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Investigating actuation strategies in active fixtures for chatter suppression

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Abstract

Active fixtures represent one of the most industrially relevant alternatives among active chatter control techniques in milling, even though control logics and actuation strategies could directly reflect on their effectiveness. Closed-loop controls targeted in the chatter frequency range are commonly adopted for this purpose, but this approach lacks of applicability when chatter frequency exceeds the achievable actuation bandwidth. The purpose of this work is to investigate the effectiveness of potential low-frequency actuation strategies in suppressing chatter vibrations. A dedicated time-domain simulation model, developed and validated by authors, is used to test different actuation strategies in order to highlight the most relevant factors in assessing actuation effectiveness. The simulation results demonstrated that employing actuation frequencies close to the first half-harmonic of the tooth-pass frequency could disrupt the regenerative effect. This allows the mitigation and suppression of chatter phenomenon, increasing the critical axial depth of cut, as discussed in the paper.

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Keywords: Active fixtures; milling; chatter; model; control;

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1. Introduction

Chatter vibrations have been a major concern during the last decades, due to their limiting effect on productivity and additional related effects, such as worse surface finishing [1], increased tool wear and potential damages to the machine tool itself [2]. Different strategies have been presented in literature with the purpose of preventing such unstable vibrations during milling operations by means of dedicated experimental tests [3] and analytical models [4-6], but the industrial application seems limited by the required expertise in modal analysis and the time consuming experimental tests. Alternative active techniques have been presented in order to overcome these limitations, as discussed by Quintana et al. [2], and intervene on the process itself to mitigate or suppress chatter vibrations by means of dedicated control logics. Among these, active fixtures [7,8] appear the most attractive for an industrial exploitation, being easily and directly retrofittable on different machine-tools unlike other techniques, such as spindle speed variation, that require dedicated hardware and control solutions for different machine tools. Nevertheless, as highlighted in [9, 10], developing effective control strategies to mitigate chatter with such active approaches directly relies on the modeling and simulation of cutting processes. For this purpose, a dedicated time-domain simulation model has been developed and validated by the authors and the main features are briefly described in this paper. Literature reports the implementation of alternative closed-loop control strategies aimed at suppressing unstable vibrations by mitigating the amplitude of the chatter frequency [7,8], but the tested applications are always limited to frequencies below 400Hz. General applications of such approaches would require wider bandwidth, but inertial forces and operability of the actuators could drastically limit it.

This paper discusses the effect of open-loop actuation strategies in mitigating the chatter instability in simulated cutting tests, highlighting the most influencing factors in defining the feasibility and effectiveness of low-frequency actuation strategies.

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2. Main features of the dedicated time-domain model

The simplest fixture architecture of an active fixture is represented by a two degrees of freedom (DOFs) compliant mechanism based on serial kinematics, as exemplified in [8]. This system can be schematized as in Fig. 1, where F_{px} and F_{py} represent the forces along the two DOFs by the actuators, generally piezoelectric ones [11].

There are different ways of modelling piezo actuators, possibly including different non-linearities like creep and hysteresis, but according to literature [12] a linear model that simply relates actuation force to input voltage could be consistent with this application, given that the purpose is not controlling workpiece position with the highest resolution.

The following relations can thus define the characteristics of the piezoelectric actuators:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K_{uu}]\{u\} + [K_{u\psi}]\{\psi\} = \{f\} \tag{1}$$

$$[K_{u\psi}]^T\{u\} + [K_{\psi\psi}]\{\psi\} = \{q\} \tag{2}$$

where: $[K_{uu}]$, $[C]$ and $[M]$ are respectively the mechanical stiffness, damping and mass matrices, $[K_{\psi\psi}]$ is the dielectric stiffness matrix, $[K_{u\psi}]$ is the piezoelectric coupling matrix, $\{u\}$ is the nodal vector displacement, $\{f\}$ is the vector of the external mechanical forces, $\{q\}$ and $\{\psi\}$ are the nodal vectors of the electric charge and scalar electric potential, respectively.

