Experimental vibration analysis of a rotary transfer machine for the manufacture of lock components

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Abstract

This study deals with vibrations in machine tools featuring rotary transfer architecture. The machine tool manufacturer aims at two long-term achievements, namely developing a reliable virtual testing tool to aid the design process of new products, and implementing a real-time system for condition monitoring and diagnostics of the cutting tool and the machining units to be equipped on-board. A seven-station rotary transfer machine with multi-spindle CNC machining units is investigated as a starting point of the research. An experimental campaign is carried out to assess the machinery vibration response. Several different experiments are conducted to estimate the modal parameters of the machine as well as to identify the elastodynamic effects induced by the nominal working cycle and by each machining operation. The result analysis permitted to identify potentially critical issues and to define the corresponding strategies to overcome them. In particular, limited modifications of the machining parameters and a partial redesign of just one machine component are suggested.

1 Introduction

The presented activity aims at investigating the operation of rotary transfer machines by means of vibration measurements. Such machineries are machine tools typically devised for the large-batch production of limited families of parts [1, 2]. In particular, the studied system is specifically designed to perform many machining processes on various parts of the lock&keys industry at high production capacity.

The research pursues two primary goals. Firstly, the manufacturer aims at developing a reliable virtual testing tool (primarily based on dynamic finite element models) for predicting the elastodynamic behavior of new machine tools, since the early phases of the design process. Indeed, machine tools are potentially affected by several sources of elastodynamic phenomena. The cutting forces between tools and workpieces can excite the system resonances in a wide frequency band (primarily determined by the tooth passing frequencies and their harmonics) and induce chatter phenomena and high vibration levels [3, 4]. Inertial loads associated with rapid movements for tool positioning, or even ground-transmitted vibrations, can trigger elastodynamic phenomena as well [5, 6]. Chatter and severe vibrations of both the workpiece holder and the machining head degrade the quality of the machined surfaces and may raise the quantity of nonconforming products, hence reducing the productivity. They also involve durability issues, by reducing the tool life and increasing wear of the mechanical power transmission chain. Hence, predicting and solving potential vibration issues is essential to enhance the performance of machine tools and to limit maintenance costs.

The second objective is the implementation of a real-time system for condition monitoring and diagnostics based on the estimation of cutting forces from acceleration signals [7, 8]. For example, cutting forces allows estimating the tool wear and its residual life [9]. The desired system is considered an economically profitable machine upgrade, also because acceleration measurements are fairly cheaper than force measurements.

This work focuses on a seven-station rotary transfer machine with multi-spindle CNC machining units, chosen as a starting point for the research. An experimental campaign is carried out to assess the machinery vibration response. Piezoelectric transducers are installed on the indexing table, the machining units and the fixed machine structure to measure acceleration signals. The natural frequencies of the machine and the frequency response functions (FRFs) between the cutting tools and the fixed structure are firstly determined. Further tests are then conducted by running the rotary transfer machine in different working conditions, in order to determine the vibration levels characterizing the machine nominal working cycle and to identify the elastodynamic phenomena induced by each machining process. In particular, the FRFs are required for the identification of cutting forces from measured accelerations. Moreover, both the free and forced vibration response are essential for implementing and validating an elastodynamic finite element model (FEM) of the complete machine tool. This FEM should also provide the guidelines to develop elastodynamic FE models of other machine tools belonging to the same family of the studied rotary transfer machine; such models are expected to predict modal parameters and FRFs without the need of experimental measurements, hence before the prototypes are manufactured. Since the rotary table architecture is similar and the machining units are modular, this strategy is deemed viable.

The experiments also revealed potential elastodynamic issues of the tested machine tool. The main results of the experimental campaign are presented and discussed.

2 Machine tool description

The system under investigation is designed to perform different machining operations on lock&keys industry components, namely Zamak lock cylinders and brass plugs (Figs. 1a, b), at high production capacity (over 1 million parts/year). It features seven functional stations which are located on a fixed plate in the inner part of the machine (Fig. 1c): the first one is devised to the automatic loading and unloading of the workpieces; the other six stations include multi-spindle CNC machining units as well as manipulating units to orient the workpieces. A rotary indexing table with vertical axis is composed of both a rotary plate (diameter 1200 mm) and the attached clamping elements (namely the clamps and their cantilever supports) that hold the workpieces (Fig. 2). In particular, each cantilever support includes two clamps, and two workpieces at a time are processed at each functional station station (double-spindle units).

