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Original citation:
Bin Raja Ahsan Shah, Raja Mazuir, Cheng, Caizhen, Jones, R. Peter and Pawar, Jasjit (2012) Shuffle frequency migration of 4WD vehicle. In: Regional Conference on Automotive Research, Kuala Lumpur, Malaysia, 14-15 Dec 2011 (No.P023). pp. 1-5.
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Shuffle Frequency Migration of 4WD Vehicle

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Keywords: Torsional model, driveability, frequency migration, system modeling, 4WD vehicle, driveline, dual mass flywheel.

Abstract. This paper explains the method to examine the driveability of Four Wheels Drive vehicle. One of key elements to assess the vehicle driveability is to expose the vehicle under harsh driving conditions such as feeding the crankshaft with wide open throttle torque within a short period of time. As a result of this abrupt torque excitation, the vehicle is expected to generate low frequency responses and deliver discomfort feelings induced by resonance effects on sensitive human organs. Understanding the interaction across vehicle component levels is imperative to address the root cause of driveability issues. Frequency migration analysis was carried out to determine the prevailing factors and sub-system components that control this occurrence. Matrices consisting of a range of frequencies have been structured and analysed to precisely pinpoint the sensitivity of vehicle shuffle frequency migration based on different operating modes.

RESEARCH MOTIVATION

The research on vibration response in Four Wheel Drive (4WD) vehicle system is important to examine the interaction between the driver and vehicle, particularly at low speed events. The vehicle generally will generate a frequency range between 2 Hz and 10 Hz that affects the human body and can cause motion sickness [1].

To study the driveability behaviour of the vehicle, a full nonlinear model with 550 Degree of Freedom (DOF) was previously developed in ADAMS platform. However, the model was only good for design verification but not for vehicle component tuning. This problem has resulted in the development of reduced order of a separate Torsional Model and a Fore-Aft Model using the same modelling environment, which were then correlated with the ADAMS full nonlinear model as well as the vehicle testing data [2]. The reduced order of these separate sub-system models were derived from the full nonlinear model using strain energy method. Nevertheless, the models were not connected and the interaction between these two subsystems was not well captured to represent the actual physical behaviour of the vehicle system.

This paper develops a method to couple these two sub-system models and demonstrates the actual components interaction in terms of the frequency migration and sensitivity to different operating modes. Dymola modelling platform [3] has been used to build the model of vehicle system based on the open-source Modelica language. From the simulation result, the interaction between vehicle system components at low frequency can be understood and identify the most influential parameters to improve the vehicle driveability. In the remaining of this paper, the modelling methods, analysis results and conclusion of this research are presented.

VEHICLE ARCHITECTURE AND REDUCED ORDER MODEL

The architecture of the vehicle model was derived from the existing 4x4 vehicle platform with 2.2L Turbo Diesel engine mounted in East-West orientation with 6 speed manual transmission. The engine produced 400 Nm torque with maximum engine speed at 4000 rpm. The driveline mode was switchable between Front Wheel Drive (FWD) to 4WD by controlling a rear differential unit.

The model consists of all drive-train subsystems, chassis components and compliances, which were constraint on longitudinal direction only except the Power Unit. The actual characterisations of the every component were signified by merging the torsional and fore-aft elements. The interaction of the drive-train and chassis systems was captured by a nonlinear tyre model in longitudinal direction, which was developed from standard tyre parameters fitted on this particular vehicle. Pajecka Magic Formula was used to generate the 3 dimensional data (*see Fig.1*). Principally, the road surface coefficient decreased as a function of vehicle speed; hence reduced the tractive force further. But this effect has been neglected in this model.

