New vision-based evidence of the nature of vibro-impacts in an impact-damped boring bar

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Abstract:
Impact-damped boring bars transfer momentum from the vibrating bar to a free mass colliding with it to damp the bar's response. Prior model-based research has suggested that two symmetric impacts of the free mass are necessary for damped stable response. However, there exists no direct experimental evidence of the behaviour of the free mass that may or not result in damped stable response. To address this, we present new vision-based experimental evidence of the vibro-impacts between the free mass and the walls of the boring bar. We process images to track motion of the free mass and the bar to reveal four families of solutions. These include cases with two stable and symmetric impacts, cases with multiple asymmetric impacts, cases with no oscillation of the free mass, and cases with transitioning of impacts. Even though the general response was irregular, impact-damped boring bars were found capable of reducing vibrations.

Keywords: Impact damper, Vibro-impacts, Vision-based tracking

1. Introduction

Machining of deep bores requires the use of slender cantilevered tools. Since such tools are flexible, cutting with them often results in chatter vibrations. Since chatter can damage elements of the machine tool system, these tools are usually dynamically stiffened and/or damped. Dynamic stiffening by changing material results in marginal improvements [1]. Hence the preferred method has been to integrate tuned absorbers within such tools [2]. The problem with absorbers is that they need to be re-tuned for different overhangs. Though self-tuning using novel elastomers [3] and automating tuning using active means is possible [4], such solutions can be complex. An alternative that is purported to be less sensitive to changes in overhangs and that forms the focus of this paper is to use impact dampers.

Impact dampers usually consist of an impacting mass like a solid rigid sphere that collides with the primary vibrating system whose response is to be damped. The momentum transfer during impacts, damps the primary system's response. Though such dampers have potential, their performance has been reported to depend on- the gap between the free mass and the end stops, on the forced excitation levels, on the number of effective impacts, and on the ratio of the free mass to the modal mass of the bar [5, 6].

Despite optimal performance of impact dampers being dependent on different parameters, due to their simple working principle and their purported robustness to changes, such solutions have found use in slender cantilevered boring bars. Seminal research by Thomas et al. [7] showed that impact dampers could increase stable material removal rates by as much as 100% in comparison to solid boring bars. However, in their design, the impacting mass was not free but supported in soft springs. A similar design was analyzed in [8]. In these two designs, the impacting mass could also behave as a potentially detuned vibration absorber making it difficult to isolate the influence of the impact damper from that of an absorber. Furthermore, in the analysis reported on in [7] the gap between the free mass and the vibrating boring bar was to be tuned within accuracies of tens of μm. Such restrictions are prohibitive and difficult to realize in practice. In other related research [9, 10], the impacting mass was placed outside of the boring bar. Since that design reduces the effective slenderness ratio, those findings are not of consequence for damping slender cantilevered boring bars.

Prior model-based research [7, 8, 10, 11] has suggested that two symmetric impacts of the free mass are necessary for damped stable response. Though such research helps understand the general behaviour of impact-damped boring bars, there are no reports that offer direct experimental evidence of the behaviour of the free mass that results in stable and/or unstable solutions. Such characterization is necessary to fully understand the motion of impact-damped boring bars which could in turn inform better designs. Hence, the main aim and new technical contribution of this paper is to track motion of the free mass during forced vibration excitation of the boring bar to offer new insights into the dynamics and stability of impact-damped boring bars. To track motion of the free mass, we leverage our prior experience with vision-based vibration measurements [12].

Our motion tracking is like tracking of vibro-impacts of a free mass within a cantilevered plate [11]. However, since the work in [11] was concerned with vibro-impacts for a base-excited system, and since response of that system is fundamentally different than a boring bar excited by the cutting process at the free end, the results and observations reported on in [11] are not of direct relevance to this paper.

Investigations in this paper are limited to one free rigid spherical mass impacting a boring bar. Since chatter in boring is governed by the flexibility in the radial direction [13], we further limit our analysis to a boring bar in which the ball is only allowed radial motion. Though cutting process-based excitation can result in radial and vertical motion of the ball, and though vertical motion can also influence performance [7], we focus herein only on radial motion.

We experimentally characterize how the vibro-impacts are dependent on gaps and forced excitation levels. Section 2 outlines the bar's design and the experimental setup and plan which is limited to forced vibration experiments that help uncover the general motion of the bar and ball to controlled excitation. Section 3 discusses how we track bar and ball motion using vision techniques. Section 4 benchmarks bar motion registered from vision with motion measured using a laser displacement sensor. Section 5 discusses four representative results to help reveal the general nature of vibro-impacts in an impact-damped boring bar.

