

Resolution of a Low Speed Vehicle Vibration Issue in EV Mode for a Hybrid Vehicle Prototype

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ABSTRACT

A vehicle vibration issue emerged for a hybrid prototype during low speed driving in EV mode. This work is focused on the effort to identify the root cause and resolve the issue. The endeavor begins by performing a motor test in moderate acceleration with an imposed constant torque load. All relevant information is simultaneously recorded, including vehicle speed, vibration of motor structure and seat track, motor rpm, voltage and current signals, etc. Then analyses are carried out to strive for a better understanding of the vibration characteristics and identify its mechanism. It is found that the torque ripple from the driving motor is the root cause of the low speed vehicle vibration in EV mode, and the torque ripple is found to be induced by the current distortion resulted from the current sensor drift and electromagnetic interference due to high current signals. Finally, a countermeasure is in place which is basically a remedy strategy involving a dynamic compensation technique, a new three-phase cable design with better shielding capability, and a revised layout configuration. As a result, the motor torque ripple is reduced and the vehicle vibration issue is resolved.

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INTRODUCTION

Due to increasingly stringent legal requirements regarding fuel economy and emission standards, the research and development of new energy vehicles are being carried out by almost all automotive OEM's today, and HEV (Hybrid electric vehicle) market penetration is continuously on the rise. HEV's differ considerably from conventional vehicles in terms of power flow and package as an HEV is generally equipped with a power motor, power battery, inverter, and electric pump et al in addition to the components found in a traditional vehicle. The motor is normally integrated into one HEV power-train system along with the engine, transmission and reducer. The structural change of HEV necessary to accommodate the added components carries with it the complexity and diversity of principles and modes, adding new challenges for NVH development effort. However, customers' expectation in NVH refinement of an HEV is still the same as that of a traditional vehicle.

Up to now, research works on HEV's NVH attribute have been carried out extensively. Toyota Motor Corporation has accomplished a series of systematic and thorough studies, and has achieved remarkable results in the field of engine start/stop NVH, driven motor NVH, powertrain system torsional oscillation, mounting system dynamic characteristics and so on [1][2][3]. Nissan Motor Corporation [4][5] has developed a shaking vibration control system

designed specifically for LEAF, a popular electric vehicle brand, and also adapted the technology to other hybrid vehicle lines. It possesses quick motor responsive characteristics and is able to eliminate discomforting vibrations even when a vehicle operates at the maximum acceleration. The problem of severe longitudinal flutter during vehicle starting in motor-drive mode in a newly developed hybrid electric car is investigated in [6], with vibration source and control scheme delved into. Combining experimental study and CAE method, the ride comfort is significantly improved. In [7], the structural characteristics of hybrid electric vehicles is analyzed and methods of vibration and noise control are described, with a case of vibration control in low speed driving presented synoptically.

According to a widely adopted control strategy of HEV's, the engine should not operate under low speed driving conditions in order to improve fuel economy and reduce emission pollution with the premise that the SOC (state of charge) of the power battery is sufficiently high [8]. Under these circumstances, the issue of low speed vehicle vibration in EV mode might surface if the parameters of the power system are not selected to be compatible [6]. From the perspective of control strategy optimization and structural improvement on motor control system, this work concentrates on the containment of vehicle low speed vibration in EV mode for a hybrid vehicle prototype.

1. HEV POWER SYSTEM ARCHITECTURE

The architecture of an HEV power system is laid out in [Figure 1](#), which includes a gasoline engine, a five-speed AMT (automated manual transmission), a 4-pole PMSM (permanent magnet synchronous motor), a nickel-hydrogen power battery, a DCDC converter, a BSG (belt start generator), and other key components such as the motor controller etc. The transmission is the electromechanical coupling type as shown in [Figure 2](#). The internal structure of the PMSM is displayed in [Figure 3](#). The most notable feature of the power system is the integrated design of the driving motor and transmission, which can help the vehicle achieve a good driving performance in EV mode.

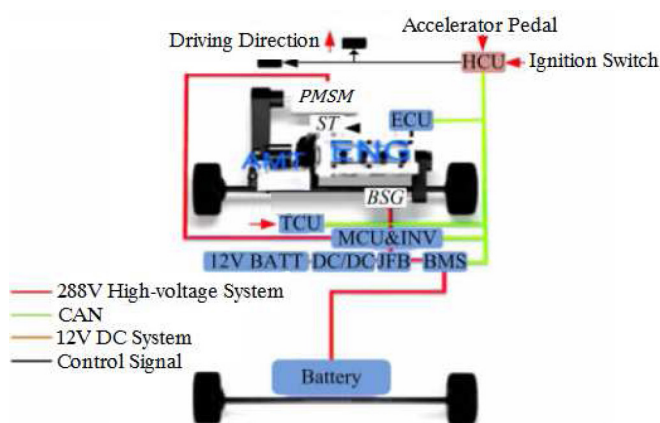


Figure 1. HEV power system architecture.

