Study on startup transient vibration of a vehicle with 3-cylinder engine

Jianghua Fu[1,2]; Jian Pang [1,2*]; Chengtai Hu[1,2]; Xiaomin Xu[1,2]; Renwei Deng[1,2]; Xiaohong Kuang[1,2]

[1] Changan Auto Global R&D Center, China

[2] State Key laboratory of Vehicle NVH and Safety Technology, China

* Correspondence author, e-mail address: pangjian@changan.com.cn

ABSTRACT

The vibration of 3-cylinder engine is bigger than the 4-cylinder engine with the same engine displacement. The startup processing is studied in order to control the shake level when the engine is started. Excitation characteristics of the 3-cylinder engine is analyzed and a CAE model to analyze the startup shake is established which is verified by the test data. The possible impact factors of the startup vibration are studied and the key control methods are provided, which are applied to an case and successful results are obtained. The results show that the powerplant mounting system has a great influence on the startup vibration of the vehicle with 3-cylinder engine. Aligning the modal frequency distribution between the 3-cylinder engine mounting system and the cranking speed of the start motor, the vehicle transient shake at startup can be effectively controlled. The paper also provides a CAE simulation method which is successfully used to predict the startup shake, which provide a guideline for powerplant mounting system design at early stage of the vehicle development.

Keywords: 3-cylinder engine, Startup vibration, NVH Simulation, Vibration Control I-INCE Classification of Subjects Number(s): 46.2

1. INTRODUCTION

Durability, safety and NVH are among the most important performaces for a vehicle usage. The customers have been paid more and more attention on noise and vibration. The startup transient shake means the transient vibration and shock during the engine startup, which is one of the most important NVH performance and directly influences the customers' first impression on a vehicle.

The design of startup transient vibration should be paid attention to in the early stage of the vehicle development. Different automobile manufacturers use different methods to optimize the transient vibration, however, many makers have to tune the system by testing to solve the startup problem in the late stage of the vehicle development. So far, there are no systemic methods to predict and control the problem.

There is few literatures about the transient vibration analysis and control in the automotive industry. Youngchan Lee [1] and Jung-Hwan Bang [2] tried to give the corresponding method in the early stage of the development to predict startup vibration, but they only analyzed it for east-west layout powerplant and didn't study influence factors of startup vibration systematically. Anandan Sivakumar[3] just evaluated the influence of different materials on the transient vibration, but not considered the mechanism of starup vibration. 3-cylinder engine has advantages over 4-cylinder engine, such as smaller engine displacement, lighter mass and smaller volume, less fuel consumption and better environmental protection, but the huge vibration issue is still one of the most prominent and most difficult problems for the 3-cylinder engine.

In order to reduce the transient vibration during startup period for the three cylinder engine, a startup model for a vehicle with a 3-cylinder engine is built up and a simulation method is provided to analyze influence factors on the startup processing. Then the corresponding control method is put forward.

---

[1] fujh@changan.com.cn

2. MECHANICS ANALYSIS OF THE STARTUP PROCESSING

2.1 Analysis of the Startup Processing

As shown in figure 1, at the moment of the engine ignition, gas pressure drives the crankshaft to rotate. The engine excites a vehicle body, which causes a interior shake. The entire startup processing can be divided into three phases: pure cranking phase by a starter motor, ignition phase and idle phase. As shown in figure 2, during the startup processing, the engine is ignited and the gas is combusted after the starter motor cranks the flywheel to a certain speed. The engine's mechanical inertia force and the force induced by combustion, transfer to the body attachment points through the engine mounting system and those transient excitation transfers to the passengers through the body. Therefore, the startup transient vibration must be studied by a whole vehicle models.

