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Development of a new low order nonlinear system experiment motivated by brake squeal problem

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ABSTRACT

The chief objective of this paper is to describe the need for a new experiment that is motivated by brake squeal problem to understand the role of several parameters. Specifically, these parameters are normal force vectors, relative sliding speed and preload. The simplified experiment is designed with a mass placed on a conveyor belt driven by an electric motor in a controlled manner. The mass is pressed against the belt via two telescopic beams from one end but attached to a fixed frame at the other end. Springs are also used on the telescopic beams to adjust the preload applied on the mass. Furthermore, telescopic beams can slide along the fixed frame so that their angular configurations may be altered. Initial tests are conducted and accelerations of the mass with four uniaxial accelerometers (at the edges) are acquired and analyzed in frequency domain. In particular, tests are performed at different electric motor speeds, preload levels and normal force angular configurations. The measured data qualitatively confirm the effects of these parameters on the nonlinear physics. Further work is required to gain a better understanding about the precise role of these parameters from the perspective of nonlinear behavior and squeal phenomena.

Keywords: Automotive NVH, Brake squeal, Experimental study
I-INCE Classification of Subject Number: 70, 72, 74

1. INTRODUCTION

Inherent nonlinearities in automotive brake systems typically lead to unstable responses causing some well-known friction-induced vibration and noise problems. High frequency brake squeal phenomenon is one of the dynamic instability problems that is observed in many practical systems [1, 2]. Several physical mechanisms leading to squeal problem have been proposed through the analysis of minimal-order mathematical models [3-8]. Recently, Sen and Singh [9] extended the models of Hamabe et al. [10] and

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Hoffman et al. [11] to better understand the hammering mechanism which is proposed as an important mechanism for initiating squeal. Sen and Singh [9] adapted several nonlinearities (kinematic, clearance and friction) in the low-order models and investigated the dynamic responses. In general, the nonlinear systems exhibit rich dynamic responses such as the generation of super- and sub-harmonics, bifurcations and chaos. A slight change in an operational parameter may shift the behavior of the nonlinear system from stable to unstable regime(s) and vice versa. Thus, it is crucial to understand the effects of these parameters on the system responses, especially using a well-controlled experiment; that is the main goal of this paper.

The chief objective of the current study is to design, build and instrument a nonlinear system experiment that can simulate the dynamics of prior low-order mathematical models (Fig. 1) including the ones suggested by Sen and Singh [9]. Hence, an experimental setup in which a mass is pushed against a sliding surface is developed. Furthermore, the focus is given on three key parameters whose effects on the dynamic responses are sought: i) relative speed between the mass and the (frictional) sliding surface; ii) normal forces acting on the mass on the sliding surface; and iii) the directions of normal force vectors.