2. Bar design, experimental setup and plan

A schematic of the boring bar with a cavity that houses a free mass is shown in Fig. 1. The boring bar has a length $L = 250$ mm. The bar's diameter D was 25 mm such that the L/D ratio becomes 10. The boring bar was clamped in a specially designed compression holder. The bar has an open slot of width $W = 15.1$ mm and an adjustable height H which houses a ball with diameter $d = 15$ mm. W is only slightly greater than d to allow only radial motion of the ball. H was varied by placing grub screws on either end. The face of these screws inside the cavity served as end stops. This allowed for easy tuning for different gaps. The gaps, $g/2$ are shown to be symmetric in the schematic in Fig. 1. Since impact dampers work best when the impacting mass is as near the cutting end [7], the cavity was made as close to the cutting edge as possible. Placing the cavity near the cutting end is precluded by the cartridge and its mounting. The cavity is open at the top to allow for vision-based ball tracking. One impacting ball that is made of steel is used for the experiments. The bar was made of steel with a ρ of ~7850 kgm^{-3} and an E of ~210 GPa.

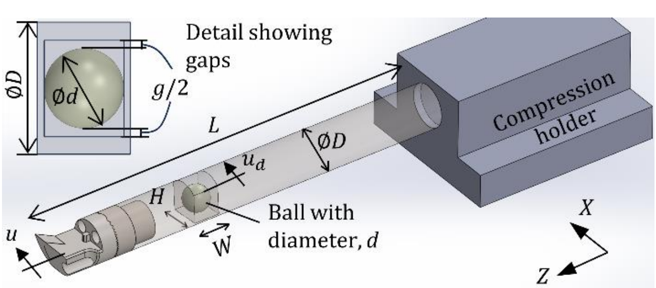

Fig. 1 Schematic representation of an impact-damped boring bar.

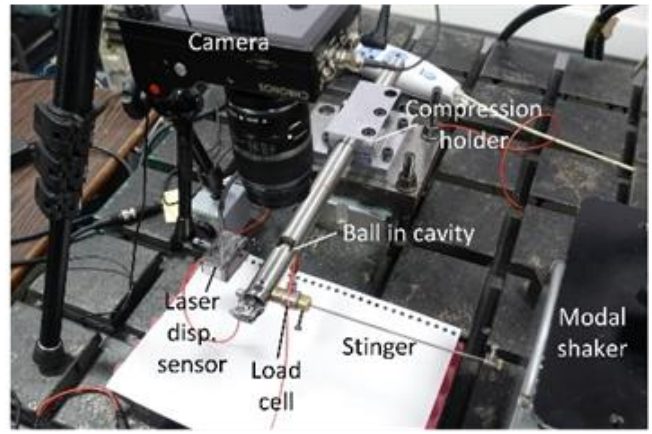

Fig. 2 Setup to measure forced vibration response.

The experimental setup to measure the forced vibration response of the bar with and without the ball is shown in Fig. 2. The setup includes a modal shaker (make B&K, model 4824) exciting the bar through a stinger and load cell (make B&K, model 8230-001). A function generator (not shown in Fig. 2) supplied signals to the shaker's amplifier (make B&K, model 2732). The vibratory response of the bar was measured at rates of 4 kHz using a laser displacement sensor (make μ-EPSILON, model OptoNCDT 1420). We also used a high-speed camera (make Chronos 2.1) with a standard 18 – 55 mm lens to record motion of the vibrating bar and the moving ball. Video was recorded at rates of up to 2996 frames per second with resolutions of 1280 × 512 pixels. A DC light source was used to properly illuminate the region of interest. Forced response was recorded for 20+ seconds and video for ~11 seconds. Synchronization was done during post-processing.

Experiments without the ball were first conducted to identify the first natural frequency, f_n of the bar with a slot. The mode was observed to be at ~253 Hz. Introduction of the free mass in the slot did not significantly change the mode. Since the first mode is the most flexible, only this mode was investigated further. Since f_n is known, forced vibration experiments were conducted in the neighborhood of the natural frequency to establish the baseline response of the bar without the ball. Forced vibrations experiments were conducted at two different force levels. The two force levels were ~4 N and ~7 N, respectively. Though these appear to be low, these force levels are typical of the oscillatory component of the cutting force. Moreover, excitation at lower force levels was observed to result in insufficient excitation of the bar for it to transfer momentum to the ball. And, since we excited the bar in the neighborhood of its natural frequency, excitation with higher force levels was observed to saturate the amplifier. For each force level, experiments were conducted at two levels of gaps: ~0.2 and ~1.6 mm. Table 1 summarizes the experimental plan.