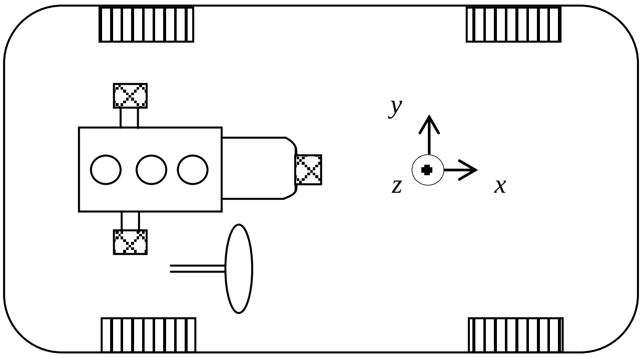

Fig.1 Schematic of the powerplant mounting system in the whole vehicle

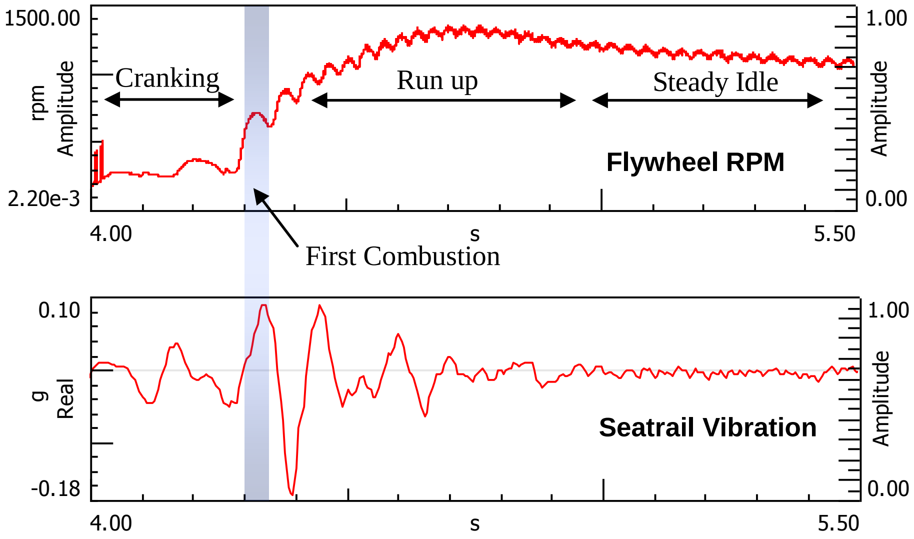

Fig.2 Process of engine startup

During the startup processing, the powerplant transits from initial static state to idle vibration. At the moment of the engine ignition, the engine excitation forces itself to rotate around its crankshaft, which causes the powerplant to rotate and do translate movement. After the engine speed becomes stable, the powerplant just rotates around the torque roll axis[4]. The rotation and movement will cause the vehicle interior vibration. Hence, the engine excitation in key on condition should be studied before the startup vibration analysis.

2.2 Excitation Analysis of Three Cylinder Engine

The engine excitations include inertia forces and combustion pressures. The excitation characteristics of the inertia forces will be described in details. Due to the similarity, the excitation caused by the combustion pressure will be simply mentioned.

(1) Inertial force excitation analysis of three cylinder engine

The initial phase angles of the three cylinder are $\theta_1, \theta_2, \theta_3$ respectively and the crankshaft of each cyliner has a 120 °phase interval, as shown in figure 3. The summation of all the inertial force on the engine block in the vertical direction is expressed as follows[5]:

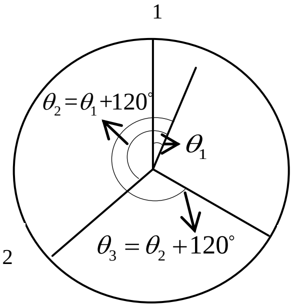

Fig.3 Crankshaft section sketch of three cylinder engine

$$N_{z_i} = mr\omega^2 \sum_{i=1}^{3} \cos\theta_i + m\lambda r\omega^2 \sum_{i=1}^{3} \cos 2\theta_i \tag{1}$$

Where N_{zi} is the vertical inertial force of the $i^{th}(i=1,2,3)$ cylinder; $m = m_1 + m_2$, m_1 is piston mass, m_2 is the mass of connecting rod projected at its small head end; ω is the angular velocity of the crankshaft; $\theta_i(i=1,2,3)$ represents the inclination angle between the crankshaft and the axis of the cylinder; r is the radius of the crank; $\lambda = r/l$, is the ratio of the crankshaft radius r and connecting rod length l.

Since $\theta_2 = \theta_1 + 120^0$ and $\theta_3 = \theta_1 + 240^0$, so,

$$\sum_{i=1}^{3} \cos\theta_i = \cos\theta_1 + \cos\theta_2 + \cos\theta_3 = 0 \tag{2}$$

$$\sum_{i=1}^{3} \cos 2\theta_i = 0 \tag{3}$$

Hence, for three cylinder engine, N_{zi} is zero i.e. the summation of the vertical inertial force from each pistion through the crankshaft to the engine block is 0. The vetical inertial forces of the three cylinder engine are balanced.

The moment around the crankshaft of the three cylinder engine is as follows:

$$M_x = \sum_{i=1}^{3} [(mr^2\omega^2 \cos\theta_i + m\lambda r^2\omega^2 \cos 2\theta_i)(\sin\theta_i + \frac{\lambda \sin\theta_i \cos\theta_i}{\sqrt{1-\lambda^2 \sin^2\theta_i}})] \tag{4}$$

Here $M_{xi} \neq 0$, namely the inertia moment of three cylinder engine around the crankshaft is unbalanced.

The inertia force will cause a rotation torque around the y axis for three cylinder engine. The inertia moment M_y around the y axis is as follows:

$$\begin{aligned} M_y &= \sum_{i=1}^{3} N_{zi}(i-1)d = mr\omega^2 d \sum_{i=1}^{3} (i-1)\cos\theta_i + m\lambda r\omega^2 d \sum_{i=1}^{3} (i-1)\cos 2\theta_i \\ &= 1.5mr\omega^2 d \cos\theta_1 + 1.5m\lambda r\omega^2 d \cos 2\theta_1 \end{aligned} \tag{5}$$

Where d is the distance between the adjacent cylinder's center in the cylinder head plane. As shown in the equation (5), $M_y \neq 0$. Therefore, the inertial moment around y axis of three cylinder engine is unbalanced.

