Study on Driveline Component Torsional Stiffness Effect on RWD Driveline Torsional Vibration Modes

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Abstract *Research and/or Engineering Questions/Objective* As driveline torsional vibration modes are very critical for RWD vehicle NVH issues, like vehicle shuffle, gear rattle, gear/axle whine, and interior noise booming, it is very helpful to find out how driveline component torsinal stiffness affect driveline torsional vibration modes, that make set the torsional vibration mode target much easier from the very start of driveline development and more effectively tune the driveline torsional vibration modes during refine stage, that way, the major goal of this paper is to find out the RWD driveline torsional vibration mode sensibility to driveline component torsional stiffness, in terms of clutch damper, propshaft, axle shaft and rules how to tune the RWD driveline torsional vibration modes to alleviate torsional vibration induced NVH issues. *Methodology* A RWD SUV driveline lumped mass model is firstly established to predict the 3 most critical torsional modes, then, in-vehicle torsional vibration measurement in this SUV is implemented, and the correlation between the prediction and measurement is judged to decide whether the model can be employed to make driveline torsinal vibration mode sensibility study to driveline component torsional stiffness or not. If the model is accurate, the clutch torsion damper stiffness, propshaft stiffness, axle shaft stiffness are chosen as the parameter, with stiffness increased/decreased 20–80 % compared to original value, to calculate relevant torsional mode for respective component torsional stiffness, hence, the sensibility study can be implemented. *Results* The model prediction correlates very well to the in-vehicle torsional vibration measurement, thus, the model is employed to make driveline torsinal vibration mode sensibility study to driveline component torsional stiffness, as aforementioned way of analysis, to conclude how the driveline

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component torsional stiffness affect the driveline torsional vibration modes. *Limitations of this study*: This study is only limited to RWD driveline, while, FWD driveline is not covered, hence, the FWD driveline torsional vibration mode sensitivity to driveline component torsional stiffness will be the following study. *What does the paper offer that is new in the field in comparison to other works of the author* This paper involves the systematic study on the driveline component torsional stiffness effect on torsional vibration modes, and give some suggestion addressing the driveline torsional modes from the very start of driveline NVH development, while, the author previous work mainly focused on specific problem solving. In this sense, the work in this paper provides study from new angle. *Conclusion* (1) axle shaft stiffness is the dominant factor for 1st torsinal mode, say vehicle shuffle (2) clutch torsion damper stiffness is the dominant factor for 2nd torsional mode, say gear rattle (3) propshaft stiffness is the dominant factor for 3rd torsional mode, say axle whine (4) the study outcome is beneficial for driveline NVH target setting and tuning direction for vehicle shuffle, gear rattle, axle whine.

Keywords Driveline · Torsional vibration · Torsional stiffness · Sensibility study

1 Introduction

Typical RWD driveline consists of engine, transmission, propshaft, rear axle, axle shaft and wheel, that has some inertia and stiffness, hence, specific torsional vibration modes. Under engine torque pulse, these modes will be excited and transmitted to body through rear suspension, leading to interior noise booming [1, 2]. It is very helpful to well distribute the driveline torsional vibration modes, getting round from the sensitive engine excitation rpm, to reduce the torsional vibration induced interior noise. Typically, RWD vehicle is more susceptible to driveline torsional excitation, compared to FWD vehicle, that way, it is very important to well manage the RWD driveline torsinal vibration modes [3].

It is known that torsional stiffness of driveline component do influence the driveline torsional vibration modes [4, 5], while, systematic investigation on how torsional stiffness of clutch damper, propshaft and axle shaft affect driveline torsional vibration modes is rare. In this paper, a RWD SUV is employed, establishing the RWD driveline model, to predict the driveline torsional vibration modes by in-house software. The prediction is validated by in-vehicle testing, therefore, the model is adopted to investigate the RWD driveline torsional vibration mode sensitivity to torsional stiffness of clutch damper, propshaft and axle shaft, as well as the relevant rules, which is meaningful to distribute the torsional vibration modes and expedite the driveline NVH process, from the very start of the vehicle driveline development.

2 Driveline Torsional Vibration Model and Modes

A typical driveline for a front installed engine and rear wheel driven vehicle is shown as Fig. 1 [6], where engine and transmission is longitudinally installed at front end, transmission is connected to rear axle through propshft, and rear axle is connected to wheel through axle shaft.

