Vibration response of a machine structure filled with high-damping material

Marco TRONCOSSI[1], Alessandro RIVOLA[1], Nicolò VINCENZI[2], Alberto MARTINI[1]

[1]Dept. of Industrial Engineering of the University of Bologna, Italy
marco.troncossi@unibo.it
[2]Bucci Automations S.p.a., Ravenna, Italy

Abstract

This work focuses on the use of a polymer concrete as a filling material of structural parts to damp vibrations in machine tools. The goal of the overall project is to improve the dynamic behavior of CNC lathe systems by limiting at most the vibrations triggered in operative conditions, in order to guarantee a high productivity of the machine tool while keeping the machining quality of the final products. In particular, this study focuses on the possible design modification of an automatic bar-feeder connected to a CNC lathe. The prototype of a new base filled with a commercial polymer concrete of an automatic bar-feeder was developed and many laboratory tests were performed to analyze the vibration response for different working conditions. This work illustrates the design of the new prototype, the performed experiments, the results of the signal analyses, and some concluding remarks.

1 Introduction

The accuracy of machine tools, is known to be highly hampered by an uncontrolled elastodynamic behavior of the machine components, mainly associated with vibrations which, triggered in a wide bandwidth by several sources [1, 2], can reduce the tool life, degrade the quality of the machined surfaces, and cause inacceptable tolerances of the final products. Limiting their effects is thus mandatory in high performance machines [3]. Focusing on CNC turning machinery, which is the object of the present study, the task is very challenging since the vibrations transmitted to the tool-workpiece area through the structures of both the lathe and its joined bar-feeder are mainly associated with the bars' critical velocities, which are extremely variable in a wide range. Indeed, the latter depend on operative factors that are not constant for all the working conditions of the system, e.g. material and geometry of the bar to be machined, working angular speed, instantaneous free-length of the bar... As a consequence, designing the machine structures in order to avoid resonances in the large broadband of the excitations is basically impossible. Hence, a successful strategy could be levering the structural components' damping to limit the vibration levels in a wide frequency band [4]. To this purpose, polymer concretes, mineral casts, and metal foams can be used as filler of machine tools and automatic machines beds. In particular, polymer concretes are mainly exploited due to their damping properties [5]. Commonly added as filling material of metal structural components, the polymer concrete efficiently absorbs the dynamic load energy and can thus limit the amplitude of vibrations triggered by the machine operations [6].

The case study presented in this work deals with a design variant of the bed of an automatic bar-feeder, filled with a commercial polymer concrete, based on its vibration response as compared to the original version.

2 Materials and methods

2.1 Preliminary work

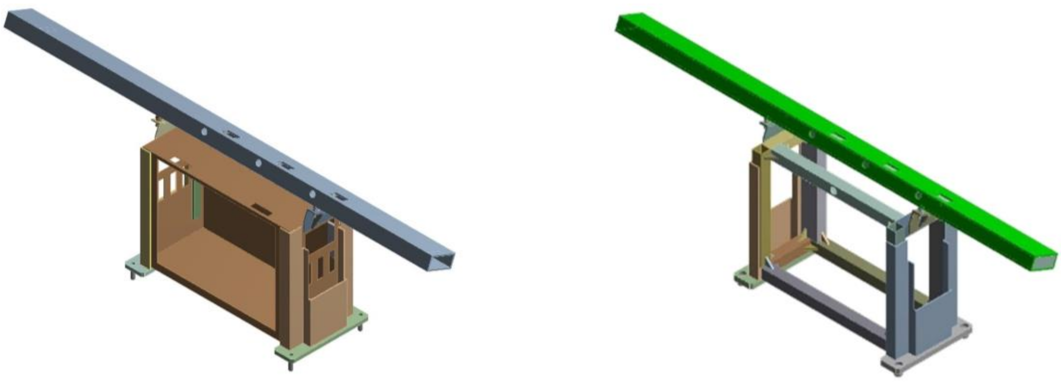
2.1.1 Identification of the material damping properties

A preliminary investigation was performed to experimentally characterize the damping properties of a polymer concrete [7], being rather minimal the technical specifications reported in the datasheet. In particular, tests were performed on beam specimens to obtain quantitative results suitable to (i) evaluate comprehensively the effectiveness of the material to damp vibrations and (ii) set reliable model parameters of the material to be used in numerical elastodynamic analyses.