(2) Gas pressure Excitation analysis of three cylinder engine

Similar to the inertia exciations, the combustion pressure excitations also produce 1st order and 2nd order moments around x-axis and around y-axis. Besides that, firing pressure will produce additional torque. When the crankshaft of three cylinder engine rotates two cycles, the three cyliners ignite once respectively, so the excitation from the gas pressure is 1.5th order.

The difference of a 3-cylinder engine from a 4-cylinder is that there exist moments around y-axis and the major torque component is 1.5th order. Only roll mode should be controlled for the 4-cylinder engine, however, both roll mode and pitch mode should be controlled for the 3-cylinder engine.

The roll mode frequency of the 3-cylinder engine must keep away from the 1.5th order excitation and its pitch mode should be avoided to occur resonance with the 1st order excitation.

3. MODELING OF THE STARTUP PROCESSING

A startup CAE model of the whole vehicle is established, which can be used to predict the vibration for the startup condition. The whole car is simplified for modeling and it should be verified by testing results to ensure calculation accuracy. The modeling and analysis method are suitable for the startup study of any kind of engine. The excitation of different engine are different. Taking the three cylinder engine as an example, the corresponding excitation is used to predict the vibration response.

3.1 Modeling of the Startup Transient Vibration

To predict startup vibration quickly, a simplified simulation model is built up[6]. As shown in fig.4, the powerplant is a rigid body, which is installed in the body model through the mounting system. The mount is simulated by Force Vector (Three - Component Force) and one force vector represents one mount. The body and the axle are connected by the generalized Force General Force Vector (Six - Component Force), which represents the suspension. The force Vector is also used to reflect the tire stiffness which connects the axle and the road and the road is fixed with the ground. In this model, the four axles and roads just move along the Z axis, which is constricted by the translational joint.

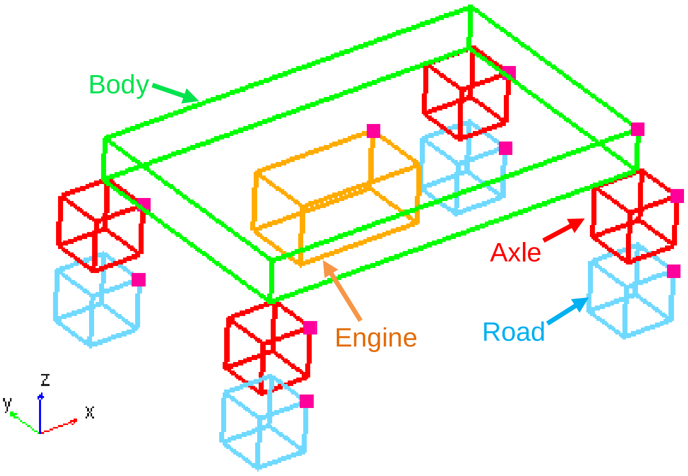

Fig.4 Simulation model of the startup vibration

To simulate the transient excitation of the engine exactly, the centroid vibration of the powerplant is calculated according to the tested vibration of each mount. Both the steady-state excitation and the transient impact are applied in the centroid to simulate the interior vibration response.

3.2 Verification of the Startup Model

In order to guarantee the accuracy of the simulation, the model is verified by the forced vibration response and powerplant modal frequency. The vehicle's seat trail vibration of the key on condition is tested and the vibration is calculated as well. As shown in fig.5, the solid line is the test results while the dotted line is the simulation results. Compared with these two lines, they are consistent with each other and the simulation results is slightly smaller than the measured values.

