Viscous fluid dissipation system model acting on the active principle

F Scheaua
“Dunarea de Jos” University of Galati, Engineering and Agronomy Faculty of Braila, MECMET Research Center, 29 Calarasilor Street, Braila, Romania
E-mail: fanel.scheaua@ugal.ro

Abstract: There are solutions in terms of seismic isolation and energy dissipation that are successfully applied all over the world to building structures but also to high-way and rail infrastructure elements represented by bridges and viaducts. These structures must remain functional even after they have been requested by a considerable magnitude earthquake. This is why research activities aiming the development and modernization of these mechanical systems, which play a decisive role in ensuring the optimal stability of these structures, are justified. Fluid dissipation systems were originally developed as passive protection systems but over time they have been constructively improved with intelligent control systems that have the potential to considerably increase the efficiency of these systems by making use direct control over the amount of energy which can be dissipated through these protection systems. Such a dissipative viscous fluid system is described in this paper as a more evolved constructive system than the passive principle model. Active control over the operation of this device is materialized by altering the working fluid flow rates through the constructional elements of the dissipation device assembly. This flow rate adjustment is made by means of a flow controller present within the control unit. The mathematical model characterizing the functioning of an active viscous fluid dissipation system is presented, as well as a numerical analysis describing the function of such a dissipative system depending on the additional mass of the isolated structure to which the protective device is attached. The numerical analysis is based on a set of specific values presented in the paper. These dissipation systems are primarily used in bridge or viaduct structures, being responsible for limiting the relative displacements between the structural elements where they are mounted. This method provides greater security through the rigid connection achieved between the structural frames acting as anchorages. Entry into action is made in the occurrence of a seismic event when the piston displacement is recorded and by changing the momentarily flow rate values of the circulating fluid the amount of energy dissipated is adjusted by means of the viscous fluid device. There are presented the advantages and disadvantages related to the use of such seismic energy dissipative systems attached to the construction structures.

1. Introduction
In the construction field, the engineers concerns are primarily related to the buildings structural stability and durability that are in project for being built.

Increased attention is directed mainly to the structures resistance to the dynamic actions represented by the seismic actions that are able to determine the foundation ground sudden movement
with the entrainment of the building in motion, with the effect of transmitting the efforts on the vertical direction from the ground to the superstructure.

In order to ensure the buildings stability and durability, several methods of structures isolation with different protection systems are used in order to ensure the best possible stability and durability degree for both new built structures and also for the rehabilitation of old buildings.

The isolation methods used in building structures are related to the use of mechanical systems that have the possibility to change structure behaviour when an earthquake occurs. This can be done by modifying the building vibration period through the isolation system action so that the structure to be able to avoid the resonance phenomenon with the frequency of terrain seismic motion.

The ratio of interest is represented by the relation between the construction vibrations fundamental period \(T_c\) and the terrain vibration period \(T_t\), at the maximum amplitude of the seismic motion.

The closer values of the two periods describe a higher dynamic amplification and the possibility of structure to enter the resonance with the terrain movement.

This phenomenon would actually occur if the ground movement had a ordered (sinusoidal) character.

The occurrence of a high magnitude earthquake involves dynamic vibration amplification, which in short time can reach high values, causing the dangerous resonance phenomenon.

For example, for the earthquake in Romania, Vrancea 1977 (Magnitude 7.4 on Richter scale and a duration of 55 s), the spectral curve, determined by the processing of seismograms measured in Bucharest, had its own maximum vibration period \(T_t = 1.5\) s;

Low-rise, rigid buildings were less affected by earthquake, while high-flexibility buildings with their own vibration period of over 1.2 seconds showed maximum dynamic amplifications.

In Bucharest, a large number of buildings built during the interwar period collapsed because they had flexible resistance structures made up of beams and pillars without reinforced concrete diaphragms.

In order to counteract these undesirable situations, in addition to classical methods of proper dimensioning of building strength, the use of modern isolation methods is increasingly used throughout the world today.

The systems used provide both isolation and dissipation of seismic energy when the structure is required by an earthquake. For the dissipative systems, devices operating on viscous fluids have been developed in order to provide a limitation of the frames relative displacements between which they are mounted.

Initially, such devices were designed to operate on the passive principle, benefiting from independent operation, and then developed and improved by adding fluid flow rates and pressure control systems considered as devices operating on the active principle.

The nonlinear mathematical model describing the operation of these device types are presented as well as numerical analysis meant to highlight the operating principle based on a viscous fluid of the dissipative system according to several values of the structure mass where is mounted [1].

2. **Constructive assembly model and mounting solution at the insulated structure**

An energy dissipation system operating on viscous fluid represents an assembly consisting of a cylinder with piston, a connecting rod between the piston and the planar or space-type gripping joint, the clamping joint mounted on the cylinder body as well as the clamping flanges to the isolated structure [2].
Figure 1. Schematically representation of an active fluid viscous dissipation device assembly.

