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Experimental analysis of the dynamics of an impact damped boring bar

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Abstract: Machining of deep bores requires the use of slender boring bars that tend to vibrate when excited by the cutting process. Since vibrations deteriorate machined surface quality, they must be damped. Impact dampers could be one solution. They involve a free mass colliding with the vibrating walls of the boring bar. The ensuing momentum exchange transfers energy from the bar to the free mass thus minimizing the bar's vibratory response. To fully characterize the performance of such a system, this paper presents the results of systematic parametric experimental analysis based on forced vibration tests. We find that reduction in the vibratory response of the boring bar strongly and nonlinearly depends on the gap between the free mass and the wall of the boring bar, the excitation frequency and force level, the ratio of free mass and the modal mass of the boring bar, and the overhang of the bar. Our experimental analysis could guide design improvements and stable damped cutting.

Keywords: Impact damper, Boring bar, Dynamics, Vibrations, Stability

1. Introduction

Machining of deep bores requires the use of slender boring bars that tend to vibrate when excited by the cutting process. Since vibrations deteriorate machined surface quality, they must be damped. Damping can be achieved by dynamically stiffening the boring bar with a material change [1], or by integrating passively tuned mass dampers with the boring bar [2, 3], or by using impact dampers [4, 5], or by active control that requires a sensor and actuator to be integrated within the boring bar [6]. Of the many possible solutions, impact dampers hold much promise due to their simple working principle and ease of construction. As such, this paper will focus on characterizing the dynamics of an impact damped boring bar to evaluate its ability to mitigate the vibrations of slender boring bars.

Impact dampers involve a free mass that collides with the primary system whose vibrations are to be damped. The ensuing momentum exchange transfers energy from the primary system to the free mass thus minimizing the primary system's vibratory response. Despite their potential, and their use across other engineering domains and applications, there are very few reports that discuss the use of impact dampers to damp the vibrations of boring bars [4, 5, 7, 8]. Amongst the most seminal of these reports, is the one by Thomas et al. [4]. Though that report included a model validated by experiments, their design was one in which an impact damper was supported by a spring – making this a hybrid damper that was a combination of a vibration absorber and an impact damper. Another significant report was by Ema and Marui [5]. Though they presented experimental investigations, they had a ring impact damper placed outside the boring bar near its free and cutting end, and since this reduced the effective working length of the boring bar, their solution too is not ideal. Other related work reported by the authors' research group [7, 8] was limited to model-based analysis and was not supported by experiments.

Since classical studies on the behavior of impact dampers [9], albeit for other applications, have shown that the performance of impact dampers is a function of: the gap between the free mass and the wall of the vibrating system, the excitation amplitude, the excitation frequency, the ratio of free mass and the modal mass of the primary system, and the flexibility of the primary system, and since there are no reports in the literature with regards to impact damped boring bars that report such systematic experimental characterization, the main aim and the new technical contribution of this paper is to create such a report by characterizing the performance of an impact-damped boring bar under the vagaries of parameters that influence its performance. Recommendations from prior models [7 - 9] guide our experimental plan.

The remainder of the paper is structured as follows. We first discuss in Section 2 a possible design of an impact damped boring bar. Section 3 then describes the experimental setup and plan to test it. We limit our experiments to exciting the boring bar with only forced vibrations. The plan includes experiments to test the bar with changing gaps, overhangs, changing frequencies and amplitudes of excitation, and changing mass ratios. Section 4 discusses the main results. The main conclusions follow.

2. Design concept of an impact damped boring bar

Our design for an impact damped boring bar is shown in Fig. 1. The diameter of the boring bar is 25 mm, and its overhang is adjustable to make the length/diameter (*L/D*) ratio 8 or 10. The boring bar was made of steel with a ρ of ~7850 kgm-3 and an E of ~210 GPa. The cutting insert is mounted on a cartridge that is in turn mounted on the boring bar with an end plug. The other end of the boring bar is to be clamped. A free spherical mass is placed inside a cavity within the boring bar. The cavity is made 40 mm from the free end. Since cutting vibrations in the radial direction govern the stability of the boring process [10], the free mass is only allowed to move radially, i.e., in the Y-direction. The gap between the free mass and the walls of the boring bar is made adjustable using screws as shown. The maximum possible gap with this design is 1.5 mm on either side. The free mass has a diameter of 15 mm, and the slot it is housed in has dimensions of 15.1 mm (X-direction) x 18 mm (Y-direction). The slot is open from the top to visualize what the ball does during experiments. Those visualizations are not reported herein. We adjust the mass ratio by changing the material of the ball. We used steel and carbide balls in this study.

