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IDEA Innovations Deserving Exploratory Analysis Project

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TUNED DAMPERS AND CABLE FILLERS FOR SUPPRESSION OF BRIDGE STAY CABLE VIBRATIONS

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EXECUTIVE SUMMARY

Incidences of large-amplitude vibrations of stay cables of cable-stayed bridges have been reported worldwide when certain combinations of rain and moderate winds exist. This aerodynamic phenomenon, known as 'rain-wind induced vibration' is a widespread problem and is a source of great concern for the long-term health of these monumental bridges. An effective way of addressing various types of cable vibration problems would be to increase cable damping. Stay cables are generally comprised of a bundle of steel strands (or wires) encased in a polyethylene or steel pipe. In U.S. practice, cement grout filler has generally been injected into the cables (within the encasing pipe) for corrosion protection.

The original concept proposed and explored in this study involved the adaptation of damping traits of various filler materials (in lieu of conventional cement grout) for improvements in damping and suppression of cable vibrations. A vibrating cable subjects the cable (and the filler material) to axial and bending strains. The intent was to maximize energy dissipation by the filler within cost and practical constraints, and thereby achieve increased cable damping. Other concepts for increasing cable damping were developed and evaluated during the course of this study. Two innovative damper concepts for stay cables were introduced and tested. These two new damper concepts addressed the primary deficiency of conventional viscous cable dampers in that the damper is restricted to the area near the ends of cables. The new dampers can be attached at any point along the length of cable thus significantly improving its damping capabilities.

These two dampers can be described as "tuned mass damper" (TMD) and "tuned liquid damper" (TLD). In the tuned mass damper concept, a mass is attached to the cable through a viscoelastic (spring/dashpot) system. Figure 1 shows a conceptual drawing of the TMD. The damper can be "tuned" to the desired frequency of each cable and can be placed at any point along the length of cable. The TLD would consist of a container placed around the cable and partially filled with a liquid. The space within the container must be such that the movement of liquid is regulated to damp cable vibrations at the desired cable frequencies. Another method of improving cable damping involving wrapping commercially available viscoelastic damping tapes around the cable was tested in this study.

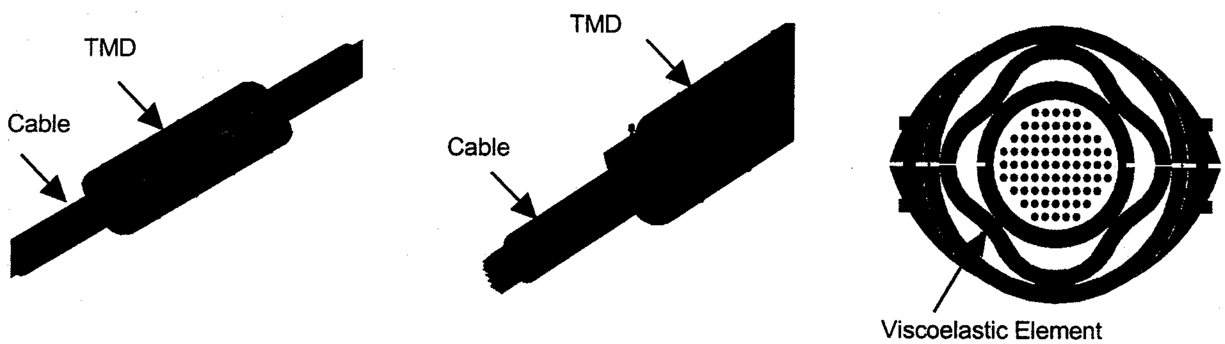


FIGURE 1 Schematic drawings of a tuned mass damper

An experimental program involving comparative damping measurements on 1/7th-scale models of a tensioned cable was performed in the laboratory. Cable damping ratios using various methods and devices were determined to assess the effectiveness. The following is a summary of various tasks performed:

- Five different grout mixes using MasterBuilders Masterflow 816 cable grout and Acryl-Set liquid polymer (latex) were prepared.
- Various physical property tests were performed on samples made with different grout mixes.
- Two cable models were made; one with "conventional" grout and the other with latex grout.

- The three new concepts proposed during the course of the study (a tuned mass damper, a liquid damper, and wrapping cable with damping tape) were tested on the two cable models. In addition, a concept involving filling the cable guide pipe with a polyurethane material was tested. Also, the effects of conventional neoprene washers were studied through the use of scaled neoprene rings.

- The "tuned mass damper" concept proved to be the most effective method. **The research team believes that the "tuned mass damper" has the highest potential for an effective, relatively low cost damper that can be applied anywhere along the length of cable.** It can be applied as a temporary measure or as a long-term solution to the problem of the rain-wind vibration. Figure 2 shows a comparison between cable vibrations measured with and without a tuned mass damper.

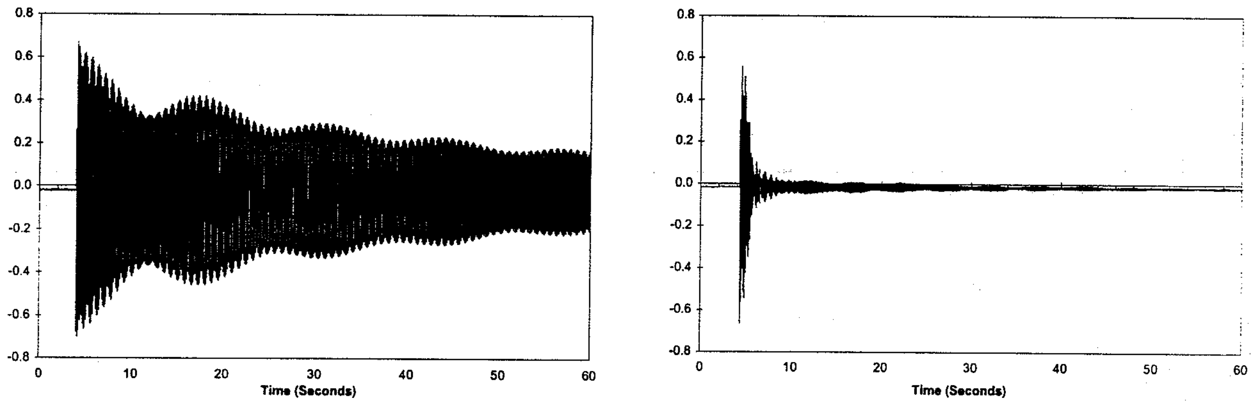


FIGURE 2 Comparison of cable responses with and without tuned mass damper

The cable with latex grout improved cable damping by 60 percent when compared to conventionally grouted cable. However, since the conventionally grouted cable had very low damping to begin with, the higher damping afforded by the latex grout was not sufficient for control of rain-wind vibrations based on the available criteria. In light of the development of the tuned mass damper concept and the fact that cables without any fillers have been used worldwide and are gaining acceptance in the U.S., the use of grout fillers for the purpose of cable damping will not be necessary.

The conventionally utilized neoprene rings also improved cable damping significantly, but the resulting cable damping was still below the threshold of rain-wind vulnerability for a large percentage of existing cables. The "tuned liquid damper" tested was not effective in raising cable damping. However, the research team believes that this concept has significant merit, but a properly designed tuned liquid damper would require substantial research effort not available within the constraints of this project.

The application of damping tape on the outside surface of the cable did not improve the damping ratio of the cable substantially. This method also poses practical challenges and durability issues, and therefore is not recommended.

In summary, the research team strongly urges that the "tuned mass damper" concept be further developed to the level of a prototype for use on an actual structure. This method is believed to offer many practical and cost advantages over the use of mechanical viscous dampers or the utilization of cross-ties. It is recommended that at least one prototype TMD be installed on a stay cable experiencing vibration problems in an actual cable-stayed bridge. Vibration amplitudes before and after installation of dampers should be monitored and compared.

IDEA PRODUCT

This NCHRP-IDEA research program has demonstrated the effectiveness of tuned mass dampers as simple and effective devices for raising the effective damping ratios of cables, thus controlling cable vibrations including the rain-wind and galloping vibrations. Unlike conventional viscous dampers, these dampers can be installed at any location along the length of cable and can provide significant damping levels. These devices can be used on new and existing cables.

This project also investigated the use of cable filler (other than conventional cement grouts) as a means of enhancing cable damping. Although the new filler substantially increased cable damping when compared with cables conventionally filled with cement grout, the level of damping achieved was not sufficient for control of rain-wind vibrations.

CONCEPT AND INNOVATION

BACKGROUND/STATEMENT OF PROBLEM

Incidences of large-amplitude vibrations of stay cables (on the order of 1 to 2 meters) have been reported worldwide when certain combinations of light rain and moderate winds (10 to 15 m/s) exist.[(1)] This aerodynamic phenomenon, known as the "rain-wind induced vibration" is a widespread problem. Formation of water rivulets on the cable is believed to be the cause of this aerodynamic instability.[(1)] Incidences of rain-wind vibrations have been reported throughout the world.[(2, 3)] Vibrations of cables of the newly constructed Erasmus Bridge in the Netherlands were reported in the Bridge Design and Engineering magazine (November 1996). Incidences of rain-wind vibrations have been reported on a number of U.S. bridges including the Burlington, Clark, East Huntington, Weirton-Steubenville, and Cochrane bridges.[(4)] This issue is a source of great concern for the bridge engineering community and a source of deep anxiety for the observing public.

As primary members of cable-stayed bridges, stay cables are arguably the most important and crucial elements of the entire structure. Therefore, such vibrations can be highly detrimental to the long-term health of cables and the bridge. Large-amplitude vibrations can adversely affect fatigue endurance of cables, particularly at anchorages. In general, stay cables consist of a bundle of 15.2-mm-diameter, seven-wire strands with a nominal strength of 1860 MPa. The strand bundle is typically encased in a polyethylene (or sometimes steel) pipe. Strands could be uncoated, epoxy-coated, or individually greased and coated with polyethylene sheathing. In U.S. practice, cement grout is commonly injected into the pipe to provide additional protection for the strands.

AVAILABLE VIBRATION CONTROL CRITERIA

Based on a series of wind tunnel tests performed in Japan,[(5)] Dr. Peter Irwin recommended the following criterion for control of rain-wind vibrations:[(6)]

$$Sc = m\xi/\rho D^2 > 10$$

In this equation, m is the cable mass per unit length, ξ is the damping ratio (relative to critical damping), ρ is the density of air, and D is cable outer diameter. The term on the left side of the above equation is the dimensionless mass-damping parameter or Scruton number (Sc).

A draft Post-Tensioning Institute (PTI) document on stay cables reports a wide range for measured damping ratios (ξ's) of cables from 0.05% to 0.5%.[(7)] As part of a research project on measurement of stay cable forces using the vibration method sponsored by the Federal Highway Administration (FHWA), Tabatabai et al. generated a database of stay cables from 15 cable-stayed bridges around the world.[(8)] This database revealed that the mean and standard deviation of ξ

values required to achieve a Scruton number greater than 10 were 0.454% and 0.107%, respectively. Considering that typical measured range of ξ values for stay cables are between 0.05% and 0.5%, it becomes clear that a very large proportion of stay cables around the world would not meet the above requirements, and may therefore be susceptible to rain-wind induced vibrations. Figure 3 shows a histogram of the cable damping ratios needed to meet the requirement of the above equation. A damping ratio of 0.7% of critical damping would be sufficient to meet the above criterion for over 90% of the cables in the database.

