IDEA

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Highway Program

Field Implementation of Tuned Mass Dampers for Suppression of Stay Cable Vibration

Final Report for Highway-IDEA Project 71

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TRANSPORTATION RESEARCH BOARD • THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
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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 Tuned Mass Dampers for improvements in damping and suppression of cable vibrations. In a tuned mass damper concept, a mass is attached to the cable through a viscoelastic (spring/dashpot) system. In the first part of this study, several visco-elastic materials and model configurations were investigated to identify models that could be considered for full-scale prototype adaptation. Simultaneous to experimenting with the various models, analytical investigations were conducted to calculate the required properties and dimensions for the full-scale versions of the models. The analytical investigations indicated a problem in adapting the scaled models to full-scale sizes due to the low frequency of vibrations of the actual bridge stay cables as compared to the scaled model of the cable.

Alternate concepts and configurations were therefore investigated to determine their feasibility in final full-scale prototype implementation. One well-developed concept studied was that of an impact damper. It was determined that a hybrid of tuned impact and tuned mass damper provided better results than only a tuned mass damper, especially at low frequency vibrations as is the case on an actual stay cable.

The tuned impact concept essentially depends on **absorbing** and **suppressing** the vibration energy by a combination of tuned mass principle and through impact of the secondary body (damper) on the vibrating object. In order to achieve efficient impact, the vibration of the damper must be slightly out of phase with the vibration of the cable. The phase difference allows the mass of the damper to impact the cable and suppress the vibration energy. In addition, the tuning, although slightly out of phase, allows further absorption of energy via the tuned mass damping concept.

A series of laboratory tests were conducted on a model cable to evaluate Tuned Impact Damper (TID) systems. In all these tests, the TID system consisted of profiled steel strips clamped on one end to the cable and free on the other end. The number of steel strips was varied from one on the top and bottom of the cable to up to four strips on top and bottom. The profile of the steel strips was adjusted to keep a distance between the free ends of the strips such that they would impact each other and the cable during vibrations. The functionality and effectiveness of TID system at lower frequencies, similar to those on actual bridge cables, were demonstrated by a series of additional laboratory tests conducted on a low frequency model consisting of a steel cantilever with a frequency of about 1 Hz. Figure 1 shows a comparison between vibrations of small scale model with and without TID system attached.

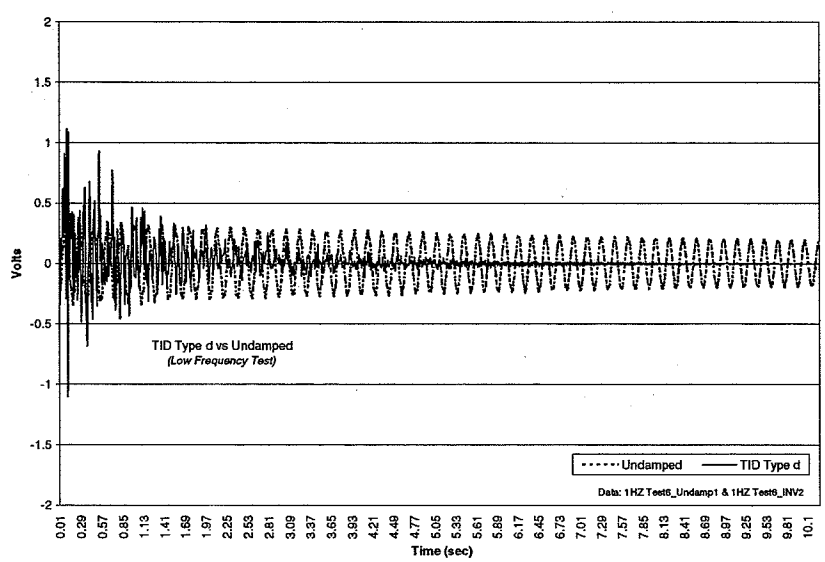


Figure 1 –Scale Model Time History with and without TID

The first review panel meeting was organized and conducted at the CTL offices on May 25, 2001. The results of the Stage 1 investigation and preliminary TID design was presented to the panel. Based on the comments and recommendation of the expert panel members, the prototype design of the TID was refined. Further studies were conducted on the material

type, layout, connection details, and fabrication requirements for the full-scale prototype. Subsequently, a refined model of the full-scale prototype was designed and detailed. One alternate of the refined model is shown in Figure 2.