When implementing trosinoal vibration calculation, the engine, transmission, propshaft, rear axle and rear wheel + body is simplified as 5 inertias, connected by spring has torsional stiffness, to formulate a lumped mass model, shown as Fig. 2.

Based on the driveline torsional vibration theory, the model vibration equation can be written as,

$$J\ddot{\theta} + K\theta = 0$$

$$J = \begin{bmatrix} J_1 & & & \\ & J_2 & & \\ & & \ddots & \\ & & & J_5 \end{bmatrix} \quad k = \begin{bmatrix} K_{12} & -K_{12} & & & \\ -K_{12} & K_{12}+K_{23} & -K_{23} & & \\ & -K_{23} & K_{23}+K_{34}+K_{35} & -K_{34} & -K_{35} \\ & & -K_{34} & K_{34} & \\ & & -K_{35} & & K_{35} \end{bmatrix}$$

In this equation, J1, J2, J3, J4, J5 stand for moment of inertia of engine, transmission, rear axle and whell + body, while, K12, K23, K34, K35 stand for torsional stiffness of clutch damper, propshaft, left and right axle shaft. The equivalent calculation of moment of inertia and torsional stiffness can be referred to [7].

A RWD SUV, equipped with 2.5 L turbocharged diesel and 6-speed MT, whose driveline lumped mass parameters are shown as Table 1.

The in-house software is employed to predict the driveline torsional vibration modes, as in,

1. The 1st mode is a whole vehicle fore-aft vibration, in which engine, transmission and rear axle vibrate torsionally, out of phase to whell + vehicle, and maximal amplitude occurs at engine side. The mode frequency is increased as gear position is higher, and corresponding frequency and shape is shown as Table 2 and Fig. 3. This mode normally is easy to be excited by engine torque pulsation, during tip-in/out maneuver, leading to vehicle fore-aft vibration.
2. The 2nd mode is transmission and rear axle mode, manifesting the modal shape as in phase transmission and rear axle torsional vibration the modal frequency increases, as gear position is lower. The modal frequency and shape is shown as Table 3 and Fig. 4. This mode is prone to be excited by engine torque pulsation, either leading to gear rattle, or transmitting to body through suspension, resulting in interior noise peak.
3. The 3rd mode is rear axle mode, manifesting the modal shape as big amplitude torsional vibration at rear axle. The modal frequency increases, as gear position is higher. The modal frequency and shape is shown as Table 4 and Fig. 5. This mode might be excited by engine torque pulsation, propshaft bending, torsional excitation, resulting in axle whine.

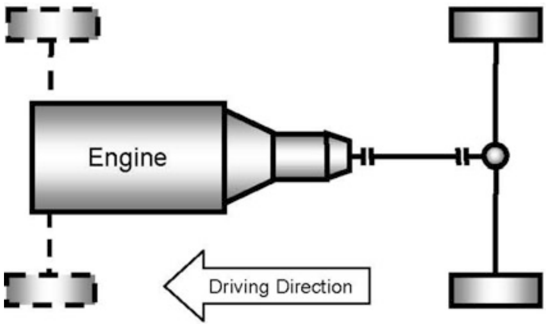


Fig. 1 Typical RWD vehicle driveline

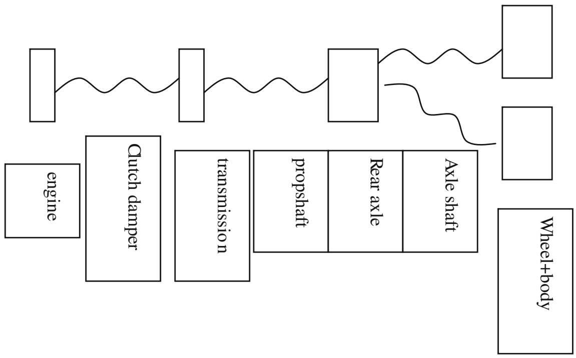


Fig. 2 Driveline model of 5 DOF

Table 1 Driveline lumped mass parameter of a RWD SUV

Item		Engine	Transmission	Rear axle	Wheel + vehicle
Torsional vibration parameter	Gear				
Moment of inertia (Kgm^2)	1	0.29	0.013	0.00055	0.41
	2	0.29	0.013	0.0013	0.93
	3	0.29	0.0152	0.00334	2.46
	4	0.29	0.018	0.0069	5.07
	5	0.29	0.021	0.0098	7.22
	6	0.29	0.025	0.014	10.47
	Reverse	0.29	0.017	0.0046	3.41
		Clutch damper		Propshaft	Axle shaft
Torsional stiffness (Nm/deg)	1	2177.2		830.3	21.6
	2	2177.2		1912.4	49.7
	3	2177.2		5034.7	130.8
	4	2177.2		10382	269.6
	5	2177.2		14784	384
	6	2177.2		21432	556.6
	Reverse	2177.2		6975.2	181.2