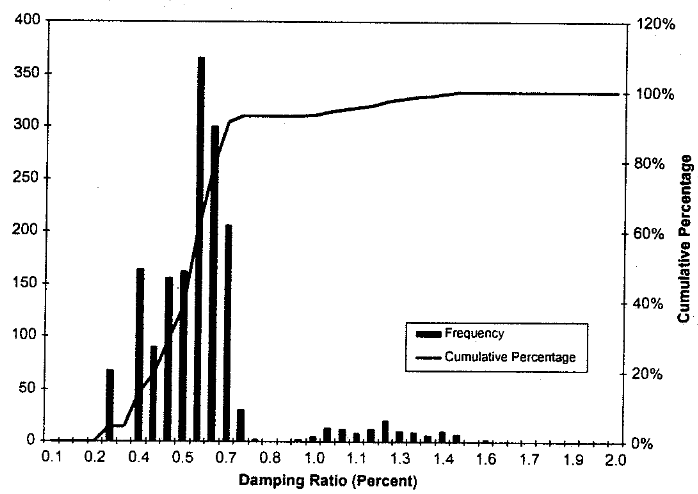


FIGURE 3 Histogram of required damping ratio for rain-wind induced vibration

Irwin also recommends the following equation for the control of the inclined cable galloping vibrations:[6]

$$U = 35fD\sqrt{Sc}$$

In the above equation, U is the critical wind speed, and f is the frequency of cable. As cable damping increases, Sc and U also increase.

AVAILABLE VIBRATION CONTROL MEASURES

In general, a number of different types of cable vibration control measures have been utilized in cable-stayed bridges. In the most common method, neoprene washers (rings) are placed in the annular space between the outside diameter of the cable and a steel guide pipe (attached to the bridge deck or tower) near the two cable anchorages. These neoprene devices serve two primary functions. First, to reduce flexural stresses at the anchorage by providing partial support for the cable at a relatively short distance away from the anchorages; and second, to provide some level of damping to the cable. The level of cable damping achieved by neoprene rings is highly dependent on the tightness of fit, the level of pre-compression, and any confinement for the neoprene. Therefore, the damping contributions from the neoprene rings may be highly variable and not easily predictable.

In another method, cross cables (or cross ties) that transversely connect different cables together are utilized. In such cases, special attention is required in the design of the cable-cross tie connection, the level of prestress in the cross cable, and fatigue considerations for the cable, cross cable, and the connection. Cross cables may also negatively impact the aesthetics of a cable-stayed bridge. The level of damping contributed by cross cables is not currently clear. Based on a set of small-scale laboratory tests, Yamaguchi concludes that there is "more or less a damping-increase function" in crossing main structural cables with secondary cables.[9] Additional damping from other cables, as well as energy dissipation in the cross cables themselves can cause the damping increment.[5] Yamaguchi suggests that the damping contribution of the cross cables would be increased if more flexible and more energy-dissipative ties were used.[9] Failure of cross cables has been noted on at least one prominent cable-stayed bridge.[10]

The third common method for vibration control of stay cables involves the use of mechanical viscous dampers attached to the cables and supported by the bridge deck. Such devices are generally attached to the cable at a distance of 2 to 6% (of cable length) from the deck level anchorage. As attachment point for the damper is moved further into the mid-region of the cable, its efficiency and potential damping contributions increase. However, as the distance of the attachment point from the cable end increases, a number of practical problems arise due to the fact that the damper force needs to be reacted against the deck.

Viscous dampers have been used on a number of bridges worldwide for suppression of cable vibrations. Tabatabai and Mehrabi present procedures for design of mechanical viscous dampers used on stay cables.[11] It should be noted that the level of damping achievable by viscous dampers located near the end of cable is considered modest. As a rule of thumb, the maximum damping ratio that can possibly be contributed by a damper located at X% of cable length from one end (when X≤6) is X/2 percent. For example, the maximum damping achievable when dampers are attached at 2, 4, or 6% of cable length are 1, 2, and 3% of critical damping, respectively. These damping levels may be sufficient for control of rain-wind vibrations but may be inadequate for control of galloping vibrations when design wind speeds are significant.

Japanese and French researchers [3,12] have proposed utilizing polyethylene sheathing that includes protrusions, dimples or spiral strakes on the surface to disorganize or break the movement of the upper water rivulet. However, this process requires special manufacturing process for the sheathing, and the effects of such modifications on drag coefficients need particular attention.

OBJECTIVES

Originally, the objective of this research was to explore the effectiveness of utilizing specific filler materials inside stay cables that would increase cable damping ratios to levels beyond the threshold of vulnerability to rain-wind induced vibrations. Other objectives were added during the course of the study to address new and innovative means of increasing cable damping.

INVESTIGATION

EXPERIMENTAL APPROACH

General

In this section of the report, the basic approaches for enhancing cable damping as developed and examined in this study are addressed. It should be noted that the concept of adaptation of fillers for cable damping enhancement was originally (as stated in the proposal) the only method to be studied. However, during the course of the research effort, a number of other promising approaches including tuned cable dampers were proposed by the investigators and included in the research plan. In the following paragraphs, various aspects of the experimental work are described.

As a first step in the study, a review of literature was performed in the areas of cable damping, damping materials, tuned mass dampers (TMD), tuned liquid dampers (TLD), and related areas. A large number of titles and abstracts were reviewed. Of those, over 40 papers, three books and two theses were obtained for further review.

Scaled Modeling

The effectiveness of various damping treatments and methods was comparatively assessed using 1/7th scale stay cable models. The extent and variety of testing necessary to adequately compare various damping treatments would have not been possible or practical if prototype cable testing were contemplated. An "average" stay cable is approximately 320 feet long and contains 53 strands.[13] Properly scaled cable models (based on the laws of similitude) offer significant experimental flexibility and provide a simple, yet reliable, vehicle for comparative assessment of various damping treatments. Basic properties of the scaled cable models used in this research are shown in Figure 4. In this model, relationships between model and prototype parameters are shown in Table 1.[14]

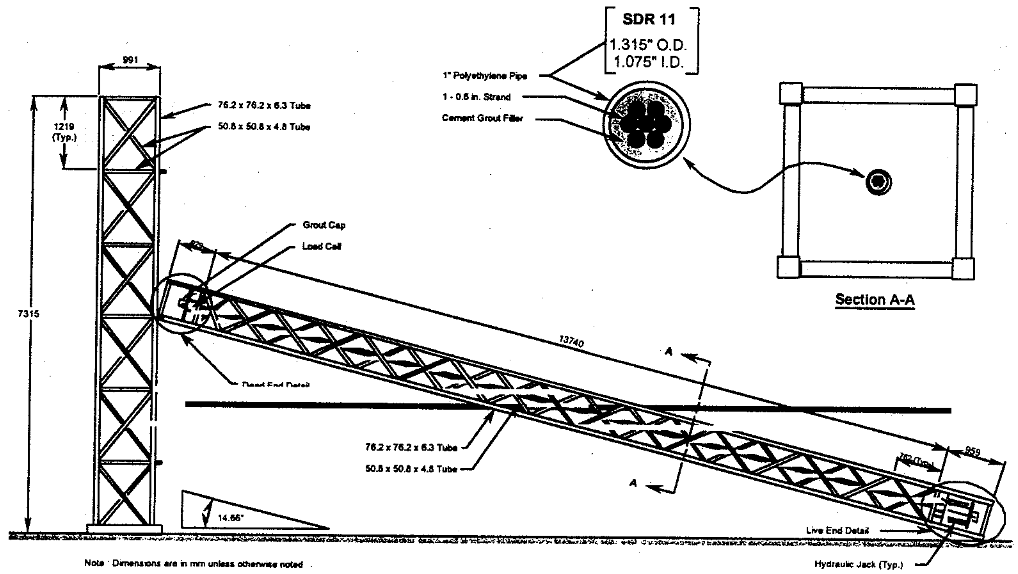


FIGURE 4 Reaction frame for laboratory tests

Since materials used for the model and prototype (such as grouts, polyethylene pipe, prestressing strand, etc.) are the same (or very similar), then material property requirements listed in Table 1 are satisfied. These include parameters such as modulus of elasticity, density, Poisson's ratio, strength, etc. Note that in Table 1, the damping ratios of the model and prototype are the same for a "true" model.

Achieving an ideal or "true" model is not entirely possible in great majority of cases. Some degree of distortion is generally present. The potential impact of such distortions must be considered and evaluated in the design of such models. For example, Table 1 shows that acceleration in the model should be n (n = length scale)times the acceleration in the prototype. Theoretically, this same requirement should apply to the acceleration of gravity. However, the model tests are conducted at 1g (the same as prototype). This introduces a distortion in the model. A true model (in this set of relationships) must be subjected to an acceleration of gravity of ng (as in a centrifuge). The effect of this distortion in the model would be an incorrect modeling of the effects of gravity such as cable sag and the sag to span ratio. However, since the important parameter of interest in this case is the damping ratio, and the sag effects do not generally affect this parameter, the gravity stresses would not introduce a significant distortion. A different set of scaling relationships (different from Table 1) can be utilized to achieve proper modeling of the sag effects. This involves attachment of lumped masses to the cable. Although theoretically feasible, this method is believed to introduce numerous other practical complications (such as distorting the damping effects by introducing damping at connection points of lumped masses). Therefore, the scaling relationships shown in Table 1 were utilized in these tests.

Another source of distortion in this case would be from the component of damping due to friction. Friction effects may not be properly modeled in a scaled model such as that utilized here. Also, overall damping can be affected in some extent by higher frequencies in the scaled model. However, since none of the damping treatments are based on friction, and a comparative (not absolute) damping assessment is made, these effects are not expected to influence the results.

TABLE 1 Dynamic Scaling Relationships[14]

Parameter	Symbol	Scaling Relationship
Stress	σ	$\sigma_m = \sigma_p$
Displacement	d	$d_m = d_p/n$
Acceleration	a	$a_m = n\, a_p$
Velocity	v	$v_m = v_p$
Spring Constant	K	$K_m = K_p/n$
Energy	E_n	$E_{nm} = E_{np}/n^3$
Dimension	D	$D_m = D_p/n$
Density	ρ	$\rho_m = \rho_p$
Material Modulus	E	$E_m = E_p$
Material Strength	F	$F_m = F_p$
Area	A	$A_m = A_p/n^2$
Volume	V	$V_p = V_p/n^3$
Mass	M	$M_m = M_p/n^3$
Strain	ε	$\varepsilon_m = \varepsilon_p$
Dynamic Time	t	$t_m = t_p/n$
Signal Frequency	f	$f_m = n\, f_p$
Damping Ratio	ξ	$\xi_m = \xi_p$
Poisson's Ratio	μ	$\mu_m = \mu_p$
Force	F_f	$F_{fm} = F_{fp}/n^2$

m = model, p = prototype,
n = length scale

Adaptation of Fillers

The originally proposed concept for this study explored the adaptation of damping traits of filler materials for suppressing stay cable vibrations. The current predominant design of cables in the U.S. (and many other countries) consists of parallel seven-wire strands encased in polyethylene sheathing and injected with cement grout. The stated objective of the cement grout filler is to provide protection for the strands by providing an alkali environment and to introduce a physical barrier to the outside elements. A vibrating cable subjects the cable (and filler materials) to axial and bending strains. These strains could potentially be used to dissipate vibration energy in the filler, and thereby increase damping. Identifying a cost-effective filler material that would increase cable damping while maintaining or improving the level of corrosion protection was therefore desired. Such a filler material could improve and simplify design, improve fatigue endurance (by controlling vibration), and enhance aesthetics of bridge by eliminating the need for external vibration control devices.

