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The principles of fluid flow within circular ducts of seismic dissipation device used in construction systems

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Abstract. The intensive development of the construction industry nowadays has made the impressive building projects ideas to become real today all over the world. There has been a constant increase in the height of the building or the opening between supporting pillars if we make reference to bridges or viaducts. These achievements are possible due to the quality of the materials, but also the use of the protection systems, which are designed to provide a good stability degree for structures to which they are mounted in time against the dynamic actions represented mainly by the seismic actions. It is presented in this paper the role of a hydraulic power dissipative system which, by mounting on a building structure has the capacity to limit the structural frames relative displacements induced by the ground seismic motion at a certain moment in time. The dissipation device design is based mainly on a cylinder type with piston and the operation involves the use of a working fluid with special viscosity and compressibility properties. In the case of an earthquake occurrence, the device ends receive the tendency to perform cyclic traction-compression movements involving in motion the piston inside the cylinder. The piston can perform translational movement only based on the forced circulation of the working fluid through the small diameter circular orifices made in the piston head, thus providing a significant energy consumption of the total energy induced by earthquake in the structure. The device's overall model and flow pattern of the working fluid through the piston circular orifices are shown, based on a numerical analysis performed on dissipation device virtual model in order to highlight the flow path-lines of the working fluid that would coincide with the real device model operation.

1. Introduction

Earthquakes are natural phenomena that occur as a result of the tectonic plates movement and fracture of rocks from a certain depth of the earth with an considerable energy discharge to the outer surface.

Depending on magnitude, earthquakes may damage construction structures such as buildings, infrastructure elements, bridges or viaducts.

The seismic design activities of the building structures have mainly been directed to increase the resistance to seismic actions by using materials with a high degree of ductility. During an earthquake, the structure must exhibit elastic behavior when the stresses induced by the earthquake in the structure are of value below the flow limit of the materials used in the resistance structure.

In reality, however, structural behavior is rarely located in the elastic or plastic range, so there is a high degree of vulnerability of the structures in the face of seismic events that may occur over time.

That is why it was necessary to design new solutions meant to isolate construction structures that can be helpful in combating the effects of the earthquake's dynamic actions.

In order to ensure the protection of the building structures, a number of mechanical devices have been developed that can be mounted to the structure of the building in order to reduce the effects of seismic actions when they require the structure in a dynamic regime. They are considered isolation but also energy dissipation systems that can consume a part of the energy induced by earthquake in the structure.

2. Model of seismic dissipation device

In order to prevent the collapse of construction structures, a number of mechanical devices have been designed and developed over time to increase the degree of insulation and the amount of energy consumed from the total energy of the earthquake.

When a seismic motion occurs, the ground motion is transmitted vertically to the structure and the specific efforts occurs as a result of the structure inertial forces due to the forced vibration that request the structure in a dynamic regime.

It is necessary that the structure to be protected from the occurrence of these harmful efforts and this can be done by using within the structure devices having the role of seismic energy dissipation.

Insulation systems that are mounted at the structure base (base isolation systems) have been designed, as well as dissipation systems that oppose to relative displacement of the structural frames between which they are mounted, achieving a significant energy consumption.

The energy dissipative system is an optimal solution due to the easy installation possibilities for the new structures, but also for the rehabilitation of the old ones.

These protective devices are presented as hydrostatic drive systems whose operation is based on a working fluid with special viscosity and compressibility properties.

The construction principle is as cylinder with piston type that divides the cylinder into two chambers and the ends of the device are connected to two distinct structural elements.

The piston has a number of orifices through which the working fluid can circulate, enabling the piston to perform translational movement within the cylinder. [1][3]