Table 2 A SUV 1st drivline torsional vibration mode

	1st gear	2nd gear	3rd gear	4th gear	5th gear	6th gear	Reverse
Modal frequency (Hz)	2.1	3	4.4	5.9	6.8	7.7	5.1

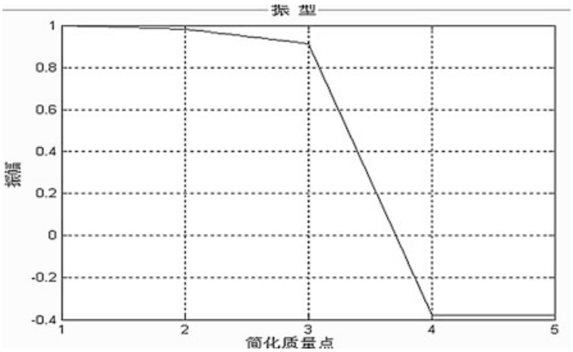


Fig. 3 1st driveline torsional vibration mode

Table 3 A SUV 2nd drivline torsional vibration mode

	1st gear	2nd gear	3rd gear	4th gear	5th gear	6th gear	Reverse
Modal frequency (Hz)	92	89	70	65	60	57	70

3 Validation to Prediction Model

To validate the prediction model and to employ this model to investigate the torsional vibration sensitivity to driveline component trosional stiffness, the in-vehicle driveline torsional vibration measurement is implemented, by installing magnetic pickup close to flywheel ring gear, input shaft gear of transmission, machined gear of rear axle companion flange, to collect the angular acceleration during WOT acceleration in 2nd, 3rd, 4th, 5th, 6th gear, then, the 2nd order angular acceleration frequency of each measurement point could be correlated to prediction results. The magnetic pickup position is shown as Figs. 6, 7, and 8 and the 2nd order angular acceleration of each measurement point is shown as Figs. 9, 10, 11, and 12.

It can be found by investigating the above figures that all 2nd order angular acceleration in each gear has a resonance peak, corresponding the driveline 2nd torsional vibration mode, whose frequency is 87 Hz at 2,600 rpm in 2nd gear,

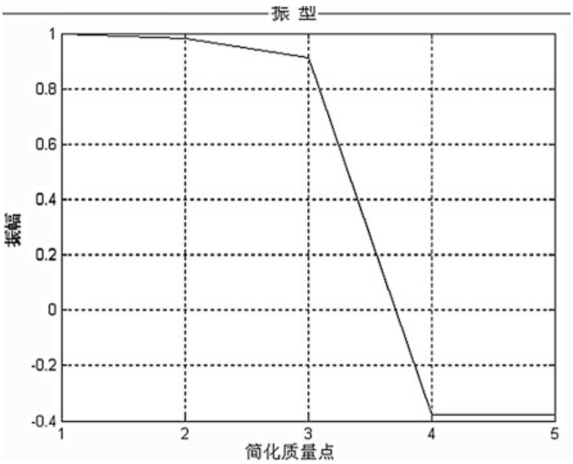


Fig. 4 2nd driveline torsional vibration mode

Table 4 A SUV 3rd drivline torsional vibration mode

	1st gear	2nd gear	3rd gear	4th gear	5th gear	6th gear	Reverse
Modal frequency (Hz)	205	210	221	234	241	249	226

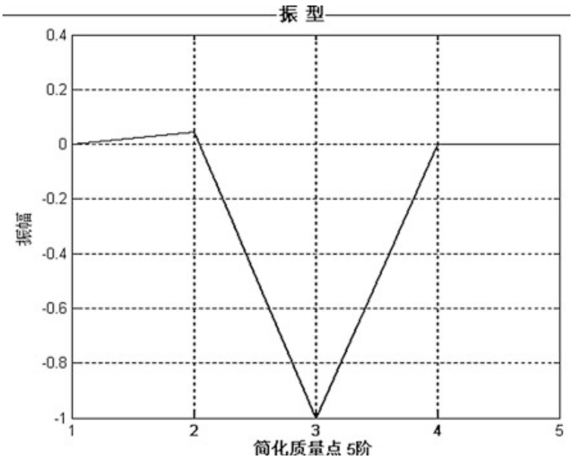


Fig. 5 3rd driveline torsional vibration mode

67 Hz at 2,000 rpm in 3rd gear, 62 Hz at 1,850 rpm in 4th gear, and 58 Hz at 1,750 rpm in 5th gear. The measurement results correlate very well to the prediction results, see Table 5 for comparison, that proves the model, adopted in this paper, can be employed for further driveline related investigation.

