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Extraction of vibration behavior in conventional and electric drive two-wheeler using order analysis

Lalsaheb Mulla[1], Piyush Khuba[1], Apeksha Dhere[1,] and Sakthivel Palanivelu[2]
[1]Department of Automotive Engineering, VIT University, Tamil Nadu-632014 India.
[2]Associate Professor, Department of Automotive Engineering, VIT University, Tamil Nadu-632014 India.

E-mail: psakthivel@vit.ac.in

Abstract: Electrification of automobiles results in new and challenging characteristics of vehicle NVH (Noise, Vibration, and Harshness) and ride comfort. Optimized architecture of electric vehicles has been evolved for appropriate placement of electric power drives. This paper presents the experiments performed for order analysis technique to predict the vibrational behavior of conventional and electric scooters which was not used in 2-wheelers earlier and used for 4-wheeler noise predictions and for vibration analysis of rotating machinery. Vibrational analysis of source alone in conventional and electric two-wheelers carried out by order analysis and the result is presented through Campbell Diagrams to observe the critical orders along with the variation of the amplitude of vibration as a function of frequency. Target locations' Vibration Dose Values (VDV) is calculated to assess rider comfort and is compared with the ISO 2631 standard. The higher amplitude of vibration has been observed at 23rd order for electric scooter while for conventional scooter it is noted at 8th and 16th order with reference to the wheel speed. Compared to the conventional scooter, electric scooter exhibits very low overall vibration level and range is away from human perception range resulting in good comfort.

1. Introduction

In recent years, the talk is on 'electric drive' mobility against its fossil fuel counterpart to meet the ecological and economic need. Strong legislation on automotive pollution control by the Environmental Protection Agency (EPA) commanded automotive industries to adopt new and more efficient technologies for vehicles called hybrid electric vehicles and electric vehicles. On one hand, weight reduction of the vehicle aid fuel economy of the vehicle and on the other hand, the vehicle tends to vibrate more and produce unwanted noise and vibration due to the vibration of various components. Higher levels of vibrations are observed in lightly damped structural components. Ride comfort in two-wheelers is characterized by the transmissibility of structural parts that are placed between the source and the rider contact points. Tires and modified suspension systems are available to reduce the vibrations excited by road undulation during tire-road interaction, while the inertial unbalance in power sources like IC engines or electric motors which are mounted on the frame and wheels as the case may be contributing to the vibrations and can easily be transmitted to the prominent locations. This paper deals with the prediction of vibration levels for a conventional and an electric scooter due to their power drives. Though the electric motor led vehicles to perform quieter and smoother than IC Engine vehicles the new NVH issues and challenges due to electrification needs to go for the new methodologies to understand the vibro-acoustic phenomena. Yu et al. [1] performed NVH analysis on the electric drivetrain and stated that, in electric vehicles, the torque fluctuation of motor and the meshing force variations causes the vibration in drive-line. Guo et al. [2] studied the NVH characteristics of the auxiliary power unit and the accessories like power steering pump, electric vacuum pump and AC compressor in a vehicle. The low-frequency torsional resonance of the power unit during start-up is a newly arrived problem which is not generally observed in a conventional engine. The order tracking method is used by Wu et al., [3] to study the interior noise generation in the cab and reported that the reason is the second order excitation of the system with respect to the engine speed. Panza et al., [4] explained different experimental methods to identify source and target responses of the system. There are many order tracking methods such as Fourier Transform based order tracking method, angle domain sampling- based order tracking also known as computed order tracking or digital resampling-based order tracking method, Kalman filter based order tracking method, time variant discrete Fourier transform order tracking method (TVDFT). Blough et al., [5] compared these order tracking methods and stated the advantages and disadvantages of each of these methods and concluded that TVDFT is the most suitable method for order tracking. Order tracking method has been used to identify the rotational behavior and the mode of vibration of the component. Guo et al., [6] worked on the vibration reduction of the engine by using Active Engine Mount (AEM).

It is well known that the vibration is a serious issue pertaining to human discomfort in automobiles, specifically in two-wheelers. There are many literatures available for four-wheelers compared to that of two-wheelers for ride studies, especially of electric power drives. The term, Whole Body Vibration (WBV) is referred to the transmission of vibration to the whole body, through the contact points of the rider. Manzato et al., [7] presented a method for two-wheeler comfort evaluation using simulation in LMS Virtual Lab Motion along with its experimental validation. Referring to vehicle characteristics, it has been stated that two-wheelers are generally harsher vehicles than other automobiles. Chen et al.,[8] conducted an extensive test run measurements for evaluating Root Mean Square (RMS) acceleration, 8-h estimated Vibration Dose Value (VDV) and 8-h estimated daily dose of static compression dose (SCD) for a bike, a scooter and a sedan car on a combination of rural, provincial and urban routes. Further, these estimations were compared with the recommended values by ISO 2631-1 and ISO 2631-5 standards [9]. It has been concluded that the WBV exposure levels of common motorcycle riders are significantly higher than those for sedan cars, even on a normal paved road [10]. This led a motivation for the research project presented in this paper.