Comparisons in the Time and Frequency domains were done between the responses to impact excitations of two steel beams, featuring a hollow cross section with and without, respectively, the core filled with the polymer concrete. Results proved very good capabilities of the material to attenuate vibrations. However, the lower natural frequencies of some modes due to the additional mass of the filler could be an issue, even possibly worsening the vibrational response of the system, depending on the specific application (i.e. the structure design and the working conditions). Hence, the overall suitability to fill the structural components of a machine bed with a polymer concrete should be specifically assessed for a certain application by means of proper elastodynamic analyses. This is the reason why a model of the material damping characteristic suitable for numerical simulations was determined. To this purpose, modal analyses of three beams made of the polymer concrete only and featuring different stiffness were carried out and the damping ratios associated with vibration modes in a wide bandwidth (40–4000 Hz) were computed and, properly synthesized, exploited in a further step (cf. Section 2.1.2).

2.1.2 Conceptual design of the new machine bed

The promising results of the above mentioned experimental study suggested to consider the filling of the automatic bar-feeder bed with the polymer concrete as a viable solution to limit the transmission of vibrations arising at the supports of the rotating bar to other parts of the lathe system. To this purpose, some design modifications were proposed and analyzed; in particular, some components of the structure had to be replaced with closed-section beams, which with respect to the open-section parts of the current version are stiffer and suitable to be filled with the polymer concrete. A number of design variants of the structure were proposed (CAD models) and evaluated based on their predicted response (structural and elastodynamic FEM analyses) to harmonic excitations set in the range 50–250Hz [7], which is the bandwidth of major interest emerging from previous field tests outcomes. Finally, from the numerical analyses, a design concept of the new machine bed featuring the main structural component (i.e. the beam which supports the operative units of the bar-feeder) filled with the polymer concrete emerged as a promising solution (Fig. 1).



(a) (b)

Figure 1: (a) original design of the machine bed; (b) new solution (the beam highlighted in green color is intended to be filled with the polymer concrete).

2.2 Experimental campaign

Based on the previous feasibility study (Section 2.1.2), the design of the modified structural components was engineered, the new parts were built, and a prototype of the machine was assembled featuring the new frame with the main structural beam filled with the polymer concrete (Fig. 2). All the remaining functional units were unchanged with respect to the current version. It is worth noting that the commercial impact of a possible mass-production of the new bed variant was considered since this stage. In particular, an increment

(a) (b) (c)

Figure 2: prototype of the new machine bed and close-up of the main structural beam filled with the polymer concrete (not visible in the first picture, due to the presence of the side cover panel).

of 6% ÷ 9% on the overall production costs would be expected (the range resulting from the approximate estimation to account for uncertainties and assumptions).

Experimental tests were then performed on a laboratory lathe-system (i.e. bar-feeder connected to a CNC lathe) to compare in terms of dynamic response the current version and the new prototypal variant of the automatic bar-feeder (being different in the structural frame only). To this purpose, vibration signals were acquired and processed for different operative conditions. The sensor setup, the test protocols, and the acquisition parameters were the same for both the tested machines. In particular:

- triaxial accelerometers were placed in six key-points of the bar-feeder structure (Fig. 3), namely IL and IR on the main structural beam mentioned above and close to the inner bearing of the rotating bar, BU at the level of a bushing placed between the bar-feeder and the lathe, EX on the outer part of the bar-feeder frame close to the lathe, and BL and BR on the frame "legs";
- six kinds of bar were loaded into the system, featuring three different cross sections (two cylindrical with 24mm and 40mm diameter, respectively, and one hexagonal 24mm wide) and two lengths each (1600mm and 2000mm). The lathe spindle was controlled to rotate the bars at different velocities, ranging from 1000 to 4000 rpm, whereas no machining operation was set (in order to keep the bars unaltered for using them in different test trials);
- for each bar and each running velocity, three runs were repeated for the sake of reliability of the measurements that were sampled at 2048Hz for a duration of 20s.

