# EXPERIENCE AND PRACTICAL CONSIDERATIONS IN THE DESIGN OF VISCOUS DAMPERS

**Philippe Duflot**
Civil Engineer
Taylor Devices Europe
Brussels, BE

**Doug Taylor**
President
Taylor Devices Inc
North Tonawanda, USA

## 1. Introduction to viscous dampers: definition and functional output

A damper can be globally defined as an element which can be added to a system to provide forces which are resistive to motion, thus providing a means of energy dissipation.

The most convenient and common functional output equation for a damper can be characterized as :

$$F = C \cdot V^{\alpha}$$

Where F is the output force, V the relative velocity across the damper, C is the damping coefficient and α is a constant exponent which is usually a value between 0.3 and 2.

Fluid viscous dampers operate on the principle of fluid flow through orifices. A stainless steel piston travels through chambers that are filled with silicone oil. The silicone oil is inert, non flammable, non toxic and stable for extremely long periods of time. The pressure difference between the two chambers cause silicone oil to flow through an orifice in the piston head and input energy is transformed into heat, which dissipates into the atmosphere.

Fluid viscous dampers can operate over temperature fluctuations ranging from -40°C to + 70°C.

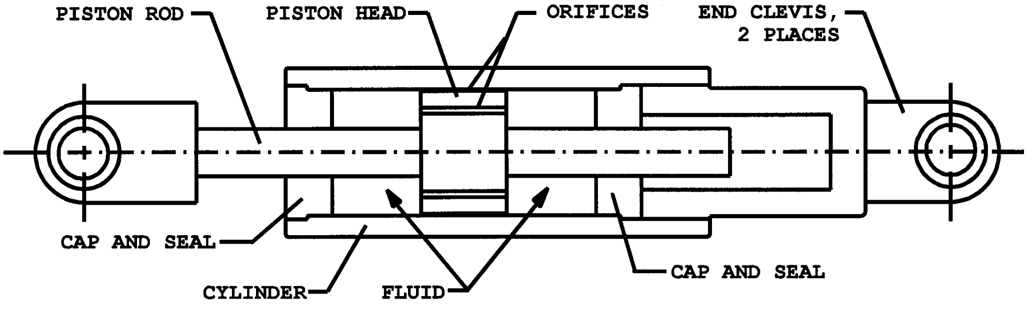

*Figure1 : Viscous Damper*

Notice that there is no spring force in this equation. Damper force varies only with velocity. For a given velocity the force will be the same at any point in the stroke. As dampers provide no restoring force the structure itself must resist all static loads.

The damper decreases the response of a structure by adding energy dissipation to a structure, which significantly reduces response to any vibration or shock inputs.

The Effect of Different Values of α, the Velocity Exponent :

Figure 2 shows the hysteresis loop of a pure linear viscous damper when subjected to a sinusoidal input. The loop is a perfect ellipse. The absence of storage stiffness makes the natural frequency of a structure incorporated with the damper remain the same. This advantage will simplify the design procedure for a structure with supplemental viscous dampers.

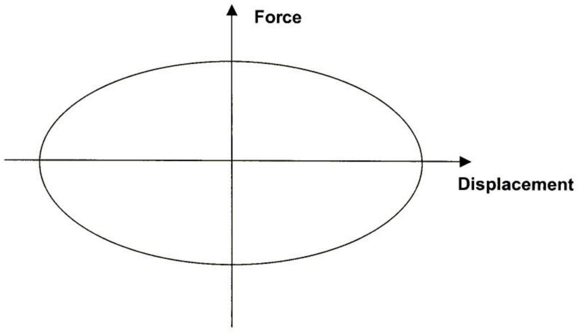

*Figure 2 : Hysteresis loop of viscous damper*

Fluid viscous dampers have the unique ability to simultaneously reduce both stress and deflection within a structure subjected to a transient. This is because a fluid viscous damper varies its force only with velocity, which provides a response that is inherently out-of-phase with stresses due to flexing of the structure.