2. Experimental Setup

Figure 1 describes the schematic and the actual test setup developed in the laboratory. Three tri-axial accelerometers and a speed sensor are connected to a data acquisition system (Siemens LMS SCADAS) using low impedance cables for data transferring. A laser-based non-contact speed sensor is used to measure the speed of the wheel. Accelerometers are installed at 3 prominent locations one near the source (wheel hub) and the other two at targets (rider's contact points: seat and handlebar) for vibration measurement. LMS Test. Lab. Software is used to define necessary channels and acquisition parameters for measurement and subsequent signal post-processing for calculation of ride metrics.

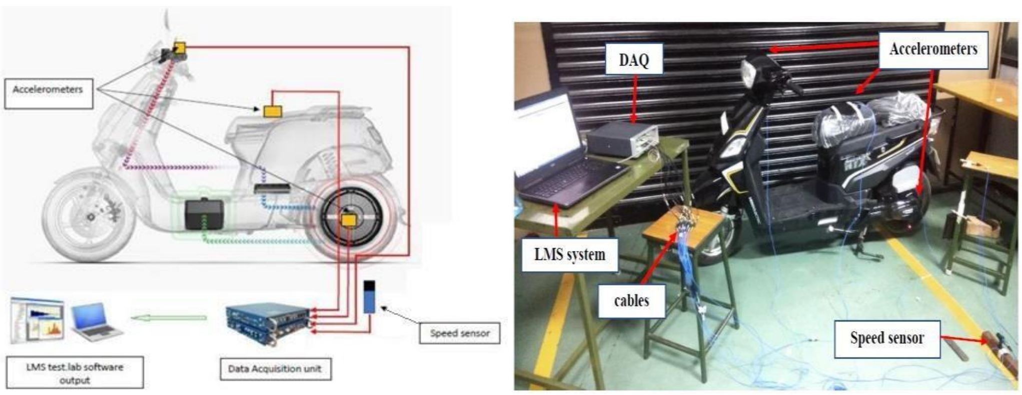
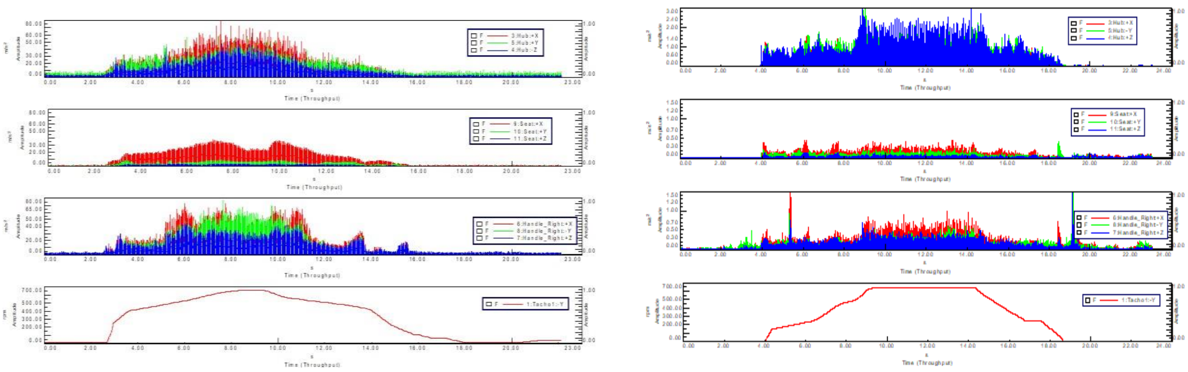


Figure 1. Schematic and the Actual test setup.

Two test scooters are chosen for testing. One for conventional IC engine powered (Hero Pleasure) and the other for electric motor powered (Hero Electric Nyx) respectively. When the test vehicles were put on their stand and powered, the engine runs at idle speed around 1100 rpm, whereas in the electric scooter with a wheel hub motor, the motor rotated only when the throttle was given. In order to match the equivalent scenario for order analysis, the rotating rear wheels of both test scooters are chosen as reference. Wheel speed from 0 rpm to 650 rpm is fixed to compare vibration behavior of both vehicles. The experiment is performed with the rider sitting on the seat to measure the vibration level at the seat and right handlebar location for run up and run down condition. Importantly, these experiments are conducted in the laboratory to account only the power drives as the source and hence the road excitation is eliminated. Though, this adheres to the objective of the current research work in real time riding of a scooter the road excitation also contributes.