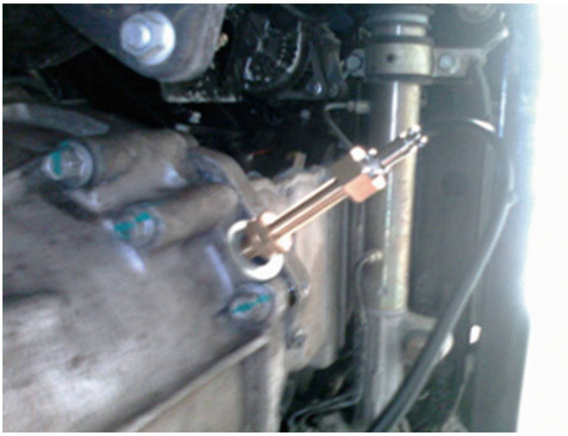


Fig. 6 Pickup at flywheel ring gear

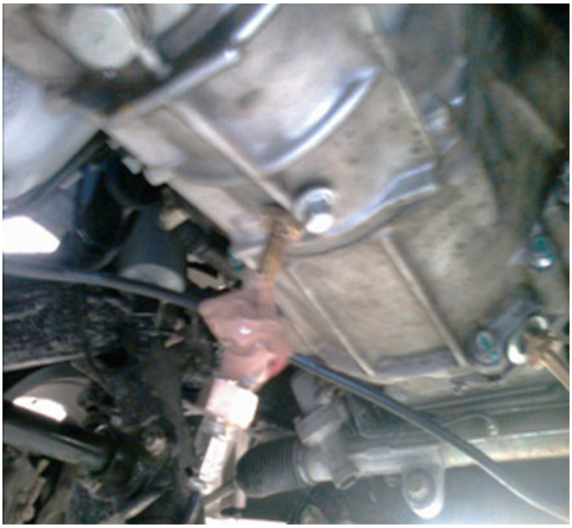


Fig. 7 Pickup at transmission input shaft gear

4 Driveline Torsional Vibration Mode Sensitivity to Driveline Component Torsional Stiffness

Driveline component torsional stiffness affects the driveline torsional vibration modes and engine torque pulsation transmission, hence, it is meaningful to investigate the driveline torsional vibration sensitivity to driveline component torsional stiffness, plus summarizing most dominant parameter to driveline modes and relevant rules, then, the driveline parameters can be chosen, from the very start of vehicle development, to reach satisfactory driveline torsional vibration target.

Fig. 8 Pickup at machined gear of rear axle companion flange

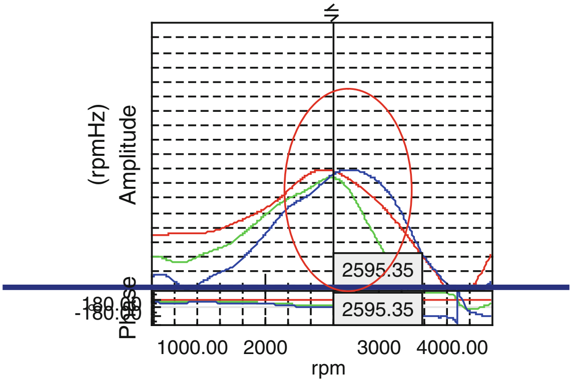


Fig. 9 2nd order torsional vibration acceleration during WOT acceleration in 2nd gear. *Red* line stands for flywheel, *green* line stands for transmission input shaft, *blue* line stands for rear axle input

