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Design and validation of a tuneable clamping table for chatter avoidance in slender parts machining

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Abstract
The research work presented in this paper is focused on the development of a new tuneable clamping table (TCT) for avoiding chatter instability in slender parts machining. The table where those slender parts are clamped is designed to be dynamically tuned in a range of frequencies and damping factor, and it allows a coupling effect between the vibration modes of the part to be machined and the modes of the table itself. This adjustable dynamic table has one predominant degree of freedom, therefore the coupling effect with slender part is given at this direction, increasing notably the machining capability. The design of the table is based on several precision engineering concepts: Light table to minimize the moving mass (optimized structure), rolling miniaturized guideways to allow movement in coupling direction, variable stiffness spring based on flexure parts for natural frequency tuning, and finally eddy currents based damping effect with tuneable capability through moving conducting plates. This paper presents the design, simulations and optimization of those concepts for the first prototype of tuneable clamping table. The table has been manufactured and validated showing notorious increase of cutting capability, with a very precise tuning and adjusting of its dynamics for different parts and applications.

KEYWORDS: Workholder, adjusting damping, precision guiding, tuneable stiffness, chatter

1. Introduction

Thin walls and slender parts machining are a quite challenging task in current manufacturing trends, where structural lightweight, resources consumption and fuel saving are values to be optimized. Considering those issues, the finishing in milling operations of turbine blades is most known, extended and demanding application where the outputs of this research could impact, improving the productivity and overall quality of manufactured parts.

Two challenges are presented in the manufacturing of those parts, static deflection errors and self-regenerative chatter. Industry has dealt with this problem increasing static stiffness of the blades, with supports in cantilever zones. Increase rigidity of the part reduce deflection and static errors and increase the cutting capability moving chatter vibration limit out of working range, but those solutions have two main drawbacks: on one hand the structures used to increase stiffness of the part are commonly very invasive and they limit tool path and milling operations, and on the other hand the clamping forces and their releasing after machining induces static error in the part, usually slight errors but they could be significant in the case that the clamping mechanisms are not enough precise.

The work presented in this paper is focused on the increasing the damping on the part, and therefore reduction of self-excited vibration effect, chatter. Those vibrations limit dramatically the productivity of manufacturing process and increasing tool wear and reducing the surface quality of parts [1].

Chatter occurs due part vibration modes therefore all actions should go to increase dynamic stiffness of the parts, not in the tool/work-head and neither in the machine structure. This way active and passive dampers use is extended with aim to increase critical parts damping Passive dampers introduce damping dissipating energy by means of **t**uned **m**ass-**d**amper system (TMD) [2], however their applicability is very difficult in complex geometries with varying dynamics. Active dampers are actuators that counteract the workpiece vibration, with several solutions given in bibliography, in this case with electromagnetic actuators [3], however this solution requires direct attachment of damper (active or passive) to slender part, being the major difficulty for a feasible and general implementation.

Mode coupling effect (like TMD) has been studied in different works and the controllable mode with high damping is tuned to be close of the frequency of the critical mode [4,5]. But comparing with TMD systems this new approach introduces damping inside the cutting force in a serial way, without any direct intervention in the cutting zone and increasing dynamic stiffness at the cutting point. Previous works cited above were focused on the study of practical effect on machining dynamics and damping increasing, but first theoretical study of this phenomena: "serial mode coupling techniques to increase the dynamic stiffness of flexible parts", it is presented by authors in this work [6].

Therefore, this paper will take theoretical approach of [6] and here it is presented the design of a **t**uneable **c**lamping **t**able (TCT) based on serial mode coupling to damp thin-walled part modes. The stiffness of the clamping table may be tuned to achieve mode coupling between the modes of the part and the table.

This paper has four sections after this introduction. The first section related with the theory of TCT and its main variables, second section focused on the architecture of the table (main structures, guiding, variable stiffness and damping), the third section with experimental validation and a final one with main conclusions.

2. TCT conception and optimization

In the same way as TMDs, the tuneable clamping table (TCT) concept aims at increasing the dynamic stiffness at the machining point by means of mode coupling. When two or more modes lie close in the frequency band, mode coupling occurs, and the mode shapes of the neighbouring modes are combined. When damping is considered, a transfer dissipation between ideal (stand-alone) modes is achieved, which can be used for decreasing the dynamic flexibility of critical modes of structures.