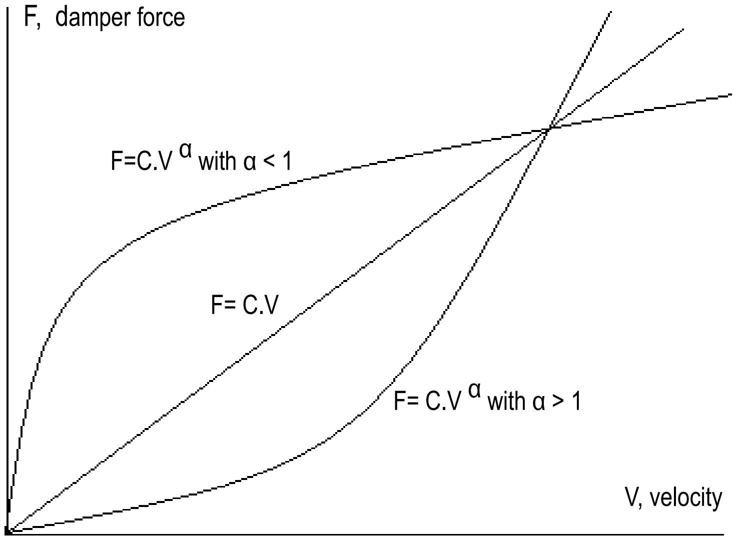

*Figure 3 : Force against velocity for different exponent values*

Fig 3 shows a plot of force against velocity for several values of α, the velocity exponent. A value of α=1 is the curve for linear damping which is a good place to start in the design of a damping system. The hysteresis loop for a linear damper is a pure ellipse as shown in fig 2. α=0.3 is the lowest damping exponent normally possible. Fig 3 shows this value provides significantly more force at lower velocities than a linear damper.

Linear damping is easy to analyse and can be handled by most software packages. Also linear damping is unlikely to excite higher modes in a structure.
Another advantage of linear damping is that there is very little interaction between damping forces and structural forces in a structure.
For most pedestrian bridges, linear dampers are therefore preferably considered to completely eliminate the biodynamic feedback between pedestrians and the bridge.

## 2. Fluid viscous dampers: design elements

The essential design elements of a fluid damper are relatively few. However, the detailing of these elements varies greatly and can, in some cases, become both difficult and complex. Fig 1 depicts a typical fluid damper and its parts. It can be seen that simply moving the piston rod back and forth, fluid is forced through the piston head orifices, generating damping force.

Major part descriptions are as follows, using Fig 1 as reference:

Piston rod: highly polished on its outside diameter, the piston rod slides through the seal and seal retainer. The external end of the piston rod is affixed to one of the two mounting clevises. The internal end of the piston rod attaches to the piston head. In general, the piston rod must react all damping forces, plus provide a sealing interface with the seal. Stainless steel is preferred as a piston rod material since any type of rust or corrosion on the rod surface can cause catastrophic seal failure. In some cases, the stainless steel must be chrome plated for compatibility with the seal material. For applications requiring a long stroke, a structural steel tube guide sleeve is used to protect the piston rod from excessive bending loads.

Cylinder: the damper cylinder contains the fluid medium and must accept pressure vessel loading when the damper is operating. Cylinders are usually manufactured from seamless steel tubing. Welded or cast construction is not permissible for damper cylinders, due to concerns about fatigue life and stress cracking.
Cylinders normally are designed for a minimum proof pressure loading equal to 1.5 times the internal pressure expected under a maximum credible dynamic input. By definition, the proof pressure must be accommodated by the cylinder without yielding, damage or leakage of any type.

Fluid: Dampers used in structural engineering applications require a fluid that is fire-resistant, non-toxic, thermally stable and which will not degrade with age. Typical silicone fluids have a flashpoint in excess of 340°C, are cosmetically inert, completely non-toxic and are among the most thermally stable fluids known to man. Since silicone fluids are produced by distillation, the fluid is completely uniform and no long-term settling will occur. Occasionally, other types of fluids are considered for special applications when necessary.