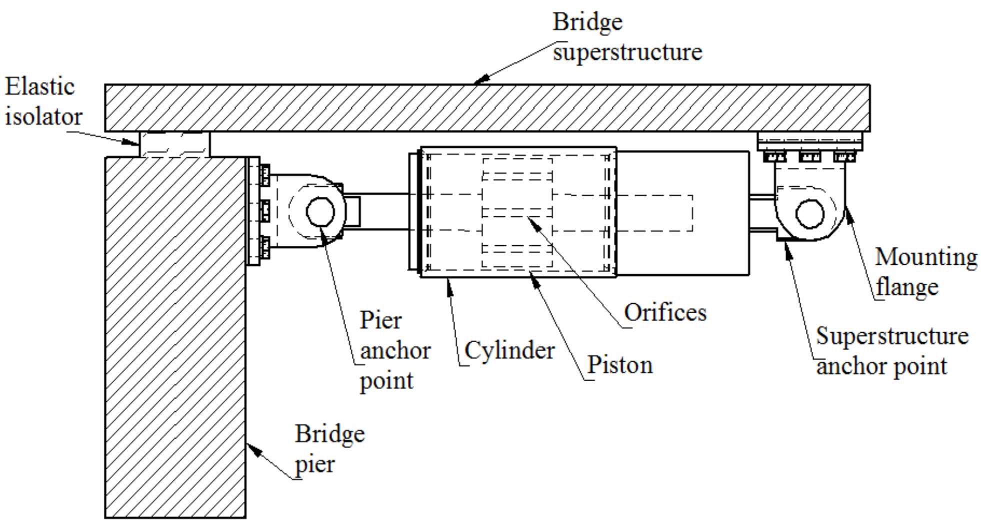


Figure 1. Dissipation device assembly mounted at bridge structure.

Piston movement can occur only when the structure is required by a seismic event and the entry into operation of the dissipation device takes place by forced displacement of the piston due to the viscosity of the working fluid and the diameter of the passage orifices. This causes the device to respond with a resistance force to the relative displacement of the structural frames between which it is mounted. By this movement limitation energy consumption is ensured that makes the effects of earthquake on the structure to be greatly diminished.

The hydraulic dissipation system assembly, as shown in figure 1, links the running path to the supporting foot of a bridge structure.

The hydraulic system offers a good anchorage to the structural elements while limiting the movements that may occur due to wind action or earthquakes, but also due to vibrations due to road or rail traffic.

It can be noticed the disconnection between the pier and superstructure by interposing between the two structural elements a resilient elastic element in order to allow the superstructure to have some relative freedom of movement relative to the pier in the event of terrain vibratory movements, that are not transmitted to the superstructure with the same amplitude.

The seismic energy dissipative hydraulic system provides a viable alternative for the structural elements failure, as these systems are capable of absorbing much of the seismic energy induced by an earthquake inside the structure.

The main functional parameter for a fluid viscous seismic dissipative system is the resultant force at the piston rod which is dependent on the relative velocity between the ends of the device.

The relationship that governs the operation of this device type is the force-velocity relationship that also depends on the characteristics of the working fluid: [1]

$$F = C|v|^{a}\,\mathrm{sgn}(v) \tag{1}$$

where:

v – relative velocity between the two articulations of the dissipation device;

C, (a) - damping constants.

Hydraulic dissipative systems are devices with a strong non-linear character and the damping exponent (a) is representative of their non-linearity.

The hysterical curve for these types of devices is represented by an ellipse and with the decrease of the damping exponent, the shape of the hysteresis curve begins to approach the rectangular shape.

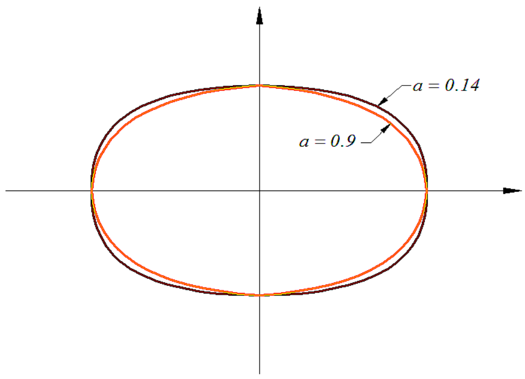


Figure 2. Hysteretic curve for dissipation device function on damping exponent.

The surface area described by the hysteresis curve represents precisely the amount of dissipated energy and the parameter responsible for the growth of this area is parameter C, which also produces an increase in the force at the dissipation device rod.

3. Fluid flow principles inside the dissipation device orifices model

Inside the circular orifices of the piston there is a forced flow of the working fluid which is expected to have a strong turbulent character due to the reduced cross section, the roughness of the orifice walls and the viscosity of the working fluid.

The turbulent fluid flow has a complex character over which three basic theories have been made that take into account the study of fluid particle mixing length or impulse transport (Prandtl), the swirl transport study (Taylor) and the theory of turbulence (von Karman).