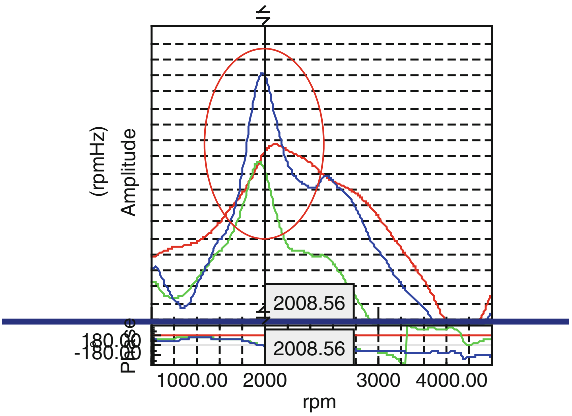


Fig. 10 2nd order torsional vibration acceleration during WOT acceleration in 3rd gear, *red* line stands for flywheel, *green* line stands for transmission input shaft, *blue* line stands for rear axle input

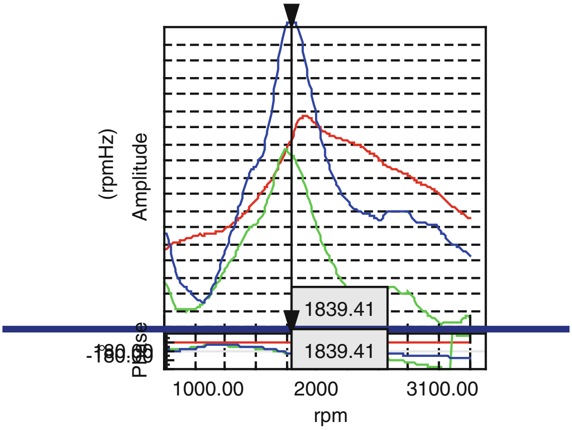


Fig. 11 2nd order torsional vibration acceleration during WOT acceleration in 4th gear, *red* line stands for flywheel, *green* line stands for transmission input shaft, *blue* line stands for rear axle input

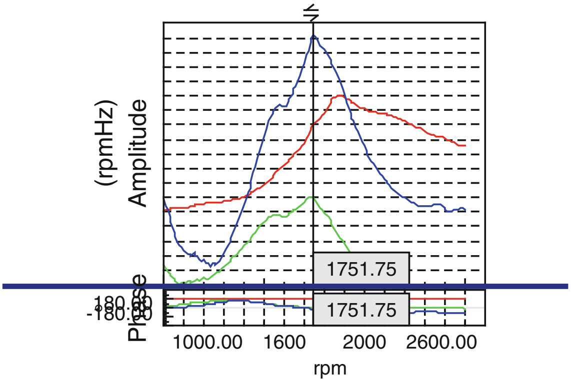


Fig. 12 2nd order torsional vibration acceleration during WOT acceleration in 5th gear, redline stands for flywheel, *green* line stands for transmission input shaft, *blue* line stands for rear axle input

Table 5 Correlation between measurement and prediction

	2nd gear	3rd gear	4th gear	5th gear
Prediction (Hz)	89	70	65	60
Measurement (Hz)	87	67	62	58
Error	2 %	4 %	5 %	3 %

Table 6 Clutch damper torsional stiffness variation

Stiffness increase compared to original value (%)	Stiffness decrease compared to original value (%)
20	20
40	40
60	60
80	80

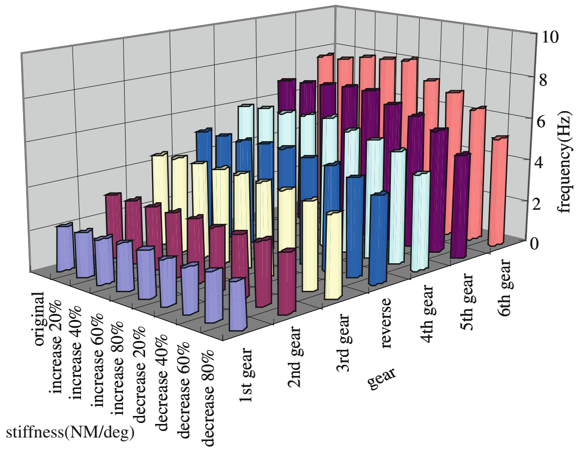


Fig. 13 Driveline 1st mode sensitivity to clutch damper torsional stiffness

4.1 Driveline Torsional Vibration Sensitivity to Clutch Damper Torsional Stiffness

The clutch damper torsional stiffness will be varied as Table 6, in regards to driveline torsional vibration sensitivity to clutch damper torsional stiffness.

Taking the stiffness into in-house software for calculation, the driveline mode sensitivity to clutch damper torsional stiffness could be collected, shown as Figs. 13, 14, and 15. Corresponding modal shape is unvaried.