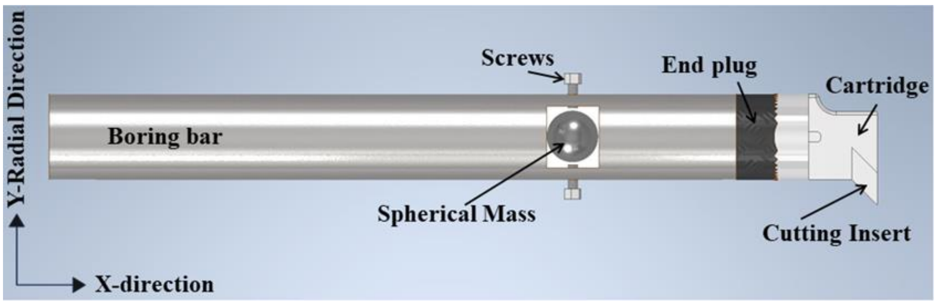

Fig. 1. Design concept of an impact damped boring bar.

3. Experimental setup and plan

The setup to excite the boring bar in its radial direction using a modal shaker (Bruel & Kjaer, 2732) that provides controlled forced excitation is shown in Fig. 2(a). The boring bar is rigidly clamped/held in a compression holder, which in turn is mounted on a rigid base. Signal is generated with a signal generator (not shown in Fig. 2), and that signal is amplified and supplied to the shaker. A stinger is connected to cartridge and the force supplied is measured using a load cell (Bruel & Kjaer, 8230-001). We monitor the response using an accelerometer (Dytran, 3035B1G) and a laser displacement sensor (Micro epsilon, ILD1420-10). All data is acquired (using NI 9234 and NI 9174) at rates of at least 4 kHz using MATLAB's signal processing toolbox.

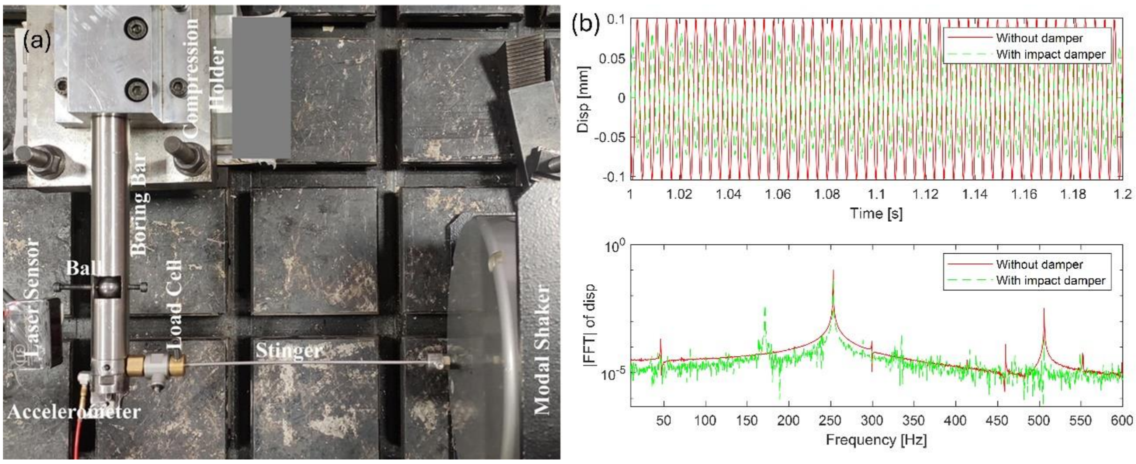

Fig. 2 (a) Experimental setup, (b) Sample response of the boring bar with and without the impact damper.

Since it is important to damp the response of the boring bar only around its dominant natural frequencies, at first, experiments were conducted to identify the dominant mode. This was done by sweeping the input signal from 20 Hz to 400 Hz. For the two overhangs of interest, the Fourier spectra of the response showed the first and dominant mode to be ~253 Hz for the *L/D* of 10, and to be ~271 Hz for the *L/D* of 8. Single frequency forced vibration excitation was then planned only at and in the neighborhood of these modes, i.e., at two frequencies just below and higher than the mode – making for a total of five different excitation frequencies. Characterizing the forced response at frequencies higher and/or lower than the natural frequency is not of interest, and hence that is not done. For every excitation frequency, we experimented by exciting the bar with forces of ~4 N and ~7 N, respectively. Since we excited the bar in the neighborhood of the natural frequency, the forces were kept low. And, for every frequency and amplitude combination, we had five different levels of gaps. These experiments were repeated by changing the steel ball with the carbide one. For both overhangs, we performed 200+ experiments. Our experimental plan is more comprehensive and exhaustive than any other such experiments reported in the literature.