Other countries in Europe and Japan have used cables without fillers, or with fillers other than cement grout. Post-Tensioning Institute (PTI) Recommendations for Stay Cable Design, Testing and Installation provides a list of alternative corrosion protection materials used for stay cables in Japan.[15] These include polymer concrete, polybutadiene polyurethane, and grease. Other applications in Europe have included flexible grout and wax fillers.

An evaluation of potential filler materials was performed in this study. The decision to select the appropriate product or combination of products was based on four important considerations:

- Physical properties and corrosion protection
- Relative cost
- Field application (injection) with conventional grouting equipment

- Cooperation from industry

Research by Yamaguchi indicates that the most efficient ways of increasing energy dissipation during vibration cycles are to increase the loss factor of the material, and to increase the modulus of elasticity of material (to improve loss due to axial strains).[22] Loss factor is the ratio of dissipated energy to the stored elastic energy in each cycle. A number of possible filler products such as wax and grease were not considered because of their low moduli of elasticity. Another important parameter is that the level of corrosion protection provided by the proposed material should be at least equal (ideally better) than conventional cement grout.

Considering the fact that the volume of filler inside typical stay cables is generally 2 to 3 times larger than the volume of the primary steel elements, the cost factor becomes very crucial. Therefore, any filler material selected had to have reasonable cost. For example, polyurethanes or various other polymers can be designed to achieve the necessary properties, but the costs of those materials would be much higher than the conventional cement grouts. The ability to utilize conventional equipment for injection of fillers and the level of cooperation from industry were the other two important parameters.

Serious considerations were given to the use of "Sika Icosit 320", which is a polyurethane-based material that is mixed with cement. This product was designed for cable applications and includes corrosion inhibiting admixtures. However, the manufacturer (Sika Chemie, Germany) informed the research team that they planned to discontinue the production of this material because of environmental issues involving the use of some admixtures. Therefore, this option was not pursued further.

Based on an evaluation of various materials, the latex modified cementituous grout was selected for further evaluation and testing. This type of grout offered a potential solution with reasonable cost, ability to inject with conventional grouting equipment, good energy absorption potential, and cooperation from the industry. Test materials utilized consisted of a mixture of two commercial products: "Masterflow 816 Cable Grout" and "Acryl-Set Liquid Polymer." Both these products are produced commercially by Master Builders, Inc. Masterflow 816 is a Portland cement-based grout designed for post-tensioning applications. It is advertised that this grout pumps easily, is without bleeding and settlement shrinkage, and meets the compressive strength and non-shrinkage requirements of CRD-C-621 and ASTM C-1107 at a fluid consistency. With the recommended water quantity of 2.17 gallons per 55-lb bag of grout, the flow cone test method (ASTM C-939) reportedly results in a 20 to 30 second flow time.

The Acryl-Set liquid polymer is designed to replace all or part of the mixing water in portland cement-based mixes. It is generally used for repair of concrete (including thin repairs), leveling concrete, bond slurries, highway and bridge paving, spraycoat applications, etc. Since this material was not originally designed for the purpose of mixing with the 816 Cable Grout, a limited number of trial mixes and property tests were performed to optimize the properties of the combined product as they relate to cable damping.

Five different latex grout mixes were prepared and tested to determine basic physical properties and find the most appropriate mix. Table 2 shows ingredients for the various grout mixes (A through E).

TABLE 2 Grout Trial Mixes

	Grout Mix				
Ingredients	A	B	C	D	E
Masterflow 816 Cable Grout (lbs)	36.7	36.7	36.7	38.5	0
Acryl-Set Liquid Polymer (lbs)	6.4	0	12.3	12.9	12.9
Masterflow 816 with Sand (lbs)	0	0	0	0	38.5
Water (lbs)	5.8	12.1	0	3.1	3.1

The five mixes were tested to determine compressive strength (ASTM C39), modulus of elasticity (ASTM C469), modulus of rupture, hysteresis (first cycle), and hysteresis after 10,000 cycles of loading. At least three cylinders (3-in. x 6 in.) and three cubes (2-in.) were used per each mix to determine modulus of elasticity and compressive strength. Three prisms (3 in. x 3 in. x 11 in.) were used to determine energy loss per cycle for each of the grout mixes. These prisms were simply supported with a span of 9 in. A strain gage was attached to the bottom of each prism at mid-span. One-third point loading was applied in increments until a strain of 100 millionths was reached. The load was then returned to zero. Then, 10,000 cycles of strain (from zero to 100 millionths and then to zero strain on the bottom fiber at mid-span) was applied. The area under the load-strain curves for the first, and the 10,000th cycles were determined. This was done to evaluate the energy dissipated per cycle in the material and the degradation of this energy dissipation capability with time (repetitive stresses). Other prisms (1 in. x 1 in. x 11 in.) were used to determine modulus of rupture of the various grouts. Based on the results of these tests, grout mix D was selected.

Two stay cable scaled models were prepared for testing. The only parameter that was varied between the two cables was the type of grout used. Each cable consisted of a single 0.6-in. diameter strand stressed to 23,400 lbs or 40% of nominal capacity (after losses). This stress level in the cable is typical under dead load conditions in stay cables. The strand was encased in a continuous high-density polyethylene pipe with an outside diameter of 1.315 in. and a minimum wall thickness of 0.12 in. (SDR ratio of 11). Grouting operations was performed when cables were placed at an inclination angle of approximately 15 degrees as shown in Figure 4.

The cable fillers used were:

1. Conventional cement grout filler (a combination of cement, water and admixtures). The mix consisted of 85.6 lbs of Masterflow 816 Cable Grout and 28.2 lbs of water. The measured flow time based on the flow cone test method (ASTM C-939) was 13 seconds.

2. Latex modified cement grout. The mix consisted of 85.6 lbs of Masterflow 816 cable grout, 28.7 lbs of Acryl-Set liquid polymer, and 19.1 lbs of water. The amount of water used was higher than the proportions used in the trial mix (Mix D) selected due to pumping difficulties with the desired trial mix. The flow cone test was not performed due to the thixotropic nature of the grout.

Tuned Dampers

Tuned mass dampers and tuned liquid dampers have been used in many Civil Engineering structures including high-rise buildings and bridges. A tuned mass damper is in the form of a mass on a spring with damping or a mass on a viscoelastic element. A TMD should ideally be located at a point of high displacement response such as an antinode.(16) Tuned mass dampers can be effective over a range of frequencies depending on the design of damper. If the spring does not have a damping or viscoelastic component, the system is called an "undamped dynamic vibration absorber."(17) Dynamic absorbers function as discrete tuned resonant energy devices.(16) A properly tuned absorber changes the original system resonant frequency into two other frequencies and reduces (or eliminates) the response at the original frequency. However, since there is no damping component associated with the spring of an absorber, the response is limited to the target frequency.

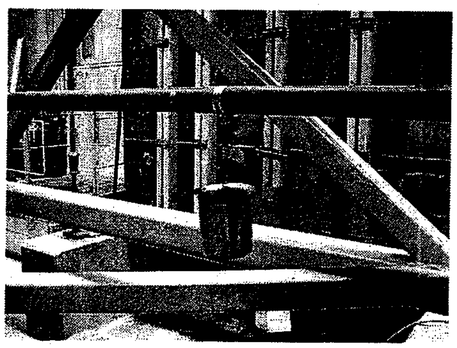
A very early application of TMD concept to the transmission (electric) lines was in the form of a "Stockbridge damper." A Stockbridge damper consisted of a piece of steel cable clamped to the line at the middle and two weights attached to the ends of the cable.(18)

A properly designed TMD can be applied anywhere along the length of a cable. Existing hydraulic or viscoelastic dampers must, by design, be located near cable ends where they are least effective. The Tuned Mass Damper concept is based on the movement of a mass attached with a viscoelastic element (spring and dashpot) to the cable. The system (mass and the spring constant) can be tuned to the cable frequency of interest.

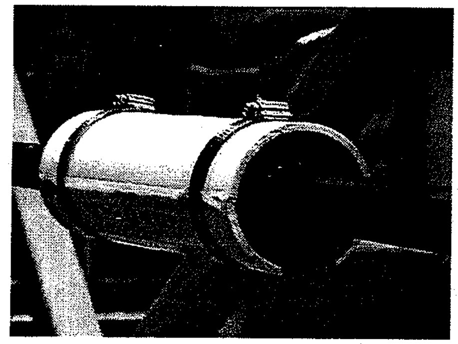
Tuned Liquid Dampers have been used on tall buildings and tower structures.(19,20,21) Existing TLD's for buildings and towers rely on the motion of shallow liquid in a rigid container placed on top of the structure for control of vibrations due to wind. There are considered to be low cost and low maintenance devices. The Tuned Liquid damper concept for cables as proposed here is based on attachment of an annular cylindrical container (partially filled with liquid). The inside of the cylinder could be hollow or contain tubular or other types of paths to regulate the movement of liquid (tuning).

Both TMD and TLD dampers have been used (or proposed for use) in buildings and bridges, but not for stay cables. These dampers are believed to be aesthetically unobtrusive, i.e., they are not expected to negatively impact the streamlined look of a cable-stayed bridge. Cross-ties (cross cables) and hydraulic dampers have sometimes been criticized for affecting the beauty of such bridges.

The test program performed on the two stay cable models were designed to address the feasibility and effectiveness of TMD and TLD applications on stay cables. Figure 5 shows the scaled "TMD" and "TLD" devices tested on cables. The "TMD" consisted of a metal bucket hung from the cable by a spring at different locations along the cable. Figure 6 shows a schematic of TMD and TLD system attached to cable model. In TMD model, the bucket contained various amounts of lead shot (to allow easy variations of system mass). Five different types of springs (different spring constants) were used for TMD model. The types of spring and spring constants (nominal) used are listed in Table 3.



TMD



TLD

FIGURE 5 Scaled model representations of TMD and TLD

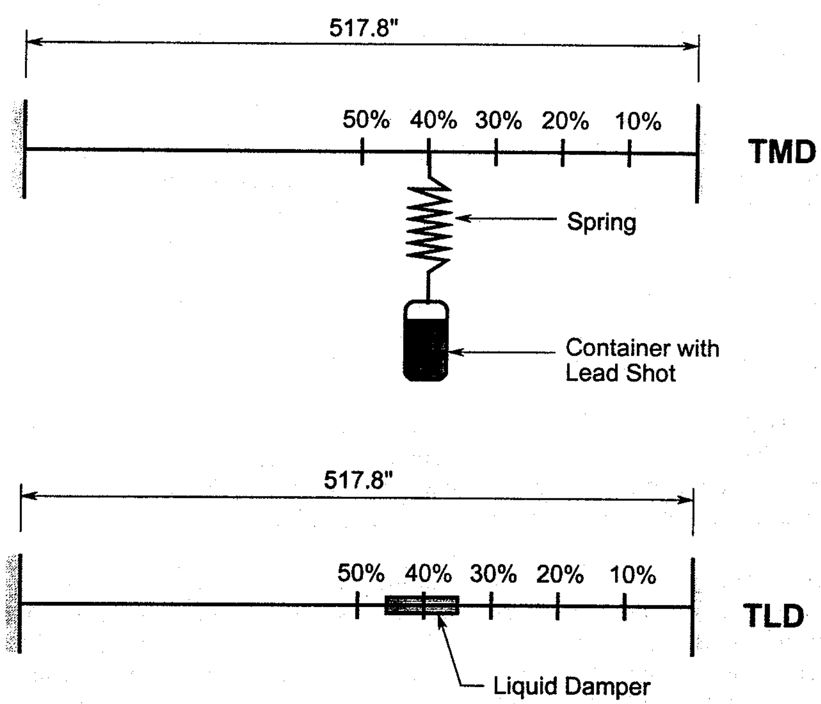


FIGURE 6 Schematics of TMD and TLD

TABLE 3 Spring Types and Constants

Spring No.	Spring Type	Nominal Spring Constant (lbs/in.)	Equivalent Prototype Spring Constant* (lbs/in.)
1	Extension	2.5*	17.5*
2	Compression	3.0	21.0
3	Compression	8.0	56.0
4	Compression	16.0	112.0
5	Compression	30.0	210.0

* This spring was non-linear at low loads with higher stiffness at lower loads.