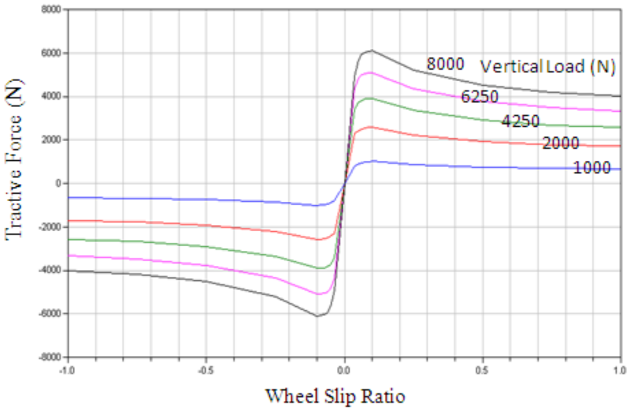

Fig. 1: Tyre model

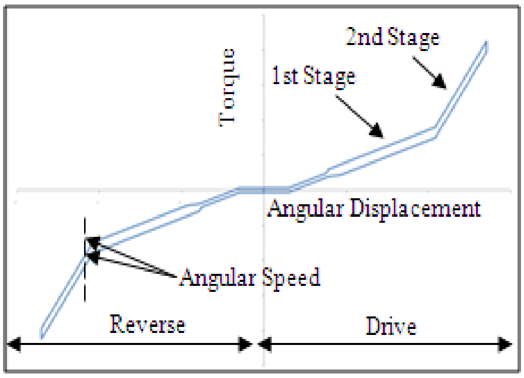

Fig. 2: DMF characteristics

The model has 40 DOF from 4 sub-systems and driver environment. Each component of the sub-systems has the combination of torsional elements, masses, inertias and compliances. The Power Unit with 3 DOF was connected to the Transmission via Dual Mass Flywheel (DMF), and its motion was restricted by left and right hands mass carrier compliances. The DMF has two stages, namely primary stage and secondary stage (*see Fig. 2*). Each of the stage was dependant of relative angular displacement and angular speed of the primary mass and secondary mass.

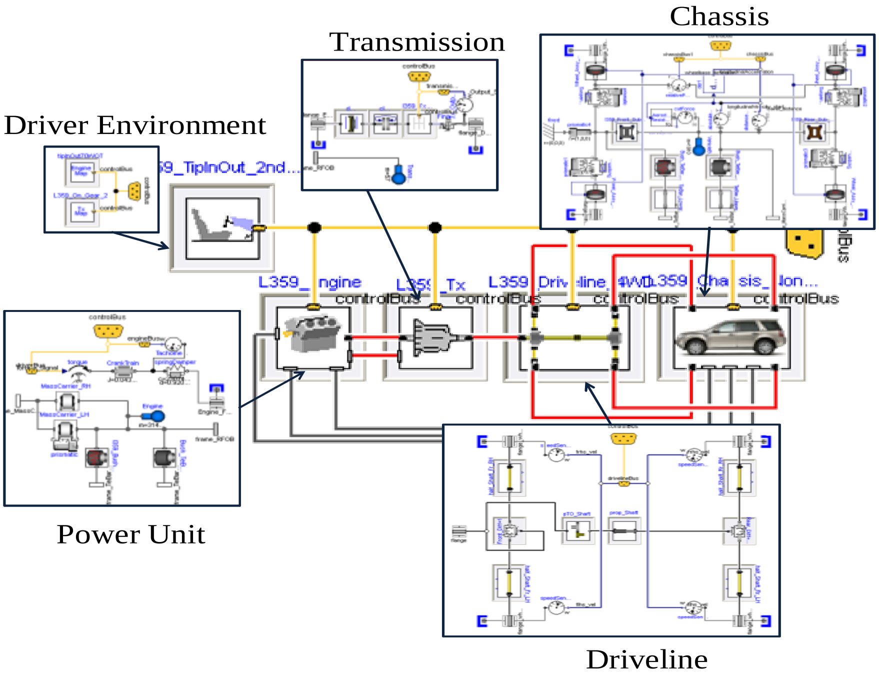

Fig. 3: Coupled model of 4WD vehicle system

The integrated front differential inside the transmission split the torque to the front half-shafts and Power Take Off (PTO) unit. The rear differential, which was connected to PTO, then provided the same speed to right and left side of the rear half-shafts. Both of the front and rear half-shafts were connected to the tyre model to provide the longitudinal force that drives the vehicle as a function of vertical load and wheel slip ratio. The mechanical losses in the gearing system were neglected. The details of the vehicle architecture are shown in *Fig. 3*.