The dissipative device assembly shown schematically in figure 1 can be mounted inside a building's structure in order to reduce the frames relative displacements during a seismic motion. The piston of the device divides the cylinder in two parts at the equilibrium mounting position, thus providing two chambers filled with viscous liquid (silicone oil). The mounting solution is made in order of achieving a bridge structure isolation by means of clamping joints one at the bridge pier and the other at the bridge beam, as shown in figure 2.

Figure 2. Mounting solution of fluid viscous active dissipation device on a bridge structure model.

The action of the viscous fluid dissipative system is directed towards an energy consumption from the total energy amount induced by the earthquake that move the structure in the dynamic regime. The operation is reversible due to the traction-compression cyclical movements and the dynamic behavior is dependent on the frequency of the vibrations produced by the seismic action. A set of adjusting devices are mounted inside the machine assembly represented by energy regulators that provide a diverse range of dissipation values depending on the adjusting commands. An electronic monitoring system for seismic vibrations controls the opening or closing of the fluid pressure and fluid flow rate regulators of the circulated working fluid between the two chambers of the dissipative device cylinder in accordance with the frequency and intensity of the vibrations that occur, thus providing different dissipation stages of the device [1, 3].

3. Energy dissipation characteristic of the fluid viscous device
The viscous fluid dissipative system is used for mounting in buildings with reduced height and also for bridge structures. Operation is based on the properties of the working fluid which, through the
controlled circulation between the two chambers of the cylinder, provides an energy consumption according to the magnitude of the earthquake that move the structure.

It is a velocity-dependent device and the response is given by the piston rod resistant force, acting against the relative displacement of the structural frames.

The device's dissipation characteristic is the law of variation of the piston rod resistance force, according with the piston stroke (equation (1)).

This characteristic of the apparatus represents the total amount of dissipated energy at a complete stroke of the piston of the dissipative device recorded during a seismic action.

The area within the parallelogram described by the movement resistant force is the energy consumed by the fluid viscous device and converted to caloric energy [1, 4].

\[
F_{rec} = \begin{cases} 
\frac{2F_0}{\delta} y; & y \in \left[0, \frac{\delta}{2}\right]; \\
F_0; & y \in \left[\frac{\delta}{2}, x_0\right]; \\
F_0 + \frac{2F_0}{\delta} (y - y_0); & y \in (y_0, y_0 - \delta]; \\
-F_0; & y \in (y_0 - \delta, -y_0]; \\
-F_0 + \frac{2F_0}{\delta} (y + y_0); & y \in (-y_0, -y_0 + \delta); \\
F_0; & y \in (-y_0 + \delta, y_0). 
\end{cases}
\]  

where:
- \(F_0\) - the dissipation force adjusted on the device;
- \(\delta\) - passive piston stroke until the entry into service of control appliances;
- \(y\) - the piston momentary stroke;
- \(y_0\) - half of the piston stroke.

Figure 3 shows the theoretical feature for resilient strength.

![Figure 3. Theoretical characteristic of fluid viscous dissipation device operation [1].](image)

The adjustment of the dissipative force of the viscous fluid dissipation device is achieved by means of regulators that interfere with the pressure and fluid flow rates between the two cams of the cylinder for both piston displacement directions dictated directly by the seismic action.
4. The nonlinear mathematical model of the viscous fluid dissipative device

In order to compile the dynamic model of the hydraulic dissipative device, two equations describing the flow rate of circulating fluid and the forces applied to the piston of the device are required. The nonlinear mathematical model is as follows in equation (2) [1]:

\[ \frac{dy}{dt} = \frac{D}{A_p} \sqrt{p} - \frac{H}{A_p} \sqrt{p} + \frac{V}{A_p \cdot E} \frac{dp}{dt} \]

\[ \frac{d^2 y}{dt^2} + \frac{C}{M} \frac{dy}{dt} + \frac{K}{M} y = \frac{g}{10} - \frac{A_p}{M} p \]

The dissipative device operational constants are determined with the equation (3) [1]:

\[ D = \frac{\pi^2 d^3}{4k} \sqrt{\frac{2}{\xi \cdot \rho}} \]

\[ H = \pi \cdot d \cdot \delta \sqrt{\frac{2}{\xi \cdot \rho}} \]

where:
- \( d \) - the diameter of the pressure regulator drawer;
- \( \delta \) - passive stroke of the drawer until opening of the pressure regulator;
- \( k \) - rigidity of the pressure regulator;
- \( \xi \) - the coefficient of local load losses at the working fluid circulation through the pressure regulator;
- \( K \) - dissipative device stiffness;
- \( C \) - the damping factor for the dissipative device;
- \( M \) - the structure mass isolated with the dissipative device;
- \( A_p \) - the piston area of the dissipative device;
- \( V \) - the working fluid volume inside the dissipative device between the piston and the regulator;
- \( \rho \) - density of working fluid;
- \( E \) - elasticity of working fluid;
- \( p \) - the adjusted pressure to a certain value.