Seal: The seal materials must be carefully chosen for the service life requirement and for compatibility with the damper's fluid. Since dampers in footbridges can often be subject to long periods of infrequent use, seals must not exhibit long-term sticking nor allow slow seepage of fluid. Most dampers use dynamic seals at the piston rod interface and static seals where the end caps or seal retainers are attached to the cylinder. Dynamic seals for the piston rod should be manufactured from high-strength structural polymers to eliminate sticking or compression set during long periods of inactivity. Typical dynamic seals materials include TeflonR, stabilized nylon and members of the acetyl resin family. Dynamic seals manufactured from structural polymers do not age, degrade or cold flow over time.

Piston head: the piston head attaches to the piston rod and effectively divides the cylinder into two pressure chambers. As such, the piston head serves to sweep fluid through orifices located inside it, thus generating damping pressure.

Orifices: the pressurized flow of the fluid across the piston head is controlled by orifices. These can consist of a complex modular machined passageway or alternatively, can use drilled holes, spring loaded balls, poppets or spools. The use of any type of spring loaded orifice raises the reliability issues and proper performance.
Dependent on the shape and area of these passages, damping exponent ranging from 0.3 to 2.0 can be obtained without requiring any moving parts in the orifice.

## 3. Performance of viscous dampers

A properly designed viscous damper will attenuate transient and steady state inputs while staying within specified performance bounds. At the same time, the damper, as it is manufactured, must not yield, leak or overheat during use.

### Transient Inputs: Frequency and Response Time

Depending on its end use, dampers can easily be designed and constructed to attenuate input transients in the range of 0-2000Hz. However, for footbridge applications, spectral inputs rarely contain much content at frequencies in excess of 10 Hz. Using conventional mechanical engineering practice for vibrating systems, a control device should be capable of operating at a frequency of at least 10 times the maximum input frequency. Thus, a frequency response range of 0-100 Hz is sufficient for most footbridge damper applications.

Impulse and frequency response of full scale dampers built for a specific project can readily be determined by drop testing where a weight is allowed to free-fall a certain distance and then impact the damper

### Transient Inputs: Magnitude of Required Damping

The magnitude of viscous damping added to a structure for the suppression of vibration, wind or other transient inputs is usually in the range of 5-45% of critical. This is a very wide range and varies with the type of structure and excitation. Obviously the amount of damping selected is the responsibility of the engineer of record but generalized damping levels from previous projects are 15 to 25% added damping for footbridges subject to vibration and/or wind inputs.

### Steady State Inputs: Wind and Vibration

Footbridges normally use fluid dampers for the control or reduction of measured or felt vibration and wind responses.

As noted previously, viscous dampers are built to mitigate the response of inputs in the 0-100 Hz range. With respect to low amplitude vibrations, fluid dampers have been used to suppress amplitudes as low as 0.025mm.

### Heating Effects

The thermal response inside a damper must be calculated to prevent overheating of internal parts during use. In most cases, overheating damage manifests itself by leakage, usually caused by a softened or melted dynamic seal.

Heat transfer calculations for footbridge dampers are relatively complex and the damper manufacturer must be given generalized motion data to properly size the damper. In general, manufacturers allow steady state heating of the damper to be no more than 40°C over ambient. If calculations indicate that overheating is an issue, then in most cases the damper will be increased in physical envelope until temperature rise during operation is low enough so as to be safely accepted by the internal parts.

### Cyclic Life – Service Life

A properly designed and manufactured damper should not require any type of periodic service. The warranty should state that no periodic fluid replenishment or periodic servicing of any type is required.

The type of dynamic seal used in dampers is limited in life by wearing of the seal as the piston rod moves back and forth. In general, seal life is measured in terms of the total number of meters of rod displacement during a damper's lifetime.

