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FLUID DAMPERS FOR APPLICATIONS OF SEISMIC ENERGY DISSIPATION AND SEISMIC ISOLATION

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ABSTRACT

Fluid inertial dampers which operate on the principle of fluid flow through orifices have found numerous applications in the shock isolation of military hardware. The adaptation of this hardware and use in civilian applications represents the object of this paper.

The application of these devices as part of seismic energy dissipation systems for buildings and bridges has been experimentally and analytically studied. The study included component testing over a range of temperatures, modeling of devices, shake table testing of one-story, 3-story building models and a bridge model, development of alternate testing methods, analytical prediction of response and development of simplified analysis procedures.

Experimental results demonstrate a significant improvement of the energy dissipation capability of the structures to which the devices are attached. This resulted in substantial drift reductions and under certain conditions in reduction of inertia forces. Within a seismic isolation system, fluid dampers enhanced the system's ability to dissipate energy resulting in substantial reduction of displacement and almost complete insensitivity of the response to the frequency content of the input. Certain devices with nonlinear viscous characteristics and marked insensitivity to temperature variations have been built and tested for application within seismic isolation systems. One such application involving dampers with strokes ±600mm and an output force of nearly 1,500 kN will be presented, in addition to two other implementations.

KEYWORDS

Damper; dissipation; fluid; hospital; implementation; inertia; military; mitigation; shock; viscous.

INTRODUCTION

A fluid damper is a device which dissipates energy by applying a resisting force over a finite displacement. The damper's output force is resistive, therefore it acts in a direction opposite to that of the input motion. Because the damper behaves in accord with the laws of fluid mechanics, the value of the resisting force varies with respect to the translational velocity of the damper at any point in time. The energy dissipated by the damper is equal to:

$$E_D = \int |F|\, dx \qquad (1)$$

Where F is the damper output force function, and x is displacement.

The means of energy dissipation is that of heat transfer, ie., the mechanical energy dissipated by the damper causes a heating of the damper's fluid and mechanical parts, and this heat energy is harmlessly transferred to the environment by transport mechanisms, usually convection and conduction.

A fluid damper has several inherent and significant advantages compared to other types of energy dissipators, such as hysteretic (friction), visco-elastic (rubber), tuned masses, and elasto-plastic (yielding metal) types. These advantages are:

1. The output of a fluid damper is essentially out of phase with primary bending and shearing stresses in a structure. This implies that a fluid damper can be used to reduce both internal shear forces and deflection in a structure.

2. A fluid damper is self-contained, no auxiliary equipment or power is required.

3. A modern fluid damper operates at a fluid pressure level of significant magnitude, thus making the damper small, compact, and easy to install.

4. Fluid dampers are generally less expensive to purchase, install, and maintain than other types. They can economically reduce the overall cost of a structure, especially when used at high damping ratios in the 15%-40% critical damping range.

5. Fluid dampers have been proven by the test of time, with over 100 years of successful large scale use, in the most severe environments, most notably by the military and aerospace industries.

HISTORY OF FLUID DAMPING

As with many other types of engineered components, the requirements, needs and available funds from the military allowed rapid design evolution of fluid dampers to satisfy the needs of armed forces. Early fluid damping devices operated by viscous effects, where the operating medium was sheared by vanes or plates within the damper. An example is shown in Fig. 1.