5. Numerical analysis regarding the operation of the fluid viscous dissipative device

In order to analyze the fluid viscous hydraulic dissipative device operation, the following variables need to be described in detail according with equations (4) [1, 5]:

\[ x = x(t); \]
\[ p = p(t); p = p(x); \]
\[ F = F(t) = A \cdot p(t); F = F(x) \]

The operation of the fluid viscous dissipation device acting on the active principle of controlling the working fluid pressure and flow rates values is analyzed using the case study with the numerical values declared in table 1.

Table 1. The numerical values used in the analysis of the fluid viscous dissipative device.

| \( k_r \) | \( d \) | \( \rho \) | \( \varepsilon \) | \( A \) | \( V_0 \) | \( M \) | \( \delta \) | \( K_s \) | \( C \) | \( E \) | \( g \) |
|-----------|-------|--------|--------|------|--------|------|--------|------|------|------|-----|
| (52;104;208) daN/cm | 0.45 cm | 0.0009 kg/cm³ | 1.8 | 115.4 cm² | 3460 cm³ | (15000;25000;35000) kg | 0.9 | 8 daN/cm | 10 daNs/cm | 16900 daN/cm² | 981 cm/s² |
The variable $x = x(t)$ representing the piston stroke of the fluid viscous dissipative device according to the time obtained by running on the numerical model is represented graphically in figure 4 for three different values of the isolated structure mass having this type of device mounted. An increase can be observed for the amount of displacements over time, proportional to the increasing value of the isolated structure mass.

![Graph showing piston displacement over time for different masses](image1)

**Figure 4.** The piston displacement according to time obtained for different structure mass values [3].

In order to represent the time-controlled pressure values, $p = p(t)$, is taken into consideration to be analyzed the variable where the isolated structure mass value is modified and running the calculation for three different values used for the of the structure mass.

The analysis obtained results diagram is presented in figure 5.

![Graph showing pressure values over time for different masses](image2)

**Figure 5.** Pressure values in time for different structure mass values [3].

The increase of the pressure values in very short time can be observed on the graphical representation of the result obtained from the numerical analysis, correlated with the corresponding increasing value of the insulated structure mass in which the fluid viscous dissipative device with active control, after which the pressure value is stabilized at a proper level for each value of the structure mass.

6. Conclusions
In order to ensure an improved behavior during seismic actions, the model of a dissipative device operating on a viscous fluid is presented as solution for bridge and building isolation.

In the constructive version with active control on fluid flow rate and pressure values, which involves the working fluid circulation through special regulators, the device is considered as an active model whose operation is constantly adjusted according to the earthquake magnitude.

The control of the dissipative device mounted to the isolated structure is accomplished with a monitoring system coordinated by a process calculator.
The active model is a more advanced version of the dissipation system that operates on the passive principle and the major advantage of the active fluid viscous dissipative device is related to the provision of several dissipation steps due to the momentary adjustments of key parameters engaged in the operation of the device with the occurrence of seismic motions requiring the isolated structure. As the vibration amplitude increases, the resistant force at device rod is modified by adjusting the fluid flow rate which results in attenuation of the piston movement.

The energy dissipation characteristic is represented by the law of variation of the resistance force in relation to the rod stroke of the hydraulic dissipative device.

This characteristic in fact represents the total amount of energy dissipated at a complete piston stroke.

The resistant force describes a parallelogram whose internal area is represented by the dissipated energy by means of the fluid viscous device.

For the active model device with resistive force adjustment based on the amplitude of the seismic motion, the value of the dissipated energy on the motion cycle may be altered according to the external controls transmitted by the monitoring system capable of recording the seismic actions that may occur at a given moment in time.

The resistant force adjustment is mainly based on the vibrations amplitude of the seismic motion being achieved through the use of pressure and flow rate controllers in special construction during the composed piston displacements corresponding to both translational movement directions inside the cylinder describing the repeated extension-compression motions of the dissipative system in the occurrence of seismic motion.

7. References

[1] Axinti G and Axinti A S 2009 Actionari hidraulice si pneumatice Vol III (Chisinau: Tehnica-Info Publishing House)

[2] Scheaua F D 2015 Description of a Composed Seismic Isolation System for Bridge Structures (Resita: Analele Universitatii “Eftimie Murgu”) no 2

[3] Scheaua F D 2013 Analiza comportarii sistemelor de disipare cu frecare uscata la actiuni dinamice PhD Thesis Dunarea de Jos University Galati

[4] Scheaua F D 2017 Special pattern of hydraulic dissipation system used for isolation of bridges against earthquakes (Resita: Analele Universitatii “Eftimie Murgu”) no 1

[5] https://www.revistaconstructiilor.eu/index.php/2014/05/07/determinarea-raspunsului-seismic-al-unei-structuri-in-proiectarea-bazata-pe-performanta/, accessed at 12.01.2019