

Prediction of Low Frequency Vibration Caused by Power Train Using Multi-Body Dynamics

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1. ABSTRACT

To predict accurately low frequency vibration caused by the power train, it is essential to consider both the non-steady state characteristics of the engine exciting force and the frequency and amplitude dependent non-linear characteristics of the various components of the transfer system. Conventional steady-state linear analysis using finite element methods (FEM) is unable to handle these characteristics, and as a result, its prediction accuracy is insufficient. This research is based on a multi-body dynamics (MBD) model that is capable of handling non-steady state and non-linear analysis, into which in-cylinder pressure prediction methods were incorporated. The technology developed took into consideration the non-linear characteristics of the transfer system and thereby enabled highly accurate predictions of all systems associated with the vibration reaching the vehicle body. Engine in-cylinder pressure predictions based on empirical formulas were combined with MBD models including those for the engine mounts, the drive shaft constant velocity universal joints and the exhaust pipe ball joints. The prediction technology was used to predict low frequency vibration caused by the power train such as cranking vibration, idle vibration, and lock-up vibration in actual operating conditions and the predicted results correlated well with actual vehicle test results. Input contribution analysis of cranking vibration and idle vibration was also carried out to clarify the mechanisms at work.

2. INTRODUCTION

To produce vehicles with competitive NV quality, Noise and vibration performance predictions are intensively carried out using FEM from initial stages of the development. However, when phenomena are transient or include frequency or amplitude dependant nonlinearity of transfer systems, it is not possible to research sufficiently because of prediction inaccuracy made by conventional steady-state linear models. To confront these difficulties, several simulation methods using multi-body dynamics analysis have been reported over the last few years.⁽¹⁾⁻⁽³⁾ Yet, the objects in these methods are limited to sub-assembly, and there is no prediction technology that considers all vehicle systems from engine input to body response for analyzing low frequency vibration. This research is an attempt to develop such prediction technology. This technology utilizes multi-body dynamics analysis and enables accurate mechanism analysis of all vehicle systems, from engine in-cylinder pressure to non-linear characteristics of the vibration in the transfer system and vehicle body. This technology was used to predict the following low frequency vibration phenomena caused by the power train such as cranking vibration, idle vibration, and lock-up vibration.

Figure 1 shows the direction of vibration force transfer between the main components associated with the low frequency vibration phenomena caused by the power train and transferred to the body.

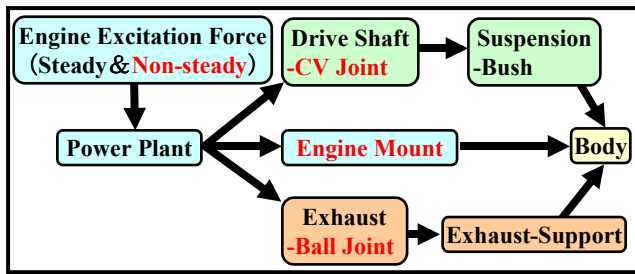


Fig. 1 Directions of Vibration Force Transfer

In analyzing cranking vibration, it is important that the non-steady state characteristics of the engine exciting force are considered. Also, to ensure a sufficient level of prediction accuracy, it is necessary to consider the non-linear characteristics of the transfer system, comprised of the engine mounts, the drive shaft constant velocity universal joints and the exhaust pipe ball joints. While for idle vibration and lock-up vibration it is typical for the steady response of a vehicle to be evaluated, it is also necessary for non-linear characteristics should be considered. This is especially true with drive shafts, which interact with the suspensions, affect the suspension vibration characteristics, and are important transfer paths for conveying drive forces in idle vibration in D-range and lock-up vibration.

3. PREDICTION METHODS

An MBD model was developed to analyze all of the vehicle systems related to the non-steady state vibration characteristics of the engine exciting force and the non-linear characteristics of vibration in the engine mounts, the drive shaft constant velocity joints and the exhaust pipe ball joints. Figure 2 shows the overview of the MBD model for a front-wheel drive vehicle with an inline 4-cylinder engine.