It should be noted that Spring No.1 was tested under two different conditions: uncoated (plain spring) and coated (spring brushed with a polyurethane compound to add damping element). Since Spring No. 1 was an extension spring, it exhibited non-linear behavior (load vs. Displacement) at lower loads when the mass attached was not sufficient to fully engage the entire spring. A large number of tests were performed with the mass-spring systems attached at different locations along the lengths of both cable models. Different springs were tested with different amounts of lead shot (mass).

The TLD model used consisted of a 12-in.-long, 3-in.-diameter (nominal) PVC pipe that was cut lengthwise in half. The two pieces of the pipe were then placed on the cable as shown in Figure 5. The two ends of the pipe were sealed. Various amounts of liquid (water or motor oil, up to complete filling) were added through an opening at the top of the pipe prior to each damping test. The center of the pipe was located at 20% of cable length in one test (cable 1), and at 42.5% in another test (Cable 2). In addition to the above, some tests were performed using lead shots in lieu of water or oil.

Damping Tapes

During the course of the review of literature, the project researchers came across a recommendation by Yamaguchi regarding a potential means to enhance cable damping.[22] Yamaguchi's suggestion was based on application of layers of damping tapes spirally around the wire strands so that "even in axial deformation of the cable, there is large energy loss due to the shear deformation in the damping tape.[22] Inducing shear strains (as opposed to axial or bending strains) in viscoelastic materials is most effective for damping enhancement. Yamaguchi did not provide experimental verification of his suggestion. It was therefore decided to experimentally assess the effectiveness of wrapping the stay cable with layers of damping tapes in this research program. The 3M Corporation (St. Paul, Minnesota) produces viscoelastic damping tapes for vibration control in panels and other structures. Several rolls of 2-in. wide damping foils (3M model 2552) were obtained for testing. These adhesive foils consisted of a viscoelastic polymer on dead soft aluminum foil. The total thickness of the tape is 15 mils (0.381 mm), and multiple layers of these tapes can be applied spirally on selected locations of the cable to increase damping. The polymers can be selected to be effective within the design temperature range of the cables (e.g. -20° to 120°F).

In this test program, the conventionally grouted cable model was first spirally wrapped with one layer of 2552 damping tape over the middle 20% of the cable length with zero overlap. Tests on damping tapes were performed only on the first cable (conventionally grouted) after all other tests on that cable had been completed. In this test, the cable was free from other treatments (i.e., no neoprene rings, etc.). Another test was performed after a second layer of damping tape was applied over the middle 40% of the cable length. Figure 7 shows the cable model with damping tape applied.

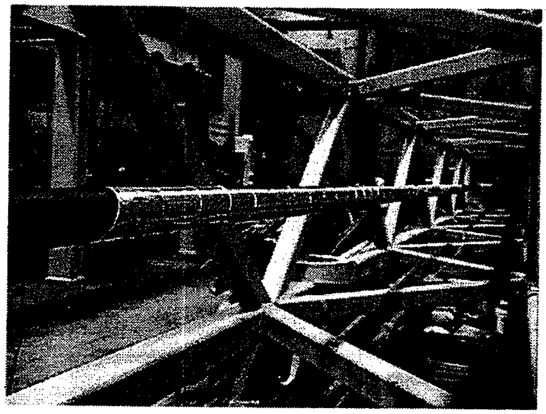


FIGURE 7 Damping tape applied on cable

Neoprene Rings

To assess the impact on cable damping of conventional neoprene rings commonly used in stay cable design, a set of tests were performed on scaled durometer 50 neoprene rings. The rings would fit snuggly inside a scaled "guide pipe" and attached to the reaction frame of the stay cable model as shown in Figure 8. The guide pipe consisted of a 12-in. long, 2.25 in. outside diameter pipe with a wall thickness of 0.065 in. The support points for the pipe were selected to represent actual (scaled) support conditions of a guide pipe from the Cochrane Bridge in Alabama. The first and second support points for the guide pipe were located at 7.25 in. and 10.25 in. from the free end of the pipe, respectively. The free end of the pipe was located 21 in. from the anchorage bearing plate. The neoprene ring was cut from a 1-in.-thick sheet of Durometer 50 neoprene to fit the inside of the pipe at a distance of 0.5 in. from the free end. This ring model would be equivalent to a 7-in.-thick neoprene ring located 3.5 in. from the free end of the guide pipe in the prototype structure. Damping measurements were made without neoprene ring, with neoprene ring on one side, and with neoprene ring on both sides.

FIGURE 8 Neoprene ring models placed inside guide pipe

Polyurethane Rings

A concept involving partial or complete filling of the guide pipe with a polyurethane material was suggested by a manufacturer (Polycoat Products) and tested. In one test, the existing neoprene ring was pushed back to a distance of 4 in. from the free end of the guide pipe and the entire guide pipe was filled with a two-component, low-viscosity liquid polyurethane rubber. Only one guide pipe (at one end of cable) was filled. The other end was free (i.e., no neoprene rings used). Originally, it was intended that the front 4 in. of the guide pipe be filled, but due to a leakage the entire pipe was filled. The polyurethane was allowed to cure for a minimum of three days before testing. In another test, the neoprene ring on one side was removed, and the entire pipe on that side was filled with the polyurethane material. The other end contained the conventional neoprene ring.

Damping Measurement Procedures

Measurement of damping was performed using the free vibration decay method. In this method, an accelerometer was attached to the cable at mid-length. The cable was deflected at mid-span using a weight (steel cylinder) hung from the cable by a string at mid-length (Figure 9). The string was then suddenly cut with a sharp knife to excite the first mode vibration of the cable. The subsequent cable vibrations (measured by the accelerometer) were recorded using a high-speed data acquisition system (Figure 9).

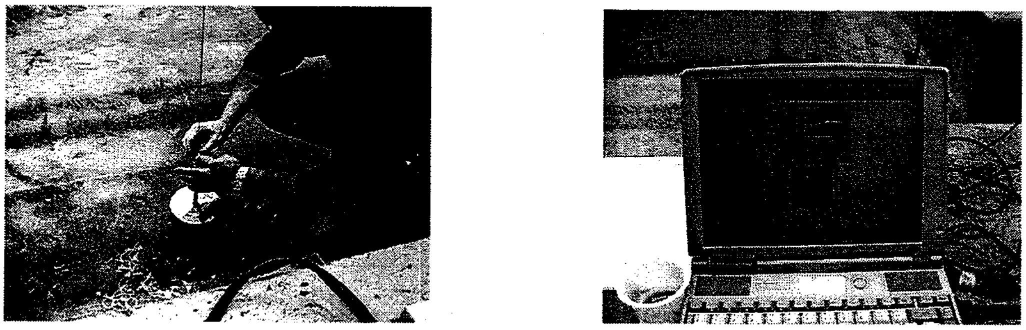


FIGURE 9 Weight hung from the middle of cable and data acquisition system

The damping ratio for the first mode can then be determined using the following equation:

$$\xi = \delta_n / 2 \pi m$$

where δ_n is the logarithmic decrement over m cycles. The logarithmic decrement is defined as:

$$\delta_n = Ln (v_n/v_{n+m}) = Ln (v_n) - Ln (v_{n+m})$$

where v_n is the peak vibration amplitude at the n-th cycle, and v_{n+m} is the corresponding peak at the (n+m)-th cycle. However:

$$m = f (t_{n+m} - t_n)$$

where f is the first mode frequency of cable (in Hertz), and $(t_{n+m} - t_n)$ is the difference in time between the peak at (n+m) cycles and the peak at n cycles. Therefore:

$$\xi = (Ln (v_n) - Ln (v_{n+m})) / (2 \pi f (t_{n+m} - t_n))$$

The procedures used\` to determine the damping ratio in these tests were as follows: (1) Plot the natural log of positive peaks of the acceleration-time history versus time. (2) Consider only the peak data greater than 10% of the highest (initial) peak (i.e., ignore the smaller peaks). (3) Draw a best-fit straight line through the data and find the slope of the line. (4) Divide the slope of the line by - $2\pi f$ to determine the damping ratio.

In many cases where mass-spring systems were attached to the cable models, the plot of the natural log of the data versus time was not linear. In such cases, two straight lines were fit to the data. All damping measurement tests were performed when the cable model was in a horizontal alignment.

TEST RESULTS

Grout Test Results

Table 4 shows the results of tests performed on various grout mixes evaluated.

TABLE 4 Test Results - Grout Mixes

Grout Mix	Compressive Strength (Age-Days) (psi)	Modulus of Elasticity (ksi)	Modulus of rupture (psi)	First Cycle Hysteresis (lb-in./in.)*	Last Cycle Hysteresis (lb-in./in.)*
A	7167 (14)	2620	NA**	551	484
B	7142 (14)	4680	314	NA**	NA**
C	6050 (14)	1380	1215	1957	1010
D	4792 (28)	1640	422	2044	778
E	3250 (28)	1840	614	3923	352

* 10,000 cycles of zero to 100 microstrains (at the bottom fiber at mid-span) were applied to the test specimen. The energy loss by the material in the first and last cycles was measured.

** Not tested due to cracking of specimens.

Based on the above results, it is clear that cyclic straining of the material for 10,000 cycles degrades the energy absorption capability of the latex grout substantially. Mix D was selected for grouting of the second cable model due to its relatively high energy-absorption capacity after 10,000 cycles, and because of its relatively high modulus of elasticity. However, during grouting of the second cable, it became clear that the grout was not injectable with the grout pump available due to its thixotropic nature. Some water was added to be able to inject grout.

Damping Test Results

Results of all damping tests are summarized in a table included in Appendix A. The measured damping ratios in some cases are given as two numbers. This is due to the fact that two straight lines instead of one could best represent the logarithmic data. In such cases, the associated amplitude (in percent of the initial or maximum amplitude) accompanies the first damping ratio. For example, in test T1-10, the measured damping ratio is given as "3.06 to 19%, then 0.11." This means that the damping ratio for all data except those with amplitudes below 19% was 3.06% of critical damping. For amplitudes between 19% and 10% (which was the lowest amplitude considered), the measured damping ratio was 0.11%.

Fillers

The time-domain response of the conventionally grouted cable (reference cable or Cable 1) is shown in Figure 10. The measured first mode frequency of the cable was 8.55 Hz. The measured damping in this case was very low (0.05%). It should be noted that in this test, there were no neoprene rings attached. The corresponding test of the latex grout cable (Cable 2) indicated a damping ratio of 0.08%. Although, there was a substantial increase in damping from a percentage standpoint (60%), the achieved damping ratio was well below the minimum damping required for control of rain-wind vibrations in most stay cables.