From above 3 figures, it can be found, as in,

1. When clutch damper torsional stiffness is varied, the effect on 1st driveline mode is very small, thus, clutch damper torsional stiffness is not the parameter tuning the 1st driveline mode.
2. When clutch damper torsional stiffness is varied, the effect on 3rd driveline mode is very small, thus, clutch damper torsional stiffness is not the parameter tuning the 3rd driveline mode.
3. When clutch damper torsional stiffness is varied, the effect on 2nd driveline mode is obvious. As the stiffness increase/decrease, the 2nd mode frequency correspondingly varies, that way, the clutch damper stiffness can be the dominant parameter tuning 2nd driveline mode. As 2nd driveline mode is very sensitive to interior noise booming. Clutch damper torsional stiffness could be optimized, to get the 2nd driveline mode out of critical engine torque pulsation rpm.

Fig. 14 Driveline 2nd mode sensitivity to clutch damper torsional stiffness

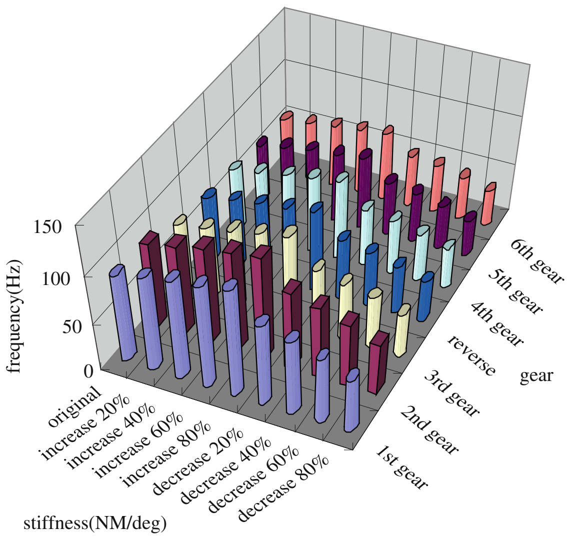
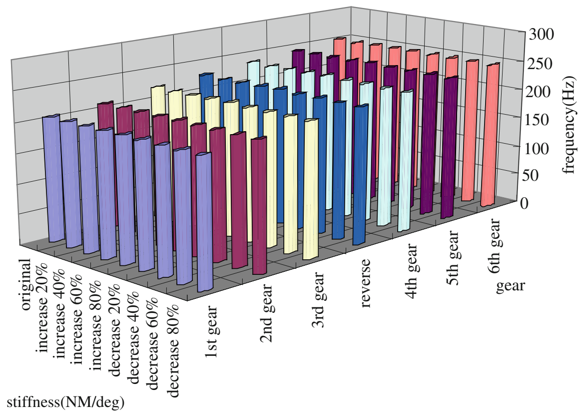


Fig. 15 Driveline 3rd mode sensitivity to clutch damper torsional stiffness



4.2 *Driveline Torsional Vibration Sensitivity to Propshaft Torsional Stiffness*

The propshaft torsional stiffness will be varied as Table 7, in regards to driveline torsional vibration sensitivity to propshaft torsional stiffness.

Taking the stiffness into in-house software for calculation, the driveline mode sensitivity to propshaft torsional stiffness could be collected, shown as Figs. 16, 17, and 18. Corresponding modal shape is unvaried.

From above 3 figures, it can be found, as in,

Table 7 Propshaft torsional stiffness variation

Stiffness increase compared to original value (%)	Stiffness decrease compared to original value (%)
20	20
40	40
60	60
80	80