The simulation parameters were set-up to be the same as the ADAMS full nonlinear model. The simulation results have been correlated with those from ADAMS full nonlinear model and vehicle measurement data [2, 4].

FREQUENCY ANALYSIS

State space method was used to study the sensitivity of the vehicle system under different operating modes. To run the modal analysis, the torque input was set to zero and the output signals were extracted from the components. Then the model was linearised using Dassl solver with *no inline integration* method. The outputs of the linearisation process include the ABCD matrix of state space representation, which were used for the modal analysis.

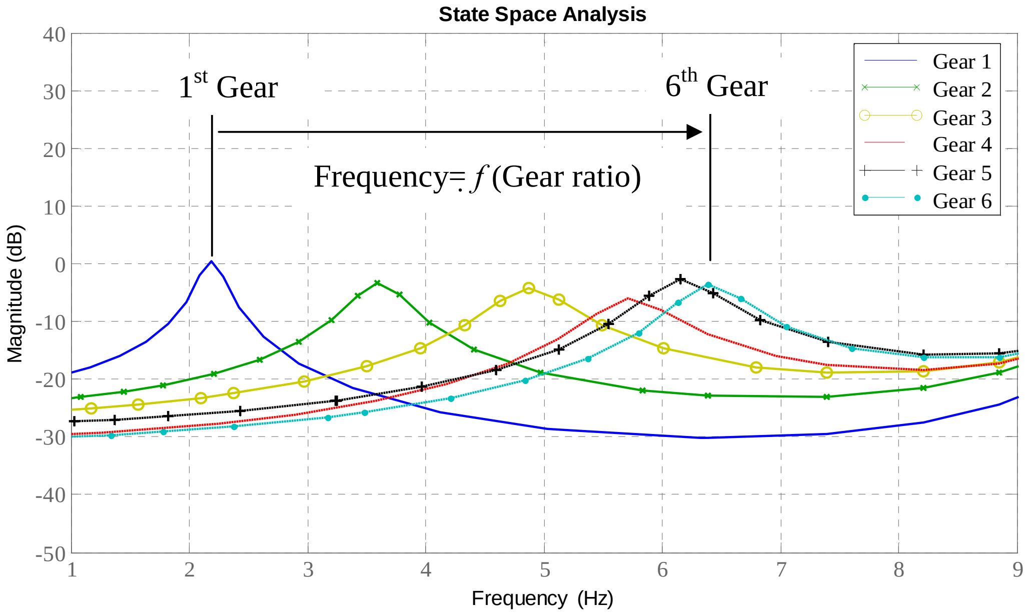

Fig. 4: Migration of driveline shuffle mode at 4WD, secondary stage, no input torque and road μ=0.85 (longitudinal seat acceleration magnitude)

Fig. 4 shows the results of the state space analysis of the driveline mode as a function of seat acceleration magnitudes. In static analysis at 4WD mode with secondary stage of DMF, the driveline shuffle frequencies is spread-out from 2.2 Hz in 1st gear to 6.4 Hz in 6th gear. It is also observed that the peak to peak distance is getting smaller as the gear is shifted up. The largest magnitude stretches between 1st and 2nd gear ratio, with a step ratio of 1.845. The close ratio between 5th and 6th gears influences the frequency gap.

