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**ENGINE MOUNT DESIGN STRATEGIES
TO MITIGATE LINEAR VIBRATIONS IN A TATA NANO**

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ABSTRACT

In 2009, Tata Motors launched the Tata Nano as a low-cost alternative to two and three-wheeled vehicles for India's growing middle class. However, the Nano failed to meet these expectations as it developed a negative perception amongst Indian consumers partly due to its poor Noise Vibration Harshness (NVH) characteristics. In this paper, we examine strategies to reduce the transmission of linear vibrations from the engine felt inside the cabin. Specifically, it includes analysis of the hardness of damping rubber in the engine mounts as well as geometry of the engine mounts. The results of this analysis suggest that Tata Motors can reduce the vibrations transmitted from the engine by decreasing the hardness of the damping rubber. Additionally, Tata Motors can further reduce the transmitted vibrations by decreasing mount angle. It was found that a reduction in mount angle from 45° to 30° reduced the amplitude of the transmitted vibrations by 23%.

INTRODUCTION

Tata Motors launched the Nano, commonly known as the "People's Car" as an entry level offering. Targeted at India's rapidly growing middle class, Tata Motors believed that the Nano would quickly capture significant market share, replacing the current two and three-wheeled alternatives. To do so, the Nano utilized a simple, low cost, and fuel-efficient design. Initially priced at one "lakh" (100,000) rupees or roughly \$2,000 USD, the Nano was branded as, "the most affordable car in the world".

With the Nano, Tata Motors believed it would provide safe and affordable transportation to more people than ever before. With these ambitious expectations in mind Tata Motors invested hundreds of millions of dollars constructing a new manufacturing facility in India. The facility launched with an annual production capacity of 250,000 units and plans to increase this capacity to a steady-state of 1,000,000 units. However, these expectations were never met as the Nano

displayed underwhelming performance in the Indian market. Sales peaked in 2011 at 75,000 units and have since declined to fewer than 20,000 units per year. [1]

Tata Motors has identified the Nano's NVH characteristics as significant contributors to the vehicle's negative perception amongst Indian consumers. Widespread customer complaints implicate that at high rpms, vibrations are transmitted to cabin and steering wheel. [2] More simply put, when a user drives a Nano it feels cheap. In fact, the user experience has been likened to that of an auto rickshaw, a traditionally lower-class vehicle.

Tata Motors believes that by improving the NVH characteristics of the Nano, it can alter the negative consumer perception and ultimately increase sales. The goal of this research is to improve the NVH characteristics by reducing the physical vibrations felt by the user

Background

The Tata Nano uses a 2-cylinder engine which are inherently unbalanced. It also has an extremely lightweight engine and chassis. Together, this results in a large amount of vibration being transferred from the engine into the cabin and ultimately to the passengers. These vibrations are dampened by three passive engine mounts located between the engine and chassis to act as springs and dampers of the system. Two of the mounts deal with linear forces from the engine, while a third mount counters any torque impulses produced by the engine.

The three mounts are called A, B and C in the vehicle specification and are arranged as shown in Figure 1.

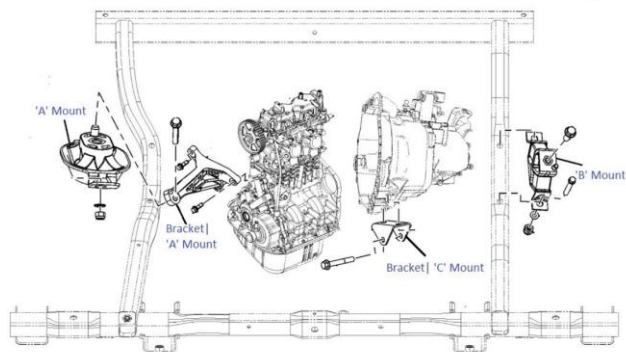


Figure 1: Engine layout and mount locations [6]

Mount A is installed on the rear-right side of the engine compartment. The top section of mount A consists of a steel frame and the mount is attached to the engine using a single bolt. The bottom half of mount A is a steel piece that is installed to the frame with two bolts and finally, all steel pieces are bonded together with over-molded rubber. Similarly, Mount B is located on the rear-left side of the engine bay and consists of a steel top and bottom frame that are bonded together with an

over-molded rubber insert. Mount C consist of two steel rings connected by a steel arm allowing for rotational degree of freedom. Mount C has an over-molded piece of rubber built into the inner portion of each steel ring.

