Finite Element Damping Simulation of Viscous Damper for Simply Supported Beam Vibration Mitigation

Bing Bai1, Jing Guo2*

1 Bridge and Tunnel Research Center, Research Institute of Ministry of Transport, Beijing, 100088, China
2 Beijing Road Engineering Cost Quota Management Station, Beijing, 100053, China
*Corresponding author’s e-mail: guojing3040@163.com

Abstract. Aiming at the issue of vibration mitigation of viscous damper, the FE simulation of the velocity dependent damper is studied. Based on the analysis of composition and mechanical performance of the damper, the key equation and parameters are identified and analyzed firstly. Thus according to the software regulations, two different element types COMBIN14 and COMBIN37 are selected to verify their damping characteristics. Adopting the commonly used simply supported beam as investigation object, the FE model is established and compared. Results show that COMBIN14 can only simulate the behavior of linear damper, while COMBIN37 has the capacity of simulating nonlinear damper. The related force-velocity equation and parameters can be achieved indirectly by modifying the element settings. And the damping effect with the change of different parameters is discussed. The results show that the attenuation effect of vibration has a positive correlation with damping coefficient C and a negative correlation with exponent α in a certain range.

1. Foreword
In bridge engineering, dampers are necessarily installed on some components to reduce the structural vibration response induced by vehicles, wind, etc.[1][2]. When design wind or small earthquake acts on the structures, the damper behaves elastically and structures possess enough lateral stiffness to meet the normal use requirement. While in strong vibration actions, the damper may enter into inelastic state (energy dissipation state) firstly and generate certain damping to dissipate the energy input to the structures, thus ensuring the unremarkable plastic deformation of main structures and keeping it safe in those strong dynamic loads.

The types of dampers can be divided into velocity dependent dampers, displacement dependent dampers (such as viscous damper) and displacement and velocity dependent dampers, i.e. hybrid dampers (such as lead viscoelastic damper). According to the materials used in dampers, it can also be divided into viscous damper, metal damper, viscoelastic damper, intelligent material damper, etc. On current the viscous dampers are most widely used in bridges.

Research on the use of viscous fluid dampers for structural vibration control began in the 1980s. Until now over hundreds of structures have adopted this as vibration control means. Both scholars and commercial company have carried out comprehensive study on this issue, The Taylor Devices Inc. has invested lots of financial and material resources in the research and development of the damper, and has formed a series of products. Constantinou and others[3]-[5] conducted a shaking table test on a structural model with viscous damper in 1990s and confirmed that the damper can reduce the structural vibration...
response effectively. Song[6] discussed the energy dissipation simulation and design of the structures with viscous dampers use. For the real engineering application, some strengthening cases[6][7] also show very remarkable effect. The vibration control with viscous damper is very promising for both scientific research and engineering application.

2. Composition and principle of the studied viscous damper
The damper studied in this paper is velocity dependent viscous damper. The general sketches of this device can be seen in Figure 1. And a brief introduction of composition and principle of viscous damper is described as follows.

![Figure 1. General sketches of the studied viscous damper](image)

Viscous damper is mainly composed of cylinder, piston rod, piston head with orifices, fluid damping material, etc. The cylinder is filled with some proper amount of fluid damping material, i.e. silicone fluid, and the piston head can do reciprocating motion in the cylinder. A number of small holes are evenly distributed on the piston head aiming at the flow of silicone fluid between the two chambers.

The working principle of viscous damper may be explained as follows: when there is relative displacement between the components connected with the damper, the piston head will move in the cylinder under the motion pressure. Due to the pressure difference between the chamber 1 and 2 in the process of movement, the fluid is forced to flow from one end of the piston to the other through the orifices, so as to generate damping force to dissipate the vibration energy of the structures. In addition, the viscous damper has no original stiffness under static condition (no vibration or relative displacement), therefore it will not produce any unexpected side effect or affect the normal use of structures.