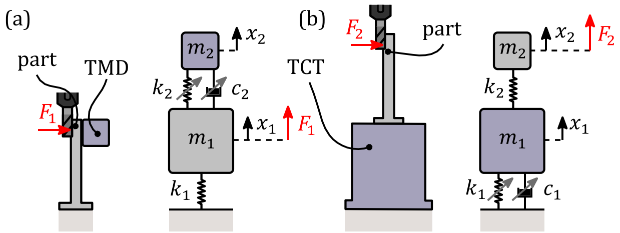

Figure 1. (a) Classical tuned mass damper (TMD) concept. (b) Tuneable clamping table (TCT) concept.

However, in TMDs, the highly damped mode is placed in parallel to the critical mode (Figure 1 (a)), whereas the TCT concept is based on placing the controlled mode in a serial configuration with the critical mode inside the flow of the excitation forces (Figure 1(b)). This allows introducing damping and, therefore, increasing the dynamic stiffness of the part at the machining point without having any device that can interfere with the cutting process clamped to it.

Theoretical development of the TCT system is presented in previous cited work [6] and even deeper in [7], so here only the main conclusions are presented for design optimization:

- Table frequency mode must be tuned by a variable stiffness (K_1) in the principal direction of the system (X).
- The combination of table moving mass (m_1), the part (m_2), and the springs stiffness coefficients (K_1 and K_2), they define the operation frequency range (f). This range should be in the range of the mode to damped.
- By the way, mass ratio defines the robustness of system. Lower is the mass of the moving part of the table (m_1) better is the fine-tuning capability and robustness of the system.
- Damping of the table must be modified looking for a proper tuning of the system, C_1.
- Overall conclusions: **Low friction in moving direction, high stiffness in other 5DoF, adjustable stiffness and damping of the table, and minimum mass for the moving part of the TCT**.

3. TCT architecture: Structure, guiding, stiffness and damping

The tuneable clamping table is designed to work in 1 DoF, aligned with the principal direction of vibration mode of critical part. In this case it will be a thin wall simulating the finishing milling of a turbine blade, therefore, other 5 DoF of the table should be enough rigid and their vibration modes enough far away comparing the mentioned blade. Prototyping of the TCT moreover requires controlling the dynamic properties of a clear mode. This entails three main design challenges: creating a stiff table with low mass to clamp the different parts and developing two mechanisms to change the stiffness and damping of moving parts of the TCT.

Consequently, a very light moving mass table is posed in order to maximise the mass ratio and ensure the robustness of the frequency tuning. The stiffness, and therefore, the natural frequency of the translational mode is controlled by a rotary spring attached to the table. And a variable damping system relaying on eddy currents is added to control the optimal damping. But those issues are described in deep in the next sub-sections of the paper.

3.1. Main structure and guidance

Considering the presence of strong magnetic field, the table is designed mainly in aluminium, to avoid problems with flux direction and in the assembly task. As shown in the Figure 2, upper face of the TCT is designed for a flexible clamping of any kind of part, but considering always the working direction of the table, modes coupling direction.

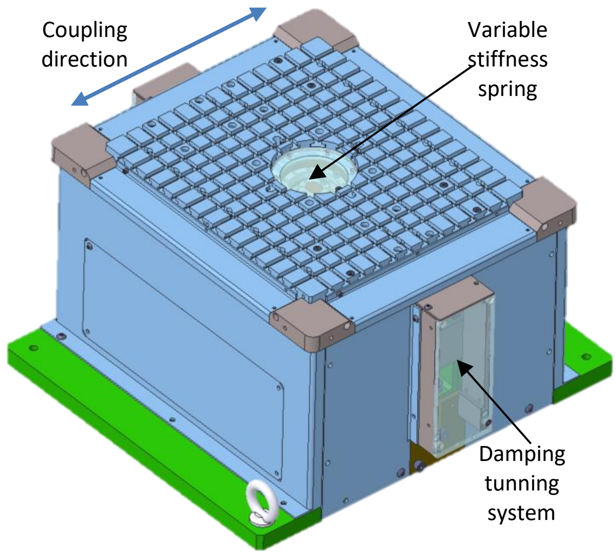

Figure 2. Overall view of tuneable clamping table TCT

In the figure 2 the stiffness variation mechanism and damping tuning systems are slightly showed. Into the circular cover in the centre of the table is the variable stiffness spring and lateral manual mechanisms move the immersion of conductive plates tuning the damping by Eddy current effect.