Inside the circular orifices made in the piston head of the dissipative device, the distribution of the working fluid velocity values is of logarithmic type.

The relation describing the total effort within the turbulent fluid flow is as follows: [2]

$$\tau_t = \eta \frac{d\overline{u}_x}{dy} + \rho l_o^2 \left(\frac{d\overline{u}_x}{dy} \right)^2 \qquad (2)$$

where:

l_o^2 - mixing length;

η - fluid dynamic viscosity;

$\frac{d\overline{u}_x}{dy}$ - fluid velocity gradient;

ρ - fluid density.

The two terms of the relationship are the stresses due to the viscosity of the working fluid as well as the mixing effort of the fluid particles.

Within the working fluid passage orifices, the flow phenomenon involves a high velocity gradient near the pipe wall in a very thin layer of fluid where practically the mixture tends to zero. This layer is a laminar substrate where the mixing effort is low and the main role is taken over by the viscosity.

At a greater distance from the pipe wall, the velocity gradient is reduced so that the fluid particle mixing effort is of maximum value. This flow region, which belongs to the fluid flow through the orifice, represents the turbulent flow stream center in time.

To establish the logarithmic velocity distribution law within the fluid flow, the relationship can be written: [2]

$$d\overline{u}_x = \frac{1}{k} v_d \frac{dy}{y} \qquad (3)$$

where:

k - fluid proportionality coefficient;

v_d -dynamic velocity;

$$v_d = \sqrt{\frac{\tau}{\rho}} = \sqrt{gIR} \qquad (4)$$

where:

I- piezometric slope;

R- the hydraulic radius.

$$R = \frac{\frac{\pi d^2}{4}}{\pi d} = \frac{d}{4} = \frac{r}{2} \qquad (5)$$

$$\overline{u}_x = 2.5 v_d \ln y + C \qquad (6)$$

Thus, the relation describing the logarithmic velocity distribution law within the turbulent fluid stream inside the circular orifices of the energy dissipative system: [2]

$$\bar{u}_x = 2.5\sqrt{gIR}\ln y + C \tag{7}$$

This law shows that the value of the average velocity over time at different points of the turbulent fluid stream changes in the area adjacent to the orifice wall just like the natural logarithm of the distance (y) between the wall and the considered point.

The results of the experimental investigations (NIKURADZE) show that this equation is applicable to the total section of the fluid passage orifice.

4. Fluid flow analysis on the virtual orifice model

In order to highlight the operational principle of the seismic dissipative device, an analysis is made for the dynamics of the working fluid inside the virtual model.

The three-dimensional model corresponding to the fluid region in which the piston with circular orifices considered as immersed solid is shown. The piston model contains a number of 4 circular orifices radial arranged.

Two cases corresponding to different values for the diameter of the circular orifices in the piston head are analyzed, namely case 1 for which the diameter of the orifices is 7 mm and the second case where the diameter of the passage orifices is 5 mm.

For each analyzed case two values for the piston displacement velocity of 0.2 and 0.3 m/s are declared successively.

The diameter of the piston is 140 mm and the length of the orifices is of 70 mm.

The roughness of the interior walls by which the working fluid circulates is declared at 0.05 mm.

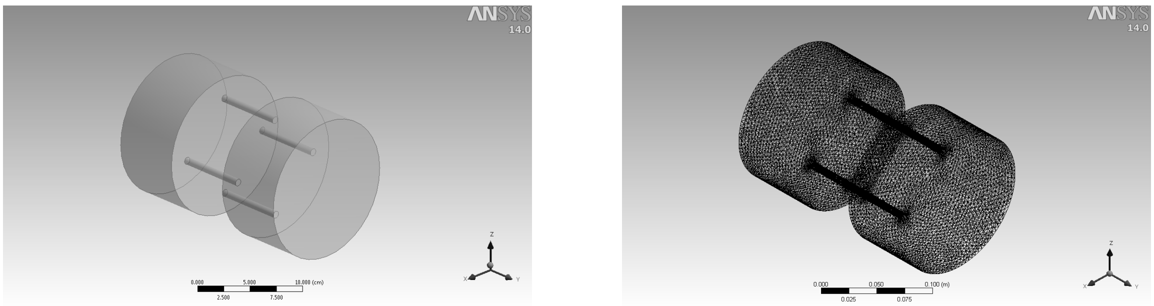


Figure 3. Fluid virtual model considered for CFD analysis and mesh network.