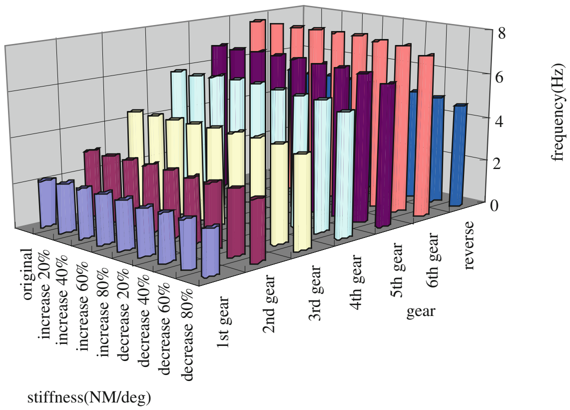


Fig. 16 Driveline 1st mode sensitivity to propshaft torsional stiffness

1. When propshaft torsional stiffness is varied, the effect on 1st driveline mode is very small, thus, propshaft torsional stiffness is not the parameter tuning the 1st driveline mode.
2. When propshaft torsional stiffness is varied, the effect on 2nd driveline mode is very small, thus, propshaft torsional stiffness is not the parameter tuning the 2nd driveline mode.
3. When propshaft torsional stiffness is varied, the effect on 3rd driveline mode is obvious. As the stiffness increase/decrease, the 3rd mode frequency correspondingly varies, that way, the propshaft stiffness can be the dominant parameter tuning 3rd driveline mode. As 3rd driveline mode is susceptible to be excited by propshaft bending and torsional excitation, propshaft torsional stiffness could be optimized, to get the 3rd driveline mode out of critical propshaft excitation frequency.

4.3 Driveline Torsional Vibration Sensitivity to Axle Shaft Torsional Stiffness

The axle shaft torsional stiffness will be varied as Table 8, in regards to driveline torsional vibration sensitivity to axle shaft torsional stiffness.

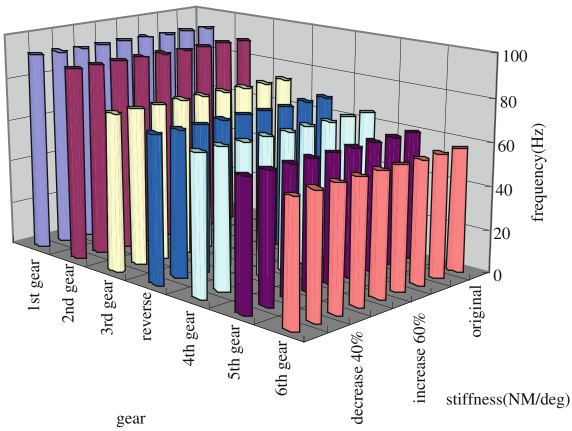


Fig. 17 Driveline 2nd mode sensitivity to propshaft torsional stiffness

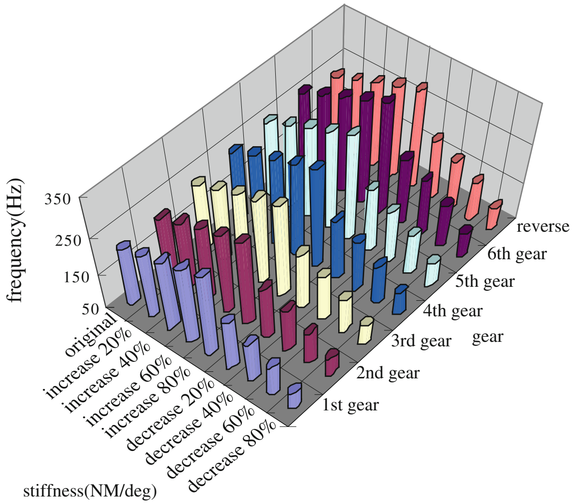


Fig. 18 Driveline 3rd mode sensitivity to propshaft torsional stiffness

Taking the stiffness into in-house software for calculation, the driveline mode sensitivity to axle shaft torsional stiffness could be collected, shown as Figs. 19, 20, and 21. Corresponding modal shape is unvaried.

From above 3 figures, it can be found, as in,

1. When axle shaft torsional stiffness is varied, the effect on 2nd driveline mode is very small, thus, axle shaft torsional stiffness is not the parameter tuning the 2nd driveline mode.
2. When axle shaft torsional stiffness is varied, the effect on 3rd driveline mode is very small, thus, axle shaft torsional stiffness is not the parameter tuning the 3rd driveline mode.

Table 8 Axle shaft torsional stiffness variation

Stiffness increase compared to original value (%)	Stiffness decrease compared to original value (%)
20	20
40	40
60	60
80	80