In the figure 3 the main guiding systems is shown where a pair of linear bearings guide the movement of the table over the fixed structure, and two rolling bearing are used to rotate the variable stiffness spring, tuning the frequency of table mode (coupling with slender part frequency) and ensuring proper guidance and stiffness in all other degrees of freedom.

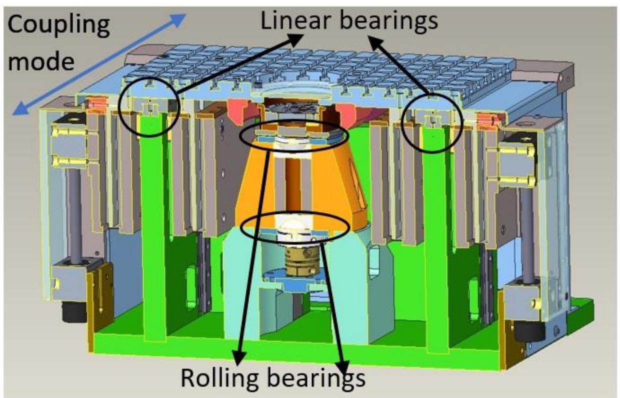

Figure 3. Cutting view of the TCT with main guiding system.

Moreover, of the rolling guiding system presented in last figure, the table is also guided by two flexure leaf with the main aim to keep the table centred at rest condition. Those flexures are shown in the figure 4, together some explanation about static and moving parts of the mechanism.

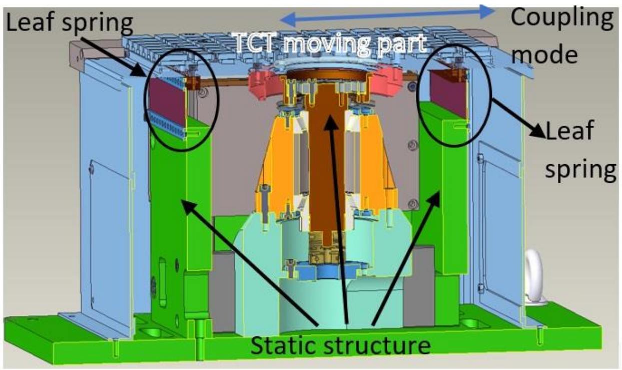

Figure 4. Spring leaves for guiding of the table, and static moving parts of the TCT.

Therefore, and summing up the main structure description, the translational mode was achieved with a guiding system composed by flexures and linear bearings, and the aluminium table was incorporated resulting in a total reflected mass of 6.5 kg.

3.2. Stiffness variation system

The solution for table frequency tuning is based on a spring with stiffness modulation in function of angular positioning [8]. In the figure 5 it can see a representation of mentioned stiffness variation spring, where rotating the spring from 0º to 90º the stiffness change from minimum to maximum.

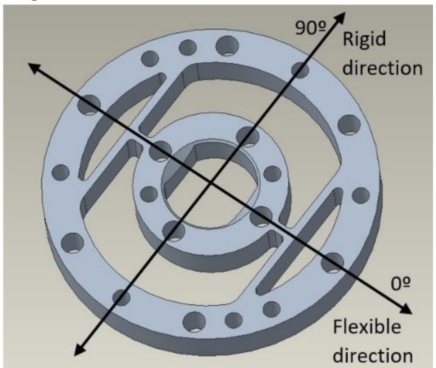

Figure 5. Tuning flexure, spring with rotation dependence stiffness.

The angular position of the rotary spring is controlled by a system composed by a motor which permits altering the stiffness of the mode externally, Figure 6. The translational mode of the table can be tuned within a frequency range of 200-400 Hz, range within which the thin-walled modes can be coupled.