A representative example of the response of the boring bar integrated with an impact damper is shown in Fig. 2(b) and is compared with the response of the boring bar without the damper. These responses are obtained with the laser sensor. For the case shown, the response with the damper is lower than without. The peak in the spectrum of the response with the damper is lower than the case without the damper. This peak occurs at the excitation frequency. The spectrum for the case with the damper contains many more peaks that potentially correspond to impacts. Since results for all 200+ experiments cannot be shown with this level of fidelity, we instead present only summary results by evaluating the percentage change in the root mean square (RMS) value of the impact damped boring bar with reference to the RMS value of the boring bar with no damper.

4. Main results

A summary of the % change in the RMS response of the impact damped boring bars is shown in Fig. 3 for the case of the *L/D* being 10, and in Fig. 4 for the case of the *L/D* being 8. Though experiments were conducted at discrete parameters, for visualization purposes, we interpolate and show 3D surface plots. The color maps in each of the figures represent the magnitude of the % change. A positive change suggests a reduction in the RMS value with using an impact damped bar over the case of a standard boring bar with no damper, and a negative change suggests a degradation in the response, i.e., instead of absorbing vibrations, the impact damper tends to increase the response over the baseline case of there being no damper in the boring bar. The frequency ratio, *r*, in Figs. 3 and 4 corresponds to the ratio of the forcing frequency to the natural frequency of the system.

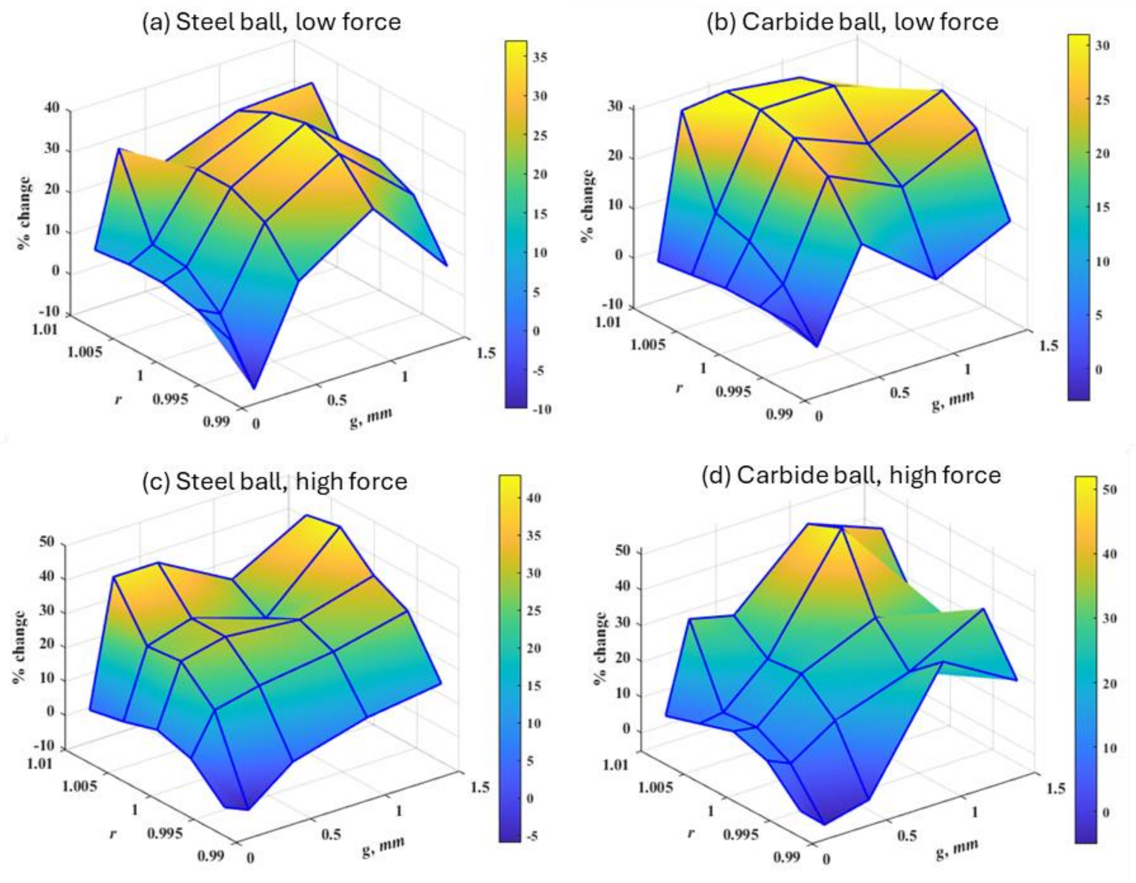

Fig. 3 For a L/D ratio of 10, surface plots of % change in amplitude of impact damped boring bar with changes in the gap (g) and frequency ratio (r) when (a) using a steel ball and the force level being low, (b) when using a carbide ball and the force level being low, (c) using a steel ball and the force level being high, and (b) when using a carbide ball and the force level being high.