In this paper, the migration of the frequency have been analysed to identify the most influential components behaviour upon the changes of effective torsional compliance as it winding up against the vehicle inertia through the wheel. From the state space analysis, the frequencies of the driveline shuffle mode in *Table 1* migrate as a function of gear ratio of the transmission. This incremental is due to the change of the effective driveline stiffness, k as the gear ratio increase, where the mass of the vehicle system, m remains the same as well as the surface coefficient of the road. The calculation for the frequency denotes by $\sqrt{(k/m)}$ which explains the pattern of the migration. The migration of the frequencies is also much dependant on the stage of the DMF. From *Fig. 1*, it can be seen the secondary stage of the DMF is stiffer than primary stage. As the input torque winding up the system to the transition point, it builds up the effective stiffness of the driveline system. Hence, increases the driveline shuffle frequency. Adding the rear halfshaft stiffness into the system by changing the operating mode to 4WD, also increases the effective torsional stiffness.

Table 1: Frequency migration at no input torque, surface coefficient and road μ = 0.85

Gear Ratio	Primary Stage		Secondary Stage	
	FWD	**4WD**	**FWD**	**4WD**
1st (3.75)	1.8	2.1	1.9	2.2
2nd (1.905)	2.9	3.3	3.1	3.6
3rd (1.194)	3.8	4.0	4.4	4.9
4th (0.833)	4.2	4.4	5.3	5.7
5th (0.652)	4.4	4.5	5.9	6.2
6th (0.54)	4.5	4.6	6.2	6.4

OFF-LINE SIMULATION OF PULL-AWAY EVENT

For the off-line simulation, the vehicle was set-up to run with two operating modes, FWD and 4WD, and accelerated from 2000 rpm at 1st gear ratio with 50% throttle position to achieve the 2nd stage of the DMF. The observation from the results in *Fig. 5* shows that the frequencies generated by both driveline modes are the same as the state space analysis results *(Table 1)*, which are at 1.9 Hz and 2.2 Hz respectively. The off-line simulation demonstrates that the driveline subsystem is the dominant factor for vehicle shuffle mode at low frequency response, which was also emphasized by previous research on the vehicle response at low speed events [4, 5].

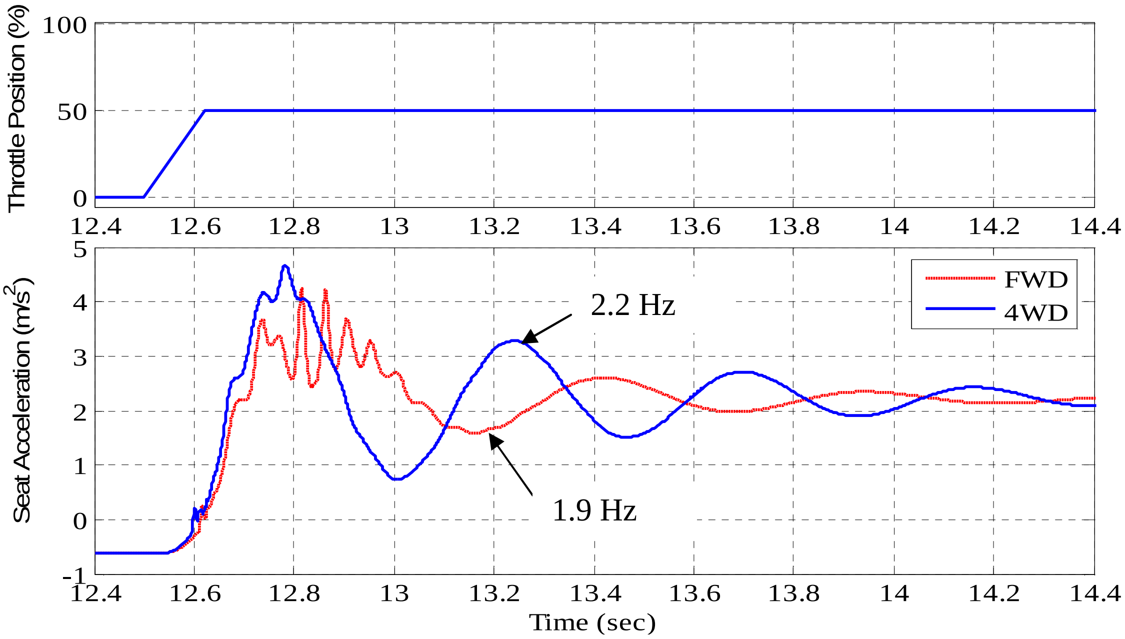

Fig. 5: Seat acceleration (Pull-away event at 1st gear, 50% throttle position and road μ=0.85)