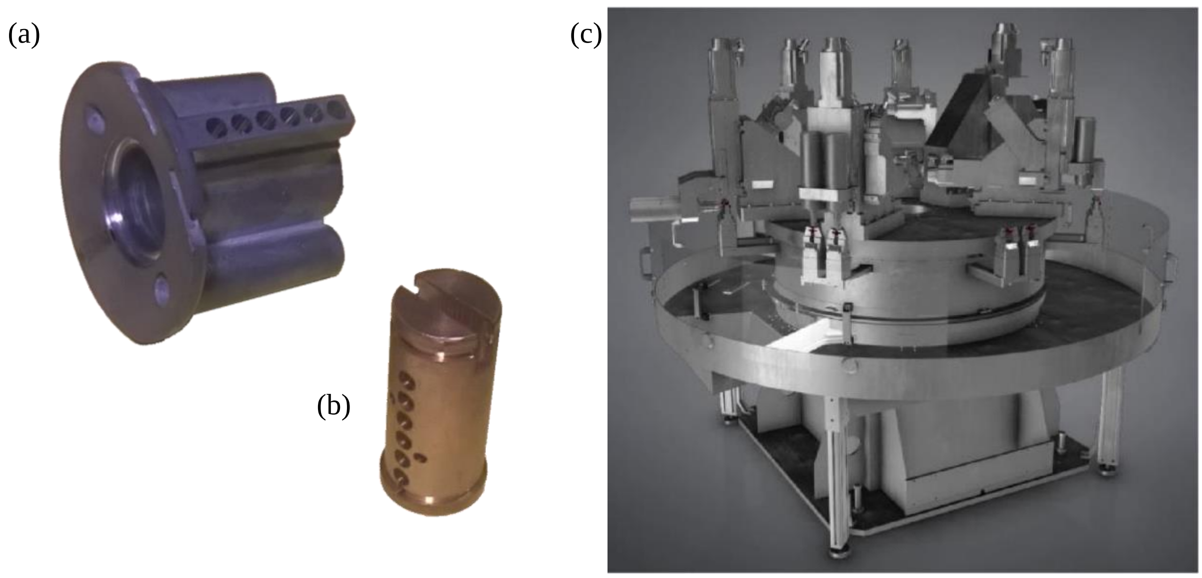

Figure 1: (a) lock cylinder; (b) plug; (c) rendered CAD model of the machine tool

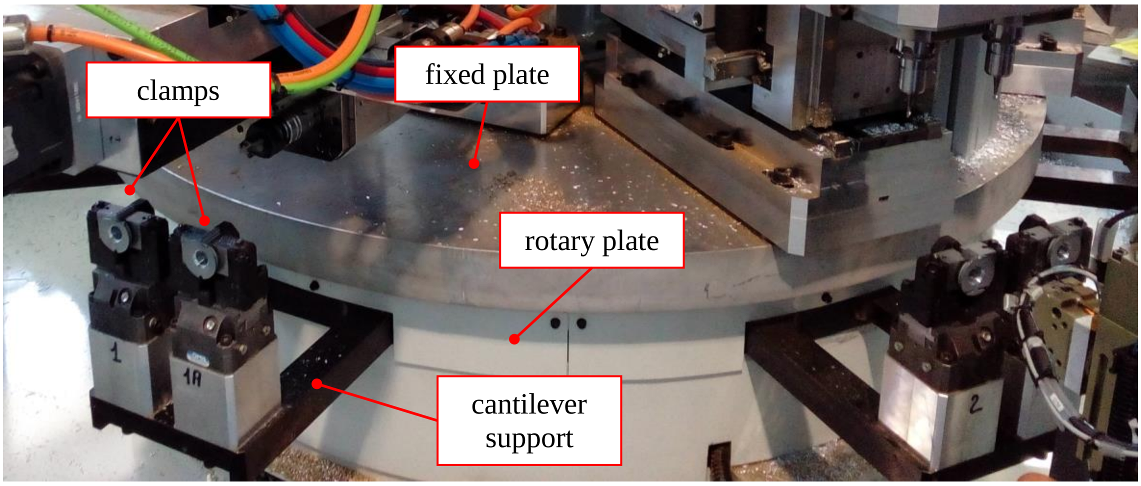

Figure 2: close up of the rotary table with clamped lock cylinders

A torque motor, by means of an absolute encoder able to grant an accuracy of ±0.5 arc seconds, directly drives the rotary table and keeps it locked during the machining operations, without the need of further couplings and hydraulic pressures (e.g. Hirth ring indexing). The rotary table has been optimized to present a relatively low inertia, by means of lightweight materials (primarily aluminum and CFRP) and high-stiffness geometries. Thanks to these features, the rotation time between stations is significantly reduced, hence limiting the Non-Productive Time (with respect to a standard Hirth based rotary table it is possible to get reductions up to -75%).