3.1 ENGINE EXCITING FORCE - In order to predict the non-steady state and transient input forces from the engine, in-cylinder pressure prediction methods based on empirical formula were adopted.⁽⁴⁾ It was possible to calculate torque and reciprocating inertia force by modeling engine parts such as pistons and crankshaft rotating mechanisms and transmission parts considering torque converter characteristics and gear ratios. Also, since non-steady states, such as due to transient vibration, cause large changes to engine speed and load during stroke cycles, calculation of the interaction of in-cylinder pressure with multi-body systems was made possible.

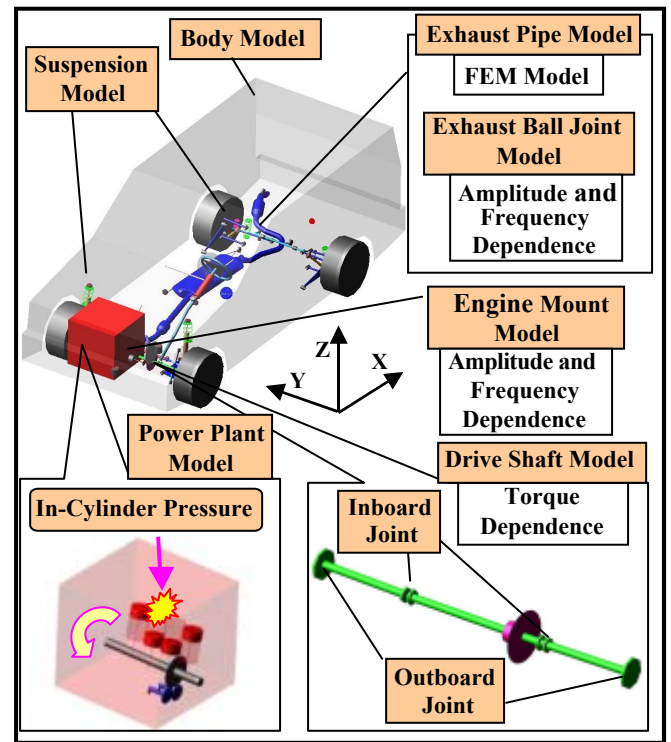


Fig. 2 Overview of MBD Model

3.2 DRIVE SHAFT CONSTANT VELOCITY UNIVERSAL JOINT MODEL - Since internal part friction increases in response to driving torque from the engine, constant velocity universal joint parts may cause changes to vibration transfer characteristics. To evaluate this influence, a bench test of the drive shaft assembly shown in Fig. 3 was carried out. The results demonstrated the existence of torque dependence, amplitude dependence, frequency dependence and rotational velocity dependence. Torque dependence was particularly high when drive shaft was not rotating, such as when the vehicle is idling, as shown in Fig. 4. Frequency dependence was particularly high when drive shaft was rotating, such as during lock-up, as shown in Fig. 5.

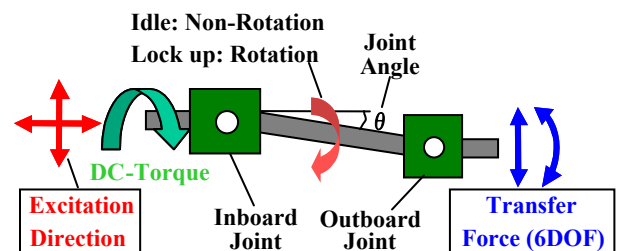


Fig. 3 Bench Test of Drive Shaft Transfer Force

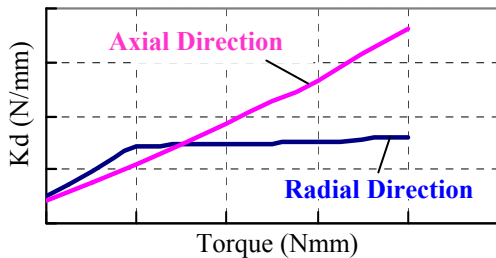


Fig. 4 Dynamic Stiffness when Drive Shaft Not Rotating

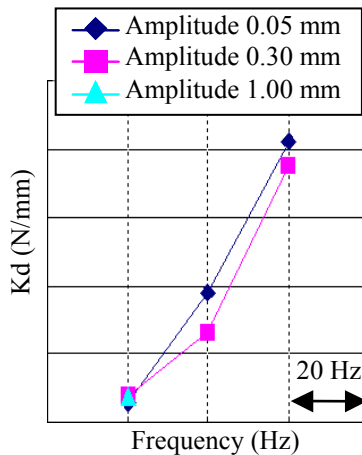


Fig. 5 Dynamic Stiffness when Drive Shaft Rotating

A drive shaft MBD model was made with the required transfer characteristics, and its basic illustration is shown in Fig. 6.