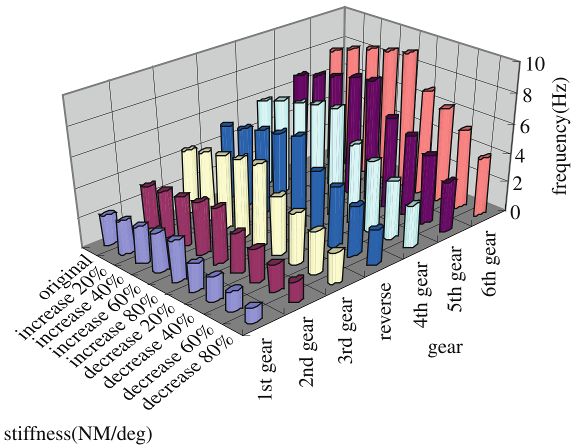


Fig. 19 Driveline 1st mode sensitivity to axle shaft torsional stiffness

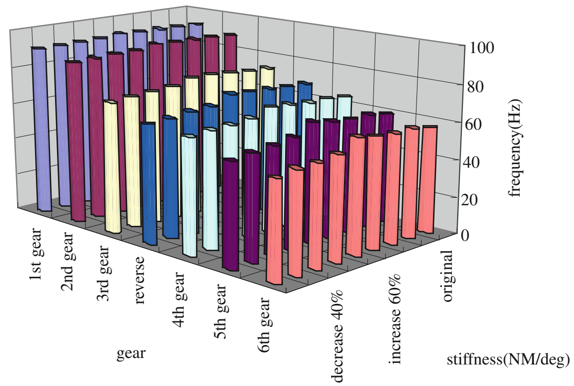


Fig. 20 Driveline 2nd mode sensitivity to axle shaft torsional stiffness

3. When axle shaft torsional stiffness is varied, the effect on 1st driveline mode is obvious. As the stiffness increase/decrease, the 1st mode frequency correspondingly varies, though not so huge, the axle shaft stiffness still can be a parameter tuning 1st driveline mode.

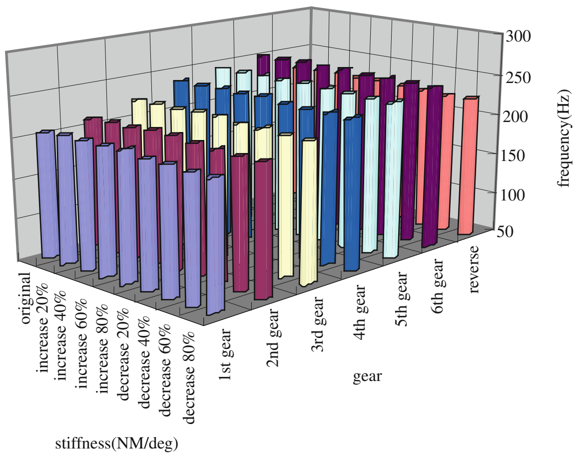


Fig. 21 Driveline 3rd mode sensitivity to axle shaft torsional stiffness

5 Summary/Conclusion

In this paper, A RWD SUV driveline lumped mass model is built, to predict the torsional vibration modes. The prediction is turned out to correlate very well to in-vehicle torsional vibration measurement, hence, the model, adopted in this paper, is employed to investigate the driveline torsional vibration mode sensitivity to driveline component torsional stiffness, then, the conclusion can be drawn out of sensitivity study, as in,

1. For 1st driveline mode, axle shaft torsional stiffness play comparatively stronger role. Within broad range variation of axle shaft torsional stiffness, the 1st driveline in high gear (6th gear) has bigger variation (5 Hz), while, minor variation in low gear (1.7 Hz in 1st gear). As matter of fact, it is unrealistic to vary the axle shaft torsional stiffness that much, like decribed in this paper, therefore, axle shaft torsional stiffness only has minor tuning effect on 1st driveline mode, and other count measures should be emphasized, like hysteresis, engine torque rising rate, etc., to control the 1st driveline mode, especially during tipin/out maneuver to say the least, the axle shaft torsional stiffness could be tuned to check how it affect the 1st driveline during the driveline concept phase. Clutch damper and propshaft torsional stiffness have little effect on 1st driveline mode.
2. For 2nd driveline mode, clutch damper torsional stiffness has dominant effect, while, little effect by propshaft and axle shaft torsional stiffness. The clutch damper torsional stiffness can be tuned, in conjuction with hysterisis, to control the 2nd driveline mode, hence, the gear rattle or interior noise booming.
3. For 3rd driveline mode, the propshaft torsional stiffness has major effect, while, little effect by axle shaft and clutch damper torsional stiffness. The propshaft torsional stiffness could be optimized to tune 3rd driveline mode.

4. From the very start of driveline development, the torsional stiffness of axle shaft, propshaft, clutch damper can be employed to respectively check the influence on 3 major driveline modes, together with other parameter, to control the driveline mode frequency and amplitude, that can expedite driveline NVH development process.

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