3 Experimental setup and tests

Measurements focus on the machinery configuration adopted to manufacture the lock cylinders made of Zamak. Indeed, the lock cylinder production process involves more demanding machining parameters (milling and drilling operations with bigger diameters, hence bigger cutting forces) than the ones adopted for the plugs, thus possibly resulting more critical for the machine operation.

Piezoelectric accelerometers are mounted on the machinery to study its elastodynamic behavior. Acquisitions are performed by using a LMS SCADAS SCM-05 system, with LMS TestLab software package. A sampling frequency of 6.4 kHz is adopted for all measurements.

Three different experiments are conducted, with the following objectives: (i) determining the natural frequencies characterizing the rotary table; (ii) investigating the vibrations induced by the machining operations; (iii) estimating the frequency response functions (FRFs) between the tools, the clamping elements and the fixed structure.

3.1 Free vibration response of the rotary table

The rotary table is considered the most critical machine part for possible vibration issues, due to its relatively lower stiffness with respect to the other structures. Hence, measurements are performed to determine its resonances and mode shapes.

Impulsive excitation is applied by means of an impact hammer to one cantilever support along three directions, namely radial (X-axis), tangential (Y-axis) and vertical (Z-axis). The vibration response of the excited support is monitored by two triaxial accelerometers mounted near the clamps, referred to as T1 and T1A (Fig. 3). The experimental FRFs are estimated and the natural frequencies of the rotary table are extracted. A Finite Element Model (FEM) of the rotary table, implemented by the machine tool manufacturer, is validated by using the measured natural frequencies. In particular, the signals of both accelerometers are processed with narrow band-pass filters around each resonance to assess their relative phases [10]; a comparison with the free vibration response of the support computed through FEM permits to achieve a correct match of experimental and FEM frequencies. The FEM is then exploited to estimate the mode shapes of the entire rotary table without the need of a complete Experimental Modal Analysis.

3.2 Forced vibrations

The focus of these tests is on the elastodynamic effects generated by the dynamic cutting forces of the machining operations. In the considered machine configuration, three stations (i.e. S1, S2 and S5 in Fig. 4a) perform machining operations (namely, drilling six ø2.65 mm holes in sequence with a Minimum Quantity Lubrication – MQL – approach, a ø12.95 mm boring and an end-milling operation, referred to as M1, M2 and M5, respectively); two stations are inactive (S3 and S4); in the last station, S6, residual chip is removed from the drilled holes by means of high-pressure air flows. Figure 4a shows a schematic diagram of the operations characterizing each station. The corresponding feed directions are also reported. The spindle rotation velocities, f_r, and the tooth passing frequencies, f_t, characterizing each machining operation are reported in Table 1.