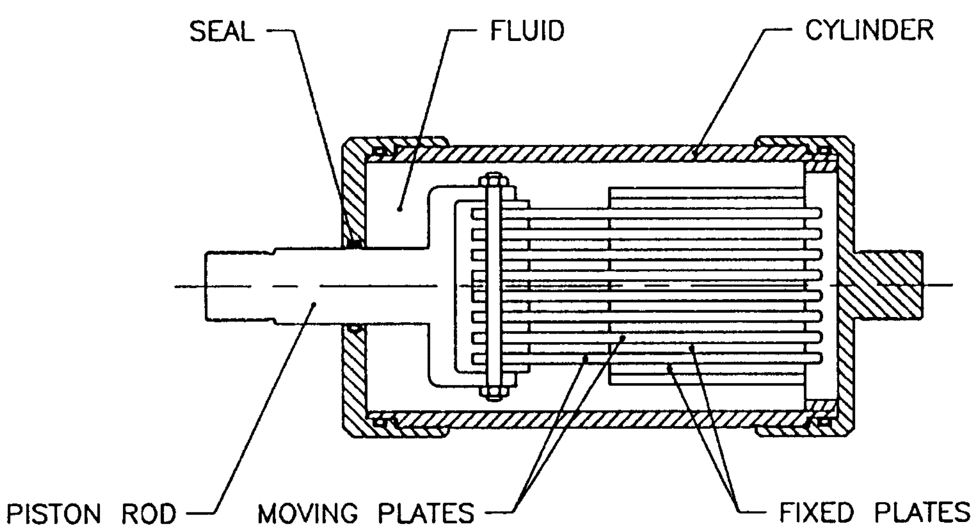

Fig. 1 - Early Fluid Viscous Effect Damper

Designs of this type were mere laboratory curiosities, since the maximum pressure available from shearing a fluid is limited by the onset of cavitation, which generally occurs at between .06 N/mm^2 and .1 N/mm^2, depending on the viscosity of the fluid. This operating pressure was so low that for any given output level, a viscous damper was much larger and more costly than other types. In addition, because fluid viscosity changes significantly with temperature, the output from a pure viscous damper changes dramatically with ambient temperature of the damper fluid. By example, even the modern silicone fluids, specifically developed to be thermally stable, will exhibit a viscosity drop of 50% over a temperature range of +20°C to +50°C.

In the late 1800's, applications for dampers arose in the field of artillery, where a high performance device was needed to attenuate the recoil of large cannons. After extensive experimentation, the French Army incorporated a unique (and "top-secret") fluid damper into the design of their 75mm gun, Model M1897. The fluid damper design used inertial flows, where oil was forced through small orifices at high speeds (in excess of 200 m/s), in turn generating high damping forces. This allowed the damper to operate at relatively high operating pressures, in the 20 N/mm^2 range. The output of this device was not affected by viscosity changes of the fluid, but rather by the specific mass of the fluid, which changes only slightly with temperature. Thus, not only was this fluid inertial damper extremely compact, but it was also virtually unaffected by temperature. Early production demonstrated an additional important feature, namely that the damper's output could be precisely controlled in mass production by conventional machining techniques. Thus, the technology of fluid inertial dampers became widespread within the armies and navies of most countries in the 1900-1945 period, but because of its secretive nature was not widely publicized.

During World War II, the emergence of radar and similar electronic systems required the development of specialized shock isolation techniques so that equipment could withstand so-called "weapons' grade" shock. During the Cold War period, the guided missile became the weapon of choice for the military, and the fluid inertial damper was again turned to by the military as the most cost effective way of protecting missiles against both conventional and nuclear weapons detonation. The transient shock from a near miss weapons detonation can contain free field velocities of 3 to 12 m/s, displacements of up to 2000 mm, and accelerations up to 1,000 times gravity. Extremely high damping forces were needed to attenuate these transient pulses on large structures, and fluid inertial dampers became a preferred solution to these problems. With the end of the Cold War in the late 1980's, much of this fully developed defense technology became available for sale to the general public. Taylor Devices, since 1955, a supplier to the U.S. Government of dampers and shock absorbers to 1,000 tonnes output, teamed with the State University of New York at Buffalo (SUNYAB) to apply these devices to buildings and bridges to improve seismic performance. SUNYAB is the site of the U.S. National Center for Earthquake Engineering Research (NCEER). Experiments began in 1991 using scaled structures and testing on a large seismic shake table.

DESCRIPTION OF DAMPER USED FOR EXPERIMENTS

The damper type selected for testing was a production fluid inertial damper based upon a military device used on the U.S. Air Force's B-2 "Stealth" Bomber. The construction of the tested device is shown in Fig. 2. It consists of a stainless steel piston, with a bronze orifice head, and a self-contained piston displacement accumulator. The damper is filled with silicone oil, normally used by the cosmetics industry in lotions and hand creams. This fluid is non-flammable, non-toxic, environmentally safe, and thermally stable. The damper had been previously tested by the military at temperatures from -50°C to +90°C, frequencies of 0 to 2,000 Hz., and had passed a 10 million cycle life test. Thus, this device includes performance characteristics considered as state of the art in fluid, sealing, and manufacturing technology.

The fluid inertial damper as tested produced a linear damping output, where output force is proportional to velocity of displacement. Other versions of this damper have been produced which provide non-linear damping, where force is proportional to velocity raised to a power, ie.:

$$F \propto V^K$$
$$\text{Thus, } F = CV^K \qquad (2)$$

Where K has a value in the range of .1 to 1.2, as specified for a given application.