3. Mechanical performance analysis of viscous damper
As stated above, the viscous damper discussed in the paper uses the viscous characteristics of its fluid materials (silicone oil) to produce damping[8]. About this, scholars have given many mechanical equations to describe the damper behavior. Although the forms are different, there is a common point that the damping force is related to the relative velocity of both ends of the damper. And the most commonly used equation[9] is as follows

$$F = Cv^\alpha$$  \hspace{1cm} (1)

where $F$ is the damping force, $C$ is the damping coefficient, $v$ is the damper stroke speed and $\alpha$ is the damping exponent. The equation actually denotes the damping force changes nonlinearly with the piston velocity. The range of damping exponent generally is from 0.2 to 1.0, the influence of its value on damping force and energy dissipation is related to velocity. Also the increase of damping coefficient means the increase of damping force and energy dissipation capacity. The performance of viscous damper can be described from the two parameters. By analyzing the physical characteristics variation of the parameters, the damper mechanical property can then be explained. Figure 2 shows the change rule of damping force versus velocity and damping exponent under the assumption of damping coefficient $C=1.0$. 


It can be concluded from the figure that when $C$ is constant, the damping force always presents positive correlation with velocity $v$. But observe it in detail, the damping force generally decreases with the increase of $\alpha$ when $v \leq 1.0$ m/s, and increases with the increase of $\alpha$ when $v \geq 1.0$ m/s. Besides, due to the nonlinear characteristics of viscous fluid, larger damping force can be exported at a smaller $v$, which fully reflects its good mechanical properties.

It is also worth noting that when $C$ equals 1.0, Equation (1) becomes the form of $F = Cv$. This means the damping force changes linearly with the velocity. Therefore, when structural components deform to the maximum, the corresponding internal force also become largest, while velocity $v$ is 0 at the moment. According to the equation, the damping force generated by the damper is the smallest. On the contrary, when the damping force produced by the damper is the maximum, the velocity $v$ of the deformed components get smallest, while the corresponding internal force reaches the minimum, in other word, viscous damper produces greatest damping force when the components move fastest and deform smallest. Hence the application of viscous dampers in bridge structures will not significantly increase the internal stress of components and disturb the normal operation of bridges.

In order to explore the relationship between damping force and excitation frequency and amplitude, some discussion is also conducted via inputting structure sine wave displacement excitation $u = A \sin(\omega t)$. By changing the amplitude $A$ and frequency $\omega$ of displacement $u$, the damping force and structural displacement are analyzed respectively.

A key index to evaluate the performance of damper is the hysteretic curve. The fullness of hysteretic force-displacement curve shows the damper energy dissipation capacity. According to the result of reference [10], if the input displacement $A$ keeps constant, say 10 mm, the corresponding hysteresis curve tends to be full with the increase of excitation frequency under the same external conditions. This implies the damper energy dissipation capacity increases with the grow of excitation frequency. However, if the excitation frequency is fixed, say 0.5Hz, with the increase of input amplitude $A$, the hysteretic curve gradually expands from inside to outside and the energy dissipation capacity also increases. To sum up, the force amplitude of the hysteretic curve is related to the displacement amplitude and frequency of the input excitation load, which further illustrates the energy dissipation capacity of the viscous damper is not only related to the parameters $C$ and $\alpha$, but also related to the amplitude $A$ and frequency $\omega$ of the excitation.

In addition to the above, the damper performance is also related to piston size, orifice shape, temperature, damping fluid and other factors. In this paper, the damper is mainly discussed to mitigate vibration induced by vehicle bumping and braking force, hence the excitation load can be assumed to be related to the vehicle force. According to this, some rough law of damping parameters on energy dissipation capacity can be obtained based on equation (1). It is already known that when damping exponent $\alpha = 1$, the damping force changes with velocity linearly, otherwise nonlinearly. However compared with linear changing, the nonlinear changing situation may generate larger damping force at lower piston moving velocity, and keep little increase when the piston velocity is high. Due to this characteristics, the damping force of nonlinear damper may be much greater than that of the linear
damper, as the relative velocity of the components generally is less than 1m/s. At this time, the output damping force of damper with $\alpha<1$ is more likely to reach a larger value in the early stage of the piston moving, while make the force increase little in the case of larger velocity. This performance may effectively protect the bridge components and joints from premature failure due to the drastic change of damping force[11]. In the following, different element types and damper parameter values will be selected to simulate and analyze the structural vibration response laws. Based on the result, the reasonable simulation method and parameters of viscous damper will be determined.