ANALYSIS

The first vibration study was done to examine the fundamental frequency of the engine block. A Holzer model [5] was created to assess the natural frequency of the engine. This model is based on the equations of motion for the system and relates the systems moment of inertia, torsional stiffness, and mass. The solutions to the model are found when natural frequencies occur. Fast Fourier Transforms (FFT) of the engine accelerations were then plotted and a strong adherence to the forcing frequencies were observed (Figure 2 and 3).

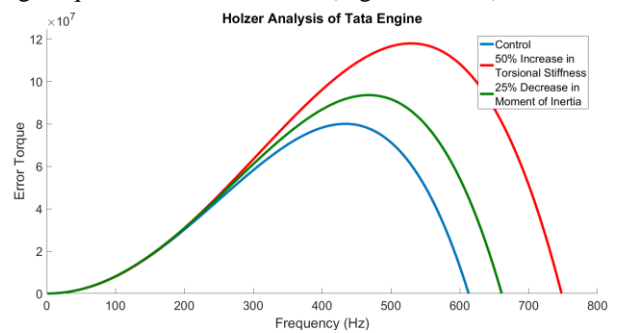


Figure 2: Holzer Model of Engine System

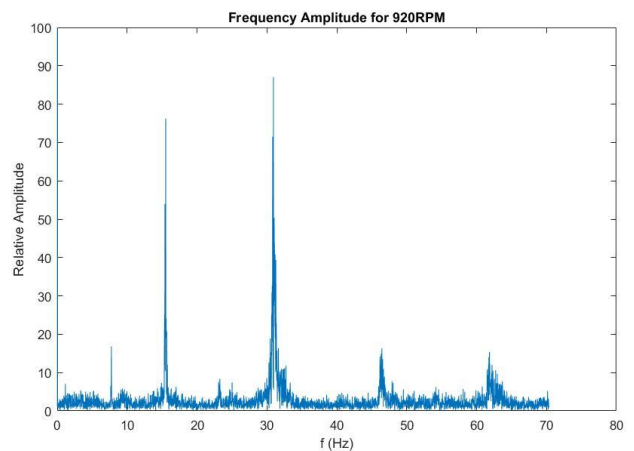


Figure 3: Frequency plot of engine at idling (920 RPM)

After this, the mounts frequency response was predicted by taking the Laplacian of the system and creating bode plots (Figure 4). The system was modeled as a single degree-of-freedom spring-mass-dashpot with forced input. The amplitude response related this input force with the expected transmission to the frame through the mounts. These plots gave insight into how to adjust mount parameters to acquire desired responses. Using these, it was found that to improve system performance,

it was desirable to increase the damping, or decrease the stiffness of the system. This information was used to guide future alternative material selection.

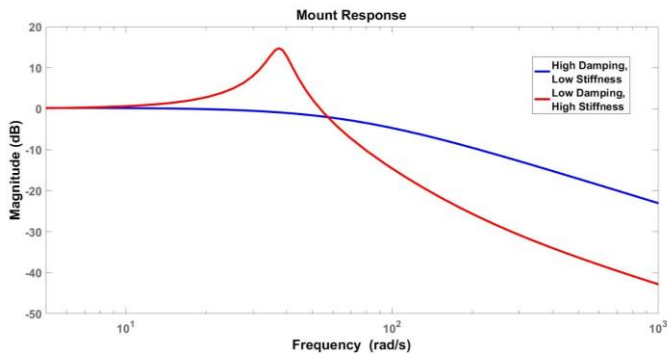


Figure 4: Bode plot of mount response

Damping mechanism

All engine mounts in the Tata Nano are elastomeric in nature, made of a metal bracket and damping rubber insert. The elastomeric mounts can be represented by a Voigt model which consist of a spring and a viscous damper. In general, material hardness, loading direction, and mounting location are the main variables in engine mount design. The next two sections focus on damping rubber material selection and damping rubber orientation.