OPERATION OF DAMPERS

The force that is generated by the fluid inertial damper is due to a pressure differential across the piston head. Consider that the piston moves from left to right in Fig. 2 (device subjected to compression force). Fluid flows from chamber 2 towards chamber 1. Accordingly, the damping force is proportional to the pressure differential in these two chambers. However, the fluid volume is reduced by the product of travel and piston rod area. Since the fluid is compressible, this reduction in fluid volume is accompanied by the development of a restoring (spring like) force. This is prevented by the use of the accumulator. The tested device showed no measurable stiffness for piston motions with frequency less than about 4 Hz. The cutoff frequency may be specified in the design. If desired, this type of damper can be manufactured without a specified cut-off frequency and the damper will then respond over the range of 0-2,000 Hz.

The existence of the aforementioned cutoff frequency is a desirable property. The devices may provide additional viscous type damping to the fundamental mode of the structure (typically with a frequency less than the cutoff frequency) and additional damping and stiffness to the higher modes. This may, in effect, completely suppress the contribution of the higher modes of vibration.

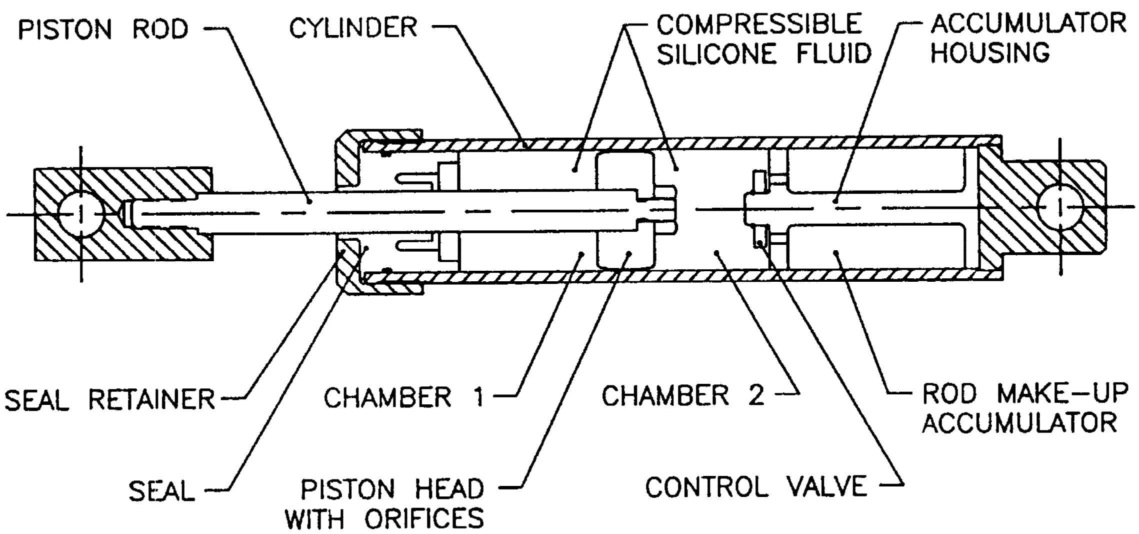

Fig. 2 - Fluid Inertial Damper

TEST RESULTS

Various structural models were submitted to shake table testing at SUNYAB in the 1991-1995 period, with and without the fluid inertial dampers. These models included 1 and 3 story steel frame building models, of 2,800 kg. mass, by Constantinou and Symans (1992). A bridge model was tested, this being of 16,000 kg. mass, by Tsopelas et al (1994). Lastly, tests were performed by Reinhorn, Li, and Constantinou (1995) on a 3 story reinforced concrete frame of 12,000 kg. mass. More than 150 individual shake table tests are documented by the research reports noted. The various models were subjected to numerous earthquake transients, including El Centro, Taft, and Pacoima Dam from the U.S., and the Japanese Hachinohe and Miyagiken records. Overall damping levels tested ranged from 20% to 60% critical. In all cases, the addition of fluid inertial dampers greatly reduced structural deflections, and in many cases, stresses decreased also, even at very high damping levels. High damping values without stress increases are possible only because of the out-of-phase response of the fluid inertial dampers, as compared to all other types. Figure 3 provides typical results on a one story steel frame building model. In this case, the addition of the dampers alone allowed the transient to be increased from 33% El Centro to 100% El Centro, without increasing stress or deflection from that of the undamped structure subjected to the lesser transient. The structure remained elastic at all times.

The seismic improvements possible with fluid inertial dampers, verified by testing and combined with their previous long years of military service, allowed this technology to be quickly implemented. Advantages of the damper will vary from application to application, depending on specific project requirements. In all of the projects to date, the incorporation of fluid inertial dampers reduced the overall cost of the project, compared to conventional seismic designs, or other types of damping devices.