4. Damper element simulation

There are two kinds of spring elements with control function often used in the FE software ANSYS[12], each of their description are as follows:

1) Spring-damper element COMBIN14. This element type has longitudinal or torsional capacity in 1-D, 2-D, or 3-D applications and no mass considered. The longitudinal spring-damper option is a uniaxial tension-compression element with up to three translation degrees of freedom at each node. No bending or torsion is considered. The torsional spring-damper option is a purely rotational element with three degrees of freedom at each node: rotations about the nodal x, y, and z axes. No bending or axial loads are considered.

2) Control element COMBIN37. COMBIN37 is a unidirectional element with the capability of turning on and off during an analysis. The element has one degree of freedom at each node, either a translation in a nodal coordinate direction, rotation about a nodal coordinate axis, pressure, or temperature.

According to the characteristics of each elements and damping simulation function, these two kinds of damping elements are studied for further comparative analysis based on the viscous damper performance equation.

To reflect the result more clearly, simply supported beams with large application in engineering are selected for analysis. The damping elements are installed respectively in the middle of the beam. And a sinusoidal load is applied near the span middle position (node 12) with additional white Gaussian noise on the whole structure. The vertical displacement of node 13 (span middle) under different damping conditions is obtained as response result. The whole FE model is illustrated in Figure 3.

![Figure 3. FE model of the simply supported beam](image)

Taking the case of damping exponent $\alpha=1$, i.e. $F=C\cdot v$ structural linear damper to analyze firstly. The response is shown in Figure 4 to Figure 10 (where displacement response unit: m, time unit: s).

From the figure comparison, it can be seen that both damping elements have good control and damping effect on the vertical response of the node, and the effects seem similar. In a certain range the larger the damping coefficient $C$ is, the greater the vertical nodal velocity attenuation is, which implies more obvious vibration mitigation.

![Figure 4. Time history of node 13 vertical displacement without damping](image)

![Figure 5. Time history of node 13 vertical displacement with $C=1e7$ using COMBIN37](image)
Figure 6. Time history of node 13 vertical displacement with $C=1e7$ using COMBIN14

Figure 7. Time history of node 13 vertical displacement with $C=5e6$ using COMBIN37

Figure 8. Time history of node 13 vertical displacement with $C=5e6$ using COMBIN14

Figure 9. Time history of node 13 vertical displacement with $C=1e6$ using COMBIN37

Figure 10. Time history of node 13 vertical displacement with $C=1e6$ using COMBIN14

According to the model analysis of COMBIN14 element, if the element is used to simulate longitudinal damping elements, the damping force exported by the element can be evaluated as follows:

$$F_x = -C \frac{dU_x}{dt}$$  \hspace{1cm} (2)

Where $dU_x$ and $dt$ are the differential of longitudinal displacement and time respectively. Thus, the control force by this element is only related to the damping coefficient and velocity, with no relationship to damping exponent. Therefore, COMBIN14 element can only simulate the case of linear damper. However, for COMBIN37 element, this element type can simulate the nonlinear behavior. As the documentation describes, the input variables can be modified using the following equations:

$$RVMOD = RVAL \cdot C_1 \cdot |CPAR|^{C_2} + C_3 \cdot |CPAR|^{C_4}$$ \hspace{1cm} (3)

where $RVMOD$ is the modified value of an input parameter value $RVAL$ (identified by KEYOPT(6)), $C_1$ through $C_4$ are other parameters, and $CPAR$ is the control parameter (identified by KEYOPT(1)). If
KEYOPT(1) is set to 2, then $CPAR$ will be considered as the velocity of node in the FE model, which fulfills the requirement preliminarily. As for the $RVMOD$ and $RVAL$, KEYOPT(6) can also be set to 1 to make the parameters recognized as damper coefficient. In this case, if we take $RVAL$ and $C3$ as 0 further, equation (3) may be transformed into the following form

$$RVMOD = C = C1 \cdot v^{C2}$$  \hspace{1cm} (4)

Thereafter, let $C2 = \alpha - 1$, the function of equation (4) will have a similar form of equation (1), which implies the nonlinear equation similar to viscous damper may be obtained by changing the equation (3) parameters. The simulation of nonlinear damping can be finally achieved in this way.