3. Measurements and Observations

The time histories of all responses were obtained with reference to ISO right hand co-ordinate axis system. X, Y, Z axes refer to the longitudinal, lateral and vertical direction of the test vehicles. Figure 2 shows the variation of wheel speed and acceleration responses measured in all three directions at the hub, seat, and handlebar as a function of time for conventional and electric scooter respectively.



(a) (b)

Figure 2. Observation of wheel speed and acceleration response for (a)Conventional scooter (b) Electric Scooter.

The increase in amplitude followed by a decrease in amplitude represents the responses during the run-up and run-down condition and the same can be seen from the variation of speed increase and decrease between 4 – 18 seconds of measurements. Vibration signatures fora conventional scooter are observed to be of higher amplitudes (up to 80 m/sec^2 in the scale) compared to that of an electric scooter (up to 3 m/sec^2). In both cases, the attenuation of vibration transferred from hub to seat and handlebar location is observed clearly. However, among all, the dominating vibrations are seen in the X direction. Hence considering the vibrations along with X directions at various target locations the comparative study has been done further. Figure 3 compares Campbell diagram for variation of auto power amplitudes along longitudinal direction for the locations wheel hub (source) and seat and right handlebar (targets) respectively between conventional and electric scooters. Wheel hub in the conventional scooter is seen to be vibrating with higher amplitude in 8th order and 16th order of the wheel with the frequency close to

86.72 Hz and 175 Hz respectively. Whereas in the case of the electric motor, the wheel hub is observed to be vibrating with higher amplitudes in 23rd and 46th order of motor speed. Seat contact location the rider feels major vibrations generated by the source. It is evident from the corresponding plots that at the same critical orders as that of the hub, seat location does exhibit the higher vibration levels for both conventional and electric scooter. Next, to the seat, the handlebar is another critical location which influences the rider's comfort. Handlebar in the conventional scooter is seen to be vibrating with higher amplitude at to 550 rpm of the wheel. The observation is seen in the frequency range of 405-450 Hz i.e. 40th and 48th order of wheel at the speed of 550 rpm and the acceleration amplitude of 6 m/s^2. In case

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of an electric motor, the handlebar is observed to have higher amplitudes at 230 rpm with the 46 order frequency of 172 Hz and amplitude of 0.14m/s^2. Also, the considerable peaks are observed in 3rd and 23rd order of the reference hub-motor speed. Electric scooters vibrate with very low amplitudes but the frequency is too high which may cause 'hand-arm vibration syndrome' when the rider is exposed for a very long time.