Material selection

Hardness of rubber is measured in units of durometer on a Shore scale. The original Tata engine mount damping rubber has a hardness of 60A measured by using a standard Shore A durometer. This was used as a baseline to select a range of soft and stiff rubber materials for testing. The durometer of damping rubber used in the tests ranges from 30A to 70A. The goal was to characterize the impact of damping rubber hardness on the vibration transmission in relation to rubber hardness.

Damping orientation

The damping rubber orientation dictates the direction in which the rubber flexes and dampens the vibration either through shear or compression. To improve damping efficiency through orientation, the predominant vibration direction needs to be understood. Accelerometers placed on the engine measure linear vibrations along X, Y, and Z axes separately. Z direction is in the negative direction of gravity, X and Y are locally defined to each mount. The graphs in Figure 5 show that vibrations (acceleration) in line with Z axis were highest. Based on this observation it was decided more shear of damping rubber in Z direction had to be introduced in prototyping.

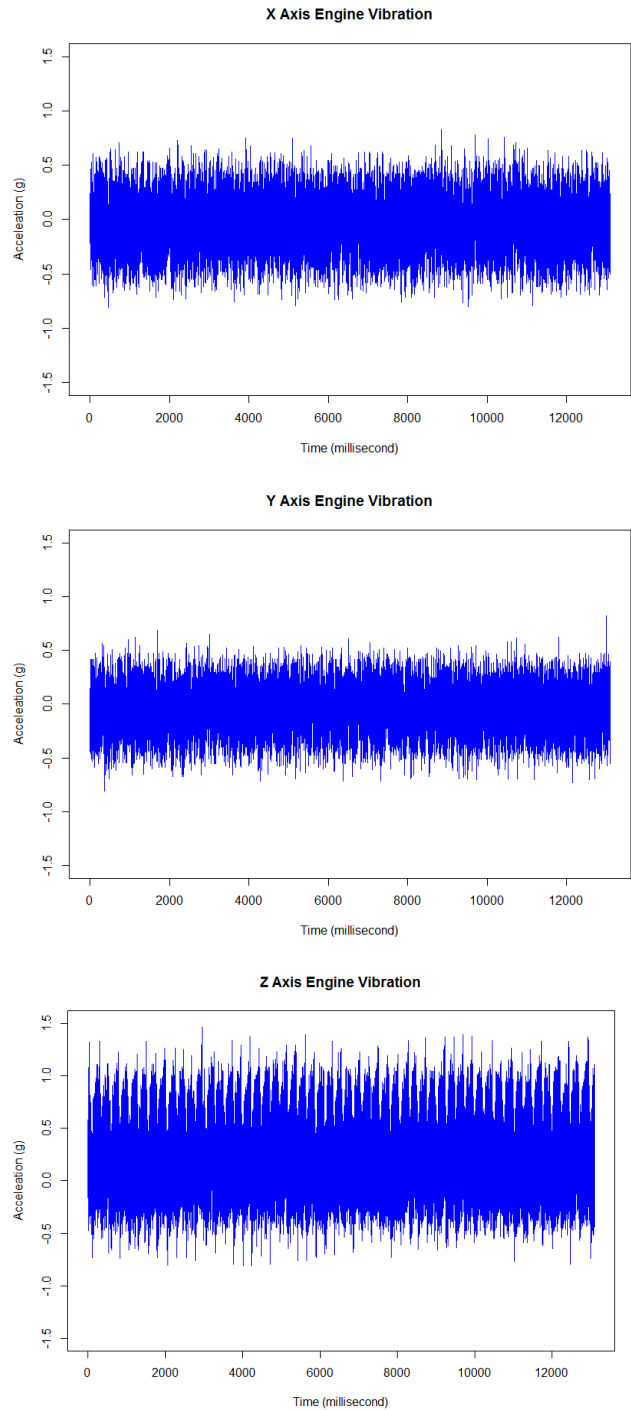


Figure 5: Vibration amplitude in X, Y, and Z direction respectively

PROTOTYPING

A series of tests were conducted to measure vibration data (acceleration over time) by mounting accelerometers across the mount (on engine side and frame side, Figure 6). In each test, rubber with specific durometer was used.