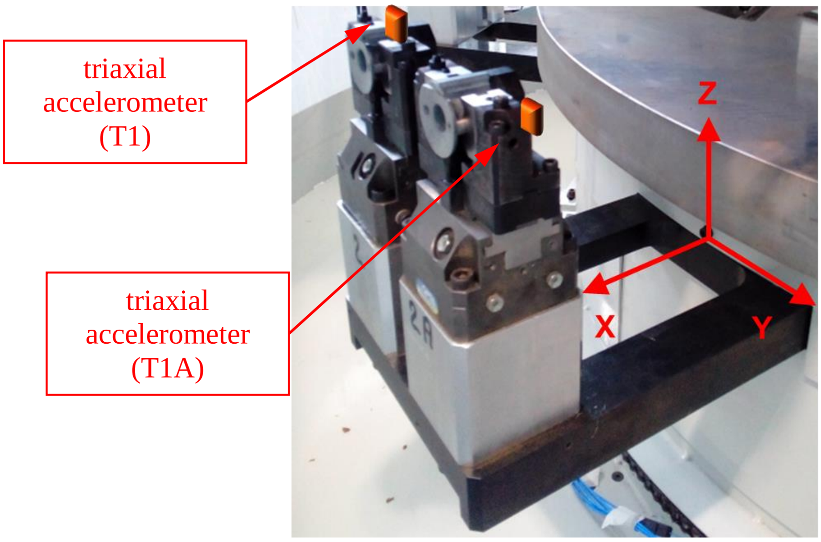

Figure 3: Clamps and fixing positions of the triaxial accelerometers

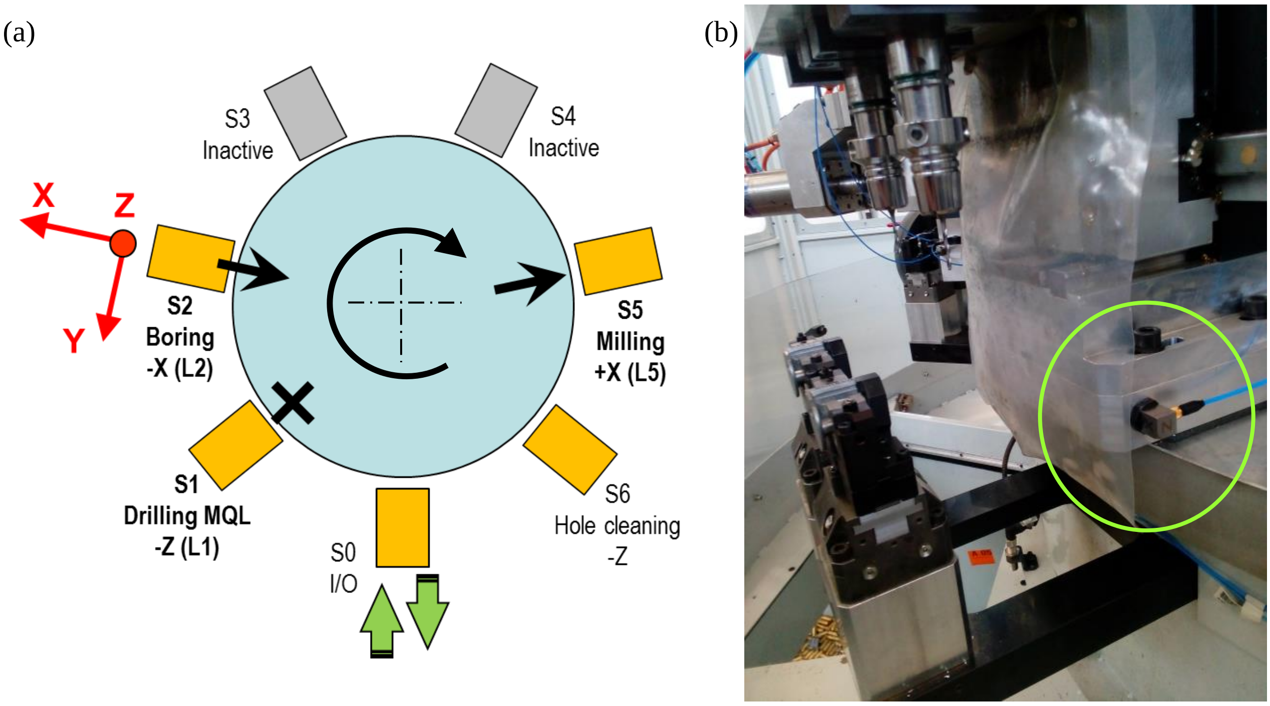

Figure 4: (a) functional diagram of the machinery and (b) accelerometer on the fixed structure

Operation	f_r [Hz]	f_t [Hz]
M1	130	260
M2	200	600
M5	166.67	500

Table 1: Machining frequencies

Measurements of forced vibrations aim at characterizing the elastodynamic behavior of the machine tool during a standard working cycle, as well as at determining the vibrations induced by each single machining operation on both the clamps and the fixed structure. These tests are expected to reveal critical phenomena possibly detrimental for both the productivity and the durability of the system. By combining the results of both free and forced vibrations it is possible to identify the sources of the elastodynamic issues and to define proper solutions to the problems, e.g. adjustment of the machining parameters or even possible modifications of the machine structure.