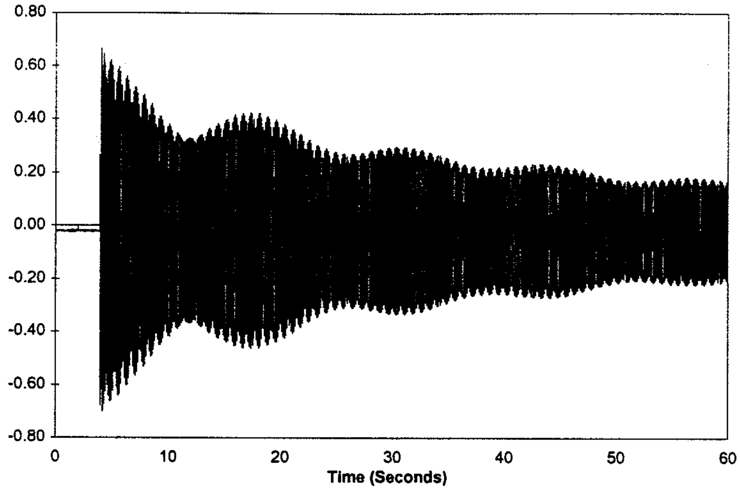


FIGURE 10 Acceleration response at mid-length of Cable 1 without damper

Neoprene Rings

When neoprene rings were installed inside guide pipes at both ends of the reference cable (cable 1), the measured damping ratio reached as high as 0.61% (or over 10 times higher than the same cable without neoprene rings). Figure 11 shows the time-domain response of Cable 1 with neoprene rings. It should however be noted that the performance of the neoprene rings is highly dependent on the tightness of fit inside the guide pipe and the level of pre-compression (or confinement) in the neoprene material. It is expected that pre-compressing the rings to fit would be helpful up to a point that such pre-compression would result in a more-or-less rigid support and result in reduced damping for the cable.

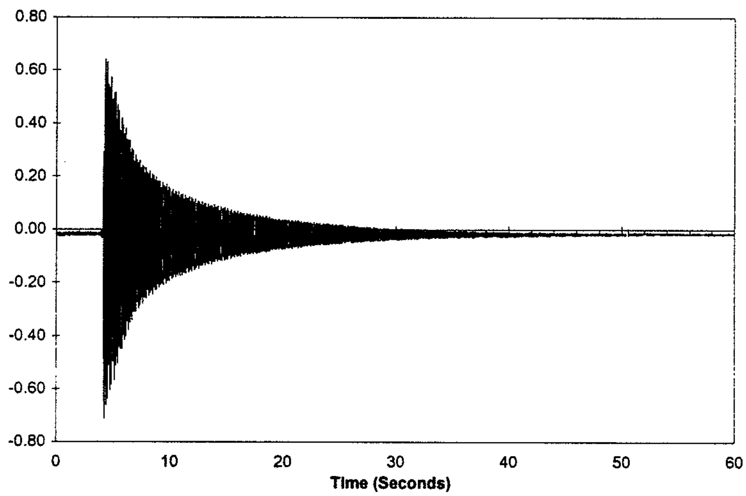


FIGURE 11 Time domain response for Cable 1 with neoprene rings

As an indication of the high degree of variability of the neoprene damping contribution, it is noted that Cable 2 with neoprene rings on both sides achieved a damping ratio of up to 0.34%. When neoprene ring was used on one side only, the resulting damping ratio was 0.26%.

Polyurethane Rings

The polyurethane material placed between the guide pipe and the cable did not improve cable damping substantially when compared to the conventional neoprene rings. In Cable 1, when polyurethane was used in combination with a displaced neoprene rings (on one side only), the damping ratio achieved was 0.34%. When a conventional neoprene ring was also placed on the other side, the damping ratio increased to 0.41%. In Cable 2, when polyurethane was used in one guide pipe (without any neoprene rings), the damping ratio achieved was only 0.14%. When a neoprene ring was added to the other guide pipe (opposite end of cable), the measured damping ratio increased to 0.38%. It should be noted that the polyurethane material used had a low modulus (Shore A Durometer Hardness of 25). It is anticipated that the damping contribution might increase if a polyurethane material with higher modulus were to be used.

Damping Tapes

Damping tapes were applied to Cable 1 only. In the case where damping tapes covered the middle 20% of the cable, the damping ratio of the cable was 0.05% or unchanged from the untreated cable. An additional layer of tape covering the middle 40% of cable length increased cable damping to 0.08%. Considering the potential practical complications in applying these tapes in the field and the poor damping results obtained, this method is not recommended for further study.

Tuned Liquid Damper

In Cable 1, the PVC container was attached at 20% of the cable length from one end. Addition of different quantities of water or lead shot did not improve damping in a substantial way. The maximum cable damping achieved was 0.08%. Similar results were obtained in tests on Cable 2 where the PVC container was placed at 42.5% of cable length from one end. In no case (with water or oil) did the damping level increase beyond 0.20%. However, it should be noted that the theoretical design of a TLD system for cables involves extensive investigations beyond the scope of this project. It is anticipated that an effective and proper combination of damper design incorporating internal paths or tubes to regulate and tune the process of movement of liquid can be found. Additional research is required to address these issues. Such a damper system could be a low-cost, low-maintenance alternative to currently available methods.

Tuned Mass Damper

Figure 12 shows the time-domain response of the reference cable (Cable 1) with a mass-spring system located at 20% of cable length. In this case, the uncoated spring No. 1 was used with a mass of 1020 grams or approximately 3% of the total cable mass (equivalent to 350 kg in the prototype structure). The damping ratio achieved in this case was 2.35%. Comparison between Figure 12 and Figure 10 (response without damper) shows significant improvement achieved by TMD.

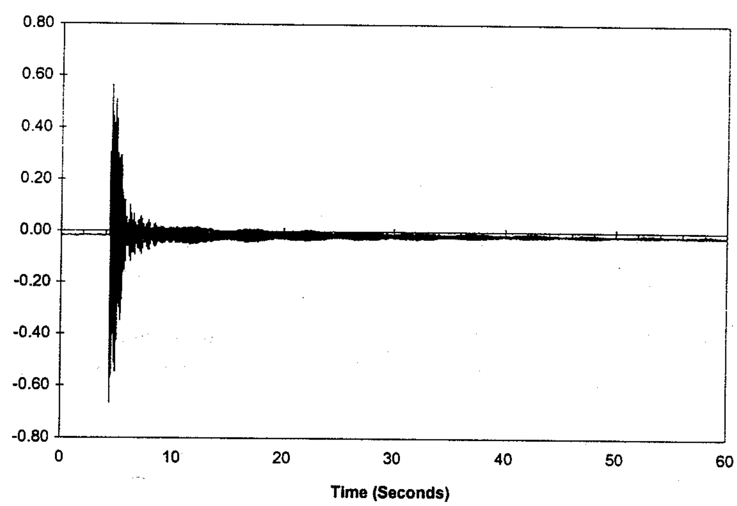


FIGURE 12 Aceleration in Cable 1 with TMD

Figure 13 shows the damping contributions by spring No. 2 at various locations along the length of Cable 2. In the tests illustrated in this figure, the mass of damper was 190 grams or 0.6% of total cable mass (Mc). Similar graphs for spring No. 3 with a damper mass of 415 g (1.3% of Mc), spring No. 4 with a damper mass of 665 g (2.2% of Mc), spring No. 4 with a damper mass of 415 g (1.3% of Mc), and spring No. 5 with a mass of 1665 g (5.4% of Mc) are shown in Figures 14 through 18. It is clear that very high effective damping levels (exceeding the required levels for suppression of rain-wind and galloping vibrations) can achieved through the use of the TMD system. It is also clear that the damping level achieved is highly dependent on the spring mass for each spring as well as the location of the TMD along the cable. Figure 18 shows variations of damping contributions with the mass of the damper when spring No. 5 was attached at 30% of cable length. Other similar graphs for Springs 3 and 4 are shown in Figures 19 and 20, respectively.

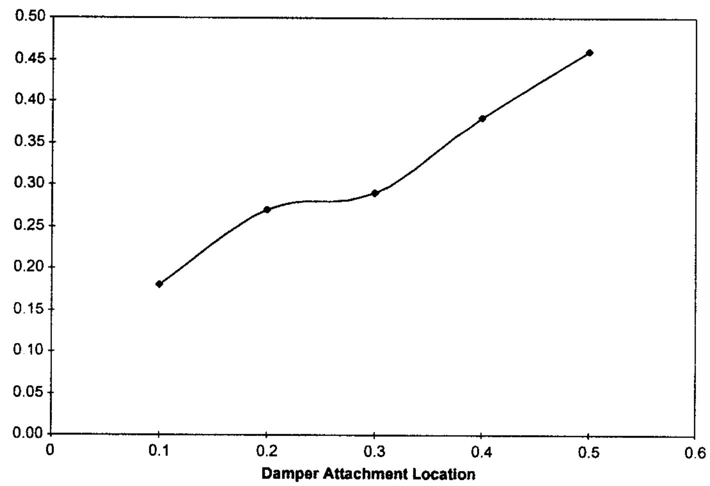


Figure 13 Damping ratios of Cable 2 with respect to damper location for Spring 2, mass of 190 gm

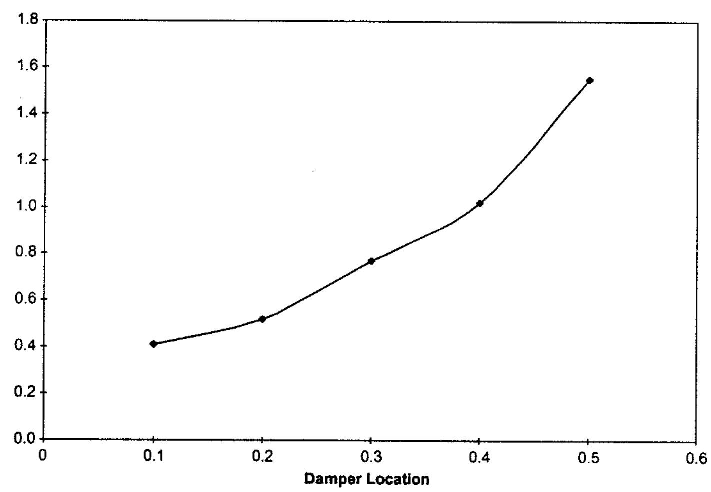


Figure 14 Damping ratios of Cable 2 with respect to damper location for Spring 3, mass of 415 gm

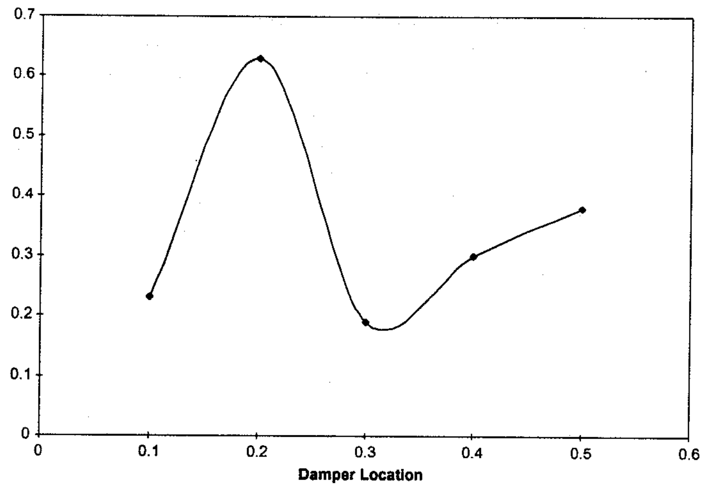


Figure 15 Damping ratios of Cable 2 with respect to damper location for Spring 4, mass of 665 gm

