Practical method of obtaining different levels of seismic energy dissipation using viscous fluid protective system on bridges

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Abstract. In order to achieve an optimal stability performance during transient vibratory actions the damping method is used for the bridge structures. Conventional approach would dictate that a structure must inherently attenuate or dissipate the effects of transient inputs through a combination of strength, flexibility and deformity. The damping level is being at low values at a conventional elastic structure and hence the amount of dissipated energy during transient vibratory actions is also in very low value. In the event of an earthquake, conventional structures usually perform high deformations which when situated beyond their elastic limits can cause the collapse. In such cases most of the dissipated energy amount is absorbed by the structure through localized damage as it fails. The concept of supplemental dampers added to a structure assumes that most of the energy amount input to the structure from a transient vibratory action will be absorbed, not by the structure itself, but rather by supplemental damping elements. Properly implemented, an energy dissipation system can be able to simultaneously reduce both stress and deflection within the structure elements.

The fluid viscous protective system concept is presented as an optimum energy dissipation solution for bridge structure types. The operation of these devices is on the hydro-static principle of fluid flow through orifices of a special diameter value. In this paper it is presented an innovative functional and constructive model of fluid viscous device based on a practical design method which allows the controlled operation regime regarding the viscous fluid flow inside the device cylinder being able to provide considerable resistant force levels to relative motions between a bridge structural frames where is mounted and achieving considerable amounts of seismic energy dissipation when an earthquake occurs. For the constructive method of fluid viscous system model is adopted a practical constructive method aiming the direct control on the circulated fluid flow rate so that the device response force should be considerably larger, acting for limiting the relative movement of the structural frames and without introducing additional stiffness to the structural system to which it is attached, due to the elasticity of the working fluid type used. It represents an innovative method because of the special design orifices for fluid flow rate control used which, depending on the specific diameter values, can provide device different response force values and implicitly different dissipated energy amount levels based on the characteristic represented by the resistant force variation law according to the piston stroke.

1. Introduction
Seismic isolation and energy dissipation are the most widely used methods of controlling the building structures behaviour and additional damping is obtained, necessary for the significant structural response reduction to the seismic movements of the structures.
Dissipation systems working on the passive principle represent viable technologies for seismic protection of building structures and bridges. The device main components are presented in figure 1 and the assembly 3D model is shown in figure 2.

A dissipation system involves adding viscous damping by using viscous-elastic dampers, viscous fluid hydraulic devices or adding hysteresis damping by using frictional force devices, metal deformation devices, or "shape memory" alloys.

Structural control systems operating with viscous fluid have damping characteristics that are ensured by the force-displacement relationship [1][3].

The main advantages provided by these devices are high reliability since they are activated by the seismic movement, having the possibility to enter into operation even at minimum displacements.

The damping force is out of phase compared to the structure elastic forces to which they are attached.

The disadvantages are related to the high cost price, as well as the possibilities of losing or changing the properties of the working liquid over time [4].

![Figure 1. The main components of the fluid viscous system assembly.](image1)

![Figure 2. 3D assembly model for viscous fluid dissipative system.](image2)

2. Main mechanical models describing fluid viscous device operation

The mechanical model of viscous fluid dissipation systems is presented using Maxwell and Voigt-Kelvin rheological models. From the experiments, it has been shown that the stem resistant strength of the viscous fluid dissipation device depends not only on velocity but also on deformation. This aspect can be modeled using the Voigt-Kelvin model which describes an elastic element connected in parallel with a viscous element (figure 3).

The equation that describes the classic model is as follows [5]:

\[ F_r = c \dot{x} + kx \]  \hspace{1cm} (1)

The equation shows the axial force \( F_r \) of the device based on the deformation \( \dot{x} \), realized with the velocity \( \ddot{x} \). \( K \) and \( C \) represent elastic element stiffness and viscous element damping coefficient.

By generalization that involves adding coefficients to the equation terms, the generalized Voigt-Kelvin model is obtained [5]:

\[ F_{rg} = c \dot{x}^a + kx^b \]  \hspace{1cm} (2)
For the Maxwell model it is considered a spring and a shock absorber connected in series (figure 4).

The two assembly elements contribute to obtaining the values of displacement and velocity according to the relations [5]:

\[ x = x_e + x_d \]
\[ \dot{x} = \dot{x}_e + \dot{x}_d \]  \hspace{1cm} (3)

The equations describe the displacement \((x_e, x_d)\) and velocity values \((\dot{x}_e, \dot{x}_d)\) of the elastic element and the shock absorber.