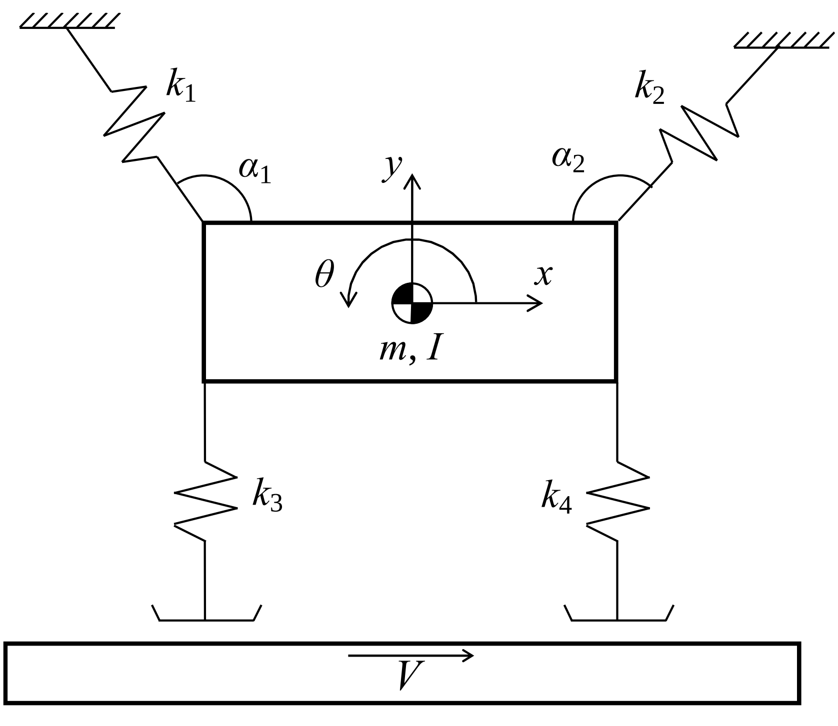

Fig. 1. Three degree of freedom brake squeal source model

2. EXPERIMENT FOR THE NONLINEAR SYSTEM MODEL

A mass sliding on the frictional surface is implemented in the experiment, as schematically illustrated in Fig. 2. The sliding surface is realized with a belt that is stretched in between two rollers, and an electric motor is directly attached to one of the rollers in order to move the belt. The mass is pushed against the belt through two telescopic beams with springs coiled around. The other ends of the telescopic (rigid) beams are attached to a fixed (rigid) frame, though those ends of the beams are allowed to slide over the frame. Thus, angles between the longitudinal axes of telescopic beams and horizontal axis can be altered by sliding them over the fixed frame. This permits to achieve alternate directions for the elastic forces that are generated with the springs. Furthermore, different preloads on springs can be obtained by adjusting the lengths of the telescopic beams through the screwed ends. The speed of the electric motor is controlled through its driver, and thus experiments at lower and higher sliding speeds are performed.

The following three physical measurements are acquired in the experiment: i) acceleration of the mass in the vertical direction; ii) torque applied by the electric motor; and iii) speed of the electric motor. Since the normal forces on telescopic beams are not directly measured in the experiment, such forces are roughly estimated from the electric motor torque.

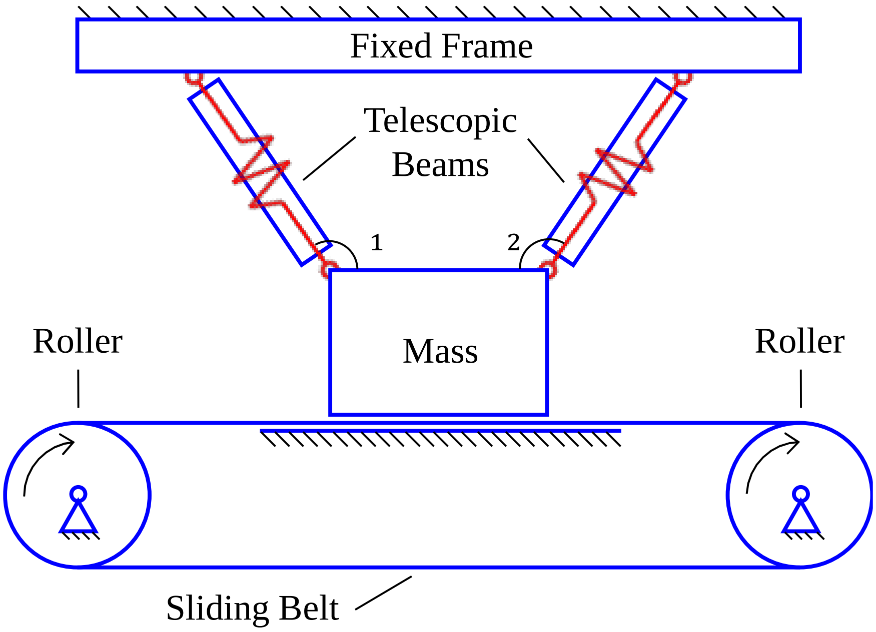

Fig. 2. Schematic of the proposed experiment

3. EXPERIMENTAL RESULTS

As mentioned before, effects of three key parameters are experimentally investigated. Hence, experiments are planned in a way where two parameters remain intact while the other parameter is changed. Typical results of the experiments are explained in the following subsections.

3.1 Effect of Sliding Belt Speed

In the first set of experiments, the effect of sliding belt speed on the dynamic response is investigated. Accordingly, experiments are carried on at five different motor speeds (10, 20, 30, 40 and 50 rpm), while keeping the other parameters (directions of the normal force vectors and torque of electric motor) intact. Furthermore, the configuration of the telescopic beams is chosen as $[\alpha_1, \alpha_2] = [90°, 120°]$. Sample spectra of the acceleration are shown in Fig. 3. Observe that acceleration spectra are similar at the lower sliding speeds (10 rpm and 20 rpm) and thus the speed has minimal effect on the dynamics at the lower speeds. Furthermore, two frequency peaks (420 Hz and 805 Hz) are seen at 10 rpm, while the peak at 420 Hz disappears at 20 rpm. Starting from 30 rpm speed, another dominant resonant frequency (at 640 Hz) emerges at which the response amplitudes become significant as the speed increases. As evident from the spectra of 50 rpm speed, super-harmonics become important at the higher speeds. Also, sidebands around the first two harmonics of 640 Hz frequency reveal that the acceleration at 50 rpm speed is amplitude modulated, where the modulation frequency is around 117 Hz. It is observed that the speed has significant effect on the dynamics and the nonlinear characteristics become important at the higher speeds.