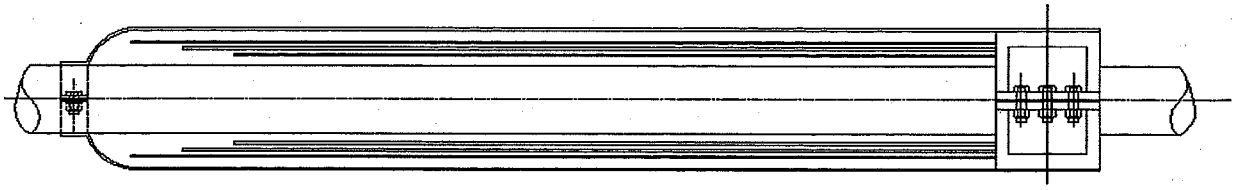


Figure 2 – Conceptual Prototype TID

Stage 2 research consisted of design and fabrication of a full-scale prototype TID, installation of this TID on a representative bridge, and monitoring and testing the effectiveness of the TID on a representative bridge. Several bridges were identified for potential field installation, and eventually, the Talmadge Bridge was selected based on availability for the installation and testing. Short-term monitoring was considered as a viable option in evaluating the feasibility and effectiveness of the TID, and tests were conducted to determine the effect of the prototype TID on various cables of the bridge.

The TID was initially installed near the quarter span-length on selected cables using a 60-foot lift truck. A rope with a quick release system and a sensitive accelerometer were attached on the stay cable in the vicinity of the TID. Each cable was winched using the rope to a calibrated magnitude, and the rope was released instantaneously using the quick release mechanism. The ensuing vibration of the stay cable was recorded by the accelerometer and the attached data acquisition system. This process was repeated several times for each stay cable. Sets of vibration readings were also obtained for each cable without the TID. The time-history readings without the TID were used as a datum for comparison purposes and in determining the effectiveness of the TID. The time-history files were then filtered and analyzed to evaluate the effect of the TID on the vibration of the cables. Figure 3 shows a comparison between oscillation of one mode of vibration of a cable tested with and without installation of TID. The test results and field observations indicated the efficiency and applicability of the TID system for increasing the cable apparent damping ratios and suppression of excessive vibrations.

