Study on Non-Linear Dynamic Characteristic of Vehicle Suspension Rubber Component

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[Abstract] The dynamic characteristic of rubber component is one of important factors that influences the NVH performances of vehicle. In common case, simulation model built on ADAMS software considers only the linear characteristic. But in some special cases, rubber components installed in the vehicle suspension always work in non-linear condition.

Aimed at the research difficulty of this kind of non-linear dynamic characteristic, a numerical fit method had been put forward based on energy analysis theory in this paper. To achieve the non-linear dynamic characteristic of rubber component in the vehicle dynamics simulation model based on the ADAMS, a user written subroutine has been compiled, and a custom solver was created, hence the non-linear analysis of vehicle dynamics can be achieved.

Key words: Vehicle Suspension   Rubber Component   ADAMS Software   Non-linear Dynamic Characteristic   Energy Analysis

INTRODUCTION

With economy growing and traffic environment improving in China, the performance of modern vehicle is required more and more strictly. In order to reduce the transference of vibration and noise, and to improve the comfortability of vehicle, the rubber component is used widely in vehicle structure, especially in some position where connect and join the parts of suspension. For example, Audi100 car has more than 10 rubber components installed in front suspension, it is to utilize the fair characteristic of rubber components to reduce vibration and noise. Since many rubber components were used in vehicle, their dynamic characteristic affect vehicle performance, especially on the dynamic characteristic of suspension.

The dynamic characteristic of rubber components is mostly obtained by testing. In common case, the dynamic characteristic of rubber components considered as linear. But in some special places, for example in the joint of low control arm and lateral stability-bar of Audi100, the dynamic characteristic of rubber component is often working in non-linear range. Based on the energy analysis theory introduced in reference [1], this paper uses dynamic trial data to deal with the nonlinear dynamic characteristic of rubber components, and puts forward the numerical fitting method based on energy analysis, and realizes non-linearization of vehicle dynamic simulation.

LINEAR DYNAMIC CHARACTERISTIC OF RUBBER COMPONENT

The dynamic characteristic of rubber components can be classed by linear and non-linear characteristic [2], and it is always described by the relationship of force and deformation. In the process of vehicle dynamic simulation, the dynamic model of rubber components seriously affects the analysis precision. The dynamic characteristic of rubber components in the linear range, can de obtained by analysis the force-deformation curve of rubber component which got by acting periodical exciting force. In the linear range, the force-deformation relationship of rubber component can be described with following equations.

Exciting displacement of rubber component can be describe as:

$$X(t) = X_0 \cos(\omega t) \qquad 1$$

Where:

X_0 —amplitude of exciting displacement;

ω —exciting frequency.

Corresponding deformation force of rubber component is:

$$F(t) = F_0 \cos(\omega t + \delta) \qquad 2$$

Where:

F_0 —amplitude of deformation force;

δ —phase difference between deformation force and exciting displacement.

In fact, the phase of deformation force precedes to that of exciting displacement, and the phase difference δ is $0 \le \delta < 90^0$.

Expanding the equation of deformation force as:

$$F(t) = F_k(t) + F_c(t) \qquad 3$$

Where:

$$F_k(t) = F_0 \cos\delta \cos(\omega t) = \left(\frac{F_0}{X_0} \cos\delta\right) X_0 \cos(\omega t) \qquad 4$$

$$F_c(t) = -F_0 \sin\delta \sin(\omega t)$$

The first equation of (4) denotes the spring force caused by the dynamic stiffness of rubber component, then the dynamic stiffness K is $\left(\frac{F_0}{X_0} \cos\delta\right)$.

The second equation of (4) denotes the damping force caused by the damping of rubber component, which can be expressed as:

$$F_c(t) = \left(\frac{F_0}{\omega X_0} \sin\delta\right) \cdot \left[-X_0 \omega \sin(\omega t)\right]$$

$$= \left(\frac{F_0}{\omega X_0}\right) \sin\delta \cdot \dot{X}(t) \qquad 5$$

The phase difference between the damping force and exciting displacement is 90^0, and equivalent damping coefficient C is $\left(\frac{F_0}{\omega X_0} \sin\delta\right)$.