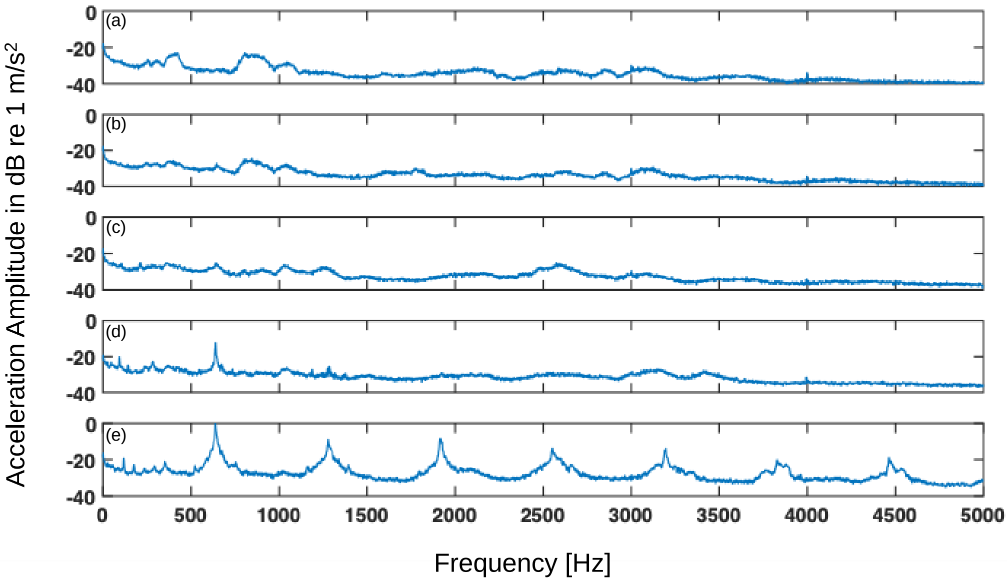

Fig. 3. Acceleration spectra of the mass at five motor speeds: (a) 10 rpm; (b) 20 rpm; (c) 30 rpm; (d) 40 rpm; and (e) 50 rpm.

3.2 Effect of Preload on Springs

The second set of experiments aims to understand the effect of the forces applied on the mass through the telescopic beams. Since these forces are not directly measured in the experiment, an investigation is carried on based on the motor torque as it is closely related to the forces applied by the telescopic beams. Experiments are done at $[\alpha_1, \alpha_2] = [150°, 150°]$ configuration of the telescopic beams. First, the experiments are performed at 20 rpm and two different torque levels (0.37 Nm and 0.60 Nm). Their acceleration spectra are shown in Fig. 4. Observe that a frequency around 70 Hz is evident at both torque levels though it is more prominent at 0.60 Nm torque. Even though there are other distinct frequencies, no significant conclusion could be drawn. Thus, experiments are repeated again at a higher speed level. In the second set of experiments, the speed of the electric motor is set as 40 rpm, and the torque levels are adjusted as 0.30 Nm and 0.50 Nm. The corresponding spectra are depicted in Fig. 5. As seen in the measured data, nonlinear effects become important at higher speed and/or higher torque levels, as evident from the emergence of super-harmonics of 640 Hz fundamental frequency.

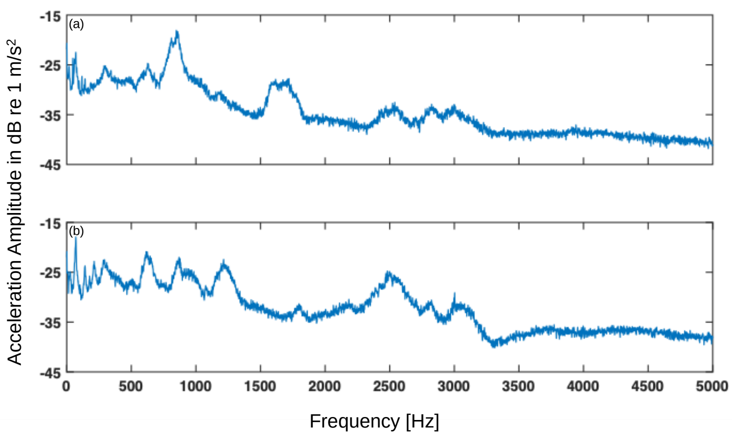

Fig. 4. Acceleration spectra of the mass at 20 rpm for two torques: (a) 0.37 Nm; and (b) 0.60 Nm.