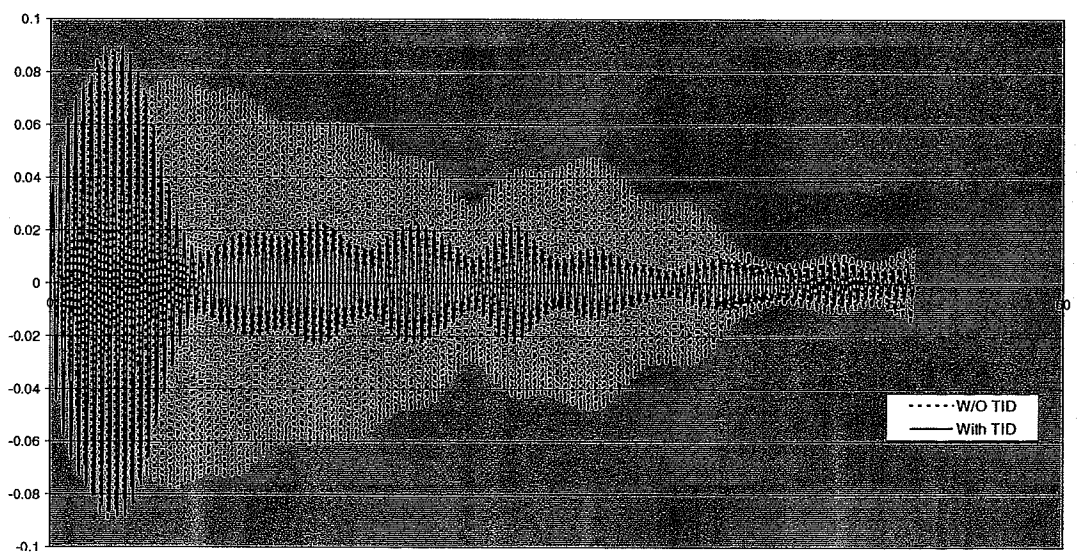


Figure 3 – Talmadge Bridge Cable Vibration with and without TID

In summary, the laboratory and field test results indicate the efficiency of the TID system in suppression of stay cable vibration and improving the stay cable performance in wind and rain-wind induced oscillations. This in turn would prolong the effective life of the cables and consequently cable-stayed bridges, by reducing fatigue

related damage and maintenance costs. This system is believed to offer many practical and cost advantages over the use of mechanical viscous dampers or the utilization of cross-ties. Future related work for introduction of this system into the bridge market should involve inclusion of the system in a bridge rehabilitation program. TID systems would be designed and manufactured for the potential bridge and the cables will be monitored for long-term performance. In recent years, CTL bridge engineering experts have been involved directly in evaluation and rehabilitation of four cable stayed bridges in the US and are in a good position to implement TID systems for installation on stay cables to be retrofitted.

IDEA PRODUCT

This NCHRP-IDEA research program has demonstrated the effectiveness of Tuned Impact Dampers (TID's) as simple and effective devices for raising the apparent damping ratios of cables, thus controlling cable excessive oscillation including the rain-wind induced vibrations. Unlike conventional viscous dampers, these dampers can be installed at any location along the length of cable and therefore can provide significant damping levels. These devices can be used on new and existing cables.

The prototype system for field implementation and performance verification was assembled using commercially available materials with minor modifications. The easy assembly and installation of the system on stay cables was quite promising. The prototype consisted of standard A36 steel strips and a steel bracket with attachments for the TID strips. The bracket was made of two circular half cylinders that were placed around the cable over a thin sheet of neoprene rubber, and bolted tightly onto the cable surface. Up to four tuned strips, 4 inches wide, ¼ inch thick, and varying in length were attached to the bracket. Typically, two TID strips were attached to the top, and two to the bottom of the bracket. The length of the TID strips ranged from 94 inches to 100 inches. The strips were reverse curved to the self-weight deflected shape to avoid excessive deformation under its own weight. For long-term use of the system on stay cables, the system as tested should be protected against corrosion and encased on a smooth envelope for weather and aerodynamic effects.

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, 2, 3] 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] 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 for achieving 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 4 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.

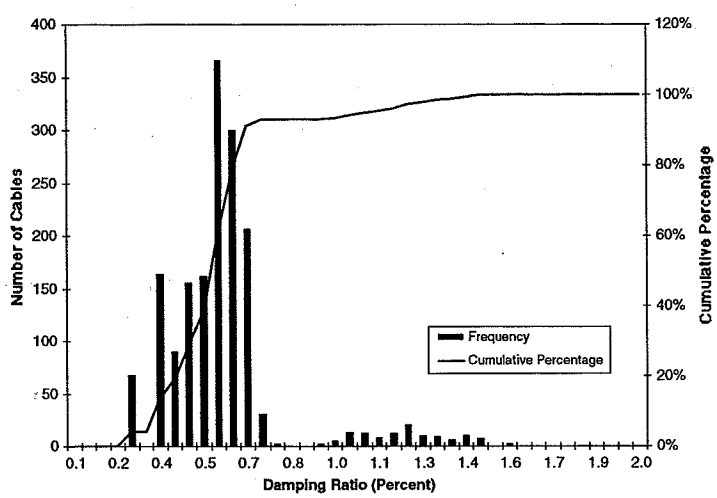


FIGURE 4 Histogram of required damping ratio for rain-wind induced vibration

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

$$U = 35 f D \sqrt{Sc}$$

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 $X \leq 6$) 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

The objective of this research was to verify the effectiveness of tuned dampers on increasing the cable damping ratios to levels beyond the threshold of vulnerability to rain-wind induced vibrations. The investigation started originally on tuned-mass damping systems, but later focused on a hybrid of tuned-mass and tuned-impact systems for higher efficiency and prototype design implementation. The concept was to be verified by field implementation and cable performance monitoring.