Table 1 Forced vibration experimental plan

			Gap [mm]	
No ball	Force level	Low	~0.2	~1.6
		High		
Steel ball	Force level	Low	~0.2	~1.6
		High		

3. Method to track motion of the impacting mass

To investigate what the impacting mass does, we track its motion from recorded video. To do so, we first crop all frames to retain only the region of interest that includes the end stops and the ball. Then, we apply an Otsu segmentation [14] on every frame to separate pixels into two classes, namely what we are interested in and background noise. We then apply a Canny edge detector [15] in every frame to get a one-pixel-thick edge. This edge is then dilated, and its centroid is tracked for motion in the direction of interest. Representative images showing what the camera sees and the algorithm processes are shown in Fig. 3. We also use the vision-based method to track velocities of the bar and the ball to deduce if their relative velocities are in the same or opposite directions. We also use the vision-scheme to identify impacts. We utilize the fact that whenever there is a collision (impact) between two objects their relative velocity will become zero. Hence, time instants at which the relative velocity crosses zero are tracked and stored as instants of impacts. This allows us to track cases of (a)symmetric and multiple impacts.

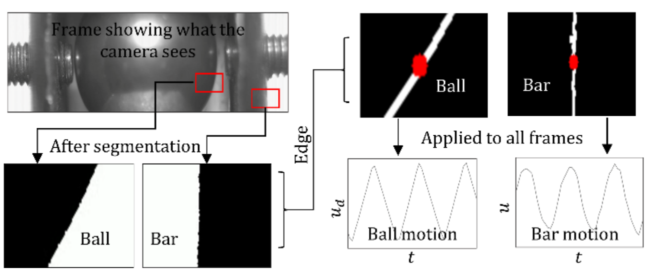

Fig 3 Overview of the vision-based method to track ball motion.

4. Benchmarking motion registered from vision

Since we use vision methods to track the motion of the ball, and since there is no direct way to benchmark that motion, we instead benchmark motion of the bar that is extracted with vision and compare it with motion estimated using the laser displacement sensor. For vision, we track the region shown in Fig. 3, and the laser sensor tracks the same wall, but from the outside. As a representative case to demonstrate that vision-based motion registration is the same as that measured using the laser sensor, we shown in Fig. 4 response for the case of a steel ball excited at 255 Hz at a low force level and for when the gap is ~1.6 mm. And, as is evident from Fig. 4, motion registration from vision can be considered to be validated and benchmarked.

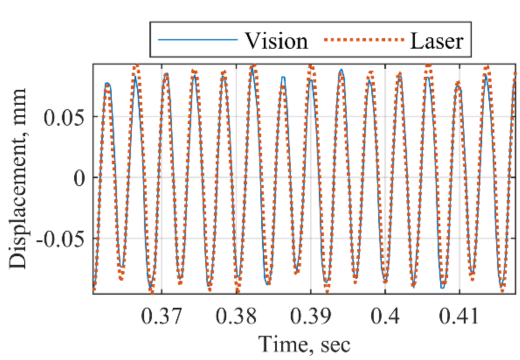

Fig. 4 Representative comparison of motion registered from vision and that measured from the laser sensor.

5. Vibro-impacts of the free mass

This section presents results for cases that reveal the interesting nature of vibro-impacts in an impact-damped boring bar. We show response for four cases that include: (i) a case of symmetric two-impacts per cycle; (ii) a case showing how the response transitions from symmetric two impacts per cycle to multiple asymmetric impacts per cycle; (iii) a case of multiple asymmetric impacts per cycle transitioning to chaotic response; and finally (iv) a case showing how response transitions from asymmetric impacts to no impacts. In every case, we also discuss the percentage improvement of the damping for a bar with an impact damper in comparison to a boring bar without an impact damper. These differences are characterized in terms of the percentage in RMS response for every case.