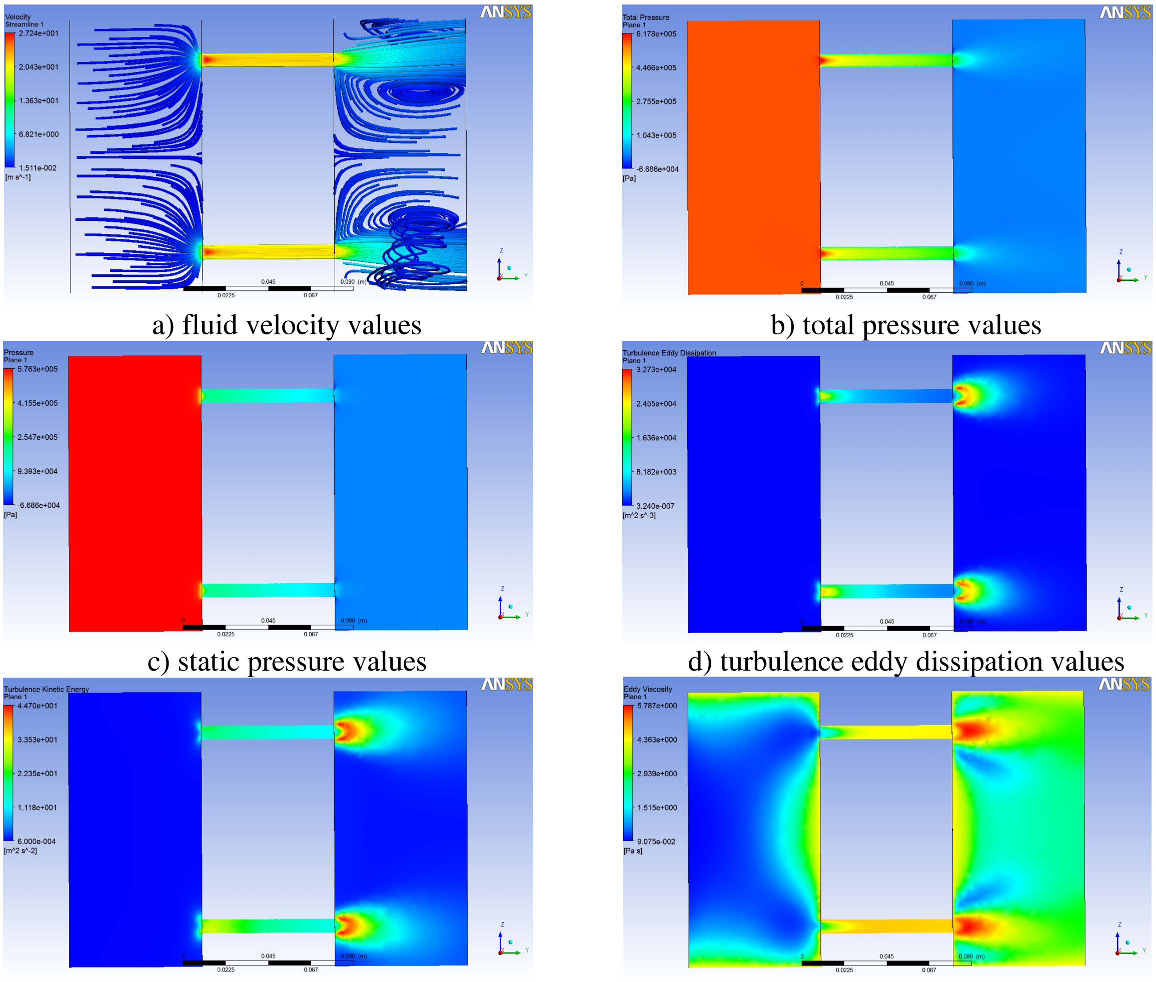
The meshing network contains tetrahedron shaped elements with a number of 47906 nodes and 240870 elements.

The piston displacement velocity values were declared at 0.2 and 0.3 m/s, indicating a displacement occurring when the dissipative device start operating with the occurrence of a real earthquake.