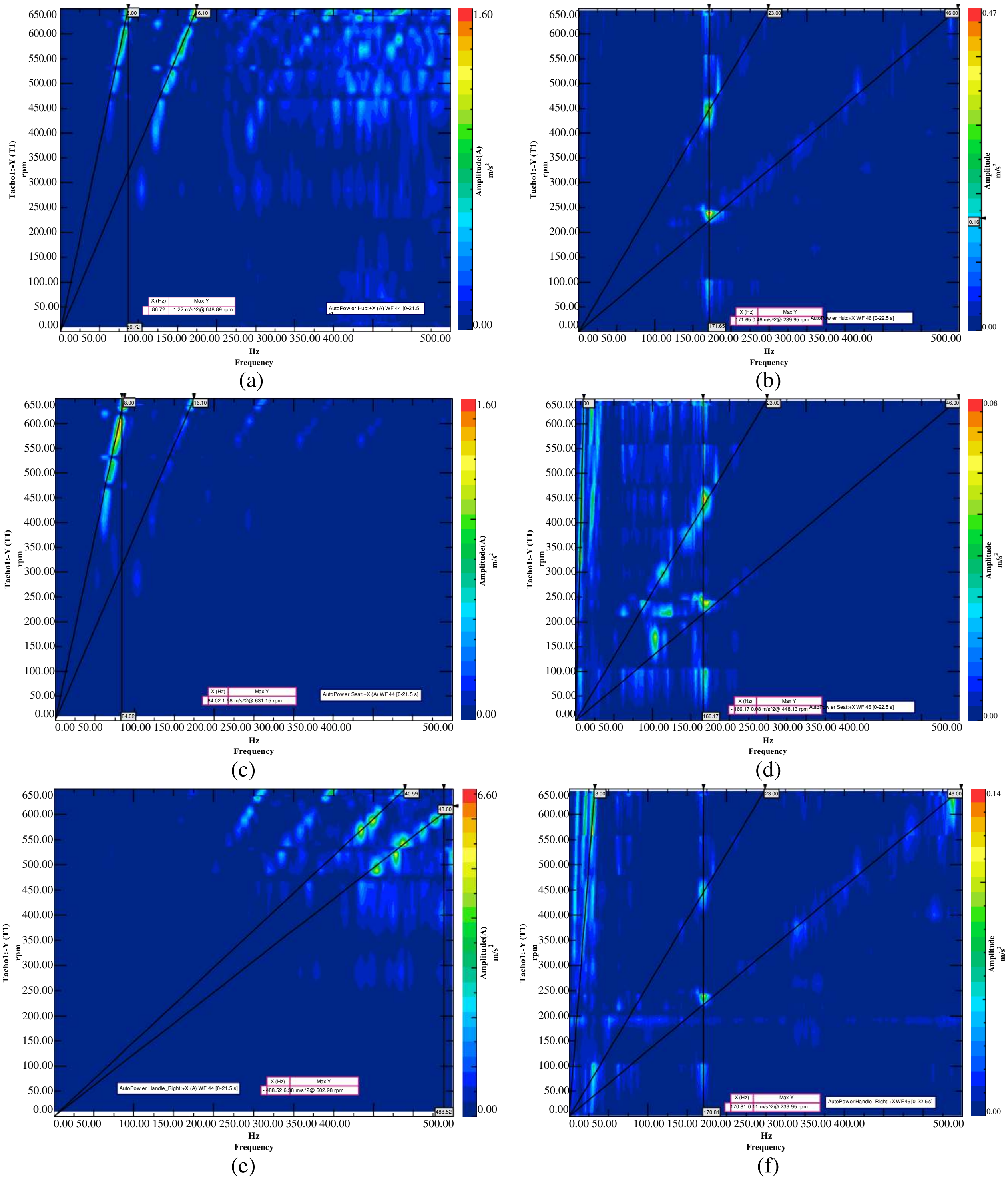
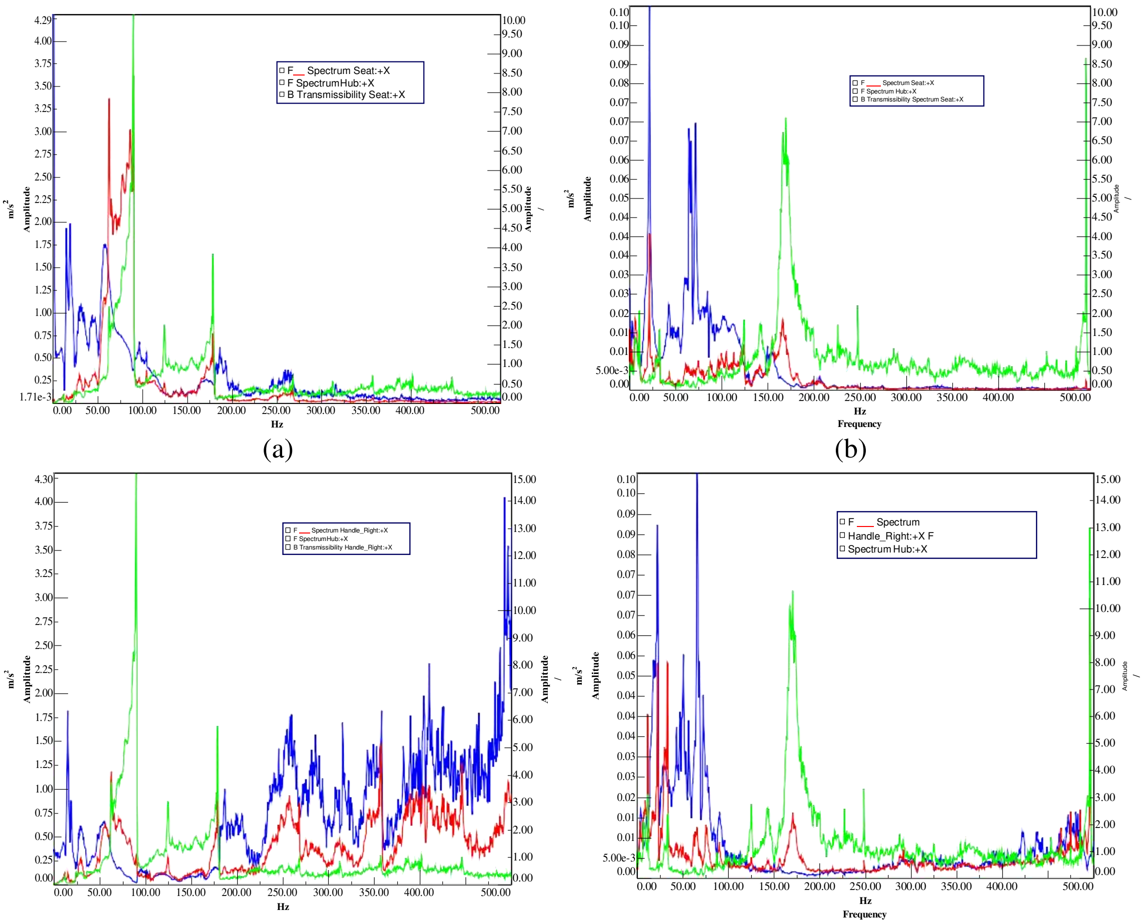