Additional transducers are installed at the connections between the fixed plate and each functional unit, to detect accelerations signals along the three directions (Fig. 4b).

Two different experiments are conducted. The first test is performed by running the machine in nominal operating conditions, i.e. with workpieces loaded in all the clamps and the functional units working simultaneously, over a complete rotation of the rotary table. The second test is carried out with the instrumented clamps standing at three stations (namely S1, S2 and S5) and the functional units operating in sequence.

3.3 FRF of machining units

The FRFs of the machinery, in particular those between the cutting tools force and the machine structure acceleration, may allow estimating the dynamic cutting forces of the machining operations from the acceleration signals (easily) measured on the fixed plate. The estimated cutting forces can be exploited to monitor the tool wear and predict its residual life.

To this purpose, additional sensors are installed on one tool tip of each machining unit. An impact hammer (PCB 086D05) is adopted for force exciting the fixed structure at the measuring points defined in Section 3.2, along the vertical, radial and tangential directions. The Maxwell’s reciprocity theorem is then assumed to practically use the FRF estimations for the mentioned purpose.

A current work in progress aims at validating the method through additional experiments on a test rig that is being developed to replicate one of the machining units and that will permit to directly measure also the cutting forces.

4 Results and discussion

The most relevant results are presented here. The results concerning the tests described in Section 3.3 are not reported, since the activity is still ongoing.

4.1 Rotary table resonances

Table 2 shows the natural frequencies measured in the band up to 650 Hz and a description of the corresponding mode shapes. A representation of the mode shapes is also reported in Fig. 5. The frequency band of interest is determined based on the machining frequencies shown in Table 1. Indeed, even if their harmonics may excite a much wider frequency band, the amplitude of vibrations for higher modes are extremely lower than for the first resonances and should not hamper the machine tool operation.

Except for mode #3, the deformations of the rotary plate appear negligible, i.e. the main contributions to the mode shapes are ascribable to the local deformations of the cantilever supports.

Mode no.	f_n [Hz]	mode shape description
1	112	cantilever support - flexural
2	231	cantilever support - torsional (counter-phased)
3	320	cantilever support (and plate) - flexural
4	460	cantilever support - torsional (phased)
5	521	counter-phased oscillation of clamps