INVESTIGATION

The investigation was divided into two stages. Stage 1 primarily consisted of laboratory testing and conceptual design of prototype damper. Stage 2 on the other hand concentrated on the fabrication and field testing, and evaluation of the full scale prototype damper.

STAGE 1 RESEARCH – DAMPER SYSTEM DEVELOPMENT AND LABORATORY TESTING

The work in this stage consisted of laboratory effort required for developing and refining efficient, practical, and viable damping systems and the transitioning of scaled laboratory models to full-scale prototype damping systems. This stage also included some analytical studies along with evaluation of possible design alternatives and substantial research into applicability of various materials for the damper components.

Feasibility of a new concept for improved design- or retrofit- stage control and suppression of bridge stay cable vibrations was explored and demonstrated in an earlier IDEA project (NCHRP IDEA Project 50). It was concluded that tuned damper concept promises an advantageous alternative when compared to available damping measures. The objective of the current product application research is to design, fabricate, and demonstrate on a cable-stayed highway bridge structure that tuned stay cable dampers would increase cable damping ratios to levels beyond the threshold of vulnerability to rain-wind induced vibrations. The original concept of a damping system for stay cables was based on the Tuned Mass Damper (TMD) concept. The initially proposed device consisted of a viscoelastic element (spring/dashpot) contained between an outer cylinder (mass) made of steel or similar material and an inner cylinder (the cable). Investigation on the effectiveness and adaptability of this system to full-scale application led to modification and evolution of the original concept. It was determined that a hybrid of tuned impact and tuned mass damper would possibly provide better results than only a tuned damper, especially at low relatively low frequency vibrations as is the case on an actual stay cable. After an extensive investigation on optimizing the shape and configuration of Tuned Impact Damper (TID) system, it was concluded that the general shape of the damper should consist of profiled and tuned steel strips clamped on the cable at one end and free on the other end.

Evaluation of Tuned Damping Systems

The TMD models based on the original concept were evaluated and tested in the laboratory using a 1/7-scale model. Several visco-elastic materials and model configurations were investigated to identify models that could be considered for full-scale prototype adaptation. The TMD models evaluated and tested during the Stage 1 work consisted of an outer cylindrical pipe section that acted as the mass portion and material filling between outer cylinder and the cable which acted as a visco-elastic spring portion of the tuned mass damping device. Several visco-elastic materials and model configurations were investigated to identify models that could be considered for full-scale prototype adaptation. Simultaneous to experimenting with the various models, analytical investigations were conducted to calculate the required properties and dimensions for the full-scale versions of the models. The analytical investigations indicated a problem in adapting the scaled models to full-scale sizes due to the low frequency of vibrations of the actual bridge stay cables as compared to the scaled model of the cable.

The problem can be explained as follows: Tuning to lower frequencies demand lower stiffness for the spring elements, which in turn results in relatively large displacements for static equilibrium of the TMD. Therefore, in order to minimize the static displacement, several alternatives were investigated. Since the mass and stiffness are proportional, there was no benefit from reducing the mass. Another option was to reduce the tuning, but the efficiency of TMD was significantly affected by the change in the tuning. Based on the evaluation of the problem, it appears that the static equilibrium displacement of a tuned prototype TMD would cause considerable difficulty in adaptation of this design for full-scale use. Hence, alternate ideas were investigated as described in the following sections.

Investigation of the Tuned Impact Damper Concept

Alternate concepts and configurations were therefore investigated to determine their feasibility in final full-scale prototype implementation. One well-developed concept studied was that of an impact damper [14, 15, 16, 17, 18, 19, 20]. Based on new literature search, it was determined that a hybrid of impact and tuned damper [14, 15] would possibly provide better results than only a tuned mass damper, especially at low frequency vibrations as is the case on an actual stay cable.