## 4. Customer controlled parameters

Fluid dampers for a specific project are essentially adjusted by the manufacturer to meet specific customer specified parameters. The parameters include:

1. maximum rated force
2. minimum safety factors to yield
3. minimum required useable deflection from neutral position
4. damping constant
5. damping exponent
6. operating temperatures
7. maximum power input
8. maximum damper envelope
9. damping mounting configuration

The maximum rated force of the damper is usually the force expected during the maximum credible event that the device is designed for. The safety factor to yield is based upon either the maximum rated force or the velocity at which this maximum force occurs. Typically, the safety factor is 1,5 to 1, meaning that the damper will not yield when subjected to a force or velocity 150% of the rated maximum.

The minimum required useable stroke or deflection is the minimum distance that the damper should be able to stroke from its neutral position taking into account the dynamic stroke (due to dynamic inputs: vibration, wind, accidental input, ...) and the static stroke (due to thermal dilatation, potential misalignment of the damper due to various tolerances of the bridge construction, ..).

The damping constant, damping exponent and temperature ranges can be easily expressed on a graph, defining allowable damper performance bandwidth at any defined operating temperature. Fig 4 provides damper performance graph for an application of footbridge.

The damper is tested in compression and in tension at different velocities as expected by the application. Force and displacement are recorded, the velocity is read at the peak force to eliminate the rise time effect. The force-velocity graph is then generated. The function must be within the foreseen tolerances, usually +/- 15%.

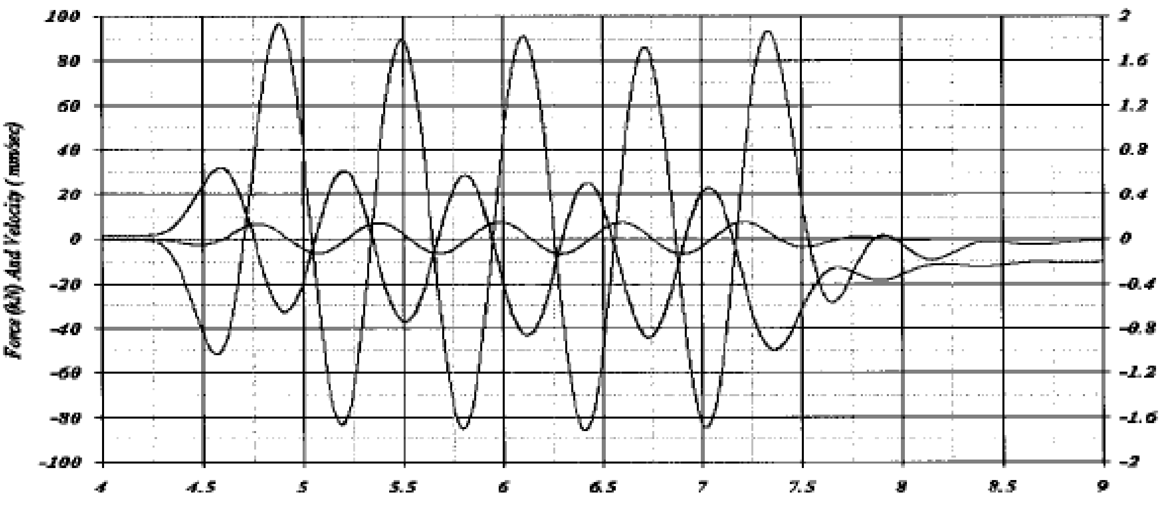

*Figure 4: Example of force, velocity and displacement vs time measured on a footbridge damper*