Table 2: Measured natural frequencies

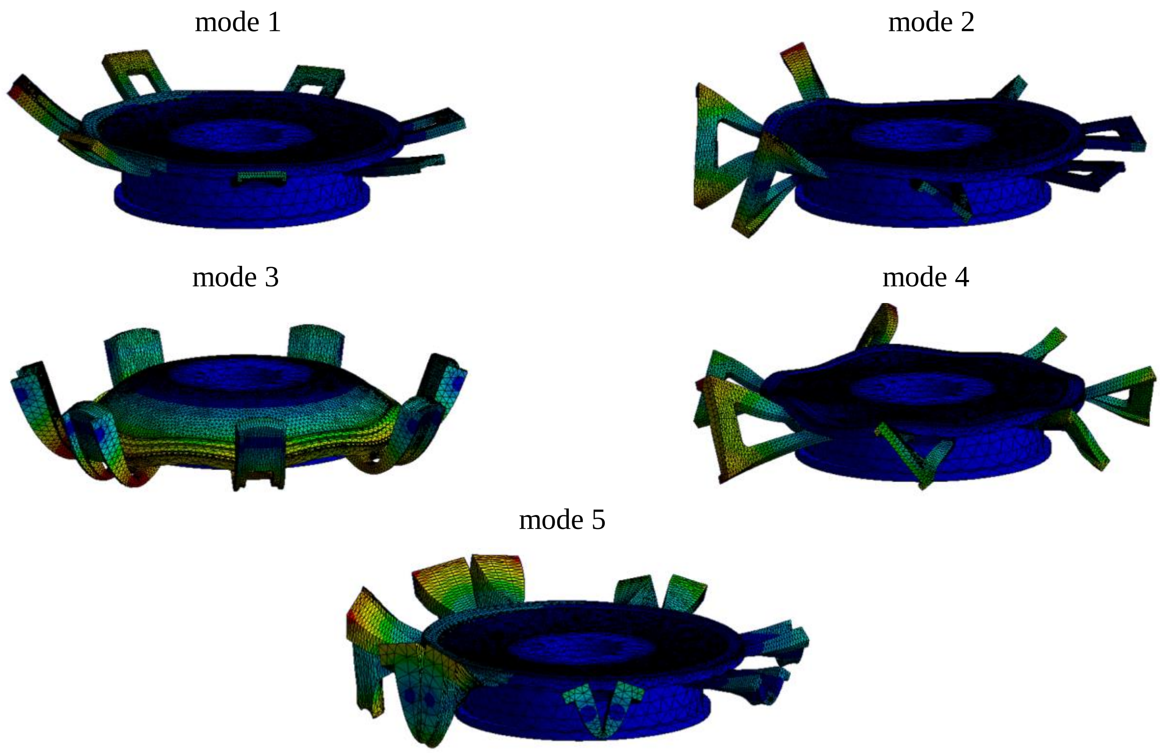

Figure 5: Mode shapes estimated through FEM modal analysis

4.2 Vibrations induced by machining operations

The analysis focuses on the signals measured on the clamps, which exhibited the most interesting features. In particular, only the signals measured by accelerometer T1 are presented and discussed, since the two sensors provided identical results.

Figure 6a shows the tangential acceleration measured at station S1 and characterizing one machine cycle in nominal working conditions (referred to as condition “all”), shown as an example. The vibrations generated by each single machining operation are also shown in Figs. 6b-d. A remarkable influence of the operation M2 on the neighboring station S1 can be observed.

The root mean square values (RMS) of the acceleration signals along all the monitored directions for the nominal operation are reported in Table 3. The station S2 exhibits extremely high vibration levels. Hence, the operation M2 is investigated in the frequency domain to find the sources of vibrations.

Figure 7a shows the Power Spectral Density (PSD) computed for the tangential acceleration signal characterizing the operation M2 in station S2. The dashed lines indicate the spindle frequency and its harmonics, whereas the solid line indicates the tooth passing frequency. The highest amplitudes are associated with the spindle rotation frequency. The contribution of its second harmonic is also significant. The contribution related to the tooth passing frequency is less significant than the spindle one. In addition, remarkable side bands possibly associated with modulation effects are clearly visible. The frequency content does not appear ascribable to excitation of the system resonances. This behavior may be associated with an improper setting of the cutting parameters [4].

A deeper investigation is performed through time-frequency analysis, by computing the Continuous Wavelet Transform (CWT) with a Morlet mother wavelet function [11]. The analysis reveals significant oscillations of the spindle frequency caused by the demanding machining operation. This frequency modulation explains the observed side bands. Oscillations of the spindle frequency were not completely unexpected, since the spindles are driven by a current control loop, but they are not controlled in speed. An optimization of the machining parameters seems advisable for limiting vibrations.

As for the other stations, the PSDs of two acceleration signals (chosen as examples), measured for nominal working conditions in stations S1 and S5, are shown in Fig. 8. The spindle frequency (and its harmonics, dashed line) and the tooth passing frequency (and its harmonics, solid line) of the operations M1, M2 and M5 are also reported with red, green and blue lines, respectively. A non-negligible contribution of the rotary table resonances to the frequency content of the signals can be observed. Even if the measured oscillations of the clamps remain acceptable, a further reduction in vibration levels would be profitable.