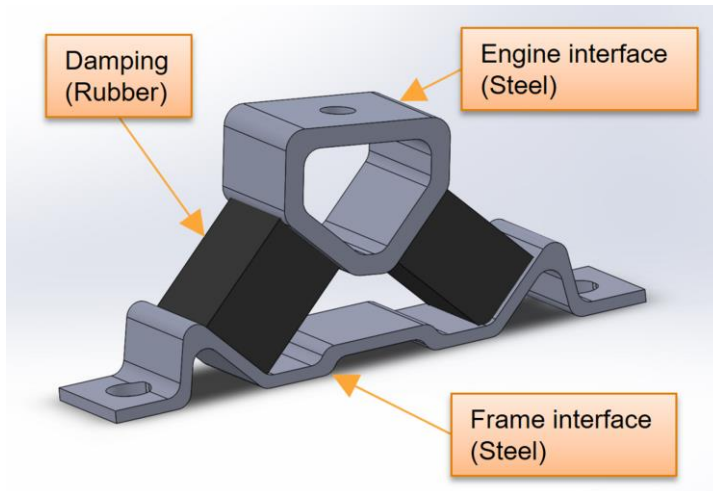


Figure 6: Various parts of a 'B' type mount

The analysis focused on mount B with the intention of obtaining valuable data and iterating faster. Mount B consists of the following parts: engine interface (Steel), frame interface (Steel) and damping (Rubber) (Figure 6).

The first iterations focused on varying the hardness of the rubber material in mount B. As mentioned in the previous section, damping rubber inserts with durometer ranging from 30A to 70A were used. After data acquisition, the maximum difference in peak-to-peak value of acceleration were calculated for comparison.

A second level of testing was performed using different orientations of the damping rubber in relation to the engine bracket. Modifying this angle allowed us to vary static and dynamic loading on the damping rubber insert. In doing so, the proportion of forces in tension, compression and shear were changed. For reference, the current mount design had an angle of 45deg. (Figure 7).

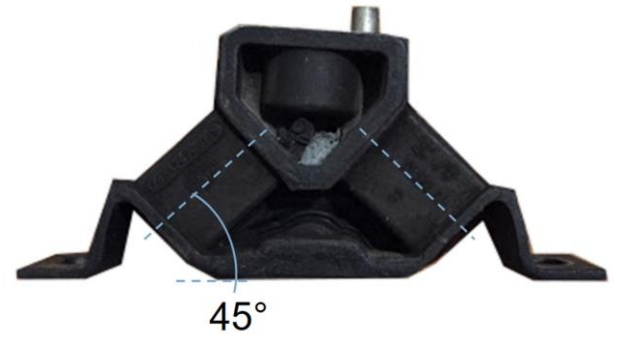


Figure 7: Mount angle on a standard 'B' type mount

To observe the response to changing rubber insert orientations, three unique mount prototypes were designed with existing mount interfaces but different angles. The angle was adjusted as follows: 50° (45 + 5°), 40° (45 - 5°) and 30° (45 - 15°), see Figure 8 below.

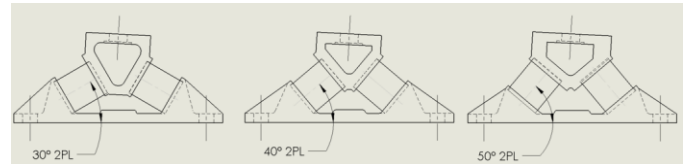


Figure 8: Angle variation in prototypes: 30°, 40°, and 50° respectively

The prototypes were 3D printed by retaining all enveloping dimensions on Tata's existing mounts (See figure 9). However, since the 3D printer uses rigid plastic and not steel, it was necessary to make modifications to provide strength.