The working fluid is a silicone oil with a density of 975 kg/m3 and a kinematic viscosity of 10e5 cSt, which is forced to circulate through the small diameter orifices of the piston.

The results obtained are presented in terms of static and total pressure and velocity of the working fluid at the level of fluid region containing the piston and the two chambers of the dissipation device cylinder model for each case analyzed in part.

The YZ cutting plan is chosen to show the result values.



a) fluid velocity values b) total pressure values

c) static pressure values d) turbulence eddy dissipation values

e) turbulence kinetic energy values f) eddy viscosity values

Figure 4. CFD analysis obtained results for case 1 (v=0.2 m/s).

The obtained results highlight the higher specific values obtained for the circulation velocity of the working fluid inside the circular orifices of the piston as well as the values calculated for the static and dynamic pressure at the level of the fluid region containing the piston with orifices.

Also the values obtained for the energy dissipation rate of the created turbulences are presented, the calculated values for the turbulences created as a result of kinetic energy and the turbulence viscosity values created at the level of fluid region.

Based on the values obtained from the flow analysis of the working fluid, a total amount of piston displacement resistance force was calculated in an absolute value of 8951.83 N in the OY direction of piston displacement. This means that the dissipative device opposes the movement between the structural frames between which it is mounted by acting cyclically on both types of displacements imposed by the traction-compression type.

This force is the response of the hydraulic dissipation device to the dynamic action of the earthquake that request the structure at a given time.

Table 1 shows the results obtained for the two analyzed cases.

Table 1. The values obtained from the analysed cases.

Case 1	Case 2

D= 7 mm; v= 0.2 m/s		D=7 mm; v= 0.3 m/s		D= 5 mm; v= 0.2 m/s		D=5 mm; v= 0.3 m/s	
Total pressure (bar)	Fluid velocity (m/s)	Total pressure (bar)	Fluid velocity (m/s)	Total pressure (bar)	Fluid velocity (m/s)	Total pressure (bar)	Fluid velocity (m/s)
1.129	6.8	2.163	9.351	4.865	12.29	9.61	19.34
2.812	13.62	5.903	18.68	11.97	24.58	23.76	38.69
4.495	20.43	9.193	28.01	19.07	36.86	37.9	58.03
6.178	27.43	12.48	37.34	26.17	49.15	52.05	77.37

The force values calculated for the analysed cases are presented in table 2.

Table 2. Values for the resistant force of the dissipation device.

Case 1		Case 2	
D= 7 mm; v= 0.2 m/s	D=7 mm; v= 0.3 m/s	D= 5 mm; v= 0.2 m/s	D=5 mm; v= 0.3 m/s
895.183 daN	1853.19 daN	3276.89 daN	7785.44 daN

Considerable values for the piston displacement resistance force are noted in the case of an external stress that describes the occurrence of a seismic earthquake when using a viscous fluid energy dissipative device. This force represents the device response to the terrain seismic motion and the tendency to move the structural frames between which the protective device is positioned.

5. Conclusion

A dissipative device operating with viscous fluid is a solution for improving the behavior of bridge or viaduct structures at the dynamic effects of an earthquake.

These devices have a special construction and involve the use of a working fluid with special properties to meet the design objectives represented by the limitation of the relative displacements during the seismic action between the structural frames between which it is mounted.

The fluid has the ability to circulate through the circular piston orifices and the dynamic flow regime is highly turbulent. This is highlighted on the basis of the values obtained from the flow analysis of the working fluid on the virtual model of the piston with orifices.

Based on the piston displacement velocity and the working fluid properties declared initially, the specific values for velocity and pressure for the working fluid at the level of the analyzed fluid region were calculated as well as the specific values for the energy dissipation of turbulence kinetic energy rates.

Also, the force value registered for the piston translation resistance was obtained, representing the dissipative response to the dynamic earthquake demand.

To change the force value resistant to piston displacement, the value of the working fluid inlet diameter must be adjusted by fitting adjustable valves that can vary the flow rate of fluid through the port according to the earthquake load value (magnitude function) to which the device is subjected.

Such devices operate on the passive principle, have a strong non-linear behavior and are designed to be mounted to new structures and to the rehabilitation of old ones requiring consolidation and for each structure it is necessary to properly dimension the devices to be used.

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