Based on the above analysis of the COMBIN37 element, the structural response with nonlinear damper is evaluated. The damping coefficient $C$ and exponent $\alpha$ are given in accordance to the definition of $F = Cv^{\alpha}$ and equation (3)–(4). The results are shown in Figure 11~Figure 13. (where displacement unit: m, time unit: s)

From figures above, it can be seen that the vibration mitigation effect of COMBIN37 element presents nonlinear inverse change with the decrease of damping exponent $\alpha$, which proves the nonlinear damping simulation capacity of the element. Moreover, it can be found that in a certain range the smaller the damping exponent $\alpha$ is, the greater the velocity attenuation is. This law shows more notable damping effect in the case of $\alpha$ staying in low level.

5. Conclusion

This paper discusses the numerical simulation of viscous damper in simply supported beam vibration mitigation. On the ANSYS software platform, the damping effect of COMBIN14 and COMBIN37 are evaluated and compared. The results show that the COMBIN37 element is more suitable for the simulation of nonlinear damping cases, and the parameter selection can be realized by the KEYOPT() settings. Applying the findings, the FE simulation shows that the attenuation effect of structural vibration

![Figure 11](image1)

![Figure 12](image2)

![Figure 13](image3)
has a positive correlation with damping coefficient $C$ and a negative correlation with exponent $\alpha$ in a certain range. The damper selection and simulation seems can benefit from this consequence.

Acknowledgements
This study is funded by the Science and Technology Innovation Foundation of Research Institute of Ministry of Transport [grant No. 2018-A0040].

References
[1] Zhou Y., Xu T., Yu G. et al. (1999) Recent advances in research, development and applications of seismic energy dissipation. Earthquake Engineering and Engineering Vibration, 19(2): 122-131.
[2] Chopra A.K. (2012) Dynamics of Structures: Theory and Applications Earthquake Engineering (4th edition). Pearson Education, New York.
[3] Taylor D.P., Constantinou M.C. (2012) Fluid dampers for applications of seismic energy dissipation and seismic isolations[EB/OL]. http://www.taylordevices.com/tayd.
[4] Makris N., Constantinou M.C. (1991) Fractional-derivative Maxwell model for viscous dampers. Journal of Structural Engineering, 117(9):2708-2724.
[5] Pipkinsay D.S., Atlurib S.N. (1996) Applications of the three dimensional method finite element alternating method. Finite Elements in Analysis and Design, 23(2-4): 133-153.
[6] Song Z. (2001) Research and application of viscous energy dissipation technology in seismic strengthening of structure. China Academy of Building Research, Beijing.
[7] Ou J., Wu B., Long X. et al. (2001) Analysis and design of seismic retrofit of Beijing Hotel with energy dissipators: time history method. Earthquake Engineering and Engineering Vibration, 21(4): 82-87.
[8] Guo R., Guo Q. et al. (1996) Fluid mechanics and its application. China Machine Press, Beijing.
[9] Housner G.W., Bergman L.A. et al. (1997) Structural Control: Past, Present and Future. Journal of Engineering Mechanics, 123(9): 897-971.
[10] Xiong W. (2007) Experimental study and structural analysis of a new viscous damper. Huazhong University of Science and Technology, Wuhan.
[11] Terenzi G. (1999) Dynamics of SDOF systems with nonlinear viscous damping. Journal of Engineering Mechanics, 125(8): 956-963.
[12] ANSYS Inc. (2006) Release 12.0 documentation for ANSYS. ANSYS, Pittsburgh.