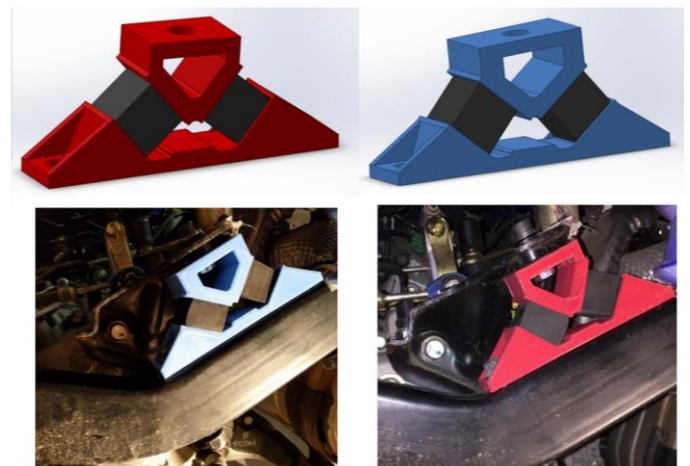


Figure 9: CAD rendering of mount (top) and 3D printed mount (bottom) in the Tata Nano

EXPERIMENTAL SETUP

Linear vibrations were measured using ADXL335 accelerometer (item# 2-5 in Figure 10) capable of measuring +/- 3g and up to 7,500Hz. The entire test setup was controlled by an Arduino Mega 2560 (item# 1 in Figure 10).

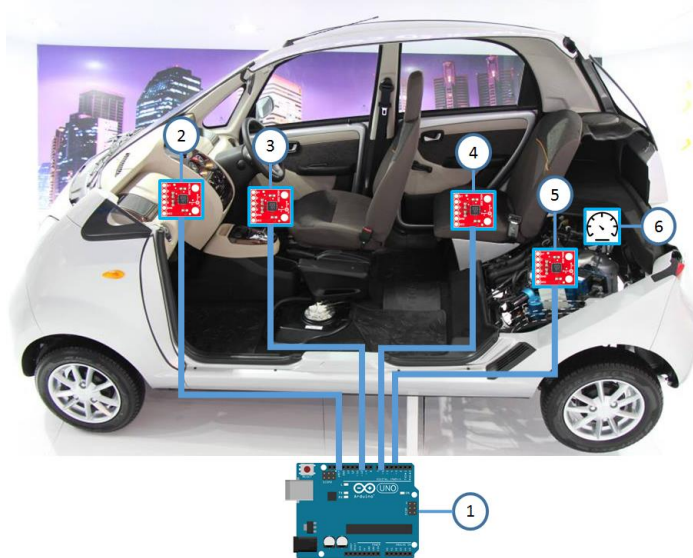


Figure 10: Sensor layout inside Tata Nano cabin [7]

A Tata Nano was modified to house accelerometers in various spots in the car (item# 2-5 in Figure 10). Using this setup enabled pinpointing the source of vibration to the engine bay. A digital tachometer (item# 6 in Figure 10) was used to measure engine Rotation Per Minute (RPM) throughout testing.

An isolated experiment focusing on the B type mount required setting up of accelerometers across the mount (Figure 11). This sensor setup helped in comparing various iterations to the design of mount.

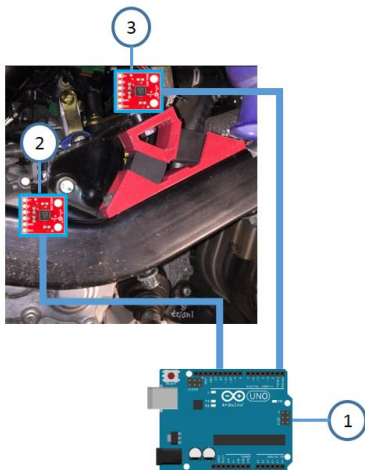


Figure 11: Sensor layout across 'B' type mount

In addition, a high-speed camera capable of recording 1200 frames per second (fps) was used to track a fiducial (square

yellow tag) placed on the mount in slow motion. Figure 12 shows our recording equipment setup, with camera marked as item# 1. The camera was isolated from the car body and leveled with respect to the ground.