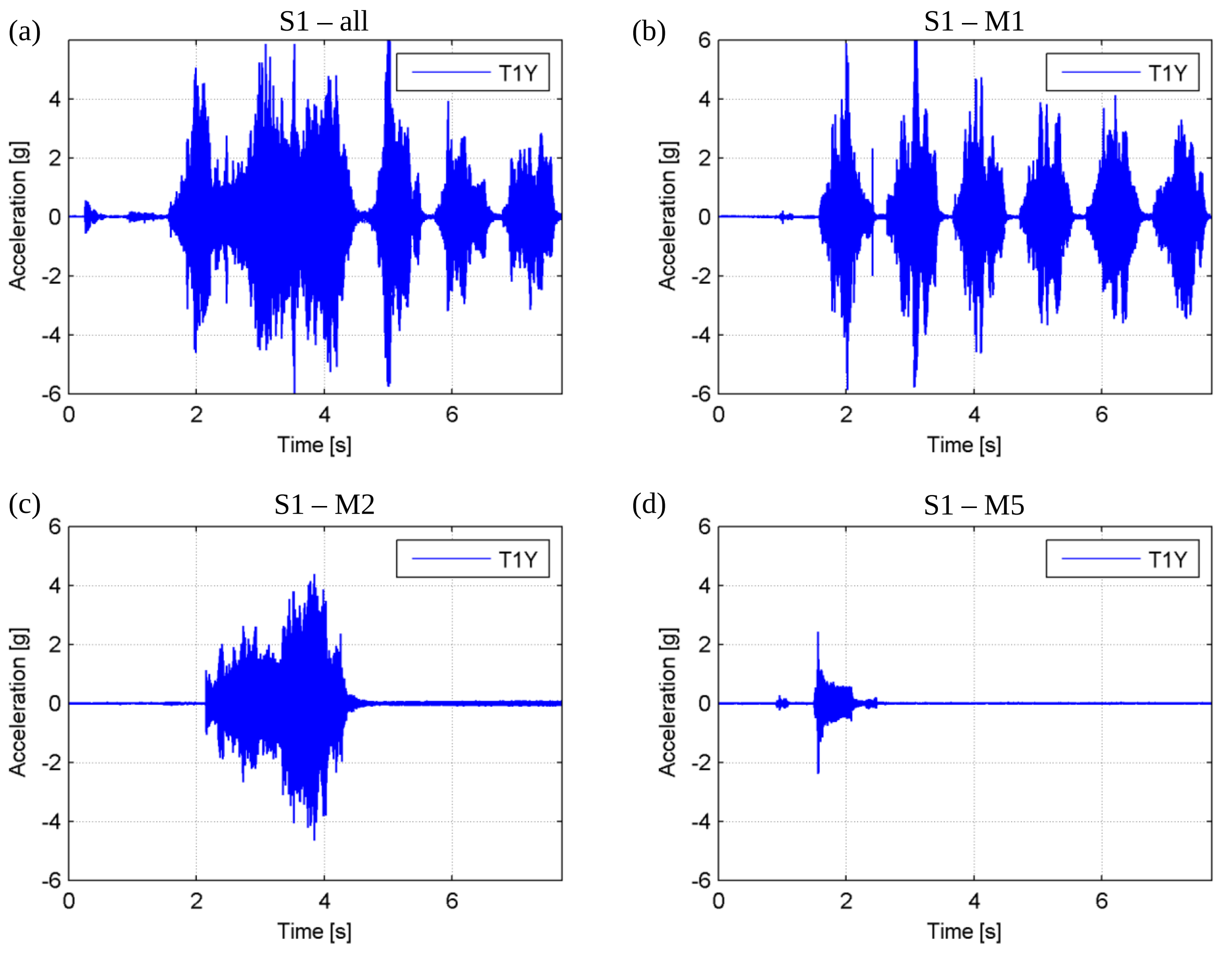

Figure 6: Accelerations signals for station S1 and conditions (a) all; (b) M1; (c) M2; (d) M5

Functional unit	T1 RMS acceleration [g]		
	X	Y	Z
S1	0.69	1.02	0.27
S2	7.77	24.44	24.19
S5	0.85	0.50	0.25

Table 3: Vibrations characterizing the clamps for nominal operation of the machine tool