5.1 Case of two symmetric impacts per cycle

For the case of an excitation with the high force level at 255 Hz, and for when the gap was ~1.6 mm, the response is shown in Fig. 5. Fig. 5(a) shows the overall response and Fig. 5(b) shows only a few cycles. We show five things on each of these figures. These include the displacement of the bar with the free mass inside it, the motion of the ball (free mass), the relative displacement and velocities, and the gap/2 – which serves as an indicator to visualize impact. Every time the relative displacement exceeds half the gap, it suggests an impact event. The same can be confirmed by a velocity reversal, i.e., a zero crossing of the relative velocity at the same time instant of an impact event.

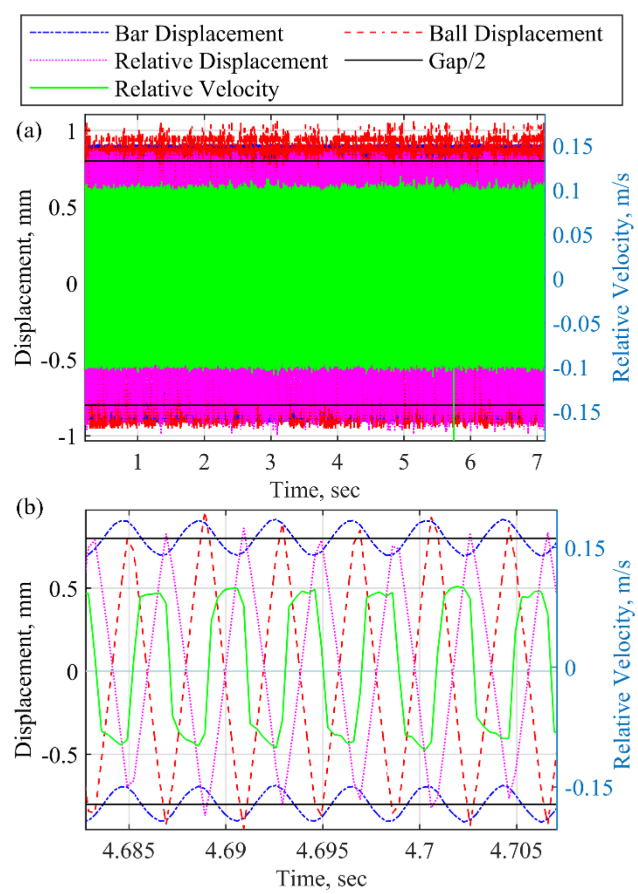

Fig. 5 Case of symmetric two impacts per cycle. (a) Full response, (b) response for few cycles.

As is evident from Fig. 5(a), the response appears to be consistent across the length of the measurement. And as is evident from Fig. 5(b), this is a case of two symmetric impacts per cycle. For this case, there is a ~41% reduction in the RMS response over the case of the response of the bar without the ball. For brevity, response of the bar without the ball at the same forcing frequency and force level is not shown herein.

It should also be noted that the peak-to-peak displacement of the bar is ~0.2 mm. This displacement of the wall of the bar about its mean position is shown in this manner to aid visualization about the end stops that correspond to the gap/2.

5.2 Case of two symmetric impacts transitioning to multiple asymmetric impacts

For the case of excitation at the low force level at 255 Hz, and for when the gap was 0.2 mm, the response is shown in Fig. 6. The full response is shown in Fig. 6(a), and Figs. 6(b) and (c) shows the response of a few cycles at different times.

As is evident from Fig. 6(a) and is confirmed from Figs. 6(b-c), the response is not consistent all through. For example, at time instants of ~1.8 seconds – see Fig. 6(b), the response follows the symmetric two impacts per cycle behavior. However, at time instants of ~2.8 seconds – see Fig. 6(c), the response appears to have transitioned to the case of there being multiple asymmetric impacts of the free mass with the walls of the boring bar. The free mass appears to contact one wall more times than the other. And, though this is not the case of the preferred symmetric two impacts per cycle, and even though the response is not steady state, there is yet a ~29% reduction in the response of the impact damped boring bar as opposed to a bar without a free mass. Since the gap and force levels are lower in this case than the case discussed in Section 5.1, to make comparisons more meaningful, response with the gap being low and force high is discussed in the next section, i.e., in Section 5.3.

The peak-to-peak displacement of the bar in this case is ~0.1 mm. This is lower than the case discussed in Section 5.1 because of the force being lower. In this case too, to aid visualization, the response of the bar is overlaid over the end stops corresponding to 0.1 mm that corresponds to a value of the gap/2.