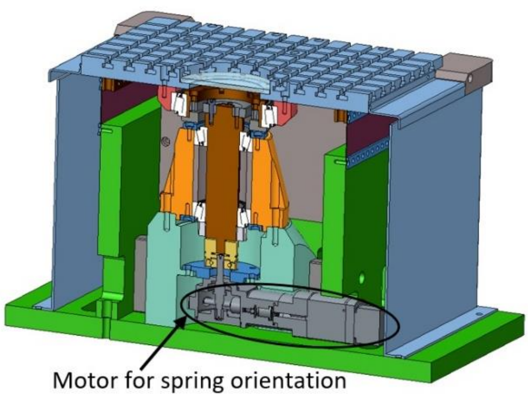

Figure 6. TCT view with stiffness control motor.

Thanks to this configuration, the table could be tuned automatically adapting the frequency to new parts or even adapting the tuning for part where large amount of material is removed, and therefore large dynamics change is expected.

However, the tuning range of TCT depends also on the additional mass (m) added by the part. A very low table mass supposes a higher sensitivity towards suffering a variation of the tuning range when additional mass is added to the table, Figure 7. This is an additional difficulty compared to TMDs, which show no variation of the device mass and the tuning range when clamped to the part.

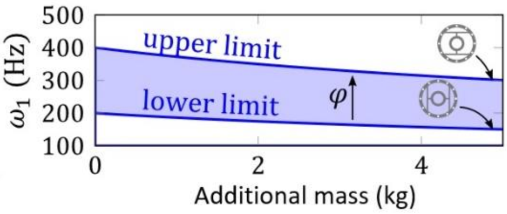

Figure 7. TCT tuning in function of spring orientation and added mass, the mass of part to be machined.

3.3. Damping variation system

The damping has been introduced by induced currents, Eddy current effect, instead of a more classical viscous effect with hydraulic dampers. The damping amount and adjustability is superior with hydraulic systems but due to the friction introduced by gaskets and O-rings, and consequent non-linearities in the system, magnetic principle was selected. Two twin damping devices are in both sided of the table, damper 1 and damper 2 of figure 8.

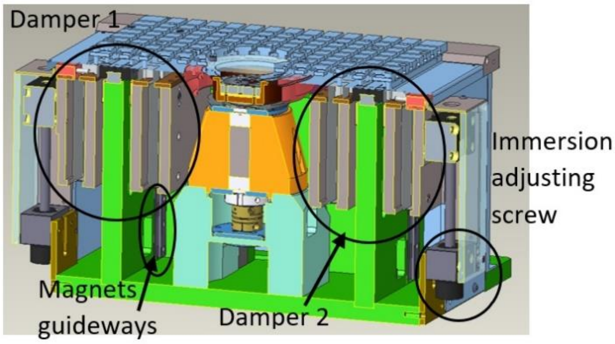

Figure 8. TCT dampers, one each side of the table, symmetrical.

For damping tuning, the table has conductive plates fixed underneath. The amount of damping is controlled altering the immersion of these plates inside a magnetic field created by permanent magnets, Figure 9.

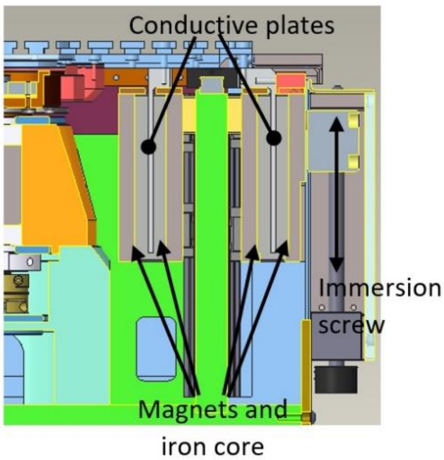

Figure 9. Detail view of Eddy Current's based damper.

4. Experimental validation

The table TCT presented in this paper was constructed and validated experimentally with several cutting tests. In the figure 10 a picture of the table is shown, with a dummy of slender part to be machined. A special part made of C45E with a clear bending mode at 380 Hz has been considered as dummy, with a replaceable part located in the tip of the part to perform successive cutting tests.