As is evident from Fig. 3 for the case of the *L/D* being 10, the response is a strong and nonlinear function of the gap, the frequency ratio, the mass ratio, and the forcing amplitude. Though there appears to be no obvious trend, the damped boring bar tends to perform better when the gaps and frequency ratio are high, and the damped boring bar fares poorly when the gap is low. When the gaps are low, the ball may tend to stick to the walls and not be able to move back and forth easily to dissipate energy from the vibrating bar. Whereas, when the gaps are relatively higher, the ball likely undergoes two symmetric impacts per cycle, which is what the best case for dissipation of energy is [9], and as such is able to damp response. It is also interesting to observe that as the force levels increase from the cases in Fig. 3(a - b) to the cases in Fig. 3(c - d), there is a slight improvement in the maximum reduction in response – changing from 36% for the case of the gap being 1 mm with the steel ball for when the force is low and *r* being 1, to a 48% reduction for when the gap is 1 mm with the carbide ball and the force is higher and *r* being 1.01. The influence of the change in mass ratio, i.e., a change of the ball from steel to carbide, is less obvious.

For the case of the *L/D* being 8, results in Fig. 4 are limited to only low force levels. The ball was observed to jump out of the cavity when the force level was increased. This is likely due to the stiffening of the bar causing stronger interactions with the ball. Stronger interactions are also evident from the response in this case being damped up to 68% for the case of the gap being ~0.5 mm with the carbide ball. In this case, too, the response is strongly and nonlinearly dependent on the gap, the forcing frequency, and the mass ratio. Though there is no general trend, the change in the mass ratio appears to play a strong role.

Also interestingly, for the *L/D* being 8, there are several combinations of parameters for which the response with the damper is worse than the bar without a damper – as evident from the negative % change. This is unlike the case of the *L/D* being 10, which has fewer cases with a negative change. These results also suggest that the performance of the impact damped boring bar is also a strong function of the overhang, and that there can be combinations of parameters that may worsen response rather than damp it, and as such care must be exercised in finding the right levels of gaps and mass ratios, for every overhang, and excitation frequency and amplitude.

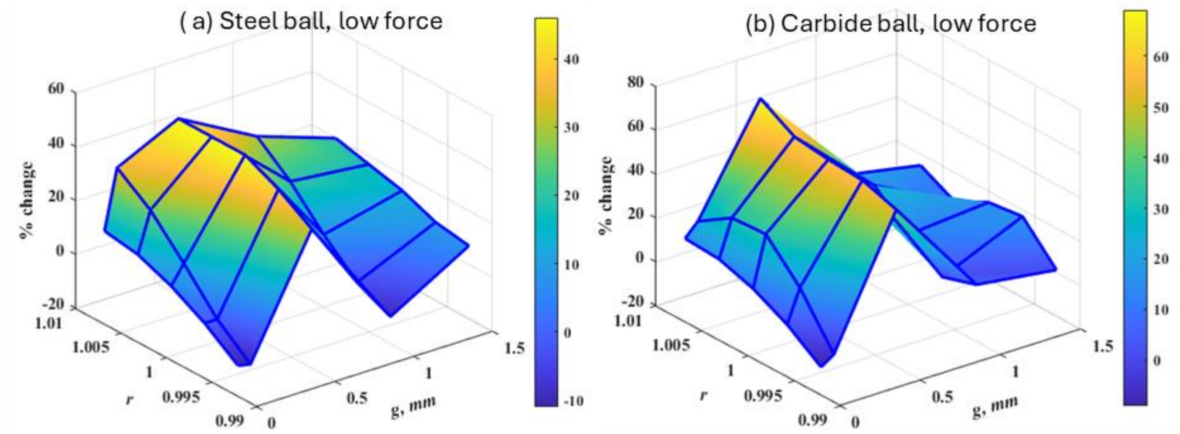

Fig. 4 For a L/D ratio of 8, surface plots of % change in amplitude of impact damped boring bar with changes in the gap (g) and frequency ratio (r) when (a) using a steel ball and the force level being low, (b) when using a carbide ball and the force level being low.

5. Conclusions and outlook

This paper presented results to experimentally characterize the damping potential and performance of impact damped boring bars. Based on a comprehensive and exhaustive experimental plan of 200+ forced vibration experiments, we observed that the impact damper appears to have the potential to reduce the vibrational amplitudes of the boring bar. However, reduction in the vibratory response of the boring bar was observed to be strongly and nonlinearly dependent on the clearance/gap between the free mass and the wall of the boring bar, the excitation frequency and force level, the mass ratio, and the overhang. We also observed cases in which the vibratory response degrades due to the impact damper adding energy to the system instead of taking some away from it. Though the solution holds promise, realizing a working design that improves damping and stabilizes cutting is non-trivial. Our analysis could guide such designs which form part of the future scope of work.

Acknowledgements

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