The relation of the resistive force to the axis of the device in axial direction is shown; where \((k)\) represents the rigidity value of the elastic element and \((c)\) the damping coefficient of the damper [5]:

\[ F = c\dot{x}_d = kx_e \]  \hspace{1cm} (4)

Also, by generalization by introducing non-linearity into the elastic element behavior as well as the shock absorber, the relation of the resistive force is thus obtained [5]:

\[ F_{rg} = c\dot{x}_d^a = kx_e^b \]  \hspace{1cm} (5)

3. Fluid viscous device functional parameters

The seismic fluid viscous device offers a viable alternative for yielding or plasticizing structural elements, as these systems are capable of absorbing much of the seismic energy induced by an earthquake in the structure.

Due to the viscosity properties of the fluid used, a resistance force to the piston displacement inside the device cylinder and the ability to convert mechanical energy into calorific energy through the working fluid is obtained.

The occurrence of a dynamic action is moving the piston rod, which causes a forced passage of the fluid through the orifices, which due to the fluid viscosity creates a pressure inside the cylinder and a resistance force to the rod displacement which acts as a vibration damping force. In this way energy dissipation is achieved.

This damping force provided by the fluid viscous device can be modified proportional to the displacement velocity, so that the dissipation device is considered velocity dependent.

By controlling the piston head orifice diameter, different energy dissipation levels can be provided.

The main functional parameter for the fluid viscous device is the resultant force at the rod which is dependent on the relative velocity between the device ends.
The relation that governs the device operation is the force-velocity relation which also depends on the characteristics of the working fluid:

\[ F = C |v|^a \text{sgn}(v) \]  

(6)

where: \( v \) - the relative velocity between the two joints of the fluid viscous device; 
\( C, a \) - damping constants.

The damping exponent \( (a) \) can have values ranged between \((0.01:1.9)\) and this coefficient can provide information regarding the amount of energy dissipated in the working cycle of the fluid viscous device.

Thus, the lower its value \((a)\), increases the energy dissipated amount by means of fluid viscous system.

The fluid viscous devices provide a strong non-linear character and the exponent \((a)\) is representative for their non-linearity.

The hysteresis curve for these device types is represented by an ellipse and with the decrease of the damping exponent \((a)\) the shape of the hysteresis curve begins to acquire the contour close to the rectangular shape as shown in figure 5.

![Figure 5. Hysteretic curve for the fluid viscous device according to the damping exponent \((a)\).](image)

The hysteresis curve shown in figure 5 is obtained based on the non-linear relation that describes the operation of the fluid viscous system and underlines the strongly non-linear character of these protective devices.

It can be observed the increase of the force at the beginning of the operation for a small variation of the movement velocity, then the force records near values for a greater range of rod velocity values.

4. Parametric study of the fluid viscous device operation

The value of the damping exponent \((a)\) can change the fluid viscous device operation, so that the device can operate linearly for \((a = 1)\), in which the rod force increases linearly with velocity, but the area of the hysteresis curve is smaller, which means a less quantity of dissipated energy.

For sub-unit values of the damping exponent \((a)\) and close to zero, a faster force increase can be observed as rod velocity function and the curve has a larger coverage area, which provides information on a larger dissipated energy quantity, for the same maximum or minimum values of the force displacements.

The force variation diagram is presented as a function of the damping coefficient \((a)\) for different values of movement velocity \((v)\).
Figure 6. Force-velocity diagrams for different values of damping exponent \((a)\) and velocity \((v)\).

It can be observed that near the zero value for the damping exponent \((a)\) the dissipating device responds with near values of resistive force, after which the exponential force increase is recorded. The dependence between the fluid viscous device stem force and the piston translation velocity is represented in figure 6 for different values of the damping exponent \((a)\) and reduced values of the damping constant \((c)\).

5. Method of obtaining different levels of seismic energy dissipation using fluid viscous device (FVD) and modelling aspects of the fluid viscous device model (FVD)

Operation of a fluid viscous damper provide a considerable response force of a structure to the seismic ground motion. For its purpose the protective device use a working fluid with specific viscosity characteristics as well as constructive solutions of the component part represented by a set of circulation orifices whose diameter allows the fluid to be laminated during operation so as to be obtained the optimum damping results.

Thus, a set of orifice diameter values is proposed for the fluid viscous damper model in order to highlight the device stem resistant strength values by numerical analysis on the virtual model.

The overall model for the fluid viscous dissipation device is made in two constructive versions. The first model (case 1) presented as a cylinder with piston assembly having orifices made in the cylinder accumulation chamber wall (figure 7(a)).