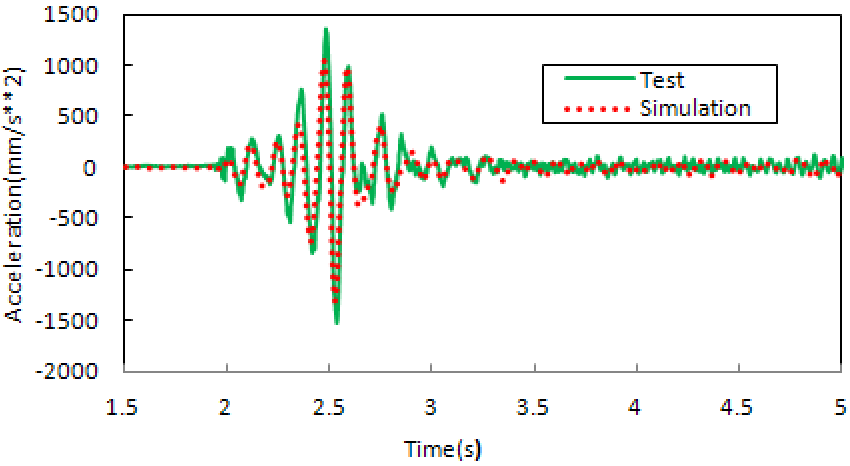

Fig.5 Compare of the simulation and test results of the seatrail

In order to verify the rigid body model, the simulated results are compared with the tested results. For north-south layout powerplant, its lateral mode and roll mode is quite important for startup processing. The simulated roll and lateral modes are 12.8 Hz and 5.85 Hz respectively. Fig.6-7 show the measured modal shapes[7] for roll mode and lateral mode with frequencies 13.6 Hz 5.9 Hz, respectively. The frequency difference between simulated and tested roll modes is 0.8 Hz, corresponding 5.9% error. The difference for the lateral modes is 0.05 Hz and error percentage is 0.8%. The cause of the error may come from the simlified model because the boundary condition of the powerplant system has difference from the actual case. But the trend of the rigid modes is consistent with the test results, thus it could be used to resprent the transfer characteristics of the powerplant system.

According to the comparisons from dynamic responses and modal frequencies, the model accuracy is proved and can be used to predict the startup vibration in the design phase, which provides a guideline for mounting layout, installation orientation and stiffness determination.

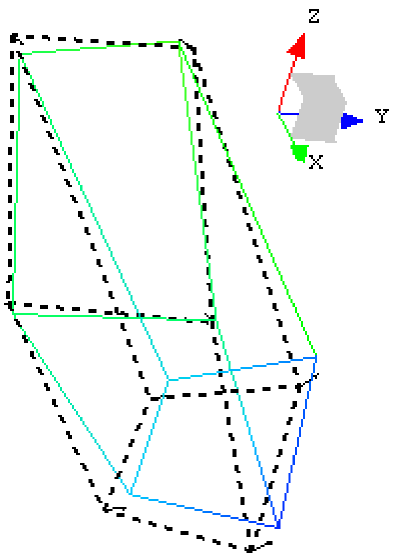

Fig.6 Roll mode frequency 13.6 Hz

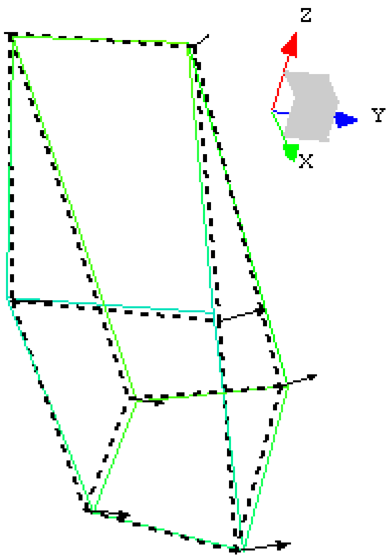

Fig.7 Lateral mode frequency 5.9 Hz

4. INFLUENCE FACTORS STUDY OF THE STARTUP VIBRATION

The interior vibration during the startup processing can be studied from two aspects: sources and transfer paths. Factors affecting the startup vibration may include the followings: engine cylinder pressure, mode distribution of the mounting system, nonlinear mount stiffness design and the starter motor cranking speed, etc.

4.1 Engine Cylinder Pressure

The engine cylinder pressure is related to the gas combustion, which is bound up with the engine electric fuel injection management system. Changing the ignition advance angle, injection volume and the intake air quantity, the engine cylinder pressure may be extensively changed. Usually, ignition advance angle and fuel injection quantity will change with the changing of engine air intake.

Changing the intake air in the maximum 20% regulation range, the gas pressure changes about 15%, as shown in figure 8. The model in this paper doesn't include the crank and connecting rod mechanism, the pressure change inside cylinder can be realized by tuning the excitation amplitude directly. The simualtion results of the startup transient vibration for tuning the eninge exciations are shown in Figure 9. Different cylinder pressure has a little influence on the startup vibration. To validate the results, changing the intake air quantity, the vibration are tested during the startup processing, as shown in fig.10-11. The vibrations for the three cases correspond to different ignition time. There is almost no difference between maximal and minimal vibrations in Z direction, but there exists a little change in Y direction. According to subjective evaluation, people feel no difference. Thus, the cylinder pressure has no influence on the startup vibration.