By modeling the tooling system (i.e., spindle, tool-holder and tool assembly) and the fixture with a two degrees of freedom (DOFs) lumped model respectively, as discussed by Altintas and Weck [5], and including the additional force generated by piezo actuator, it is hence possible to model the cutting process with over imposed fixture actuation.

Time-domain model detailed description can be found in [13], along with the supportive results of the experimental validation, conducted comparing simulated and measured forces compensated with adequate procedures [14].

3. Simulation set-up

In order to realistically investigate the effectiveness of different actuation strategies on active fixtures, the features of a real prototype have been implemented in the time-domain model and realistic cutting conditions have been recreated.

3.1. Active fixture design

The prototype fixture, which features have been implemented in the simulations, is shown in Fig. 2. The fixture integrates flexure hinges to decouple actuation directions and ensure the required stiffness. Each axis is driven by four piezoelectric actuators, whose specifications are reported in Table 1, and adequate preload is applied by disc springs in order to prevent tensile stress on the actuators.

Table 1. Main specifications of the selected piezo actuators.

Blocking force	Max. displacement	Max. voltage	Stiffness
3200 N	32 μm	200 V	100 N/μm

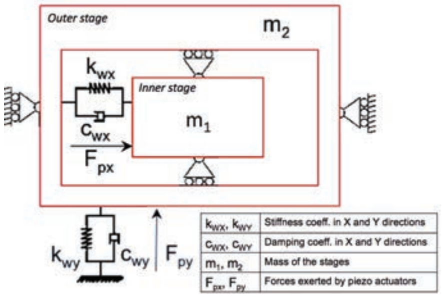

Fig. 1. Basic architecture of an active fixture with two DOFs.

The modal parameters required for the time-domain model have been extracted by curve fitting in the actuation direction of the frequency response function of the fixture, obtained by finite element analysis, with a single DOF. The identified parameters are reported in Table 2, along with the tooling parameters, discussed in the following section.

Table 2. Fixture and tooling identified modal parameters.

	Inner stage	Outer stage	Tooling
Stiffness, k	4.28e^8 N/m	4.39e^8 N/m	1.15e^7 N/m
Damping coeff., ζ	0.0432	0.0432	0.0231
Natural freq., f_n	2689.8 Hz	1782.8 Hz	1836.6 Hz

3.2. Cutting conditions

Cutting conditions have been recreated starting from data identified in the experimental validation tests of the time-domain model, discussed in [13]. Tool-tip dynamics, reported in Table 2, have been extracted by experimental tests, while cutting force coefficients of Aluminum 6082-T4 have been experimentally identified with the procedure reported in [15]. Main simulated cutting tests parameters are summarized in Table 3. The dominant frequency of the tooling, responsible for chatter instability, is sensibly higher than the ones reported in previous work on active fixtures [7], as common in many practical applications.

Table 3. Cutting tests parameters and identified cutting coefficients.

Number of flutes, z	2	Radial depth of cut	Slotting
Feed per tooth, f_z (mm)	0.05	Tool diameter, D (mm)	10

K_{tc} (N/mm^2)	K_{te} (N/mm)	K_{rc} (N/mm^2)	K_{re} (N/mm)
1086.66	764.29	139.03	33.32

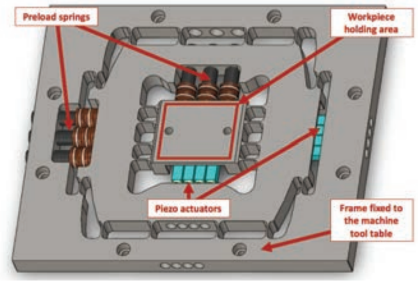

Fig. 2. Active fixture prototype design.