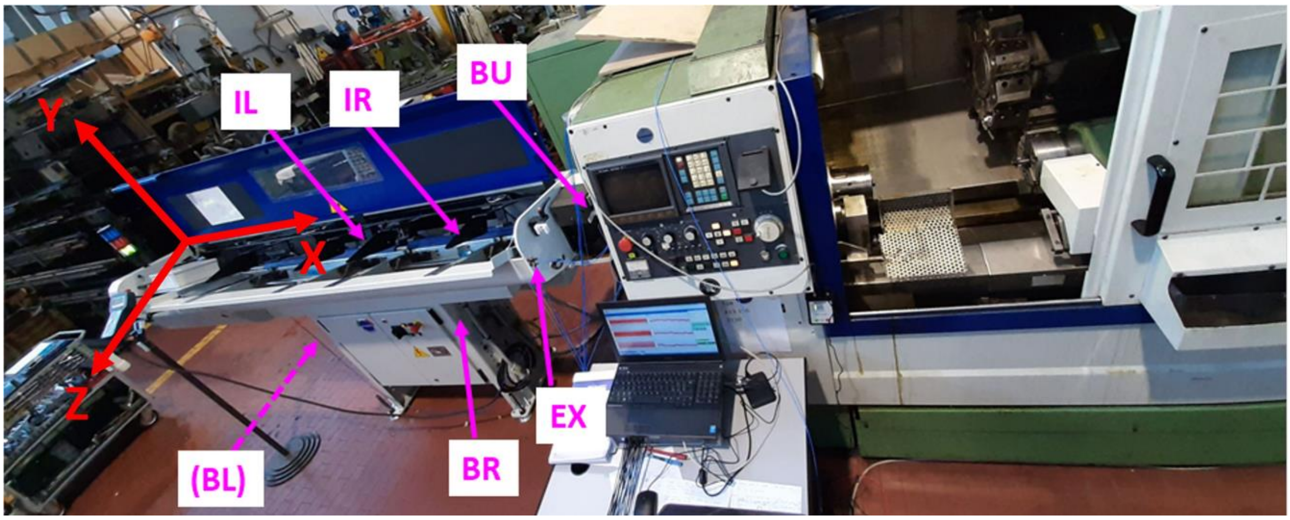


Figure 3: test setup.

3 Results and discussion

After a preliminary statistical analysis, which assured the repeatability of the measurements, the acquired signals were processed in the Time and the Frequency domains. Overall, for both the tested machines, the following preliminary conclusions were retrieved from the analysis of the huge dataset that was processed:

- on average, the circular section bar with 40mm diameter and 2000mm length proved to trigger the most severe vibrations by far;
- with reference to Fig. 3, the signals that prove significant as presenting – on average – greater intensity are those measured by the accelerometers placed in points IR and IL (limited to channel in direction Y), EX (X and Y directions), and BU (Y and Z directions);
- signals measured at points BR and BL always featured very low amplitudes, meaning that mode shapes involving the lower part of the frame (which would dangerously entail high displacements in the upper part, where the functional unit of the bar-feeder is working) are never excited.

Aiming to assess whether the proposed design modification of the bar-feeder frame is worthy of further development for mass-production (with the main structural beam filled with damping material), a global and straightforward evaluation of the vibrational behavior of the two design solutions (i.e. the current version and the new prototype) is needed. Though many processing techniques were implemented for the comparative analysis, the RMS value of the acceleration signals has proven simply to be the most effective metrics to represent the severity of vibrations transmitted through the bar-feeder structures.