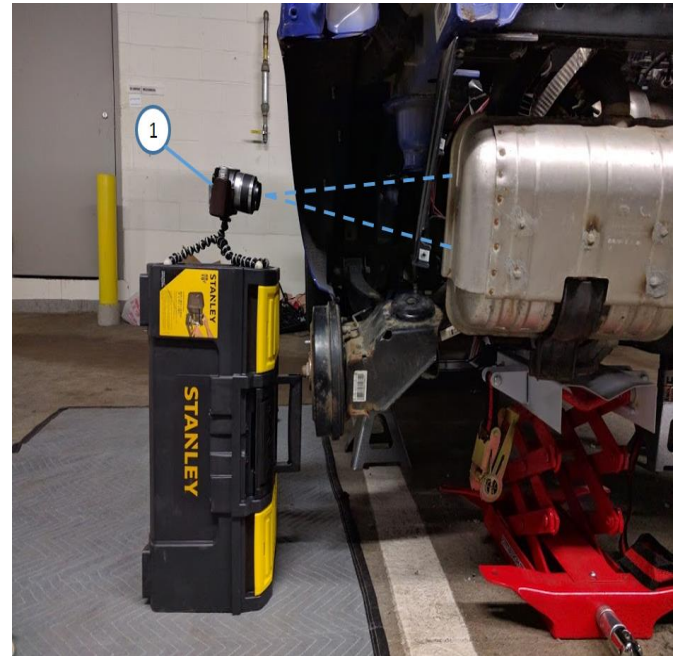


Figure 12: Slow motion video recording of mount movement

The fiducial was placed on the bottom steel portion of the mount, marked as item# 1 in Figure 13. Each frame of the slow-motion video was then processed in MATLAB to track item# 1.



Figure 13: Yellow tag on mount

The MATLAB algorithm converted all video in 5 second grayscale format. This provided necessary contrast to

distinguish between the dark background and a light-yellow tag. The tag location was then plotted on a scatter plot to identify any trend in mount motion. One such plot is shown in Figure 14. The point cloud in Figure 14 cluster about a central axis (dotted line) and show the engine mount's preferred direction of movement.

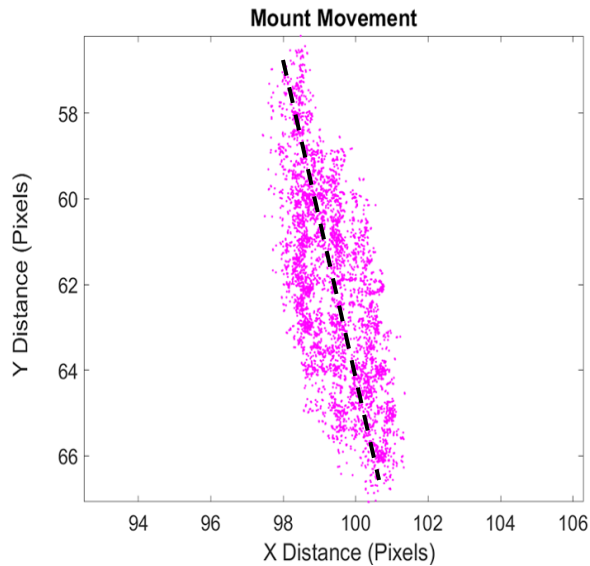


Figure 14: Scatter plot of mount movement at given RPM

RESULTS

Hardness of the damping rubber was explored as a variable to reduce transmission of vibrations. Figure 15, seen below, shows the amplitude of vibrations measured on the frame when neoprene rubber of varying hardness (30A-70A) was used. As seen in Figure 15, the gains of using anything softer than 50A were marginal and thus it was decided to use 50A for further testing. This also helped in avoiding bottoming out of the mount at start-up.