Figure 7. Fluid viscous damper models considered for numerical analysis cases.
The second model made (case 2) presents circulation orifices for the working fluid in the cylinder wall of the containing the piston having a supplemental cylinder chamber that takes over the working fluid during the piston displacement (figure 7(b)) [7][8].

Both considered models are based on the working fluid flow through orifices, once the piston performs translation movement inside the cylinder, corresponding to the occurrence of the seismic movement.[6]

6. CFD analysis on fluid viscous device virtual model
For the two constructive variants fluid flow analysis on the virtual model is performed using Ansys CFX. [9][10]

The working fluid is a silicone oil with a density of 975 kg/m³ and a dynamic viscosity of 12500cP [11]. Different values are considered for the fluid flow orifices diameter values in the range 0.5-0.7 cm.

For the initial conditions a displacement velocity of 0.4 m/s is considered for the piston corresponding to the occurrence of a seismic motion.

![Figure 8. Main analysis domain.](image)

For both cases a main cylinder with a total length of 0.5 m and a diameter of 0.2 m is made.

In case 1, the proposed model (figure 8a) has a set of 14 radially arranged orifices made in the separating wall between the piston chamber and the accumulation chamber.

For the case 2 it is proposed a model (figure 8b) with 14 orifices made in the cylinder inner wall, the height of the orifice cylinder being of 2 cm. The mesh network details are presented in figure 9(a) for case 1 (440322 nodes and 301824 elements) and in figure 9(b) for case 2 (546457 nodes and 375020 elements).

![Figure 9. Mesh network details.](image)

7. Results
Following the working fluid flow analysis on virtual models of fluid viscous damper in two different constructive configurations, results were obtained that highlight the functional character of these devices materialized by the provided stem resistant force of certain values achieved for the piston movement.

The results of the flow analysis are in terms of the velocity and pressure recorded at the level of the analyzed fluid region for each analyzed case (figure 10-13), as well as the specific rod-resistant force value on the main axial direction of piston movement inside the cylinder.
Figure 10. Fluid velocity, temperature and pressure values for case 1 (0.5 cm orifice diameter).

Figure 11. Fluid velocity, temperature and pressure values for case 2 (0.5 cm orifice diameter).
Figure 12. Fluid velocity, temperature and pressure values for case 1 (0.7 cm orifice diameter).

Figure 13. Fluid velocity, temperature and pressure values for case 2 (0.7 cm orifice diameter).

The resistant force values obtained from the performed numerical analysis are presented in table 1 for both analyzed cases.

| Orifice diameter values (mm) | Force values (N) | Case 1 | Case 2 |
|-----------------------------|-----------------|--------|--------|
| 5                           | 148262          | 162828 |
| 7                           | 59810           | 34820  |

The values of the resistant force were recorded on the axial direction of movement of the piston for which the velocity value of 0.4 m/s was declared.

8. Discussions
Based on the performed numerical analysis results, the dissipation characteristics of the analyzed models can be highlighted.

Thus, starting from the translation movement in the axial direction of the piston, specific values of velocity and pressure are recorded on the analyzed fluid region with high velocity values in the area of the fluid circulation orifices where are also recorded low pressure values.

On the main piston movement direction specific values of the rod resistant force are recorded. The highest value of 162828 N is obtained from the case 2 analyzed model for the 5 mm of fluid flow orifices diameter. For the 7 mm value the same model obtains the lowest value of 34820 N.

The case 1 analyzed model obtains the value of 148262 N for 5 mm orifice diameter and 59810 N for the case of 7 mm orifice diameter.
Thus, the visible differences in the resistant force obtained values are highlighted, depending on the fluid flow orifice diameter values for the case of using the same working fluid type and at the same declared piston velocity value of 0.4 m/s.

Such differences can also be observed on the fluid low velocity and pressure values for the two analyzed cases.

9. Conclusions
The isolation and energy dissipation modern techniques use in order to improve the dynamic behavior of buildings during seismic actions is a general trend at the present time all over the world.

Fluid viscous dissipation systems represent a solution for both bridges and buildings endowment.

Two constructive solutions of fluid viscous dissipation system were analyzed in this paper and the results show acceptable values for the rod-resistant force for the case of the small diameter values of the fluid passage orifices.

The higher values of the resistive force correspond to the model with orifices made in the cylinder wall, but the recorded values are relatively close for both analyzed cases.

The results are obtained for the case of using a high viscosity silicone oil (12500 cP), as well as a translation velocity value of 0.4 m/s corresponding to the occurrence of a seismic motion.

10. References
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