Hence, considering also the inferences listed above, the summary of results reported in Table 1 is thought to comprehensively synthesize the overall outcome of the presented investigation. In particular, the relative variations of the acceleration RMS values measured for the new prototype with respect to the current version are reported, limited to the significant channels (see above) for the different angular velocities. Negative (positive) values, highlighted with green (red) color, are associated with a better (worse) dynamic response of the new solution proposed, as the severity of vibrations which are transmitted through the structure – limited to the reported sensor channels' measurements –proves lower (higher). *CH_mean(w)* are the mean values computed, for each channel, as the speed varies and globally represent the vibration response variations in a certain area of the system across all operating speeds (for example, BU_Y and BU_Z describe what happens at the bushing placed between the loader and the lathe). Complementarily, *W_mean(ch)* are the mean values of signals measured at the different channels computed for each speed and are associated with the vibratory response of the bar-feeder as a whole as a function of the working speed. The mean value of the six *CH_mean(w)* values, –28 %, obviously equal to the nine *W_mean(ch)* average, can be thought of as a synthetic indicator of the overall comparative analysis. This is a very high-level way to assess the dynamic performance of the two tested machines; however, at least from a qualitative point of view, it can be stated that the new solution proposed for the design of the bar-feeder is certainly promising and worthy of further development.

	Bar speed [rpm]									
	1000	1500	1800	1900	2000	2500	3000	3500	4000	***CH_mean(w)***
IR_Y	-84%	9%	-53%	-39%	-22%	27%	-29%	-53%	-67%	**-35%**
IL_Y	-15%	10%	-35%	22%	-6%	23%	19%	-17%	-53%	**-6%**
EX_Y	-89%	1%	-32%	-21%	4%	44%	-9%	-45%	-35%	**-20%**
EX_X	-60%	-40%	-64%	-18%	-44%	-81%	-61%	-60%	-70%	**-55%**
BU_Z	-79%	-24%	-40%	-16%	7%	33%	-26%	-68%	-63%	**-31%**
BU_Y	-87%	13%	-56%	-40%	-14%	73%	-11%	-43%	-47%	**-23%**
W_mean(ch)	**-69%**	**-5%**	**-47%**	**-19%**	**-12%**	**20%**	**-19%**	**-48%**	**-56%**	**-28%**

Table 1: vibrational response comparison between the current and the new prototypal variants of the bar-feeder, estimated through the relative difference between the RMS values of acceleration signals measured at different rotational velocities (the most significant sensor channels measurements are reported, cf. Fig. 3).

4 Conclusion

The experimental investigation on the effectiveness a polymer concrete, used as filler of structural components of an automatic bar-feeder serving a CNC lathe, to damp vibrations is presented in this work. Based on previous studies, the prototype of a new machine bed was developed and tested. The comparative analysis performed on vibration signals acquired on both the current version and the new design solution highlights the suitability of the damping material to significantly attenuate the vibrations triggered by the high-speed rotating bars and transmitted through the system structure. A preliminary cost analysis was studied to assess the economic impact of the new design implementation for a possible mass-production of the machine. The proposed design variant seems a viable and promising solution also from this standpoint of view, hence further work is in progress with the purpose to engineer the new design.

References

[1] Altintas Y. Manufacturing automation: metal cutting mechanics, machine tool vibrations, and CNC design. Cambridge: Cambridge University Press, 2012.

[2] Gegg BC, Suh CS and Luo ACJ. *Machine tool vibrations and cutting dynamics*. New York: Springer Science & Business Media, 2011.

[3] Munoa J, Beudaert X, Dombovari Z, et al. “Chatter suppression techniques in metal cutting”, *CIRP Annals*, 2016, **65**:785–808.

[4] Mohring HC, Brecher C, Abele E, et al. “Materials in machine tool structures”, *CIRP Annals*, 2015, **64**:725–748.

[5] Bedi R, Chandra R and Singh SP. “Reviewing some properties of polymer concrete”, *Indian Concr J*, 2013, **2013**:1–68.

[6] Bruni C, Forcellese A, Gabrielli F, et al. “Hard turning of an alloy steel on a machine tool with a polymer concrete bed”, *J Mater Process Technol*, 2008, **202**:493–499.

[7] Troncossi M., Canella G., Vincenzi N. “Identification of polymer concrete damping properties”, *Proc IMechE Part C: J Mechanical Engineering Science*, 2022, **236**(21):10657-10666