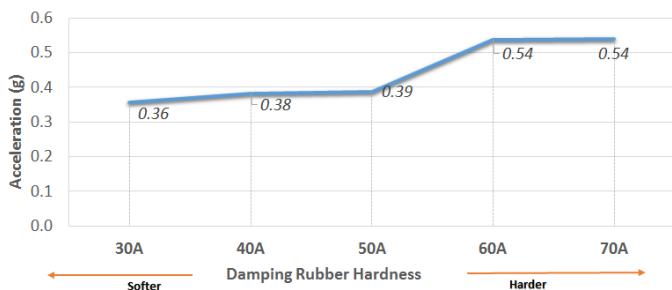


Figure 15: Measured frame vibration amplitude for neoprene damping rubber with varying hardness

Orientation of rubber inserts within the engine mount was explored as another variable by which the transmission of vibrations from the engine to the frame could be reduced. To adjust the geometry of the mount, the mount angle was varied

by using different mount frames. Figure 16, shows the amplitude of vibrations measured on the frame when a 50A neoprene damping rubber was used with a 40° mount angle (prototype), a 45° mount angle (original), and a 50° mount angle (prototype).

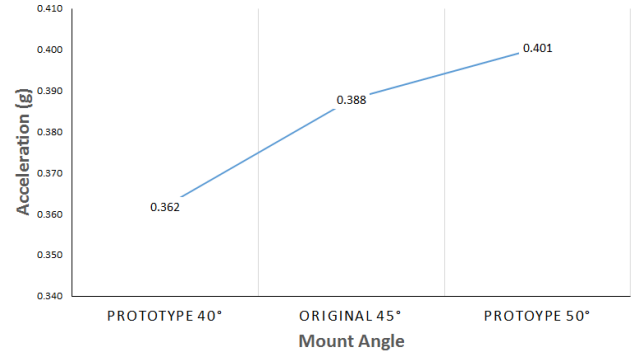


Figure 16: Measured frame vibration amplitude with a 50A neoprene damping rubber and mount angles of 40°, 45°, and 50°

To further validate the results shown in Figure 15 and Figure 16, an additional test was conducted. This test involved a new prototype with 30° mount angle and the original Tata Motors supplied damping rubber taken from the Nano. The results of this test showed a measured frame vibration amplitude of 0.24g, a 23% reduction from the 0.31g value measured using the mount currently included in the Nano.

CONCLUSION

The results of rubber insert material hardness analysis suggests that for a given rubber material as hardness decreases, the amplitude of the vibrations transmitted from the engine to the frame also decreases. However, the neoprene damping rubbers used in this analysis were less effective in reducing transmitted vibrations than the original damping rubbers found on the Nano. Therefore, Tata Motors should explore the possibility of reducing the hardness of its current damping rubber material, while also considering the implications on material durability and strength.

The results of the analysis of the mount geometry however, suggest that as mount angle decreases, the amplitude of the vibrations transmitted from the engine to the frame also decreases. Of the various mount angles tested, the mount angle that achieved the greatest reduction in transmitted vibrations was 30°. When the mount angle of 30° was tested with the original Nano damping rubber it achieved a 23% reduction in transmitted vibration when compared to the original mount found in the Nano. It is possible that an even greater reduction can be achieved by further decreasing the mount angle. Therefore, Tata should further optimize, to determine the mount

angle that results in the greatest reduction of transmitted vibrations for a given damping material and hardness.

After completing initial designs, both suggested implementations, reducing material hardness and optimizing mount angle, can be integrated into the existing production framework at little to no added cost.

FUTURE WORK

This paper outlines the interaction of elastomer material selection and engine mount geometry for 'B' type mounts in the Nano. A similar study on other mounts is necessary for an overall reduction of linear vibration transmitted from the engine to cabin.

Most of our testing was performed at idling speed, and it is worthwhile exploring results over a wider RPM range and in motion to better represent road driving condition. The use of 3D printed mounting frames allowed us to iterate faster but cannot be used in production. A validation test of proposed rubber insert's orientation using production ready steel frames is pending.

Lastly, the durability of the new mounts is a key metric that remains to be tested. After a redesign of all mounts it will be crucial to do a life cycle test to qualify all mounts for production use.

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