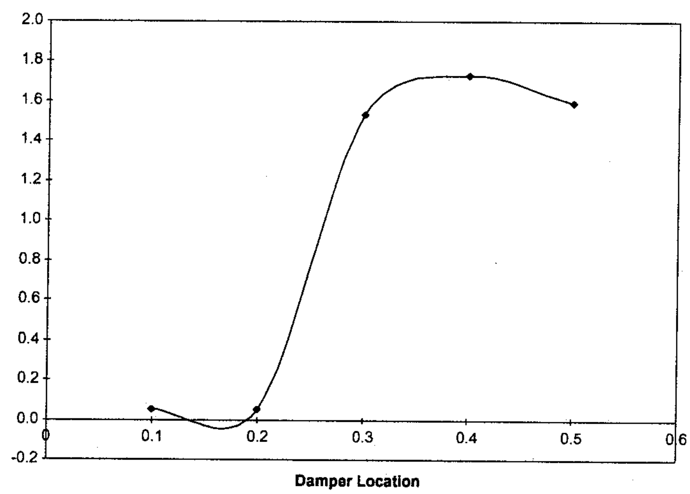


Figure 16 Damping ratios of Cable 2 with respect to damper location for Spring 4, mass of 415 gm

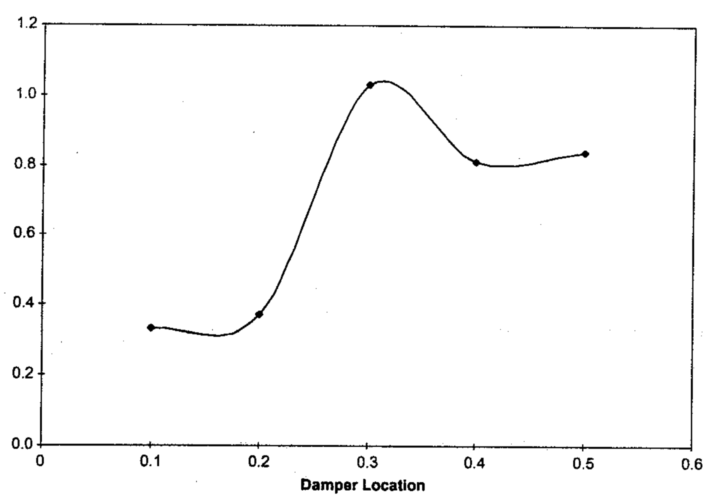


Figure 17 Damping ratios of Cable 2 with respect to damper location for Spring 5, mass of 1665 gm

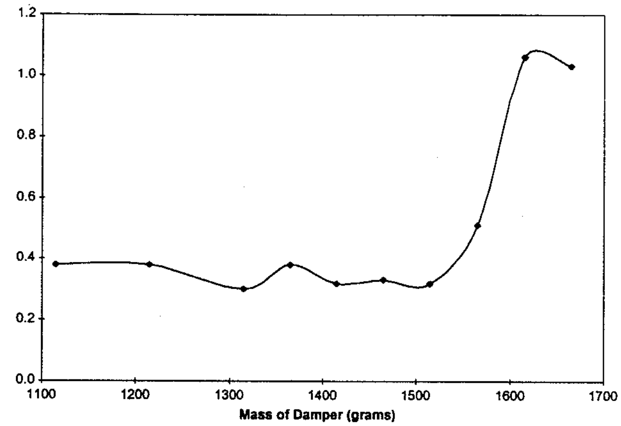


Figure 18 Variation of damping with mass for Spring 5 at 30% of cable length

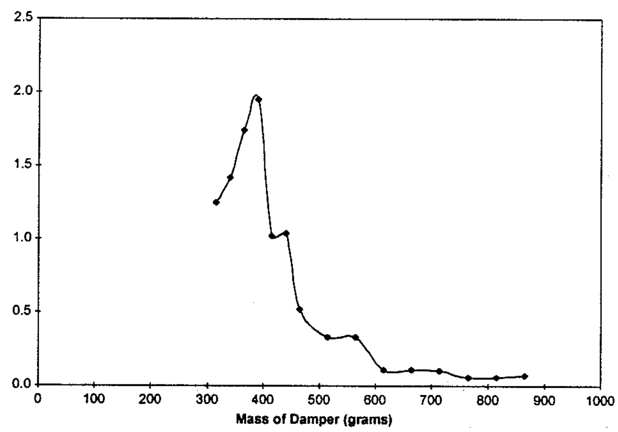


Figure 19 Variation of damping with mass for Spring 3 at 40% of cable length

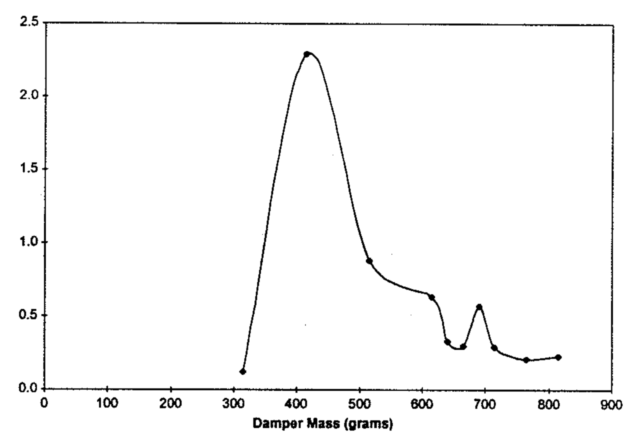


Figure 20 Variation of damping with mass for Spring 4 at 40% of cable length

The TMD concept proved very successful in raising the effective damping ratio of cable beyond the threshold of vulnerability to rain-wind and galloping vibrations. It is also expected to be a low-cost, low maintenance vibration control option that can be applied to both existing and new stay cables. The advantages of TMD compared to conventional viscous dampers or other alternatives can be described as follows:

- Relatively high effective cable damping ratios achievable.
- Reasonable expected cost (estimated on the order 1/4 to 1/3 the cost of viscous dampers).
- Not limited to the ends of cable (can be attached anywhere along the length).
- Relatively small size and mass.
- Expected to be low maintenance.
- Aesthetically more pleasing. In fact the positioning of dampers in different cables can be used to highlight a specific pattern.

CONCLUSIONS

Based on the results of this investigation, the following conclusions can be made:

- The "Tuned Mass Damper" concept was by far the most effective method tested. It has the highest potential for an effective, relatively low cost damper that can be attached anywhere along the length of cable.
- The model cable containing latex grout improved cable damping by approximately 60% when compared to the conventionally grouted cable. However, the total effective damping achieved was not sufficient for control of rain-wind vibrations.
- The "Tuned Liquid Damper" tested was not effective in this case. However, it is believed that the concept has significant merit and requires further design and development work.
- Application of damping tapes did not improve cable damping substantially. These tapes also pose practical and durability challenges and therefore are not recommended.
- Filling of guide pipes with low durometer polyurethane improved cable damping somewhat, but not to the extent of a properly installed neoprene ring. A higher stiffness polyurethane filling is believed to be more effective in such applications.

PLANS FOR IMPLEMENTATION

The research team strongly believes that the tuned mass damper concept should be developed further to a marketable product. To achieve that goal, a number of steps must be taken. These include detailed design and fabrication of a prototype TMD, testing and evaluation of the TMD in the field, and securing collaborative agreements with potential users of the product. In the following paragraphs, various aspects of the research team's plans for implementation of this concept are addressed.

TMD CONCEPT AND DESIGN CONSIDERATIONS

As stated earlier, the tuned mass damper concept should contain a damping element in combination with the spring to extend the effective frequency range of the damper. The required spring constant for the proposed stay cable TMD will be relatively small and fatigue considerations for the spring is an important consideration. To address these issues, it is envisioned that the TMD "spring" would consist of a viscoelastic "structure" contained between an outer cylinder (mass) and an inner cylinder (the cable). The viscoelastic element would also provide for the damping component. Conceptual drawings are presented in Figure 1. The viscoelastic element can be formed in various shapes (such as an arch) to achieve the desired spring constants.

It should be noted that viscoelastic material properties are highly dependent on temperature. The elastomeric materials for tuned dampers should, within the expected temperature range, be in a "rubbery" region where small changes in temperature do not have a large effect on properties such as stiffness. [16] The cylindrical shape of the "spring" in this case allows control of cable movements in all directions. The conceptual system will consist of two half cylinders bolted together on the cable with watertight connections provided at the seams and the ends. The cylinder (most likely steel) can be coated with several layers of protection against corrosion. The system should also allow for field tuning (adjustment of mass or stiffness in the field).

FURTHER WORK AND FIELD VERIFICATION

It is proposed that additional work be performed to field verify the effectiveness of the prototype TMD in controlling vibrations of one or more stay cables currently exhibiting rain-wind vibrations. The research team has been involved in an evaluation of stay cable vibrations on the Cochrane Bridge in Mobile, Alabama. This bridge will be retrofitted with a large number of mechanical viscous dampers for stay cables in the year 2000. This bridge or the Charles River Bridge in Boston (under construction) could potentially be used to test this device. It is proposed that cable vibration measurements be taken for a period of at least 2-3 months before and after installation of damper. Such monitoring is currently planned for the new conventional damper installations on the Cochrane Bridge.

It is also proposed that additional analytical work be also performed to prepare optimum design charts for selection of damper size and locations. Durability testing on the prototype damper would also be another area deserving consideration.

COLLABORATIONS WITH POTENTIAL USERS

At this point, at least one stay cable manufacturers has expressed strong interest in commercial development of these dampers. It is expected that, if and when contacted, other such users would also express interest. Cable suppliers can furnish these dampers as an integral part of their cable systems or provide them as retrofit measures on existing cables.

INVESTIGATOR PROFILE

The Principal Investigator, Dr. Habib Tabatabai, P.E., S.E., has been prominently involved in various aspects of stay cable testing and evaluations in the last decade. Design of stay cable test fixtures, qualification testing of stay cables, development of laser-based stay cable force measurements, damage detection in cable-stayed bridges, development of procedures for design of viscous dampers for stay cables, and non-destructive testing of stay cables in the field are among his accomplishments.

The co-investigator, Dr. Armin Mehrabi, P.E., has been involved in analytical and experimental assessment and non-destructive testing of structures. He has participated in development of laser-based stay cable force measurements, damage detection in cable-stayed bridges, development of procedures for design of viscous dampers for stay cables. For his achievements in non-destructive testing of cable-stayed bridges, he was selected as one of the Top 25 Newsmakers of the Year 1997 by ENR.

REFERENCES

1. N. Matsumoto, N Shiraishi and H. Shirato. Rain-Wind Induced Vibration of Cables of Cable-Stayed Bridges. *Journal of Wind Engineering and Industrial Aerodynamics*, 41-44, 1992, pp. 2011-2022.

2. T. Yoshimura. Aerodynamic Stability of Four Medium Span Bridges in Kyushu District. *Journal of Wind Engineering and Industrial Aerodynamics*, 41-44, 1992, pp. 1203-1214.

3. M. Matsumoto and others. Inclined-Cable Aerodynamics. *Proceedings of the ASCE Structures Congress*, San Francisco, 1989, pp. 81-90.

4. A.T. Ciolko and W.P. Yen. An Immediate Payoff From FHWA's NDE Initiative. *Public Roads*, May/June 1999, pp. 10-17.

5. T. Saito, M. Matsumoto and M. Kitazawa. Rain-Wind Excitation of Cables on Cable-Stayed Higashi-Kobe Bridge and Cable Vibration Control. *Proceedings of Conference on Cable-Stayed and Suspension Bridges*, Deauville, France, October 12-15, 1994, pp. 507-514.

6. P.A. Irwin. Wind Vibrations of Cables on Cable-Stayed Bridges. *Proceedings of the ASCE Structures Congress*, Vol. 1, 383-387.

7. *Recommendations for Stay Cable Design, Testing and Installation*, draft of 4th edition, Post-Tensioning Institute, Phoenix, Arizona, 1999.