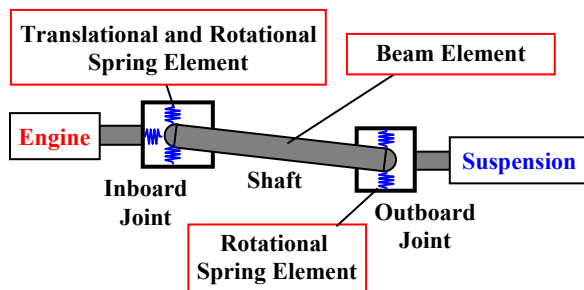


Fig. 6 Drive Shaft Model

The drive shaft model incorporates inboard joint with a translational spring plus damping in the axial direction and a rotational spring plus damping around the radial direction, and outboard joint with a rotational spring plus damping around the radial direction.

3.3 ENGINE MOUNT MODEL - Since the engine mounts modeled for this research include an amplitude and frequency-dependent hydraulic type, a simple physics model as shown in Fig. 7 was used. In the figure, k_1 and k_2 are non-linear elements in proportion to the displacement and the cube of the displacement, and c_1 is a non-linear element in proportion to the velocity and the square of the velocity. Parameters were

identified to represent actual dynamic stiffness and damping characteristics, and the results of which are shown in Fig. 8. The results suitably match the amplitude and frequency dependence of the measured characteristics.

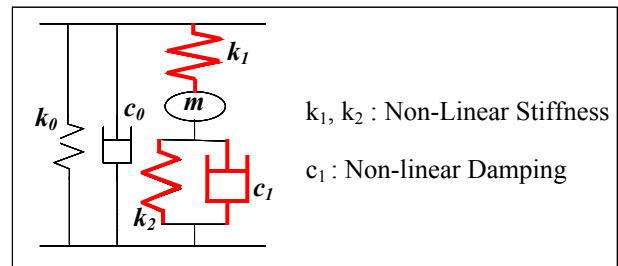


Fig. 7 Engine Mount Model

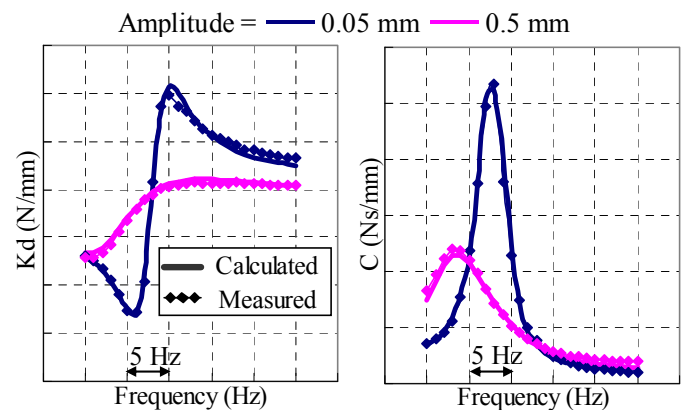


Fig. 8 Identification Results for Hydraulic Engine Mount Model Parameters

3.4 EXHAUST PIPE BALL JOINT MODEL - The construction of an exhaust pipe ball joint used to connect the exhaust pipes, is shown in Fig. 9. The exhaust pipe vibration characteristics include amplitude and frequency dependence caused by the ball joints. Considering these factors, a simple physics model shown in Fig. 10, that also expresses stick-slip, was used. As with the engine mount model, parameters were identified to represent actual dynamic stiffness and damping characteristics, and the results of which are shown in Fig. 11. The results correlate well with the amplitude and frequency dependence of the measured characteristics.

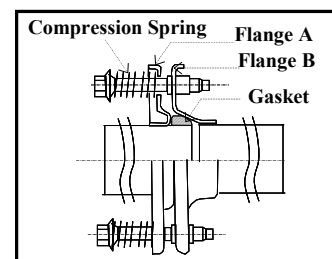


Fig. 9 Ball Joint