Dynamic stiffness K and equivalent damping coefficient C of rubber component can be obtained after F_0 X_0 and δ be measured. Commonly, X_0 and δ are functions of exciting frequency ω. So dynamic stiffness K and equivalent damping coefficient C are also functions of exciting frequency ω [1].

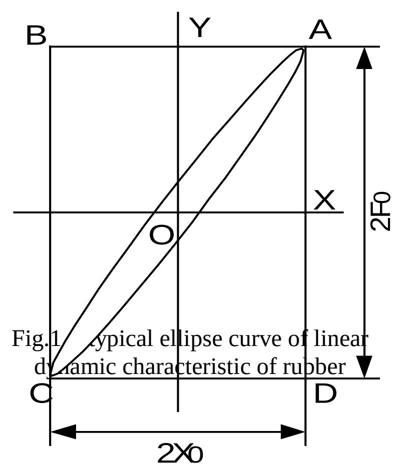


Fig.1 Typical ellipse curve of linear dynamic characteristic of rubber

After removing the items relating with time from the equation of exciting displacement and deformation force, the curve of dynamic exciting displacement-deformation force is:

$$\left(\frac{X}{X_0}\right)^2 - 2\left(\frac{X}{X_0}\right)\left(\frac{F}{F_0}\right)\cos\delta + \left(\frac{F}{F_0}\right)^2 = \sin^2\delta \qquad 6$$

This equation defines an ellipse curve, seeing Fig.1. This is the feature of the linear dynamic characteristic of rubber component. δ can be calculated with the function of exciting displacement and deformation force or the coordinates of A B C D.

ANALYSIS OF NON-LINEAR DYNAMIC CHARACTERISTIC

When the exciting force acted on the rubber component exceed a certain range, the curve of exciting displacement-deformation force will no longer be an ellipse, and that changes gradually to crescent, seeing Fig.2. At this time, the dynamic characteristic of rubber component analysis method with the linear analysis assumption appears obvious shortcomings. On the basis of dynamic testing of rubber component, a numerical fitting method described the non-linear dynamic characteristic of rubber component which base on the energy analysis is put forward in this paper.

Obviously, the curve of loading and unloading is closed. The area enclosed by the curves denotes the energy consumed by the damping of rubber component that provided by external exciting displacement $X(t) = X_0 \cos(\omega t)$.

The energy consumed by damping of rubber component in a circle is:

$$\begin{aligned} W &= \oint F(t)dX(t) \\ &= -\int_0^{2\pi} F_0 X_0 \sin(\omega t)\cos(\omega t+\delta)d(\omega t) \\ &= \pi F_0 X_0 \sin\delta \end{aligned} \qquad 7$$

Loading-unloading curve of rubber component is also a closed curve in the non-linear dynamic characteristic testing. So we can assume:

Loading curve: $F_a(x) = \sum a_i x^i + b \quad x \in (x_0, x_t)$

Unloading curve: $F_r(x) = \sum c_i x^i + d \quad x \in (x_0, x_t)$

Where: i is integer and dependent by the precision of vehicle dynamic analysis.

Now the energy consumed by damping of rubber component in the non-linear dynamic characteristic testing is:

$$W = \int_{x_0}^{x_t} F_a(x)dx - \int_{x_0}^{x_t} F_r(x)dx \quad x \in (x_0, x_t) \qquad 8$$