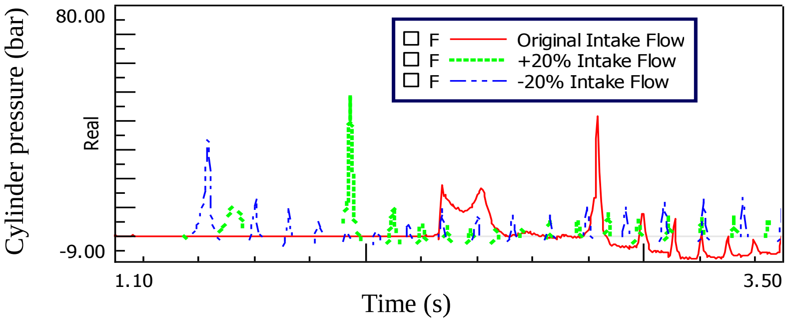

Fig.8 Cylinder pressure curve for different air intake

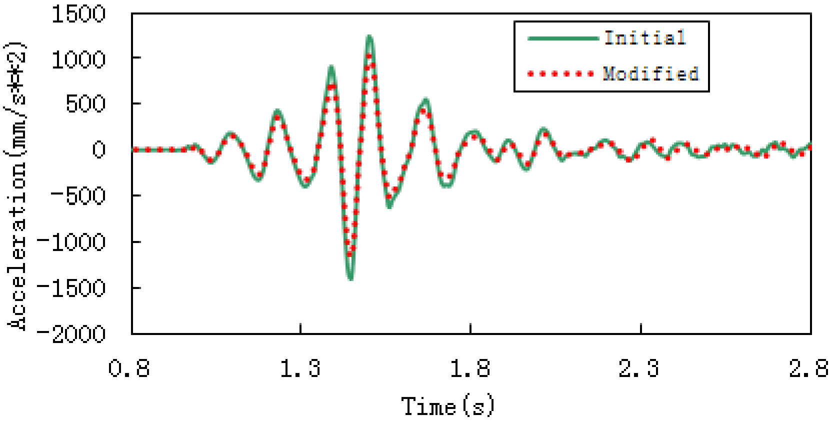

Fig.9 Comparison of the interior vibration of startup processing

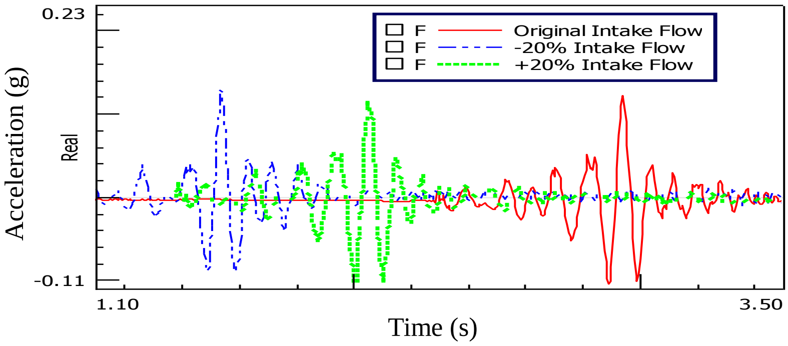

Fig.10 Vibration of the seatrail in Y direction

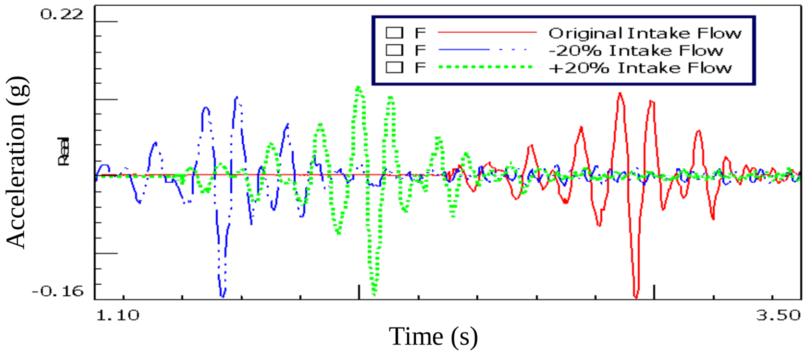

Fig.11 Vibration of the seatrail in Z direction

4.2 Mode of the Mounting System

It's found that the powerplant modes have huge influence on the interior vibration of the startup processing through the analysis of the whole car modes[8]. The calculated powerplant roll mode frequency is 12.8 Hz, while the lateral mode frequency is 5.85 Hz. After redesigning the mount parameters, the roll mode frequency is 11.6 Hz, and the lateral modal frequency is 5.1 Hz. The interior vibration response are calculated respectively with the same excitation, as shown in fig. 12.

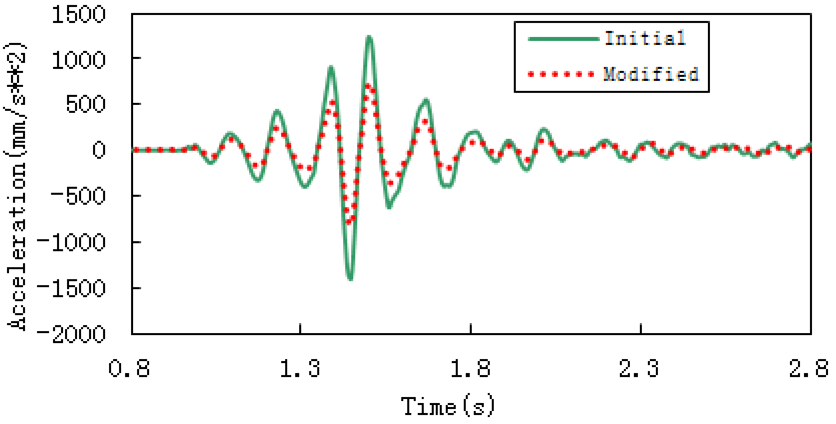

Fig. 12 Interior vibration with different modes of mounting system

After the nonlinear section of the mount stiffness is reduced, the vibration has little change, as shown in fig. 13. Using a mount with a higher stiffness, the powerplant displacement is decreased and the startup vibration is improved, however the idle vibration becomes worse.