5.3 Case of multiple asymmetric impacts transitioning to c haotic response

The full response for excitation at 255 Hz, and for when the force level was high, but the gap was low and maintained at ~0.2 mm is shown in Fig. 7(a). And response at two different time instants within the full response are shown in Fig. 7(b) and Fig. 7(c), respectively.

As is evident from Fig. 7(a), this too is a case of the response not being consistent across the length of the measurement. The response appears to transition from the case of multiple asymmetric impacts – see Fig. 7(b) to the case of irregular and chaotic response with no clear trend of there being (a)symmetric impacts – see Fig. 7(c). Even though this is a case of asymmetric and irregular response, there is still a ~40% reduction of the response of this impact-damped boring bar in comparison to a bar without a damper. This is contrary to expectations and well-understood working principles of impact-damped boring bars.

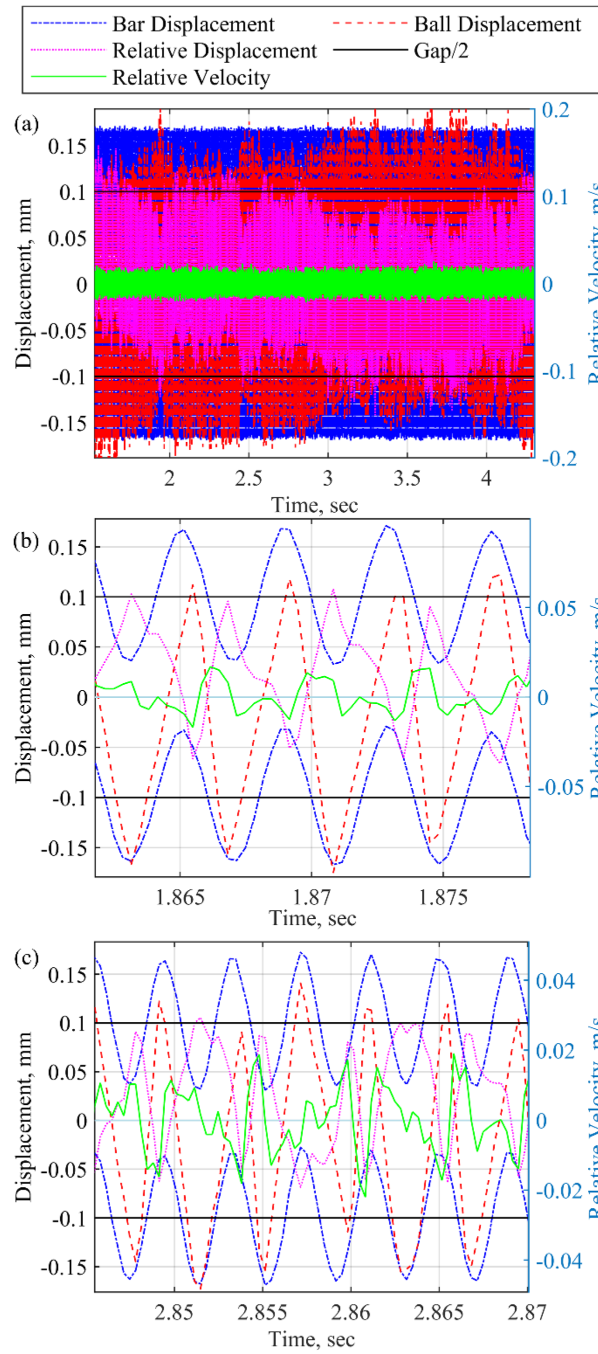

Fig. 6 Case of two symmetric impacts per cycle transitioning into multiple asymmetric impacts. (a) Full response, (b) symmetric response for few cycles, (c) asymmetric response for few cycles.

Since the force level in this case is like the case discussed in Section 5.1, the peak-to-peak displacement of the bar too is the same and of the order of ~0.2 mm. Again, for visualization, this response is overlaid on the end stops corresponding to a value of 0.1 mm, i.e., for gap/2.

5.4 Case of multiple asymmetric impacts transitioning to n o impacts

The final case discussed herein corresponds to the case with excitation at a low force level at 255 Hz, with the gap being set to ~1.6 mm. The full response for this case is shown in Fig. 8(a), and Figs. 8(b) and (c) shows only a few cycles of response at different time instants.