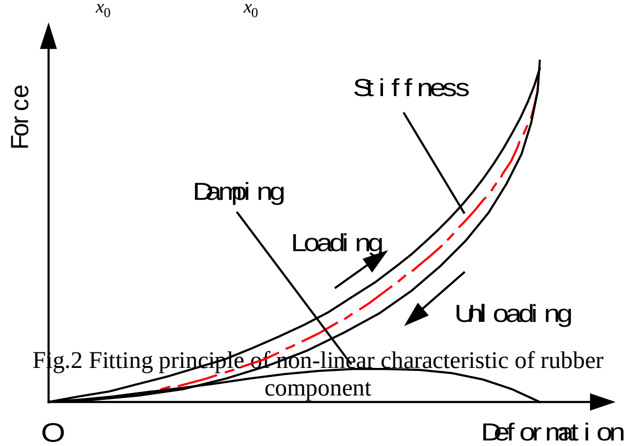


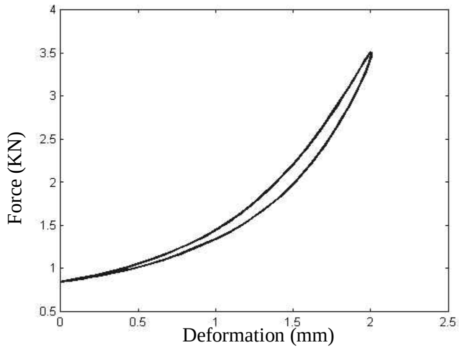
Fig.2 Fitting principle of non-linear characteristic of rubber component

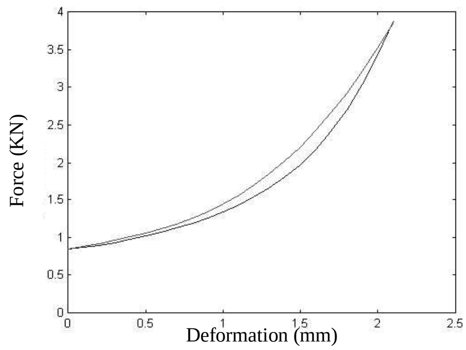
If the stiffness of rubber component is represented with the mean value of loading and unloading curve (seeing Fig.2), the non-linear dynamic characteristic of rubber component can be denoted as:

$$\begin{aligned} K &= \frac{d\left([F_a(x)+F_r(x)]/2\right)}{dx} \quad x \in (x_0, x_t) \\ &= \sum (a_i + c_i) i x^{i-1} \end{aligned} \qquad 9$$

The function of damping relative to exciting displacement can also be obtained:

$$\begin{aligned} C &= \frac{dW}{dx} = F_a(x) - F_r(x) \\ &= \sum (a_i - c_i) x^i + (b-d) \end{aligned} \qquad 10$$

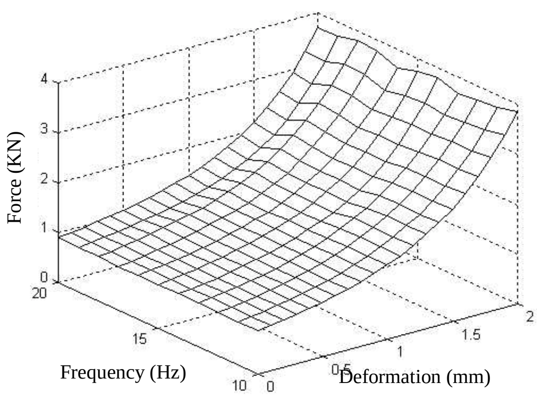


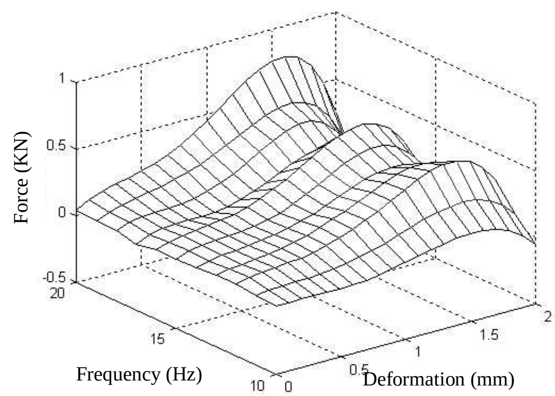


TEST DATA PROCESS AND EXAMPLE ANALYSIS

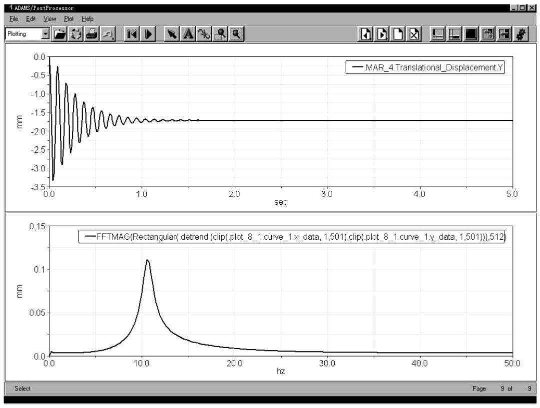
According to the method educed above, a numerical fitting works for the dynamic testing of suspension rubber bushing of a domestic car is carried out. The fitting result is presented by Fig. 3~Fig.6.