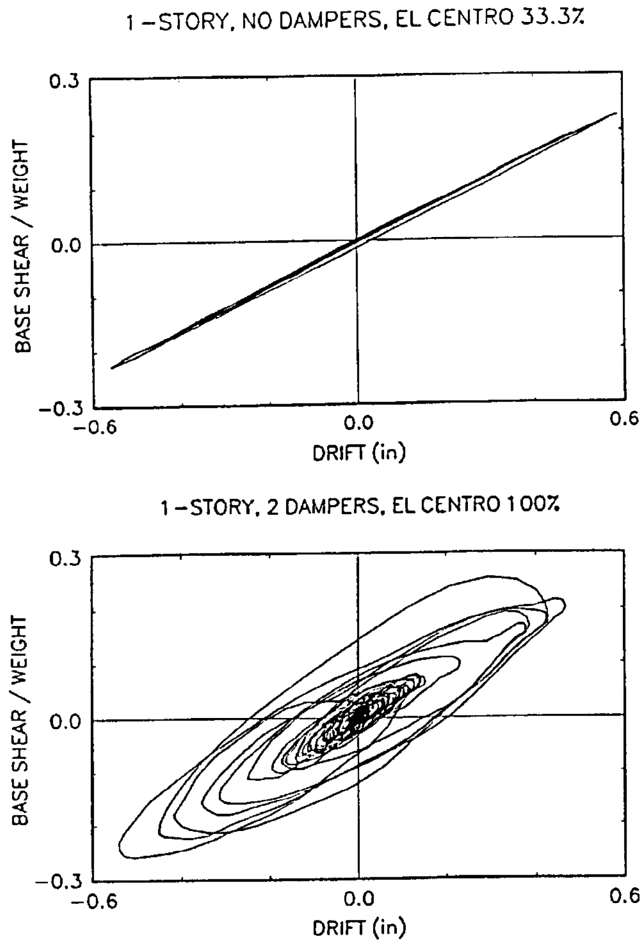

Fig. 3 - Test Results

IMPLEMENTATION EXPERIENCE

Use of fluid inertial dampers for seismic energy dissipation on full size civil engineering structures began in 1993. The first application was on five buildings of the San Bernardino County Medical Center Replacement Project, totalling 84,000 m^2 floor area. Located in a high seismic zone east of Los Angeles, California, the buildings were being designed to remain occupied and in service during and after seismic transients of up to 152 cm/s peak translational velocity. All hospital buildings were intended to be base isolated on high damping rubber bearings, but deflection was unacceptably large, in the range of ± 1500 mm. Using the test results from SUNYAB, the design group evaluated the improvements possible from adding dampers in parallel with base isolation bearings. A fluid inertial damper with nonlinear damping of $F=CV^{.4}$ was selected for use in the project. It was determined by analysis that fluid damping levels in the 45% to 50% critical range were possible before shear stress increases occurred. The resulting building base displacements were reduced to ± 560 mm. An additional advantage of the fluid inertial dampers was that the long period rubber bearings would be able to fully reset the building after a seismic event with no permanent offset. Other types of dampers that were hysteretic or of yielding material type would cause a large offset due to their essentially hysteretic response.

The detail design of the fluid inertial dampers was taken directly from a previous U.S. Military program. This prior application was that of a 2000 kN, 1000 mm deflection damping device used to attenuate weapons' attack ground motions on the MX Intercontinental Ballistic Missile. In this form, the damper dissipated the energy of a transient having more than 12 m/s velocity. A proprietary element incorporated into this design allowed the damper to fully and properly respond even to step function inputs, where peak transient speeds are reached in less than 1 millisecond. This design feature was incorporated into the San Bernardino fluid inertial dampers. Subsequent interest by the structural engineering community about step function transients was generated from earthquake records of the 1994 Northridge, California and 1995 Kobe, Japan earthquakes. Interest was such that Taylor Devices, Inc. now incorporates this feature into all fluid inertial dampers produced for structural use.