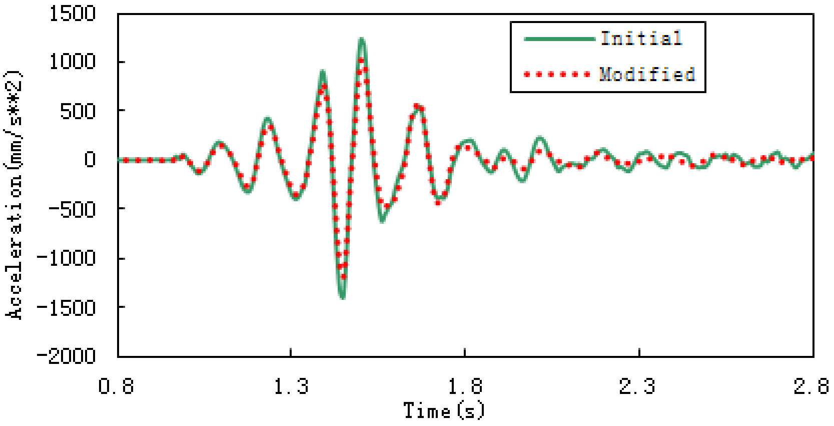

Fig. 13 Influence of nonlinear length of the mount on the startup vibration

4.3 Cranking Speed of the Start Motor

The cranking speed of the starter has influence on the startup vibration. During the cranking period, when the excitation frequency of the starter at a certain speed is close to the natural frequency of the powerplant, the resonance will happen in a short of time.

For some cases where the resonance cannot be inevitable, two methods are often adopted. One is to increase the damping and the second is to pass through the resonance area quickly. The effectiveness using rubber damping to avoid resonance is limited, so the second method is used. Increasing the power of the starter motor will make it quickly pass the resonance area, which will shorten the time of the resonance and reduce the vibration energy accumulation, hence the startup vibration is improved.

In the early stage of the vehicle development, using the CAE analysis method to arrange the powerplant rigid modes, which should be kept away from the 1st order and 1.5th order engine vibration excitation and the cranking excitation frequency of starter, the startup vibration can be alleviated.

5. STARTUP VIBRATION CASE ANALYSIS

5.1 Description and Analysis of the Problem

There is a startup vibration problem for a developing car, which vibration is bigger than the competitive vehicle and subjective evaluation is that the startup vibration is obvious and unacceptable. The vibration is tested, as shown in fig.14. The seat trail vibration is larger than the competitive car about 0.04 g.

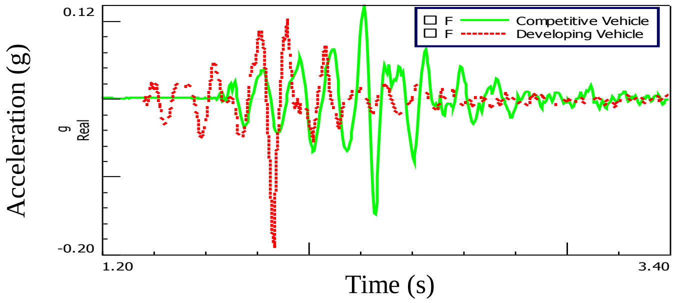

Fig.14 Comparison of the interior startup vibration

According to previous analysis, the largest contribution to the startup problem comes from the mounting system. Therefore, the mount vibrations of engine side and body side are analyzed. According to fig. 1, the powerplant is excited by the moment around the crankshaft i.e. rotation around x axis during the startup processing. The excitations are applied on the mounting system in Y and Z direction simultaneously. Therefore, the Y and Z direction of the mounting system are the main excitation directions. Taking the right mount for example, as shown in fig.15, the isolation of the mount in Y direction is poorer i.e. the mount vibration quantity of engine side and body side are very close.