8. H. Tabatabai, A.B. Mehrabi, B.J. Morgan and H.R. Lotfi. *Non-destructive Bridge Evaluation Technology: Bridge Stay Cable Condition Assessment.* Final report submitted to the Federal Highway Administration, Construction Technology Laboratories, Inc., Skokie, IL., 1998.

9. H. Yamaguchi. Passive Damping Control in Cable Systems. *Proceedings of Building for the 21st Century*, Y.C. Loo, Editor, EASEC-5 Secretariat, Griffith University, Australia, pp. 1189-1194.

10. R.W. Poston. Cable-Stay Conundrum. *Civil Engineering*, ASCE, August 1998, pp. 58-61.

11. H. Tabatabai and A.B. Mehrabi. Design of Mechanical Viscous Dampers for Stay Cables. Approved for publication in the *Journal of Bridge Engineering*, ASCE, 1999.

12. O. Flamand. Rain-Wind Induced Vibration of Cables, *Journal of Wind Engineering and Industrial Aerodynamics*, 57, 1995, pp. 353-362.

13. H. Tabatabai and A.B. Mehrabi. Bridge Stay Cable Condition Assessment Using Vibration Measurement Techniques. *Proceedings of Structural Materials Technology III, An NDT Conference*, SPIE Vol. 3400, March 31-April 3, 1998, pp. 194-204.

14. H. Tabatabai, D. Bloomquist, M.C. McVay, J.J. Gill and F.C. Townsend. *Centrifugal Modeling of Underground Structures Subjected to Blast Loading*. Report No. AFESC/ESL-TR-87-62, Air Force Engineering Services Center, Tyndall Air Force Base, Panama City, Florida, March 1988, 319 pp.

15. *Recommendations for Stay Cable Design, Testing and Installation*, 3rd edition, Post-Tensioning Institute, Phoenix, Arizona, 1993.

16. A.D. Nashif, D.I.G. Jones, and J.P. Henderson, *Vibration Damping*, John Wiley and Sons, Inc., New York, 1985.

17. C.F. Beards, *Structural Vibration: Analysis and Damping*, Arnold Publishers, London, 1996.

18. J.P.D. Hartog, *Mechanical Vibrations*, McGraw-Hill Book Company, New York, 1956.

19. Y. Fujino, L. Sun, B.M. Pacheco and P. Chaiseri. Tuned Liquid Damper (TLD) for Suppressing Horizontal Motion of Structures. *Journal of Engineering Mechanics*, ASCE, Vol. 118, No. 10, October 1992, pp. 2017-2030.

20. Y. Fujino and K. Fujii. Tuned Liquid Damper and its Application to Tower-Like Structures. *Proceedings of ASCE Structures Congress*, San Francisco, May 1989, pp. 490-499.

21. T. Wakahara, T. Ohyama and K. Fujii. Suppression of Wind-Induced Vibration of a Tall Building Using Tuned Liquid Damper. *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 43, No. 3, October 1993, pp. 1895-1906.

22. H. Yamaguchi and R. Adhikari. Energy-Based Evaluation of Modal Damping in Structural Cables With and Without Damping Treatment. *Journal of Sound and Vibration*, Vol. 181, No. 1, 1995, pp. 71-83.

APPENDIX A

DAMPING TEST RESULTS

CABLE	TEST	TYPE OF CABLE ATTACHMENT	LOCATION OF ATTACHMENT	ADDITIONAL MASS (GRAMS)	EXCITATION LOCATION	FIRST MODE FREQUENCY	MEASURED DAMPING (%)
1	T1-6	NONE / GROUTED	NA	0	MIDDLE	8.55	0.05
1	T1-7	NONE / GROUTED	NA	0	MIDDLE	8.55	0.05
1	T1-9	SPRING 1/UNCOATED	20%	820	MIDDLE	8.45	0.1
1	T1-10	SPRING 1/UNCOATED	20%	920	MIDDLE	8.43	3.06 to 19% then 0.11
1	T1-11	SPRING 1/UNCOATED	20%	970	MIDDLE	8.43	2.65
1	T1-12	SPRING 1/UNCOATED	20%	1020	MIDDLE	8.40	2.35
1	T1-13	SPRING 1/UNCOATED	20%	1070	MIDDLE	8.40	1.89
1	T1-14	SPRING 1/UNCOATED	20%	1120	MIDDLE	8.95	1.9
1	T1-15	SPRING 1/UNCOATED	20%	1220	MIDDLE	8.95	0.96
1	T1-16	SPRING 1/UNCOATED	20%	1420	MIDDLE	8.55	0.06
1	T1-25	SPRING 1/POLY COATED	20%	1020	MIDDLE	8.88	1.91
1	T1-30	SPRING 1/UNCOATED	20%	1020	20%	8.40	1.95
1	A1-1	PVC CONTAINER EMPTY	20%	0	MIDDLE	8.47	0.05
1	A1-3	PVC CONTAINER W WATER	20%	210	MIDDLE	8.45	0.05
1	A1-6	PVC CONTAINER W WATER	20%	375	MIDDLE	8.43	0.05
1	A1-8	PVC CONTAINER W WATER	20%	540	MIDDLE	8.42	0.08
1	A1-10	PVC CONTAINER W WATER	20%	710	MIDDLE	8.40	0.06
1	A1-12	PVC CONTAINER W WATER	20%	875	MIDDLE	8.38	0.06
1	A1-13	PVC CONTAINER W/LEAD SHOT	20%	400	MIDDLE	8.42	0.05
1	A1-15	PVC CONTAINER W/LEAD SHOT	20%	1200	MIDDLE	8.35	0.05
1	A1-18	PVC CONTAINER W/LEAD SHOT	20%	2400	MIDDLE	8.22	0.06
1	B1-1	NEOPRENE RINGS BOTH SIDES	BOTH ENDS	0	MIDDLE	8.92	0.61 up to 33% then 0.25
1	B1-3	NEOPRENE + POLY. IN GUIDE PIPE AT ONE SIDE & NEOPRENE RING IN THE OTHER SIDE	BOTH ENDS	0	MIDDLE	8.95	0.41 up to 45% then 0.17
1	B1-5	NEOPRENE + POLY. IN GUIDE PIPE AT ONE SIDE	ONE END	0	MIDDLE	8.77	0.34 up to 71%
1	B1-6	WRAP ALONG 20% OF LENGTH	MIDDLE	0	MIDDLE	8.47	0.05
1	B1-9	1ST LAYER (20%) + 2ND LAYER	MIDDLE	0	MIDDLE	8.35	0.08
1	B1-10	SAME AS B1-9 LARGER AMP	MIDDLE	0	MIDDLE	8.33	0.05

ADDITIONAL MASS FOR EACH SPRING IS THE MASS OF CUP (120 GRAMS) PLUS LEAD SHOTS (NOT INCLUDING THE SPRING)
MASS SHOWN FOR PVC CONTAINER DOES NOT INCLUDE 800 GR MASS OF CONTAINER ITSELF

CABLE	TEST	TYPE OF CABLE ATTACHMENT	LOCATION OF ATTACHMENT	ADDITIONAL MASS (GRAMS)	EXCITATION LOCATION	FIRST MODE FREQUENCY	MEASURED DAMPING (%)
2	D2-1	NONE / UNGROUTED	NA	0	MIDDLE	10.47	2.46
2	D2-6	NONE / GROUTED	NA	0	MIDDLE	8.73	0.08
2	D2-9	SPRING 1/ UNCOATED	10%	620	MIDDLE	8.73	0.08
2	D2-10	SPRING 1/ UNCOATED	10%	820	MIDDLE	8.70	0.09
2	D2-11	SPRING 1/ UNCOATED	10%	920	MIDDLE	8.70	0.13
2	D2-12	SPRING 1/ UNCOATED	10%	970	MIDDLE	8.70	0.1
2	D2-13	SPRING 1/ UNCOATED	10%	1020	MIDDLE	8.70	0.11
2	D2-14	SPRING 1/ UNCOATED	10%	1070	MIDDLE	8.70	0.11
2	D2-16	SPRING 1/ UNCOATED	10%	1170	MIDDLE	8.70	0.56 up to 53% then 0.10
2	D2-17	SPRING 1/ UNCOATED	10%	1220	MIDDLE	8.70	0.81 up to 20% then 0.06
2	D2-18	SPRING 1/ UNCOATED	10%	1270	MIDDLE	8.68	0.71
2	D2-19	SPRING 1/ UNCOATED	10%	1270	30%	8.68	0.54 up to 17% then 0.06
2	D2-20	NONE / GROUTED	0	0	30%	8.72	0.09
2	D2-21	SPRING 1/ UNCOATED	10%	1370	MIDDLE	8.75	0.21 up to 45% then 0.10
2	D2-22	SPRING 1/ UNCOATED	10%	1470	MIDDLE	8.73	0.09
2	D2-24	SPRING 1/ UNCOATED	30%	620	MIDDLE	8.68	0.22
2	D2-25	SPRING 1/ UNCOATED	30%	720	MIDDLE	8.18	0.25 up to 58% then 0.13
2	D2-26	SPRING 1/ UNCOATED	30%	820	MIDDLE	8.17	0.12
2	D2-27	SPRING 1/ UNCOATED	30%	920	MIDDLE	8.30	2.05 up to 35% then 0.06
2	D2-28	SPRING 1/ UNCOATED	30%	970	MIDDLE	8.27	2.13 up to 26% then 0.07
2	D2-29	SPRING 1/ UNCOATED	30%	1020	MIDDLE	8.25	1.24 up to 24% then 0.06
2	D2-30	SPRING 1/ UNCOATED	30%	1070	MIDDLE	8.23	1.70 up to 25% then 0.10
2	D2-31	SPRING 1/ UNCOATED	30%	1170	MIDDLE	9.12	1.23
2	D2-32	SPRING 1/ UNCOATED	30%	1270	MIDDLE	9.05	1.31
2	D2-33	SPRING 1/ UNCOATED	30%	1470	MIDDLE	8.67	0.44 up to 51% then 0.06
2	D2-34	SPRING 1/ UNCOATED	30%	1570	MIDDLE	8.52	0.17
2	D2-35	SPRING 1/ UNCOATED	30%	1670	MIDDLE	8.63	0.08
2	D2-36	SPRING 1/ UNCOATED	30%	1770	MIDDLE	8.58	0.08
2	D2-37	NONE / GROUTED	NA	0	MIDDLE	8.55	0.08

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MASS SHOWN FOR PVC CONTAINER DOES NOT INCLUDE 800 GR MASS OF CONTAINER ITSELF