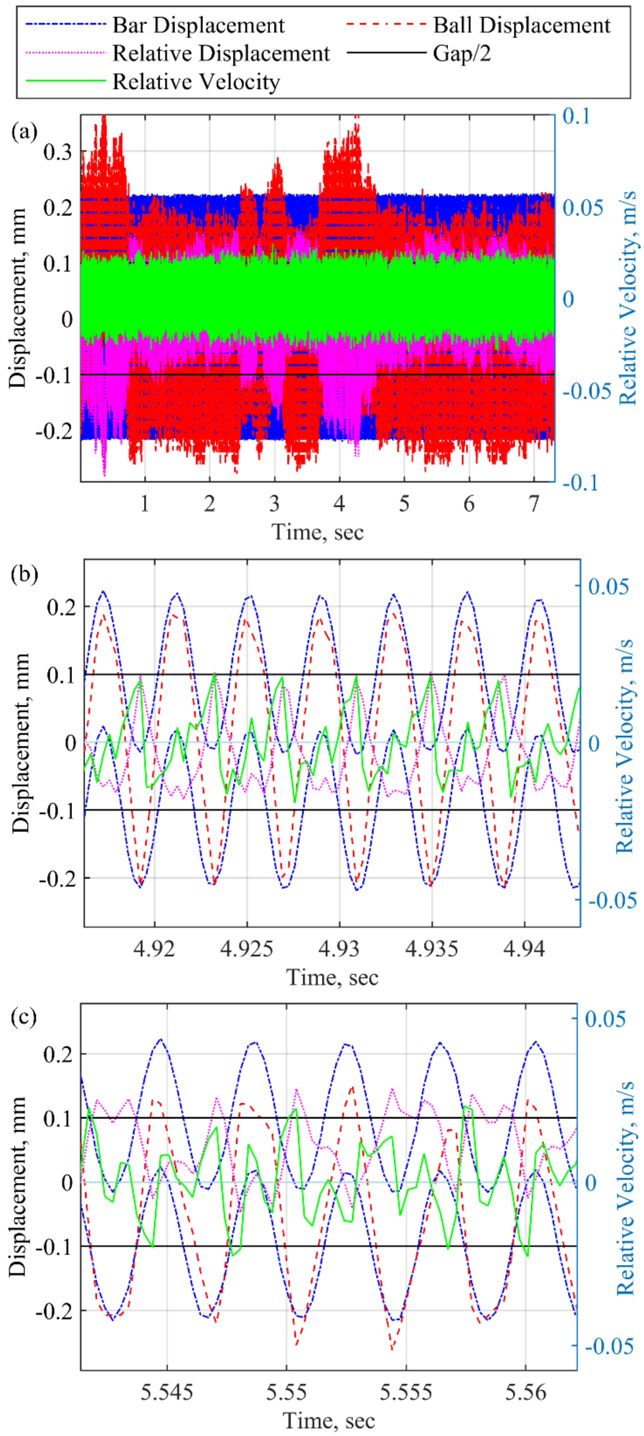

Fig. 7 Case of asymmetric impacts per cycle transitioning into chaotic, irregular response. (a) Full response, (b) asymmetric response for few cycles, (c) chaotic response for few cycles.