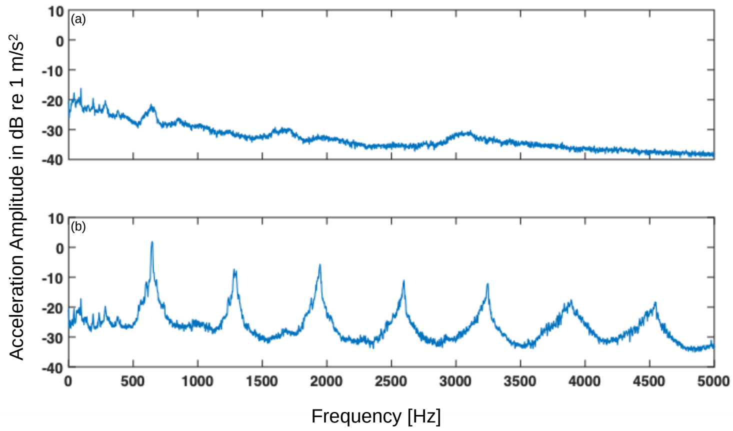

Fig. 5. Acceleration spectra of the mass at 40 rpm at two torques: (a) 0.30 Nm; and (b) 0.50 Nm.

3.3 Effect of Normal Force Angular Configuration

The configuration of the normal force vectors is adjusted by sliding the telescopic beams over the fixed frame (as shown in Fig. 2). Thus the following configurations are experimentally implemented: i) $[\alpha_1, \alpha_2] = [90°, 135°]$; ii) $[\alpha_1, \alpha_2] = [135°, 135°]$; iii) $[\alpha_1, \alpha_2] = [150°, 150°]$; iv) $[\alpha_1, \alpha_2] = [90°, 120°]$; v) $[\alpha_1, \alpha_2] = [180°, 180°]$; and vi) $[\alpha_1, \alpha_2] = [180°, 135°]$. Furthermore, experiments are done at two different speeds (at 10 and 50 rpm). The acceleration spectra for the lower speed case (at 10 rpm) are shown in Fig. 6. The beam configuration does not have a significant effect on the response at the lower speed. However, the differences between beam configurations become important at the higher speeds (say at 50 rpm) whose acceleration spectra are displayed in Fig. 7. As seen in the figure, nonlinear effects are not strong for the configurations (d) and (e). However, super-harmonics start to emerge at the other configurations, and the effect of nonlinearities seems to be prominent in the configuration (c).

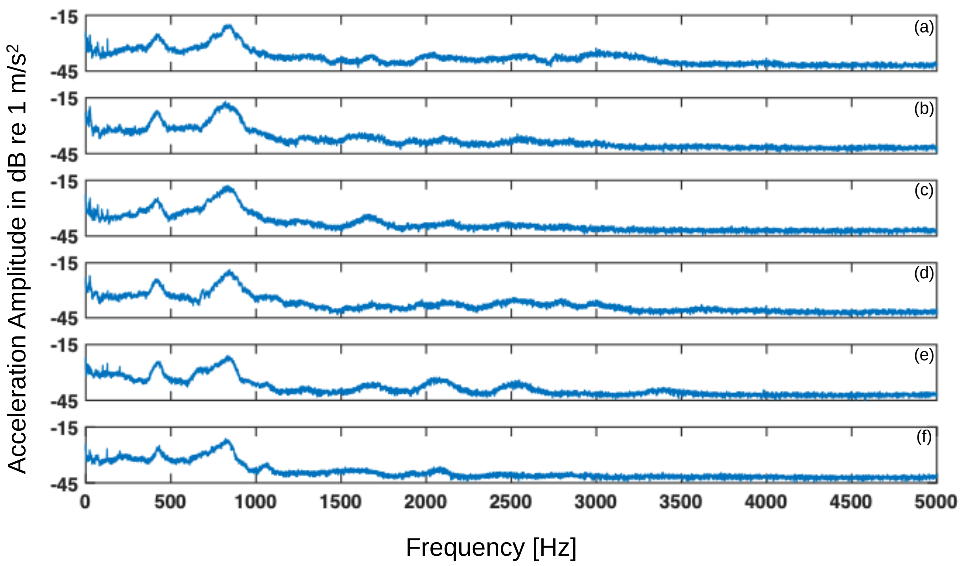

Fig. 6. Acceleration spectra of the mass at 10 rpm for 6 beam configurations: (a) $[\alpha_1, \alpha_2] = [90°, 135°]$; (b) $[\alpha_1, \alpha_2] = [135°, 135°]$; (c) $[\alpha_1, \alpha_2] = [150°, 150°]$; (d) $[\alpha_1, \alpha_2] = [180°, 135°]$; (e) $[\alpha_1, \alpha_2] = [180°, 180°]$; and (f) $[\alpha_1, \alpha_2] = [90°, 120°]$.