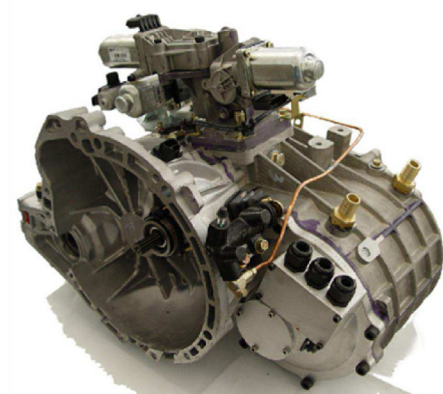


Figure 2. Electromechanically coupled transmission.



Figure 3. Internal structure of PMSM.

2. ANALYSIS OF LOW SPEED VEHICLE VIBRATION

After an HEV starts in EV mode, with both the accelerator pedal and brake pedal released, the vehicle will keep cruising on horizontal pavement or crawling upward on a gentle slope at the lowest stable speed of about 5 km/h. Under these conditions, an obvious low frequency vibration on seat and steering wheel can be felt. If the vehicle slowly accelerates to higher speeds in EV mode or HEV mode, at some point the engine will start, and after that the tangible vibration will disappear immediately.

2.1. Data Acquisition

As the phenomenon only occurs in EV mode, a preliminary judgment would be that the vibration is excited by the driving motor and is transmitted through the drive system to the passenger compartment. Accordingly, acceleration transducers are placed on the seat track and the driving motor housing as pictured in [Figure 4](#). The HEV starts and accelerates slowly with a constant torque of 20 Nm which is imposed by a CAN bus on a horizontal pavement, and the vibration acceleration of seat track and motor housing, vehicle speed, rotational speed and phase current of the motor are acquired synchronously.

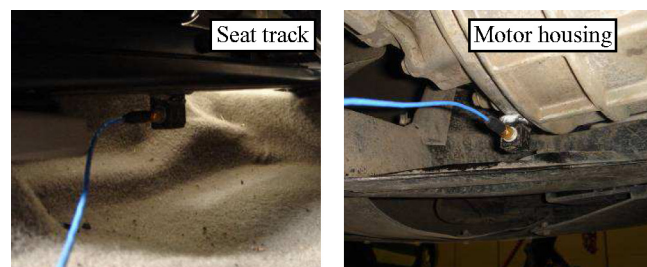


Figure 4. Acceleration transducer placement.

2.2. Data Analysis

2.2.1. Vibration Analysis

The frequency-domain spectrums of motor speed fluctuation, the accelerations of seat track and motor housing in Z direction are displayed with respect to the motor rotational speed as shown in [Figures 5](#), [6](#) and [7](#) respectively. It can be seen that all spectrums have a 4th order content coinciding with the number of motor poles. In light of this observation together with the research results on NVH characteristics of the motor reported in [9], it is evident that the major vibration and noise orders generated by the motor are the multiples of the number of motor poles. Therefore it can be concluded that the torque ripple gives rise to the motor speed fluctuation that excites the low speed vehicle vibration in EV mode.

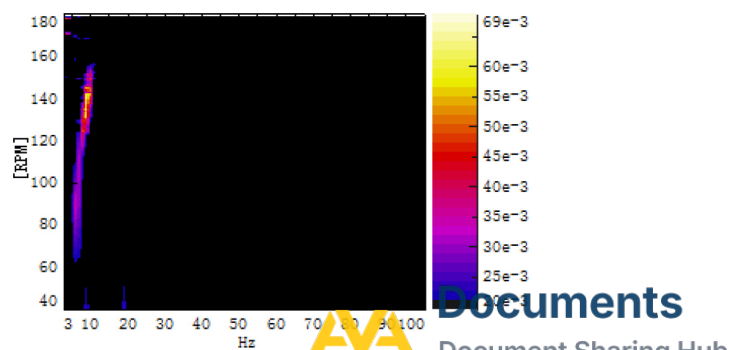


Figure 5. Spectrum of motor speed ripple.

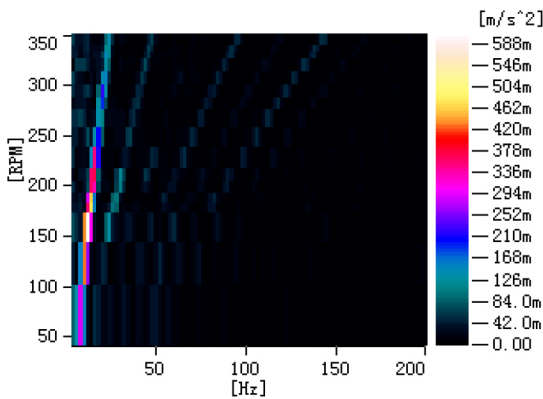


Figure 6. Spectrum of seat track acceleration in Z direction.