Note that no significant airlag, backlash or compressibility is accceptable

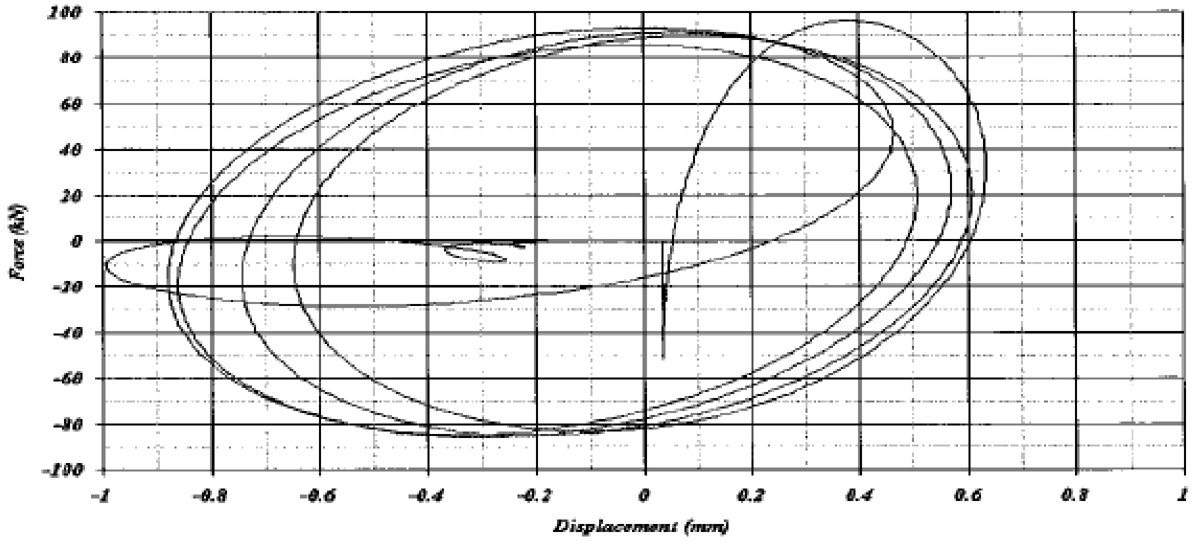

*Figure 5: Force vs displacement*

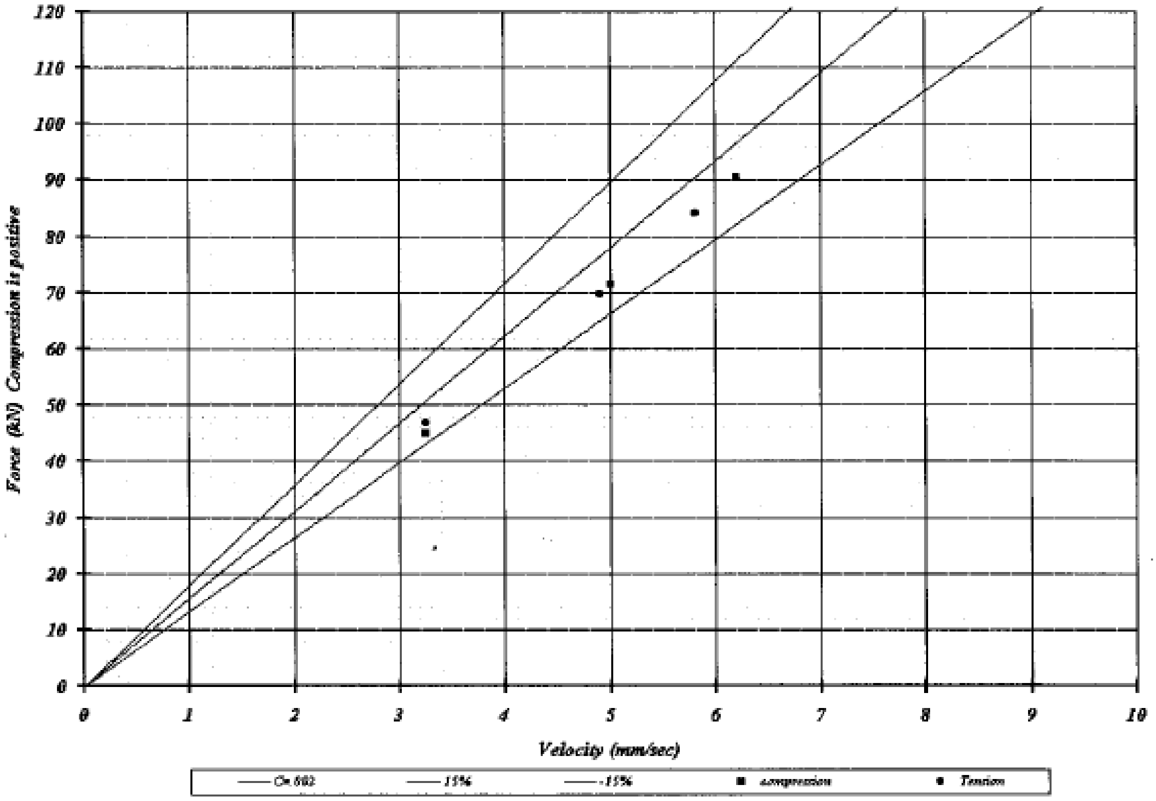

*Figure 6: Force vs velocity*

A nominal function is the middle line in the plot with high and low tolerance limits applied. Operating temperature is 0°C to 60°C and the damper's output must fall within the +/- 15% tolerance at all velocities, at any defined operating ambient temperature, both before and after the damper has absorbed the energy of a maximum credible event.

Performance at small amplitude of the damper must be controlled. The static friction is usually limited to 1% of total damper force.

Specific applications may impose diameter or length restrictions on the damper and these maximum values can also be customer specified. In most cases, a diameter limitation is much more common than a length restriction.

The usual way to attach dampers to a bridge is to bolt them to the structure. The dampers are equipped with maintenance free spherical bearings at each end and are connected to the bridge using mounting pins. The typical plus or minus 5° rotation angle of a spherical bearing will accommodate out of plane motion for the relatively small drifts encountered with the installation. However, bearings can be provided that are capable of up to +/- 20° rotation angle.

