding machines. Another method for enhancing the machine's dynamic behaviour is to increase damping using passive or active dampers [7].

Damping enhancement techniques have the ability to act directly on the dynamic behaviour of the grinding system to increase the stable working area without the need for process knowledge. Active damping has been applied in conventional grinding processes for wheel holders [8] or workpieces [9,10]. In centerless grinding machines, active solutions have been barely used although some attempts of introducing piezoelectric actuators have been proposed [11].

This paper presents a novel active damping system based on inertial actuators that can increase the stable working area and process productivity in centerless grinding. The effectiveness of this chatter suppression technique is analysed using process simulations and validated experimentally in infeed operations.

2. Dynamic characteristics of a centerless grinding machine

A centerless grinding machine with a 400 mm wheel width is used to demonstrate the effectiveness of the active damping system (Fig. 1a). In this machine, both wheel headstocks are movable to maintain a fixed workpiece feeding point.

The performed cutting tests show that chatter grows in frequencies between 60 and 110 Hz. This wide frequency range is due to the fact that two different modes at 62.2 and 97 Hz are mainly responsible for chatter vibrations. An experimental modal analysis shows that the two critical modes generate an opening/closing relative movement of the grinding wheels, as it can be seen from the modal parameters of Table 1. Fig. 1b shows the large modal displacements on both grinding and regulating wheel heads for one of these critical modes. Indeed, the dynamic compliance of both sides is in the same order of magnitude and frequency. Thus, it is important to damp both sides of the machine.

* Corresponding author.
E-mail address: dbarrenetxea@ideko.es (D. Barrenetxea).

https://doi.org/10.1016/j.cirp.2018.04.093
0007-8506/© 2018 Published by Elsevier Ltd on behalf of CIRP.

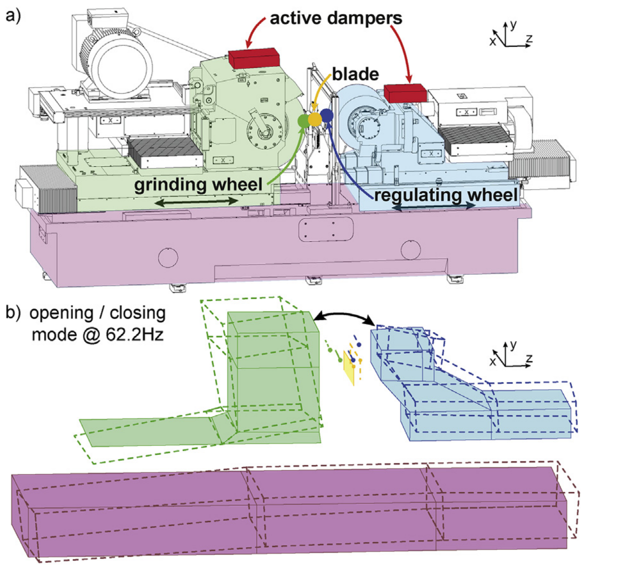

Fig. 1. (a) Centerless grinding machine with active dampers, (b) mode shape of the critical mode causing chatter vibrations.

Table 1
Modal parameters of the centerless grinding machine.

Natural frequency (Hz)	Damping ratio (%)	Modal stiffness (N/μm)	Modal mass (kg)	Modal vector (x, y, z)		
				Grinding wheel	Blade	Regul. wheel
62.2	8.6	543	3555	−0.19, −0.39, 0.61	0.16, −0.20, −0.36	−0.55, −0.48, −0.68
66.4	2	7519	43255	−0.88, −0.43, 0.19	−0.18, −0.34, −0.36	−0.65, 0.01, −0.11
82	2.6	2884	10862	0.89, −0.30, 0.34	−0.12, −0.22, −0.22	−0.18, −0.41, −0.47
97	2.6	671	1805	0.37, 0.09, −0.14	−0.19, 0.04, 0.14	−0.89, −0.01, 0.44
115.3	5	2826	5388	−0.35, −0.14, −0.07	0.10, 0.08, −0.68	−0.41, 0.69, 0.60
120.5	2.1	12569	21905	−0.22, 0.27, 0.01	0.23, −0.04, 0.94	−0.99, 0.09, −0.14

Passive techniques are classically used to increase damping. However, as shown in Table 1, the equivalent mass of 3555 kg of the most flexible mode at 62.2 Hz would require using heavy dampers (more than 300 kg). Moreover, several modes have to be damped at the same time, and the machine dynamics can vary due to the variation of the grinding wheels weight. Hence, passive dampers reveal to be too bulky to damp the wide critical frequency range of the centreless grinding machines.