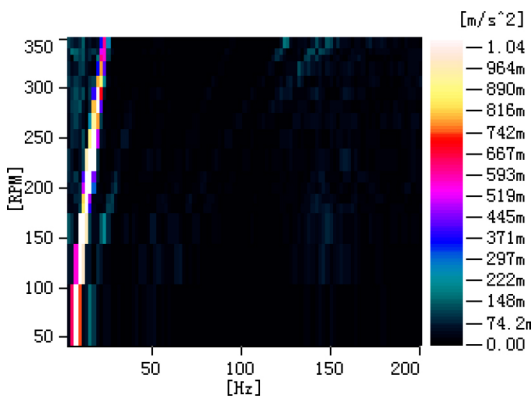


Figure 7. Spectrum of motor housing acceleration in Z direction.

2.2.2. Phase Current Analysis

Five segments are extracted from the time-domain signals of Phase-C current chronologically and the waveforms are displayed in Figure 8. It is apparent that there exists a current waveform distortion for the driving motor, which becomes more and more pronounced with the elapse of time. Moreover, the spectrum of Phase-C current of the motor is processed with respect to the motor rotational speed and the result is shown in Figure 9, where the 4th motor order shows up as well.

The formula for calculating the PMSM torque is as follows [10]:

$$T = 1.5 \times \frac{EI}{\Omega},$$

where T is the motor torque, E is the counter electromotive force, I is the phase current and Ω is the angular velocity of the rotor.

According to the above formula, the motor torque is proportional to the phase current, and therefore the current distortion directly leads to the generation of motor torque ripple. Consequently, controlling the waveform distortion of the motor phase current is one of the effective methods to resolve the issue of low speed vehicle vibration for this HEV.

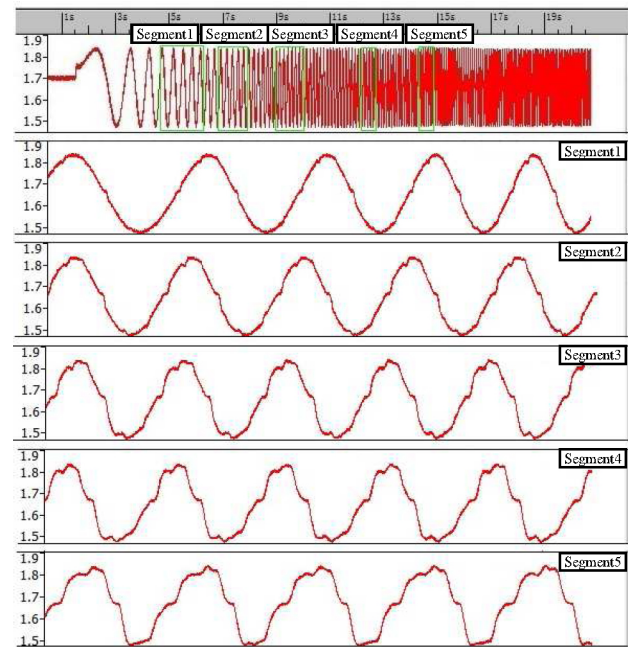


Figure 8. The waveforms of Phase-C current of driving motor.

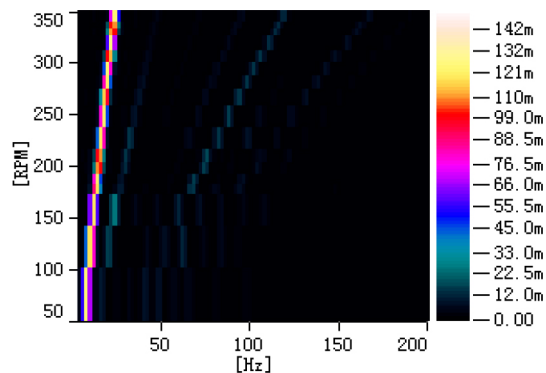


Figure 9. Frequency-domain spectrum of Phase-C current.

3. ANALYSIS AND OPTIMIZATION OF CURRENT WAVEFORM DISTORTION

The current waveform distortion, one of the major root causes of PMSM torque ripple, has been the subject of much research endeavor in an effort to control the distortion and stabilize the motor torque output. The mechanism of phase current waveform distortion is analyzed theoretically in [11], and a current compensation scheme is proposed and applied to the suppression of periodic torque ripples. The mechanism of current waveform distortion in PMSM is elucidated in [12] as well, and a control strategy is proposed, which can effectively remedy the current waveform distortion. The adverse impact of sensor drift on the fluctuation of the PMSM torque is discussed in [13], and an online calibration strategy is proposed for current sensor drift based on a spectrum analysis of sampled current and a predefined compensation strategy, which can eliminate the offset due to sensor drift.