Schematics of the mounting attachment is provided in Fig 7. The mounting pins used to attach the dampers to brackets are often supplied by the damper manufacturer. In most cases, the manufacturer will also provide the brackets used to connect to the structure. The reason for this is that the pins must be fitted very closely to the clevises and spherical bearings, to insure that the connection has no discernible play. The maximum total free play at each bearing is then usually to be 0.01mm. Note that bolted connection must have tight tolerance holes or a slip critical connection to ensure that the no slippage occurs during continuous dynamic loading.

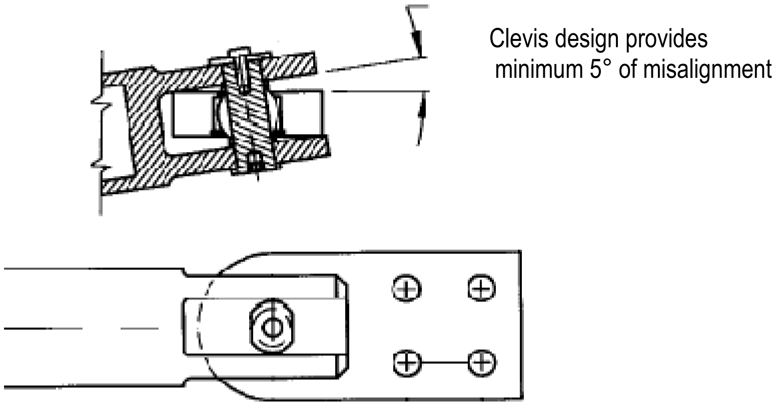

*Figure 7: mounting attachment*

Note that the engineering analysis should take into account the dynamic stiffness of the dampers and the surrounding elements, especially in applications where the damper forces are high and the deflections are small. This dynamic stiffness accounts for the flexibility of the mechanical elements of the damper, its clevises, the mounting bracket, the mounting pin, and the structure itself. It is important for this to be analysed properly so that the actual deflection and the input velocity are accurately predicted to assure proper motion control of the structure. If the structure or any mechanical element transmitting the damping force is too flexible, this would prevent the damper from stroking properly and therefore absorbing the correct amount of energy.