CABLE	TEST	TYPE OF CABLE ATTACHMENT	LOCATION OF ATTACHMENT	ADDITIONAL MASS (GRAMS)	EXCITATION LOCATION	FIRST MODE FREQUENCY	MEASURED DAMPING (%)
2	D2-39	SPRING 1/ UNCOATED	42.50%	620	MIDDLE	8.55	0.27
2	D2-40	SPRING 1/ UNCOATED	42.50%	720	MIDDLE	8.27	2.38 up to 33% then 0.34
2	D2-41	SPRING 1/ UNCOATED	42.50%	820	MIDDLE	8.22	1.14 up to 39% then 0.07
2	D2-42	SPRING 1/ UNCOATED	42.50%	920	MIDDLE	8.18	1.31 up to 39% then 0.09
2	D2-44	SPRING 1/ UNCOATED	42.50%	1220	MIDDLE	9.13	1.63
2	E2-2	SPRING 1/ POLY COATED	42.50%	620	MIDDLE	8.60	2.72
2	E2-3	SPRING 1/ POLY COATED	42.50%	720	MIDDLE	8.60	2.12
2	E2-4	SPRING 1/ POLY COATED	42.50%	820	MIDDLE	9.03	1.55
2	E2-5	SPRING 1/ POLY COATED	42.50%	920	MIDDLE	9.03	1.25
2	E2-6	SPRING 1/ POLY COATED	42.50%	1220	MIDDLE	9.12	1.37
2	F2-6	PVC CONTAINER EMPTY	42.50%	0	MIDDLE	8.18	0.20 up to 51% then 0.14
2	F2-7	PVC CONTAINER W WATER	42.50%	500	MIDDLE	8.08	0.17 up to 42% then 0.08
2	F2-8	PVC CONTAINER W WATER	42.50%	600	MIDDLE	8.07	0.18 up to 53% then 0.08
2	F2-9	PVC CONTAINER W WATER	42.50%	700	MIDDLE	8.05	0.07
2	F2-10	PVC CONTAINER W WATER	42.50%	800	MIDDLE	8.03	0.18 up to 63% then 0.07
2	F2-11	PVC CONTAINER W WATER	42.50%	900	MIDDLE	8.00	0.18 up to 24% then 0.07
2	F2-12	PVC CONTAINER W WATER	42.50%	1000	MIDDLE	7.98	0.08
2	F2-14	PVC CONTAINER W OIL	42.50%	200	MIDDLE	8.15	0.18 up to 37% then 0.08
2	F2-15	PVC CONTAINER W OIL	42.50%	300	MIDDLE	8.13	0.18 up to 49% then 0.09
2	F2-16	PVC CONTAINER W OIL	42.50%	500	MIDDLE	8.10	0.17 up to 53% then 0.08
2	F2-17	PVC CONTAINER W OIL	42.50%	600	MIDDLE	8.07	0.1
2	F2-18	PVC CONTAINER W OIL	42.50%	800	MIDDLE	8.03	0.09
2	F2-19	PVC CONTAINER W OIL	42.50%	980	MIDDLE	8.02	0.08
2	R2-1	NEOPRENE RING ON ONE SIDE	ONE END		MIDDLE	8.83	0.26 up to 42% then 0.16
2	R2-3	NEOPRENE RING BOTH SIDES	BOTH ENDS		MIDDLE	8.97	0.34 up to 30% then 0.22
2	P2-1	POLY. FILLED GUIDE PIPE ONE END	ONE END		MIDDLE	8.93	0.14 up to 45% then 0.07
2	P2-3	POLY. FILLED GUIDE PIPE ONE END & NEOPRENE RING AT OTHER END	BOTH ENDS		MIDDLE	9.13	0.38 up to 63% then 0.12

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MASS SHOWN FOR PVC CONTAINER DOES NOT INCLUDE 800 GR MASS OF CONTAINER ITSELF

CABLE	TEST	TYPE OF CABLE ATTACHMENT	LOCATION OF ATTACHMENT	ADDITIONAL MASS (GRAMS)	EXCITATION LOCATION	FIRST MODE FREQUENCY	MEASURED DAMPING (%)
2	I2-3	SPRING 2 / UNCOATED	10%	190	MIDDLE	8.75	0.18
2	I2-7	SPRING 2 / UNCOATED	20%	190	MIDDLE	8.75	0.27
2	I2-10	SPRING 2 / UNCOATED	30%	190	MIDDLE	8.75	0.29
2	I2-13	SPRING 2 / UNCOATED	40%	190	MIDDLE	8.77	0.38
2	I2-16	SPRING 2 / UNCOATED	50%	190	MIDDLE	8.77	0.46
2	I2-19	SPRING 3 / UNCOATED	10%	415	MIDDLE	8.72	0.41
2	I2-24	SPRING 3 / UNCOATED	20%	415	MIDDLE	9.67	0.52 up to 27% then 0.10
2	I2-28	SPRING 3 / UNCOATED	30%	415	MIDDLE	9.85	0.77 up to 35% then 0.07
2	O200-1	SPRING 3 / UNCOATED	40%	315	MIDDLE	8.35	1.25 up to 25% then 0.07
2	O225-1	SPRING 3 / UNCOATED	40%	340	MIDDLE	8.32	1.42 up to 25% then 0.08
2	O250-1	SPRING 3 / UNCOATED	40%	365	MIDDLE	10.48	1.74 up to 21% then 0.21
2	I2-30	SPRING 3 / UNCOATED	40%	390	MIDDLE	8.13	1.95 up to 42% then 0.07
2	I2-31	SPRING 3 / UNCOATED	40%	415	MIDDLE	8.08	1.02 up to 39% then 0.08
2	I2-32	SPRING 3 / UNCOATED	40%	440	MIDDLE	9.80	1.04 up to 42% then 0.07
2	I2-33	SPRING 3 / UNCOATED	40%	465	MIDDLE	9.65	0.52 up to 45% then 0.08
2	I2-34	SPRING 3 / UNCOATED	40%	515	MIDDLE	9.40	0.33 up to 47% then 0.06
2	I2-35	SPRING 3 / UNCOATED	40%	565	MIDDLE	9.25	0.33 up to 58% then 0.07
2	I2-36	SPRING 3 / UNCOATED	40%	615	MIDDLE	9.15	0.11 up to 42% then 0.06
2	I2-37	SPRING 3 / UNCOATED	40%	665	MIDDLE	9.08	0.11 up to 58% then 0.05
2	I2-38	SPRING 3 / UNCOATED	40%	715	MIDDLE	9.03	0.10 up to 49% then 0.04
2	I2-39	SPRING 3 / UNCOATED	40%	765	MIDDLE	9.00	0.06
2	I2-40	SPRING 3 / UNCOATED	40%	815	MIDDLE	8.98	0.06
2	I2-41	SPRING 3 / UNCOATED	40%	865	MIDDLE	8.97	0.07
2	I2-45	SPRING 3 / UNCOATED	50%	415	MIDDLE	8.52	1.55 up to 40% then 0.09

ADDITIONAL MASS FOR EACH SPRING IS THE MASS OF CUP (115 GRAMS) PLUS LEAD SHOTS (NOT INCLUDING THE SPRING)
MASS SHOWN FOR PVC CONTAINER DOES NOT INCLUDE 800 GR MASS OF CONTAINER ITSELF

CABLE	TEST	TYPE OF CABLE ATTACHMENT	LOCATION OF ATTACHMENT	ADDITIONAL MASS (GRAMS)	EXCITATION LOCATION	FIRST MODE FREQUENCY	MEASURED DAMPING (%)
2	I2-48	SPRING 4 / UNCOATED	40	315	MIDDLE	8.23	0.12 up to 26% then 0.06
2	I2-47	SPRING 4 / UNCOATED	40	415	MIDDLE	8.60	2.29 up to 42% then 0.10
2	I2-49	SPRING 4 / UNCOATED	40	515	MIDDLE	8.57	0.88 up to 36% then 0.09
2	I2-50	SPRING 4 / UNCOATED	40	615	MIDDLE	8.05	0.63 up to 47% then 0.12
2	I2-58	SPRING 4 / UNCOATED	40	640	MIDDLE	8.02	0.33 up to 22% then 0.07
2	I2-59	SPRING 4 / UNCOATED	40	665	MIDDLE	10.37	0.30 up to 26% then 0.07
2	I2-51	SPRING 4 / UNCOATED	40%	715	MIDDLE	7.90	0.29 up to 33% then 0.10
2	I2-52	SPRING 4 / UNCOATED	40%	765	MIDDLE	7.80	0.21
2	I2-54	SPRING 4 / UNCOATED	40%	815	MIDDLE	7.70	0.23 up to 24% then 0.10
2	I2-63	SPRING 4 / UNCOATED	50%	665	MIDDLE	7.95	0.38 up to 39% then 0.10
2	I2-67	SPRING 4 / UNCOATED	30%	665	MIDDLE	8.07	0.19 up to 24% then 0.06
2	I2-72	SPRING 4 / UNCOATED	20%	665	MIDDLE	8.58	0.63 up to 56% then 0.11
2	I2-77	SPRING 4 / UNCOATED	10%	665	MIDDLE	8.68	0.23 up to 49% then 0.08
2	O10-1	SPRING 4 / UNCOATED	10%	415	MIDDLE	8.53	0.05
2	O20-1	SPRING 4 / UNCOATED	20%	415	MIDDLE	8.47	0.05
2	O30-1	SPRING 4 / UNCOATED	30%	415	MIDDLE	8.40	1.53 up to 45% then 0.05
2	O40-1	SPRING 4 / UNCOATED	40%	415	MIDDLE	8.35	1.73 up to 33% then 0.05
2	O50-1	SPRING 4 / UNCOATED	50%	415	MIDDLE	8.33	1.59 up to 22% then 0.15

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CABLE	TEST	TYPE OF CABLE ATTACHMENT	LOCATION OF ATTACHMENT	ADDITIONAL MASS (GRAMS)	EXCITATION LOCATION	FIRST MODE FREQUENCY	MEASURED DAMPING (%)
2	I2-85	SPRING 5 / UNCOATED	30%	1115	MIDDLE	7.97	0.38 up to 51% then 0.11
2	I2-86	SPRING 5 / UNCOATED	30%	1215	MIDDLE	7.88	0.38 up to 45% then 0.09
2	I2-87	SPRING 5 / UNCOATED	30%	1315	MIDDLE	7.78	0.30 up to 40% then 0.09
2	I2-88	SPRING 5 / UNCOATED	30%	1365	MIDDLE	7.73	0.38 up to 34% then 0.08
2	I2-89	SPRING 5 / UNCOATED	30%	1415	MIDDLE	7.67	0.32 up to 36% then 0.13
2	I2-90	SPRING 5 / UNCOATED	30%	1465	MIDDLE	7.62	0.33 up to 34% then 0.09
2	I2-91	SPRING 5 / UNCOATED	30%	1515	MIDDLE	7.57	0.32 up to 37% then 0.10
2	I2-92	SPRING 5 / UNCOATED	30%	1565	MIDDLE	7.50	0.51 up to 42% then 0.17
2	I2-93	SPRING 5 / UNCOATED	30%	1615	MIDDLE	7.45	1.06 up to 42% then 0.11
2	I2-94	SPRING 5 / UNCOATED	30%	1665	MIDDLE	7.38	1.03 up to 39% then 0.11
2	I2-95	SPRING 5 / UNCOATED	30%	1715	MIDDLE	7.33	0.92 up to 31% then 0.13
2	I2-97	SPRING 5 / UNCOATED	10%	1665	MIDDLE	8.95	0.33 up to 42% then 0.09
2	I2-99	SPRING 5 / UNCOATED	20%	1665	MIDDLE	9.30	0.37 up to 33% then 0.10
2	I2-100	SPRING 5 / UNCOATED	40%	1665	MIDDLE	7.23	0.81 up to 36% then 0.12
2	I2-101	SPRING 5 / UNCOATED	50%	1665	MIDDLE	7.17	0.84 up to 28% then 0.11
2	QO10	SPRING 5 / UNCOATED	10%	1615	MIDDLE	8.83	0.55 up to 49% then 0.11
2	QO20	SPRING 5 / UNCOATED	20%	1615	MIDDLE	9.40	0.64 up to 33% then 0.09
2	QO30	SPRING 5 / UNCOATED	30%	1615	MIDDLE	7.45	1.00 up to 36% then 0.11
2	QO40	SPRING 5 / UNCOATED	40%	1615	MIDDLE	7.30	1.22 up to 36% then 0.11
2	QO50	SPRING 5 / UNCOATED	50%	1615	MIDDLE	7.25	2.7 up to 36% then 0.11

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