Implementing a closed-loop control targeted in the chatter frequency band would imply actuating at around 2 kHz, higher than the outer stage natural frequency, that is practically made impossible by inertial forces and electrical operability of actuators. The authors decided to test open-loop actuation strategies constrained below 300 Hz (the estimated bandwidth in safe operative conditions), with the purpose of disrupting the periodicity of the regenerative phenomenon that can determine chatter. Taking all these factors into account, the authors decided to focus on sinusoidal actuation since this is more easily implementable in a physical fixture.

3.3. Proposed evaluation approach

Actuation strategies effectiveness was assessed based on maximum depth of cut (ap_{limit}) achievable in stable condition. ap_{limit} was identified performing process simulations, increasing the depth of cut (ap) till reaching unstable cutting. Feed was set in the direction controlled by the outer-stage actuators. Depth of cut resolution was set to 0.02 mm and chatter was detected on the basis of tool-tip displacement frequency spectrum when a dominant frequency (chatter frequency) exceeds the amplitude of nominal chatter-free spectrum (tooth pass frequency and its harmonics), as in [3].

This approach is repeated for several spindle speeds in order to numerically compute the Stability Lobe Diagram (SLD). First of all, nominal SLD (without actuation) obtained by the proposed model was compared with the analytically predicted one [4] (Fig. 3), often used as reference. Fig. 3 shows a good agreement between the two diagrams, differences are in line with ap resolution. The comparison proves model capability of predicting stable and unstable conditions.

4. Results

First, actuation frequency (f_A) was investigated: a sine signal at different frequencies was provided by actuators, virtually operated at maximum voltage, on both directions in order to reach a fixed displacement (A≈0.03 mm along each axis). In Fig. 4, 187 Hz and 300 Hz effect on 3000-7500 rpm range is shown. For most of the spindle speeds, the maximum depth of cut in stable condition is increased. By actuating the workpiece at a specific frequency an adequate shift is produced to disrupt the periodicity of the regenerative effect, reflecting in an extension of the stability limits.

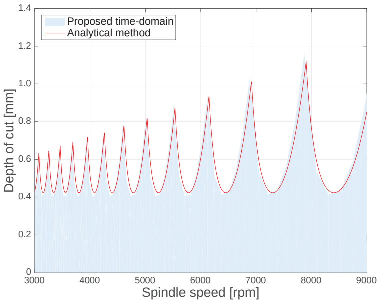

Fig. 3. Validation of SLD obtained via proposed method

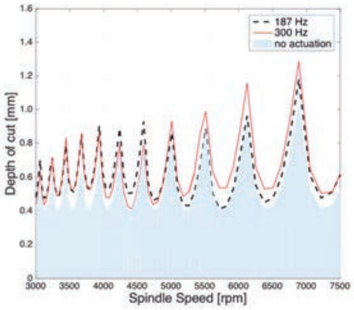

Fig. 4. SLD with open-loop actuation at different frequency

In Fig. 5, chatter suppression effect is highlighted for 705 rpm and 0.6 mm depth of cut: 300 Hz actuation is switched on after 2 s and the instability is damped. This effect on stability limit is not the same all over the spindle speed range (Fig. 4). Actuation does not significantly influence chatter phenomenon as actuation frequency gets close to the tooth pass frequency (f_{tp}) and its harmonics. For example, 300 Hz actuation is not effective at 4500 rpm (f_{tp}=150 Hz) and 3000 rpm (f_{tp}=100 Hz), where 300 Hz represents respectively the second and the third harmonic of the tooth pass frequency. As expectable, indeed, an excitation at the tooth pass frequency does not influence chatter regenerative effect, because it does not alter the periodic nature of the process. On the contrary at different spindle speeds a significant increase of depth of cut limit can be obtained (till about 30% for 300 Hz). This aspect is even clearer arranging data according to Fig. 6, where the effect of different frequencies is reassumed: ap increase is shown as a function of actuation frequency (f_A) to rotational frequency (f_R=n/60) ratio.