Active dampers can overcome these limitations since the mass is reduced considerably, and a single active damper can damp a wide frequency range. As opposed to the piezoelectric solutions applied to similar grinding machines [11], the inertial actuators are located in parallel to the force flow which is advantageous for system robustness.

3. Active damping design and implementation

3.1. Hardware description

The force capability of the actuator is a critical parameter to ensure successful chatter suppression. Time-domain simulations of the effect of the active dampers on the process could be used to determine the necessary force to stabilise a given grinding process as it has been done for milling processes in Ref. [12]. In this work, two electromagnetic inertial actuators ADD-2D-1 kN from Micromega® with a total mass of 50 kg and a size of 270 × 450 × 110 mm are used (Fig. 2a). The actuators are a mixture between a linear motor and a voice coil, and can generate up to 1000 N using Lorentz forces in the feed direction (z). The moving mass, where permanent magnets are placed, is guided with respect to the static part where coils are located. Fig. 2b shows the frequency response function G_{act} between the commanded voltage and the performed force where both force/current and current/voltage relations are considered. The force/current relation is dominated by the electromagnetic force and the inertial mass suspension mode at 21 Hz which does not interfere with the frequency range required for this application. The current/voltage relation can be considered as constant with a value of 2A/V up to 800 Hz. Finally, the system is completed by two accelerometers ensuring collocated actuator-sensor pairs and a dSPACE controller which is responsible for closing the feedback loop at 4 kHz.

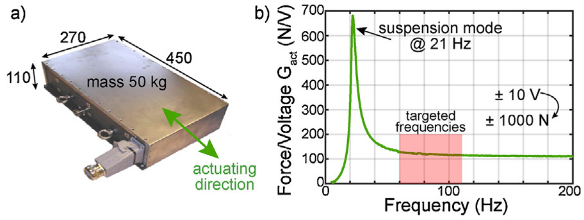

Fig. 2. (a) Inertial actuator dimensions, (b) force characteristics.

3.2. Control law

The selection of a proper control law is one of the most important decisions when active systems are employed. Several control laws have been proposed in the literature [13]. Some of them are model-based and require the knowledge of the system dynamics [14]; others are model-free and have the advantage that the vibration suppression is achieved without a detailed model of the structure. In this work, direct velocity feedback, which is the most common model-free strategy, has been used as it can adapt its behaviour to the different modes causing chatter vibrations. Such control law is one of the most effective methods for chatter suppression [12]. It is based on the measurement of vibration velocity $\dot{r}(t)$ and its negative feedback to produce the actuation force: $F_{act}(t) = -G\dot{r}(t)$, where $G = G_{act} \cdot G_{control}$. The active control effect can be analysed on a simple orthogonal case in Eq. (1), where M, C and K are the original mass, damping and stiffness matrices of the machine, being r the vibration of the structure and F_c the cutting force. It can be seen in Eq. (2) that the commanded force can be considered as a damping increase.

$$M r(t) + C\dot{r}(t) + K r(t) = F_G(t) + F_{act}(t) \quad (1)$$

$$M r(t) + (C + G)\dot{r}(t) + K r(t) = F_G(t) \quad (2)$$

Since accelerometers are used to measure the vibration, a high pass filter at 15 Hz has been introduced on the control loop in order to remove the low frequencies amplification carried out by the integration of the signal. Besides that, a low pass filter at 300 Hz has also been introduced to neglect high-frequency noise. The control filters are tuned so that the actuator force is in phase with the velocity of the vibration in the frequency range of interest. Hence, the modal parameter identification is not needed.

3.3. Implementation on a centerless grinding machine

The best location for the inertial actuators is at the maximum modal displacement point of the critical modes, where these poles are observable and controllable [15]. Thus, the actuators have been located on top of the grinding wheel fence and regulating wheel support. At those positions, the actuators are not interfering with the original machine components and are far from the cutting and feeding areas. Moreover, the installation of this system on existing machines can be envisaged without significant machine modification (Fig. 3a).

Please cite this article in press as: Barrenetxea D, et al. Increased productivity in centerless grinding using inertial active dampers. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.04.093