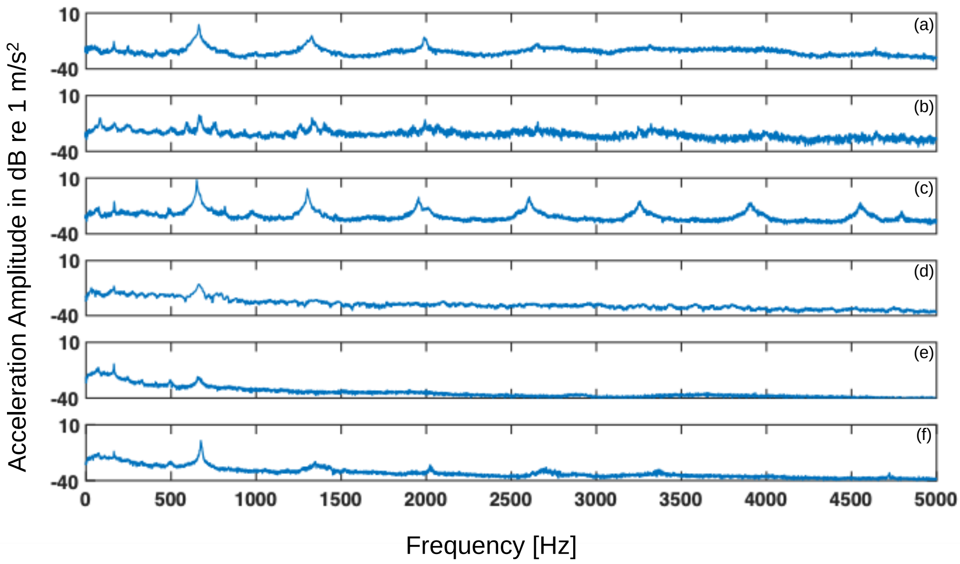

Fig. 7. Acceleration spectra of the mass at 50 rpm for six beam configurations: (a) [α_1, α_2] = [90°, 135°]; (b) [α_1, α_2] = [135°, 135°]; (c) [α_1, α_2] = [150°, 150°]; (d) [α_1, α_2] = [180°, 135°]; (e) [α_1, α_2] = [180°, 180°]; and (f) [α_1, α_2] = [90°, 120°].

4. CONCLUSION

This paper has described the need for a new experiment that is motivated by brake squeal problem to understand the role of normal force vectors, relative sliding speed and preload. The simplified experiment (while simulating a low-order model suggested by Sen and Singh [9]) is designed with a mass placed on a conveyor belt driven by an electric motor in a controlled manner. The mass is pressed against the belt via two telescopic beams from one end but attached to a fixed frame at the other end. Springs are also used on the telescopic beams to adjust the preload applied on the mass. The telescopic beams can slide along the fixed frame so that their angular configurations may be altered.

Initial measurements of acceleration spectra show interesting observations. First, the higher speed levels (30, 40 and 50 rpm) are more prone to excite the system nonlinearities and the system response does not change significantly at lower speeds (10 and 20 rpm). Second, the experiments are carried on at different load levels. The results of lower speed experiments reveal that the system response does not depend on the load levels, i.e. similar frequency responses are obtained at 0.37 and 0.60 Nm torques. But, the system responses at higher speeds can be significantly affected at high torque levels (0.50 Nm). It is then concluded that the preload does have an effect on the system response, though it may not trigger any nonlinear effect at the lower speeds. Third, the effect of normal force angular arrangements is studied via six different configurations and it is observed that system response is almost identical at the lower speeds (10 rpm) irrespective of the configuration. However, different angular arrangements dictate the responses and nonlinear interactions at the higher speeds (50 rpm). In summary, it is observed that all the parameters chosen to be experimentally studied have important effects on the system responses and nonlinearities.

5. ACKNOWLEDGEMENTS

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