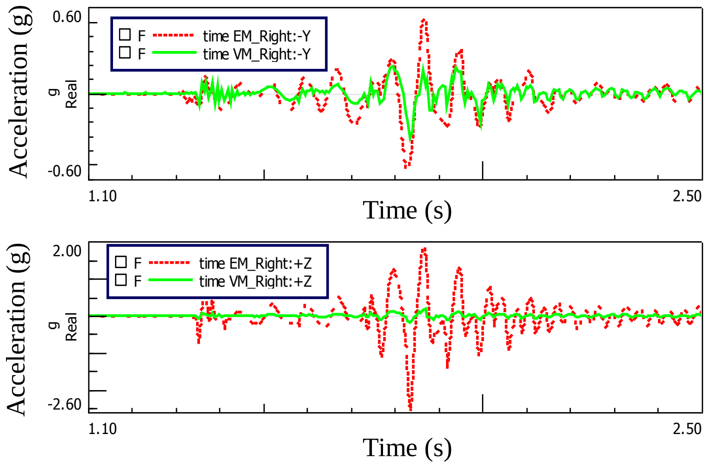

Fig.15 Right mount vibration comparison of engine side and body side

5.2 Optimization of the Startup Vibration

The startup vibration is optimized by the above analysis method. According to practical projects, the least change is often advised to get the biggest improvement effect. Therefore, only the mounting system is optimized in this case.

The startup vibration is optimized under the same engine excitation[9-10]. The optimization target is the peak vibration value of the startup processing in the seatt rail and the design variables are the mount stiffness, installation location and orientation. Restricted by the mount's space, the orientation of the left and right mounts can be changed from 25 to 50 degrees; the left and right mounts can be only moved forward 40mm in X direction; the left and right mounts are not moved in Y and Z direction.

The optimization of the mount stiffness and location has little impact on the problem, however, the orientation of left mount has a obvious effect, as shown in figure 16.

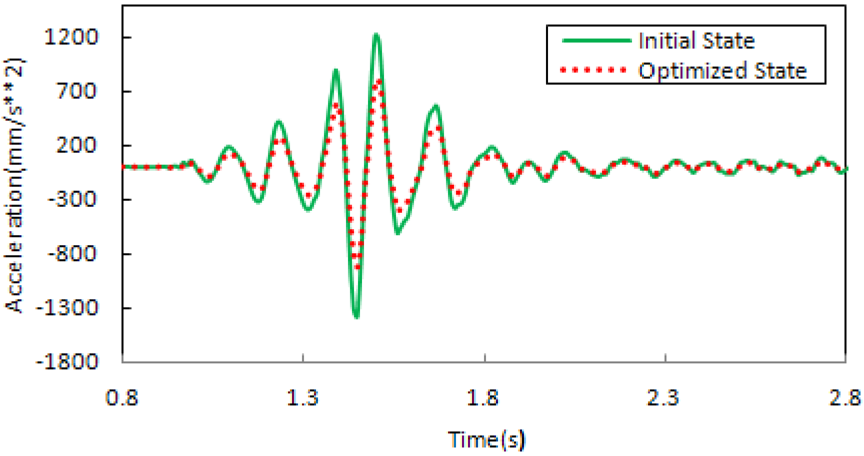

Fig.16 Startup vibration comparison of the orientation of the left mount

Figure 16 shows that the optimized vibration has been reduced than previous case. Figure 17 shows the changing of the left mount orientation, i.e. decreasing the θ, from the 45 degrees to 30 degrees, where θ angle between the left mount and the bracket beam.

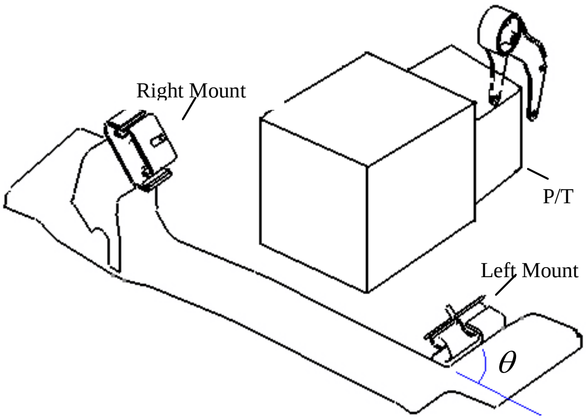

Fig.17 Optimized schematic of the mounting system

5.3 Validation of the Optimized Mount System

To realize the change in fig. 17, the beam where the left mount is installed is concaved, as shown in figure 18. The left mount is attached at the concave side of the beam, therefore, the inclination angle between the left mount and the beam is reduced.

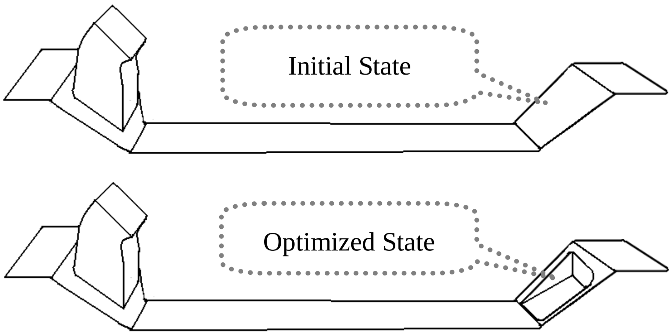

Fig.18 Change of the orientation of the left mount

The startup vibration of the car with the optimized mounting system is tested as shown in fig.19-20. After the optimization, the peak vibration of seatrail in Y and Z direction is reduced to 0.05g and 0.11g, respectively. Subjective evaluation shows that is the startup vibration is acceptable.