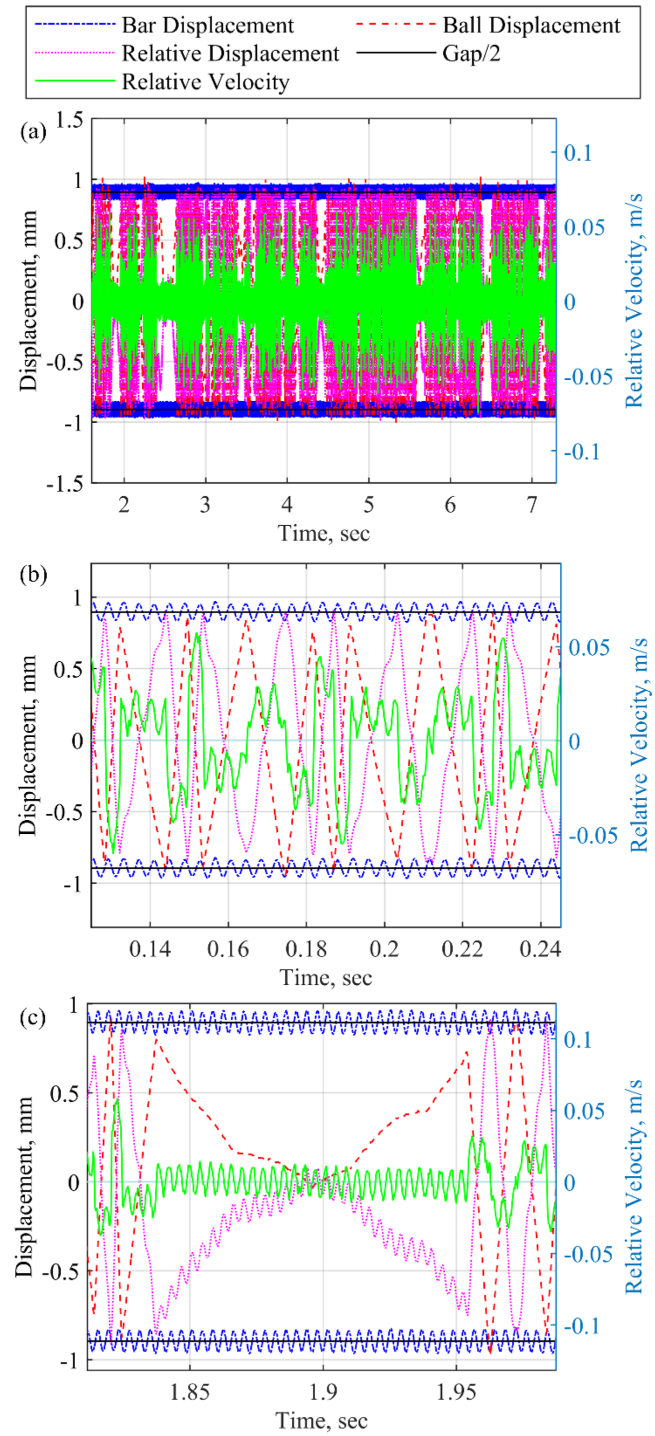

Fig. 8 Case of multiple asymmetric impacts per cycle transitioning into response with no impacts. (a) Full response, (b) asymmetric response for few cycles, (c) no impacts for few cycles.

Of the four cases being discussed herein, the response for this case is the most irregular of all – see Fig. 8(a) that shows how inconsistent the response is over the length of the signal. For example, at time instants of ~0.2 seconds and ~1.9 seconds, response for which is shown in Fig. 8(b) and Fig. 8(c), there are several instances of no impacts. This is evident from the multiple reversals of velocities that do not correspond to the relative displacements between the bar and the ball being equal to half the gap.

One possible explanation for this irregular behavior is that since the force is low and the gap large, the ball is unable to overcome the rolling friction at the bottom interface with the cavity of the bar. And even when it does overcome this resistance and impacts one of the walls, it still does not gain enough momentum from the collision for it to overcome the rolling friction resistance to roll over to the other wall on the other side to collide with it.

In this case too, the peak-to-peak response of the bar is ~0.1 mm. This is like the case discussed in Section 5.2 which had the same force level as this case. Again, for visualization, the response of the bar is overlaid on the distance corresponding to one wall, i.e., for when the distance equals the gap/2.

Interestingly, even though the response in this case is highly irregular, there is still on average a ~18% reduction in the response of the impact-damped boring bar in comparison to the response of the bar without a damper. This observation is also contrary to expectations and reports about the general motion of the impact-damped systems.

5. Conclusions and outlook

This paper offered new insights into the nature of vibro-impacts in an impact-damped boring bar. We experimentally investigated the response of the bar changing with the gap between the free mass and the walls of the boring bar and with changing forced excitation levels. By using vision techniques to track the motion of the free mass, we were able to help reveal the general response of the bar to be nonlinear, irregular, and chaotic. Though only four representative cases characterizing ball motion were discussed, we observed four families of possible (ir)regular ball motions and solutions. In one case, we observed the classic symmetric two impacts per cycle. In two other cases, we observed the response transition from symmetric two impacts per cycle to multiple asymmetric impacts and irregular and chaotic response. In the fourth case, we observed the ball oscillate about its mean position without impacting either of the end stops. Interestingly, even though response was generally irregular, the impact-damped boring bar was still found to be able to reduce vibrations in comparison to a boring bar without a damper.

Future work could explore investigating how the response changes with changing excitation frequencies, overhangs, mass ratios, and for intermediate levels of gaps.

ACKNOWLEDGEMENT

We acknowledge support from the Government of India's SERB grant CRG/2020/001010 and the DST's technology grant DST/TDT/AM/2022/148.

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