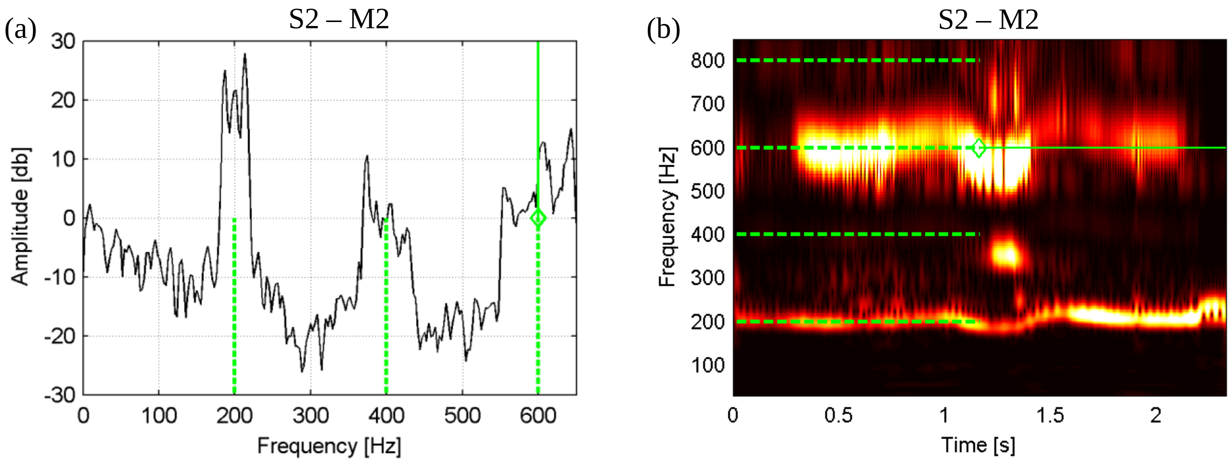

Figure 7: (a) PSD and (b) CWT of tangential acceleration for condition S2 – M2

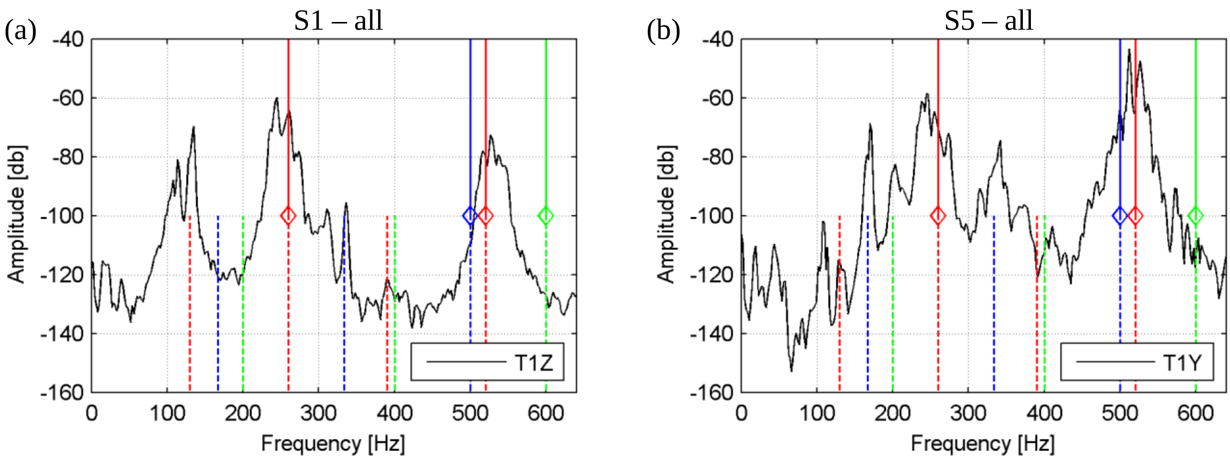

Figure 8: PSD of accelerations measured in (a) S1 and (b) S5, for a nominal machine cycle

Figure 9: Rendered CAD model of the new cantilever support, bottom view

As observed in Section 4.1, the mode shapes of the rotary table mainly involve deformations of the cantilever supports, whose modification is relatively cheap. Hence, a partial redesign of the cantilever supports to moderately increase their stiffness appears an economically convenient solution to reduce the clamp oscillations. Indeed, even if the excitations basically spans the entire spectrum, mode shapes with higher natural frequencies are expected to exhibit smaller vibration amplitudes in terms of displacement.

The new cantilever supports include welded stiffeners (Fig. 9). FEM calculations predict increments of about +140% in the first flexural resonance and +40% in the first torsional resonance. The redesigned supports have been successfully adopted for a new rotary transfer machine featuring nine functional units.

5 Conclusion

The elastodynamic behavior of a rotary transfer machine was experimentally investigated. The test results allowed the identification of two potential elastodynamic issues related, respectively, to severe vibrations induced by the second machining operation and to the excitation of the local modes of the clamp supports. The analysis permitted to define affordable solutions for both issues. In particular, the supports of the clamps were partially redesigned to increase their stiffness. The new supports have been adopted for a new rotary transfer machine featuring nine stations.

The data provided by the experimental campaign are currently being adopted to validate an elastodynamic FEM of the complete machine tool. The model will be used for estimating the system FRFs by means of harmonic analysis. The numerical FRFs will be compared with the experimental ones to assess their reliability.

Finally, in the future developments of the research, the validation of the procedure for cutting force estimation will be concluded, and a prototypal algorithm to monitor the cutting tool wear will be implemented and tested on the investigated rotary transfer machine.

Acknowledgments

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