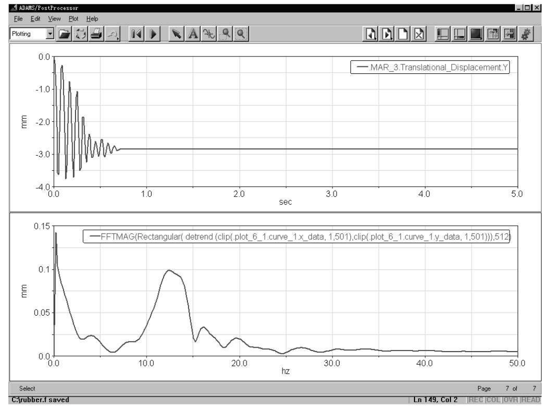
Fig.3 is the curve of non-linear exciting displacement-deformation force of rubber component under external exciting, the frequency of external exciting is 11 Hz. Fig.4 is the curve of dynamic characteristic after fitting. It is clear that the fitting result agrees with the testing result consistently.





The 3D-surface of exciting frequency deformation and dynamic stiffness are showing on Fig.5 while the exciting frequency changed from 10 Hz to 20 Hz , it is obtained by fitting the testing result of rubber component. Fig.6 shows the 3D-surface of exciting frequency deformation and damping. A parameter table of non-linear dynamic characteristic of rubber component can be built within the frequency range when the external exciting frequency changed. By means of judging the exciting frequency of model, the non-linear dynamic characteristic of rubber component can be obtained by the interpolation method based on the table. As a result, the effect of linear and non-linear dynamic characteristic of rubber component to vehicle can be considered in the process of vehicle dynamic analysis.





According to this method, an ADAMS user subroutine was compiled and an ADAMS custom solver was created, and a free vibration system that consists of a part supported by a rubber component is analyzed with the solver. The stiffness of rubber component is using the dynamic stiffness while the exciting frequency is 11Hz. According to the linearization assume, The stiffness of rubber component is 1.4KN/mm, the damping ratio is 0.2, and mass of the part is 245Kg. The calculation result is shown in Fig.7. Meanwhile, Fig.8 shows the analysis result when the non-linear dynamic characteristic of rubber component was taken into account. In the Fig.7 and Fig.8, the top drawing is the displacement-force curve, the bottom drawing is the vibration frequency-amplitude curve. The calculation result indicates that the system will vibrate with inherent frequency about 11 Hz, and it is a typical linear and one degree of freedom vibration system. Considering the non-linear stiffness characteristic of rubber component, the response frequency is abundance, which shows the typical characteristic of non-linear and one degree of freedom vibration system, and manifests the effect of non-linear stiffness characteristic of rubber component to system vibration.

CONCLUTION

The method of energy analysis is simple and practical, which can be applied to study the non-linear dynamic characteristic of rubber component of vehicle suspension. The analysis result of one degree of freedom vibration system indicates that the method of dealing with the non-linear dynamic characteristic of rubber component of vehicle suspension put forward in this paper can be used reasonably to the dynamic analysis of vehicle. The study method makes up the shortage of linearization assume of rubber component of vehicle suspension, and provides a feasible method for the simulation of non-linear dynamic of vehicle.

REFERENCE

1 Guo Konghui, Influence of tire dynamic side-slip characteristic on vehicle shimmy, Automobile Technology, 1995.4

2 [Japan]Hu Yuan Chun Yan, Mu Chuanwen Translate, Antivibration Rubber and Its Application, China Railway Publishing Company,1982

3 Cai Yanchun, Li Chengde, The Transient Response and Analysis of Automobile Non-linear System, Chanchun Automobile Research Institute, 1989.5.11

4 Wen Qiang, Yu Zhuoping, Zhang Lijun, Zhang Jianqiang, Wu Liangshou, Testing Research of Rubber Bearing of Suspension and Its Static and Dynamic Stiffness Characteristic. Shanghai Automobile, 1998.8