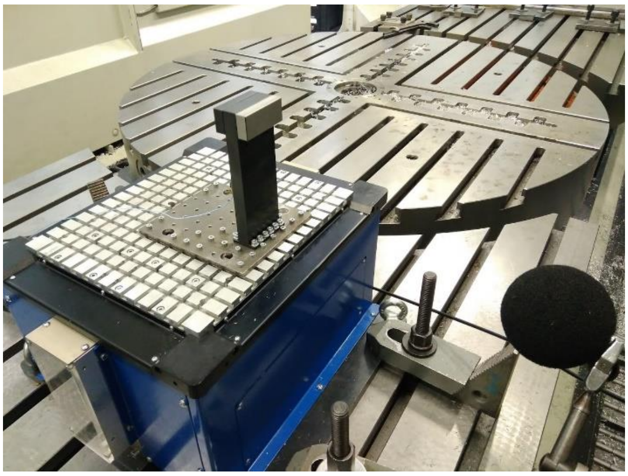

Figure 10. Picture of TCT table during experimental validation tests.

To verify the increase of stability given by TCT table developed in this project, several cutting tests were carried out on the part. The tuning and dynamic analysis of the table was carried and presented in previous cited work [6].

The operation is a flank milling up-milling with 1.25% radial engagement carried out with a diameter 16 mm and 4-fluted tool, which resembles a typical operation on thin-walled parts in the aerospace industry. The stability lobe diagrams obtained by semidiscretisation [9] for both clampings are shown in Figure 11a.

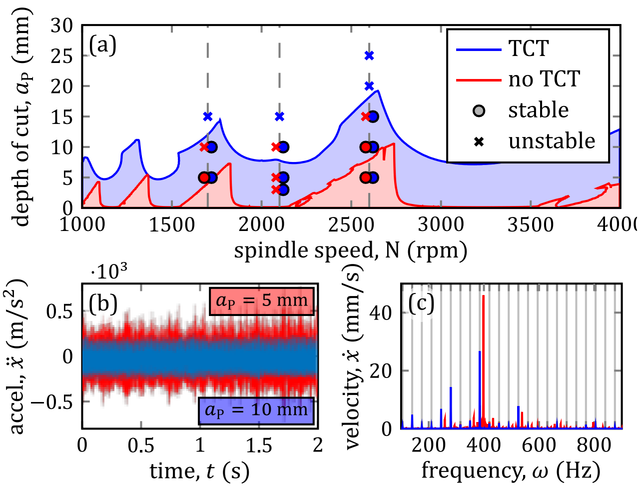

Figure 11. Experimental results of the test part machining without the TCT and with TCT. (a) Stability Lobe Diagram. (b) Acceleration signal during the machining for N = 2100 rpm. (c) Vibration severity for N = 2100 rpm.

The milling stability is clearly enhanced for the entire spindle speed range. The stability simulations predict a huge increase in the critical stability limit from 0.15 mm to 5 mm. The cutting tests verified the stability increase. At a spindle speed of 2100 rpm, a stable cut is achieved up to 10 mm of depth of cut, while without TCT chatter arises at 395 Hz already for 3 mm (Fig. 8c). Moreover, the vibration level of the damped clamping case remains inferior to the regular clamping case for double the axial depth of cut (Fig. 8b), resulting in noticeably inferior roughness values.

5. Conclusions

It was developed and presented a novel solution for slender parts machining at stable conditions, ensuring high productivity and good quality parts free of chatter. The tuneable clamping table (TCT) was designed following the requirements of dynamic stability specifications, but many of the solutions are based on precision engineering concepts to ensure a fine-tuning capability, low friction and as linear as possible response.

All these structures, guiding systems, flexures and dampers were calculated and optimized following the dynamic requirements presented above. The mass of the table was reduced as much as possible optimizing the structure and placing heavy parts of the system (i.e.: magnets, rotary mechanism, etc.) in the static part. Stiffness variable spring was designed to fit with expected frequency range. This system includes an automatic orientation mechanism to adapt the stiffness to new tuning frequencies. Moreover, the damping also can be modified (manually in this case) with accessible adjusting screws. This way, the two main variables of TCT can be easily modified to adapt it for new dynamics. The TCT prototype was constructed and validated experimentally, showing a high increase on cutting capacity.

But the industrial application of this concept will require the improvement of the actual design to achieve a lower moving mass of the table while maintaining a high stiffness of the clamping and to try to target higher natural frequencies. Materials with high stiffness to density ratio based on composites should be considered for future prototypes.

Acknowledgement

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