A total of 186 dampers were fabricated for the San Bernardino project, each having an output force of 1456 kN, and a maximum energy dissipation rate per damper of 2.17 megawatts. Figure 4 is a photograph of the completed device. Due to the large size and high capacity of these devices, testing of the production dampers presented difficulty, in that no suitable sine wave cycling testing machine was available. After extensive evaluation and demonstration, the time honored military method of drop testing was adapted for this project. A drop test consists of impacting the vertically mounted damper with a large free falling weight. By dropping the weight at varying heights, the dampers force-velocity function can be determined, even at very high force levels. For the San Bernardino project, validation testing was performed on a 1/6 force scaled damper with both a hydraulic actuator located at SUNYAB and with a drop tester. Sine wave cyclic test output from the actuator was compared to a series of drop tests from different free fall heights. Comparison of measured force and velocity from both test methods showed virtually no discernable differences in results, thus validating the test method. The results also verified that the damper's measured force-velocity relationship was the same with either test technique, and was virtually unaffected by extreme testing temperatures. Each of the full size production dampers were then drop tested at various velocities up to the maximum of 1456 kN force at 1.5 m/s velocity. Taylor and Constantinou (1995) report on testing of the production dampers.

A second significant project was an emergency communication services building in Sacramento, California, owned by Pacific Bell. The building was of braced steel frame construction with a fixed base, 3 stories in height, and of 15,000 m^2 floor area. The dampers were installed into chevron braces throughout the structure. A total of 62 fluid inertial dampers were used, each of 130 kN output force. Damping level was of sufficient magnitude to keep the frame fully elastic under a maximum level earthquake. This allows for immediate occupancy after a seismic event, assuring minimum loss of emergency services. The damper design utilized for the Pacific Bell project originated on the U.S. Navy Standard Surface to Air Missile Program.

A third significant application was the Woodland Hotel, located in the city of Woodland, California. This historic 4 story structure dates to 1927, and is of non-ductile concrete construction with a so-called "soft" first story. The owner wished to improve the earthquake resistance of the building, while maintaining its historic appearance. Fluid inertial dampers proved to be the most cost effective retrofit strategy, as compared to conventional shear walls or braces. An arrangement of 16 fluid inertial dampers, each of 450 Kn. force output, were utilized in this construction. The dampers were installed into the walls of the structure with chevron braces. Miyamoto and Scholl (1995) provide an extensive report on the project effort. The damper design utilized for the Woodland Hotel project originated with the U.S. Navy, from a classified application on submarines.

As of December 1995, fluid inertial dampers are being utilized in a total of 13 engineered structures, for the purpose of seismic or wind energy dissipation. A detailed listing of these projects is provided in Table 1. Additional project applications are pending.

Fig. 4 - Fluid Inertial Damper, 1456 kn Output

CONCLUSIONS

Fluid inertial dampers, used extensively in military applications, have direct applications on civil engineering structures. These products can be used for the purpose of dissipating seismic energy or wind energy as a primary element of design.

Comprehensive shake table testing at the University level has demonstrated that fluid inertial dampers have a response that is essentially out of phase with structural shear stresses. Thus, they have the capability to simultaneously reduce both shear stresses and deflections in a structure. Extensive shake table testing has demonstrated the benefits of the out of phase damper response. The benefits of damping levels of up to 60% critical have also been demonstrated by test, and these levels are now achievable in a compact device, proven by the test of time in applications dating to 1897.

Large structures are now utilizing fluid inertial dampers for seismic and wind energy dissipation. Many of these applications utilize fluid inertial dampers which have been taken directly from proven military production of the Cold War period. Benefits obtained from fluid inertial dampers include reduced project cost, lower column stresses and deflections, reduced construction materials, and preservation of architectural attributes and enhancements. As of December, 1995, a total of 13 civil engineering structures are now utilizing this technology.

Table 1

Recent Structural Applications of Fluid Viscous Dampers

Name and Location of Structure	Type and Number of Dampers	Date of Installation	Load
North American Air Defense Command Wyoming, USA	Quantity, type and size classified	1984	Nuclear Attack
Rich Stadium Buffalo, NY, USA	50 kN, ±460mm stroke Total: 12	1993	Wind
Pacific Bell Center Sacramento, CA, USA	130 kN, ±50mm stroke Total: 62	1995	Seismic
San Bernardino County Medical Center (5 buildings) Colton, CA, USA	1460 kN, ±600mm stroke Total: 186	1995	Seismic
Hotel Woodland Woodland, CA, USA	450 kN, ±50mm stroke Total: 16	1995	Seismic
Langenbach House Oakland, CA, USA	130 kN, ±150mm stroke Total: 4	1995	Seismic
Petronas Twin Towers Kuala Lumpur, Malaysia	10 kN, ±50mm stroke Total: 12	1995	Wind
28 State Street Boston, MA, USA	670 kN, ±25mm stroke Total: 40	1996	Wind
CSUS Science II Building Sacramento, CA, USA	220 kN, ±50mm stroke Total: 40	1996	Seismic

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