The frequency response seen on the 1st peak of the FWD mode is higher than 4WD. In FWD mode, the engine torque is delivered 100% to the front wheels and when the vehicle starts to accelerate, the weight is transferred to the rear ends. From *Fig. 6*, as the front halfshaft winding up against the tarmac, the wheel's tractive force reduces significantly once it enters the nonlinear region *(see Fig. 1)* and generates higher slip. Since the vehicle acceleration is a function of wheel slip ratio, it responses the same behaviour as the wheel slip together with the interaction of the nonlinear compliance of the system.

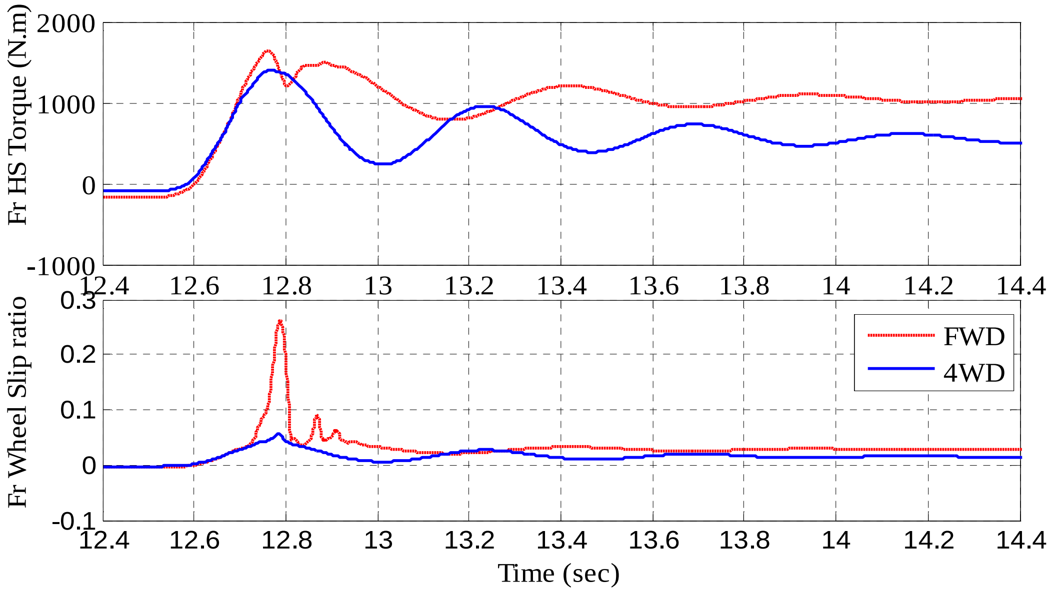

Fig. 6: Halfshaft torque and wheel sip ratio (Pullaway events at 1^{st} gear, 50% throttle position and road μ=0.85)

CONCLUSION

The Dymola coupled model of 4WD vehicle system has performed equally as good as the ADAMS full nonlinear system. From state space analysis, the frequencies migration is observed at different operating modes between 1.9 Hz to 6.4 Hz. The migration is very much influenced by the gear ratios, driveline and DMF. The results were also verified by the off-line simulation, where it generated the same frequencies at the same operating mode. The vehicle model has produced frequencies that can affect the human organs during low speed events. The oscillation was mainly dominated by the driveline, where these frequencies can be shifted by tuning its mechanical properties or implementing an engine active damping strategy, which are part of the future works for this project.

ACKNOWLEDGEMENT

The authors would like to thank Jaguar Land Rover and Warwick Manufacturing Group (WMG) for providing us the support and information in this research project.

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