The resultant dynamic stiffness of the components transmitting the damping force is usually modelled as a simple linear spring in series with the damper.

## 5. More damper design issues

The application of viscous dampers to a footbridge results in additional major design issues, some of which may be unique to the particular structure.

One primary issue is to address the fact that the dampers must continuously cycle. It may be understood that that majority of the cycles would take place at low amplitude, but the total number of cycles required by the owner can be based on a 50 year bridge life. For an average frequency of 0.8 Hz, this equates to more than $10^9$ cycles of life, far in excess of normal values for any sort of conventional damping device. Ideally, the damper should be maintenance free for the entire life cycle.

Another issue is that the damper must respond to very small deflections as low as 0.025 mm with high resolution. Otherwise the suppression of feedback would not be possible until the footbridge is already well into resonance or under unacceptable motion. Damper frequency response requirements are usually defined as D.C.–20 Hz with a high fidelity output over this entire bandwidth. This issue can be compounded by the fact that due to wind, thermal, and static loadings, total deflections of plus or minus 250 mm or more can be required.

A third issue is that the damper response must have low hysteretic content, to avoid pedestrians sensing the classical “stick-slip” motion of a conventional sliding contact fluid seal, with the resultant perception of instability in the bridge structure. This requirement becomes even more difficult when taken in context with the extremely long cyclic life. This is because conventional hydraulic practice is to use seals with heavy interference for long life under dynamic cycling. These high interferences in turn generate high seal friction, accentuating the “stick-slip” motion.

A fourth issue is that several distinct designs of dampers are often required, each of which require different output forces, deflections, component equations, and envelope dimensions. This is because there might be different modes of vibration to suppress and because of volume, length, or mounting location limitations on the bridge.

A fifth design issue is environmental in nature. The dampers are located outdoors, sometimes over a waterway. The design life is such that all major operating elements of the dampers need to be constructed from inherently corrosion resistant metals that would not degrade over time.

## 6. Frictionless hermetic damper

To address all these additional various design issues, a unique and patented damper can be proposed, previously used exclusively for space based systems. These previous applications have similar requirements for long life and high resolution at low amplitudes, but required relatively low damper forces from small, lightweight design envelopes.

A cutaway of a typical frictionless hermetic damper is shown in Figure 8. The most unique elements of this damper are the frictionless seals made from a welded metal bellows. This type of seal does not slide, but rather flexes without hysteresis as the damper moves. Two metal bellows seals are used to seal fluid in the damper. As the damper moves, the two metal bellows alternately extend and retract, by flexure of the individual bellows segments. Since the seal element elastically flexes rather than slides, seal hysteresis is nearly zero. The volume displaced by the compressing bellows passes through the crossover ports to the extending bellows at the opposite end of the damper. While this is occurring, damping forces are being produced by orifices in the damping head, and the pressures generated are kept isolated from the metal bellows by high restriction hydrodynamic labyrinth bushings. Because hydrodynamic bushings are used, no sliding contact with the piston rod occurs, assuring frictionless performance.