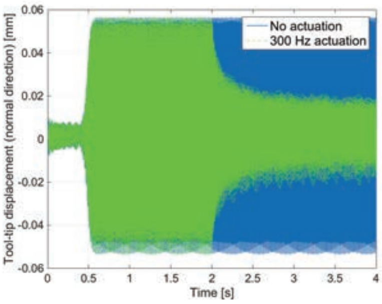

Fig. 5. 300 Hz Actuation effect on tool-tip vibrations (starting at 2s, 7051rpm, 0.6mm depth of cut)

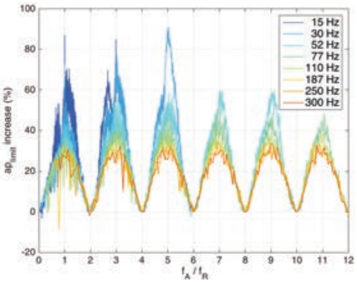

Fig. 6 Actuation frequency effect on rotational frequency

For every actuation frequency tested (15÷300 Hz), the minimum increase is obtained with actuation frequency equal to tooth pass frequency and its harmonics (f_A/f_R = 2, 4,… for 2 fluted endmill). Moreover, low frequency actuation seems to provide higher effects. These results were confirmed extending the simulations to higher number of flutes and suggesting the optimal actuation frequency equal to:

$$f_A = z\left(k + \frac{1}{2}\right) f_R \qquad k = 0,1,2,\dots \qquad (3)$$

5.5 Actuation amplitude and feed per tooth

Lastly, the effect of feed per tooth (f_z) and displacement amplitude (A) on SLD actuation was analyzed. Results show that actuation strategy effectiveness is directly proportional to displacement and inversely proportional to feed per tooth. This is possibly due to an increase of chip thickness (directly proportional to f_z), considering that the proposed actuation strategy is disrupting chatter phenomenon by altering chip thickness periodicity. In order to present the influence of both f_z and A, depth of cut increase was identified for single spindle speed (n=7051 rpm) varying the two parameters at 300 Hz actuation. Results are shown in Fig. 7 as a matrix in a 3D bar plots. A/f_z ratio seems to be one of the key parameter in assessing an effective actuation. Indeed, the main matrix diagonal reporting tests with the same A/f_z (equal to 0.3) shows very similar depth of cut improvement (blue bars).

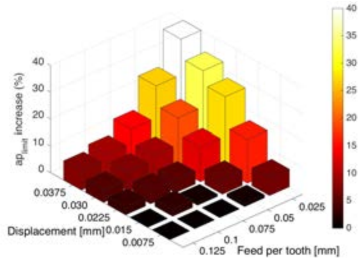

Fig. 7 Depth of cut increase for 7051 rpm, varying actuated displacement and feed per tooth

Additional parameters, such as actuation direction, phase and different tooling dynamics have been investigated, but their influence has appeared to be limited and are hence not discussed for sake of brevity. Nevertheless, shall be pointed out that actuating in cross-feed direction would increase slot width and it could be unacceptable for some applications.

Conclusions

This paper presents the investigation of different open-loop actuation strategies of an active fixture for chatter suppression in milling with a dedicated time-domain simulation model. An effective single frequency actuation strategy is developed and tested. Proposed actuation disrupts chatter phenomenon by altering the periodic nature of the milling process, increasing stable depth of cut. Best actuation frequency is suggested, far from tooth pass frequency and its harmonics. Actuators embedded in the fixture should provide enough workpiece displacement at that frequency to influence chip thickness. Displacement to feed per tooth ratio is hence a key parameter in assessing chatter suppression performance.

Developed actuation strategy could be an effective alternative to renowned closed-loop controls since it allows employing low-frequency actuation even for chatter frequencies that exceed the achievable actuation bandwidth. The fixture prototype is under assembly and further activities will be focused on testing the proposed actuation strategies on real cutting tests to experimentally validate the results.

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