Figure3. Campbell diagram illustrating orders of frequency at different locations. Campbell diagram at hub for, (a) conventional scooter (b) electric scooter. Campbell diagram at seat for, (c) conventional scooter (d) electric scooter. Campbell diagram at handlebar for, (e) conventional scooter (f) electric scooter.

4. Results and discussions

4.1 Transmissibility

Transmissibility of vibrations from the source is identified by observing the displacement spectrums near the source and at the target. The graphs in figure 4 represent the transmissibility function between target and source on the right vertical axis; on the left vertical axis the response spectrum of the source (hub) and target (seat and handlebar) as a function of frequency. In both conventional and electric scooter, the displacement transmissibility appears to be very high below 100Hz causing amplification in energy transfer to seat with corresponding acceleration amplitudes and beyond 100Hz the vibration isolation is clearly observed. It is interesting to note, on one hand, the vibration response of the handlebar of a conventional scooter is amplified beyond 100 Hz and at the frequency of 178Hz is shows the maximum value. And the same has also been observed in the respective Campbell diagram in 40th and 48th order with respect to wheel speed. On the other hand, handlebar in an electric vehicle is showing amplified vibrations below 100Hz and beyond that good vibrational isolation is observed.



(d)

Figure 4. Acceleration responses on the left vertical axis and transmissibility ratio of target locations on the right vertical axis. Transmissibility at the seat for (a) conventional scooter, (b) electric scooter. Transmissibility at handlebar for (c) conventional scooter, (d) electric scooter.

4.2 Vibration Dose Value (VDV)

Vibration Dose value is one of the important metrics to assess the perception of the overall vibration level of the rider. VDV always accumulates for the vibration exposure and does not decay during periods of the low value of vibration magnitude. As recommended by the ISO 2631 standard, daily vibration dose value (VDV) in the region of 15 ($m/s^{1.75}$) usually causes severe discomfort and health-related problems. The assessment of vibration in a vehicle depends upon the method of measurement and evaluation of human responses. ISO 2631 and ANSI S3.18 are mainly used to evaluate the whole-body vibrations of a driver in a vehicle. Table 1 compares the mean VDV for a conventional and electric scooter for the target locations in all three directions. In the conventional case, the mean VDV obtained for seat contact in all the three directions is more than daily vibration dose value and at handlebar only in the longitudinal direction, the value is severe. Whereas in the case of the electric scooter it is observed that the mean VDV value at both target locations is below 1 m/s$^{1.75}$, which are well within the ISO2631 standards for good ride comfort.

Table 1. Comparison of Vibration Dose Value (VDV) (m/s^1.75) at target locations.

Test Vehicle	Conventional Scooter			Electric Scooter		
Location	X direction	Y direction	Z direction	X direction	Y direction	Z direction
Handle bar	26.312	5.656	2.353	0.200	0.116	0.062
Seat	30.561	28.753	18.996	0.451	0.261	0.225

5. Conclusion

The order analysis method is used to extract the critical orders and frequency to understand the vibration behavior in scooters having different excitation sources like engine and hub motor. 8th and 16th orders are observed to be critical for engine operated scooter due to engine excitations and 23rd and 46th orders are observed in motorized wheel scooter having wheel speed as reference speed. It is concluded that the vibration level perceived in electric scooter is far lower than that of its conventional counterpart and higher resonating frequencies are not perceived by driver which improves drivers comfort whereas in conventional scooter the lower resonating frequencies causes high discomfort for rider due to frequencies within human perception range also displacement transmissibility and VDV values are estimated to support the observations. However, this observation is limited by considering power drive sources alone. Further investigation is needed to account another important source due to tire-road interaction. The coupled effect of both power drive and road interaction will bring in the actual rider comfort/discomfort level.

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