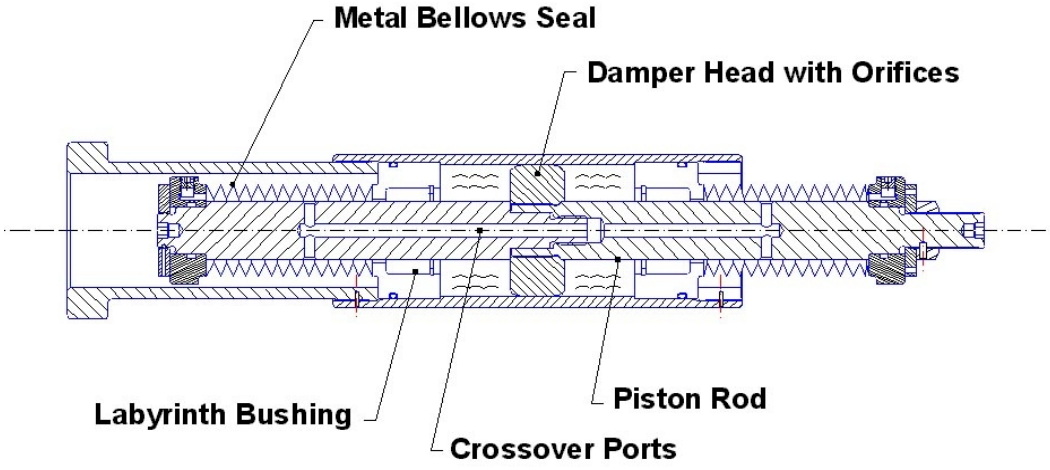

*Figure 8 : cutaway of frictionless damper*

All parts, including the metal bellows, can be designed with low stress levels to provide an endurance life in excess of 2 x $10^9$ cycles. The metal bellows and other moving parts are constructed from stainless steel for corrosion resistance.

## 7. Project examples

The Millennium Bridge in London, England was the first application of frictionless hermetic dampers on a footbridge. A total of 37 dampers were constructed, of 7 different types, and are listed in Figure 9.

| DAMPER TYPE | QUANTITY | DESCRIPTION | USE | STROKE (mm) | LENGTH (m) |
|---|---|---|---|---|---|
| V1 | 5 | Chevron Damper | Lateral Mode | 25 | 0.7 |
| V2 | 10 | Chevron Damper | Lateral Mode | 25 | 0.7 |
| V3 | 2 | Chevron Damper | Lateral Mode | 25 | 0.7 |
| | | | | | |
| V4 | 4 | Vertical to Ground Damper | Lateral and Vertical Modes | 275 | 2.3 |
| | | | | | |
| V5 | 4 | Pier Damper | Lateral and Torsional Modes | 60 | 7.8/3.3 |
| V6 | 8 | Pier Damper | Lateral and Torsional Modes | 60 | 8.2/3.6 |
| V7 | 4 | Pier Damper | Lateral and Torsional Modes | 60 | 8.3/4.6 |

*Figure 9 :list of dampers for the Millennium Bridge*

To assure a high resolution output, it is required that all damper attachment clevises be fabricated with fitted spherical bearings and fitted mounting pins, such that zero net end play exists in the attachment brackets.

Testing consisted of three well-regulated crossings on the bridge by a specific crowd at three different walking speeds. A fourth and final crossing was essentially random, with the crowd being told that additional food and refreshments were available at an off-bridge site on a first-come, first-served basis. All of these four final tests proved to be totally anticlimactic – the bridge behaviour being generally described as “rock solid” by the crowd. More importantly to the engineering team, the damped bridge structure performed superbly:

- Peak measured accelerations reduced from 0.25 g undamped to 0.006 g damped.
- Dampers reduced the dynamic response by at least 40 to 1 for all modes.
- No resonance noted of any mode.
- No observable biodynamic feedback occurred.

Since then, frictionless dampers have been used for other structures, among others, the Passerelle Simone de Beauvoir connecting the Bercy and Tolbiac sections in Paris.

| DAMPER TYPE | QY | DESCRIPTION | USE | STROKE (mm) | LENGTH (m) |
|---|---|---|---|---|---|
| Transverse | 1 | Transverse damper – BNF side | Lateral Mode | 130 | 1.2 |
| Transverse | 1 | Transverse damper – Bercy side | Lateral Mode | 130 | 1.2 |
| Longitudinal | 1 | Longitudinal damper | Vertical Mode | 100 | 0.9 |

*Figure 10: list of dampers for the passerelle Simone de Beauvoir*