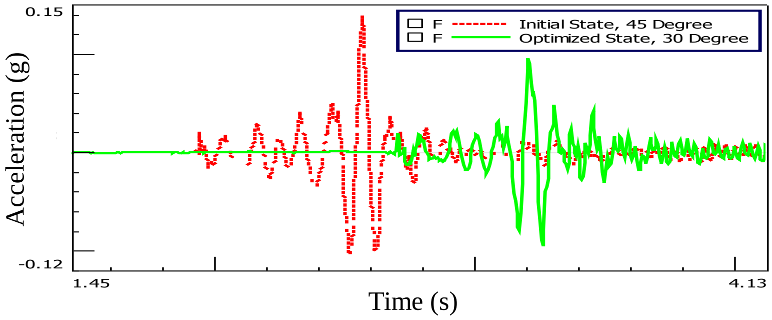

Fig.19 Vibration of seatrail in Y direction before and after the optimization

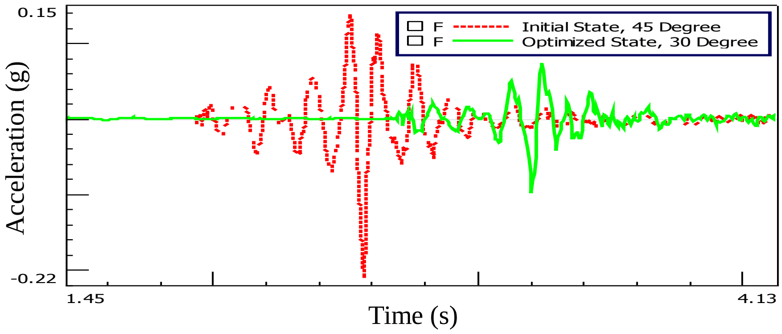

Fig.20 Vibration of seatrail in Z direction before and after the optimization

Using the above simulation method, together with the engineering practice, the optimization scheme is provided, which solves the startup vibration problem successfully. Development target for the startup vibration can be determined by either the existing vehicles or the competitive vehicle's vibration level. After the development goal is finalized, the simulation method can be used to design and optimize the startup transient vibration.

6. CONCLUSIONS

Through the study of this paper, the following conclusions can be given:

(1) The powerplant rigid mode frequency should be rationally distributed, which should avoid the 1st order and 1.5thorder vibration excitation of three cylinder engine and excitation frequency of starter as well. When the powerplant roll mode of the three cylinder engine couples with its lateral mode, the engine and the whole car will have an obvious startup vibration.

(2) The startup vibration will be improved by restricting the displacement of the powerplant centroid, but the idle vibration will become worse.

(3) The CAE method of the startup processing can be used to solve the startup transient vibration problem, especially for guiding mounting system design at the early stages of whole vehicle development.

REFERENCES

1. Youngchan Lee. Study on Transient Vibration Response Characteristics of Front Transverse Power Train at the Key On/Off[C]. SAE:2007-01-2283.
2. Jung-Hwan Bang, Hee-Wook Yoon and Kwang-Min Won. Experiment and Simulation to Improve Key ON/ OFF Vehicle Vibration Quality[C]. SAE: 2007-01-2363.
3. Anandan Sivakumar, Ashish Tiwari, etc. Elastomer Blend for Vibration Isolators to Meet Vehicle Key on - Key off Vibrations and Durability[C].SAE:2010-01-1986.
4. Jae-Yeol Park and Rajendra Singh. Effect of Engine Mount Damping on the Torque Roll Axis Decoupling[C].SAE:2007-01-2418.
5. Jianghua Fu. Performance Match of Key Rubber Isolators for Light Bus[D]. Jilin University, Changchun, China. 2011.p.22-24.
6. Hee-Woo Yoon,Jung-Hwan Bang and Jae-Hyun Park. Development of Engine Mount System for Low Frequency Vibration Improvement[C].SAE:2008-01-0885.
7. Pengfei Chen,Yunqing Zhang, Gang Qin and Jinglai Wu. Interval Analysis Method of a Powertrain Mounting System with Uncertain Parameters[C].SAE:2010-01-0905.
8. C.Q. Liu. A Computerized Optimization Method of Engine Mounting System[C]. SAE: 2003-01-1461.
9. Hajime lgami and Michael Thompson. Automotive Powertrain Mounting System Design Optimization[C].SAE:2008-01-0879.
10. Hiroshi Sugimura,Yasushi Donoue,Masayuki Takei and Hiroo Yamaoka.Prediction of Low Frequency Vibration Caused by Power Train Using Multi-Body Dynamics[C]. SAE: 2009-01-2193.