The tuned impact concept essentially depends on **suppressing** and **dissipating** the vibration energy by a combination of tuned mass principle and through impact of the secondary body (damper) on the vibrating object. In order to achieve efficient impact, the vibration of the damper must be slightly out of phase with the vibration of the cable. The phase difference allows the mass of the damper to impact the cable, and **dissipate** the vibration energy through the impact [14, 15, 21]. In addition, the tuning, although slightly out of phase, allows further suppressing of motion via the tuned mass damping concept.

Laboratory Tests on Scaled Cable Model

A series of laboratory tests were conducted on a model cable. In all these tests, the general shape of the Tuned Impact Damper (TID) system was constructed using profiled steel strips clamped on one end to the cable and free on the other end. The number of steel strips was varied from one on the top and bottom of the cable to up to four strips on top and bottom. The profile of the steel strips was adjusted to keep a distance between the free ends of the strips such that they would impact each other and the cable during vibrations. Two types of TIDs were considered as described below:

- TYPE I: The damper consisted of a steel strip clamped on the cable at one end and cantilevered out with a concentrated mass attached at the other end (Figure 5). The ratio of mass of the impact damper to that of the cable was targeted at approximately 0.5%. The tuning was varied in the range of 0.3 to 0.6.

- TYPE II: This system consisted of thin steel strips clamped at one end on the cable and cantilevered on the other side. No additional mass was added, and the mass ratio was varied from 0.3% to 1.18% (i.e. 2 strips to 8 strips were used). The tuning was kept close to 1.0, and the strips were arranged so that there would be impact between each strip and the cable. At rest, the strips were separated approximately ½" from one another at the tip.

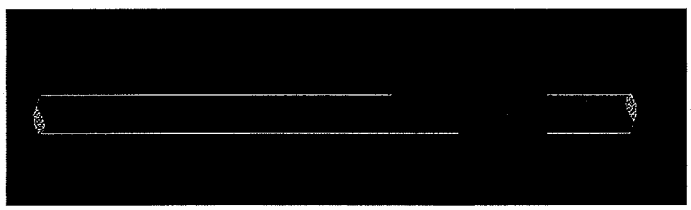


Figure 5 – Type I TID

Figure 6 –Stay Cable Model

The setup included a 1:7 scaled model (Figure 6) of a representative stay cable set in a horizontal position on the test floor. The vibration time-history of the model cable was recorded via an accelerometer attached to the midpoint of the cable. The stay cable was set into its natural vibration by releasing a load attached near the midpoint of the cable. The vibration response was compared for the cable with and without the TIDs. Type I TIDs were attached at the mid-length of the cable, whereas two locations for the attachment of the Type II TIDs were considered: one close to the mid-length of the cable, and the other at the quarter-length of the cable.

The following observations were made based on the collected acceleration data:

1. The TIDs were more effective in damping the cable vibrations than the previously tested TMDs.

2. Tuning and impact together were important in achieving the best damping. Tuning without impact or impact alone was not as effective as the combination of tuning and impact.

3. The effectiveness of the TID in damping the cable vibrations was directly proportional to the number of steel strips. It is possible that this is either due to the increase in the number strips or due to increase in the proportion of the weight of the TID to that of the cable.

4. The Type II TIDs were more effective than the Type I TIDs. (See Figures 7 and 8.)

5. The Type II TIDs attached at mid-length of the cable were more effective than those at the quarter-length of the cable. The Type II TIDs attached at the quarter-length of the cable were more effective than the Type I TIDs at attached at the mid-length of the cable.

Although the TIDs performed satisfactorily on the cable model, it was decided to test their functionality and effectiveness at lower frequencies similar to those on actual bridge cables. The frequency of vibration on the scaled model of the cable was in the range of 8 Hz, whereas the average frequency of vibration on most bridge stay cables is

around 1 Hz. Based on their effectiveness, the Type II TIDs were selected for further low frequency testing and eventual adaptation for full-scale prototype testing.

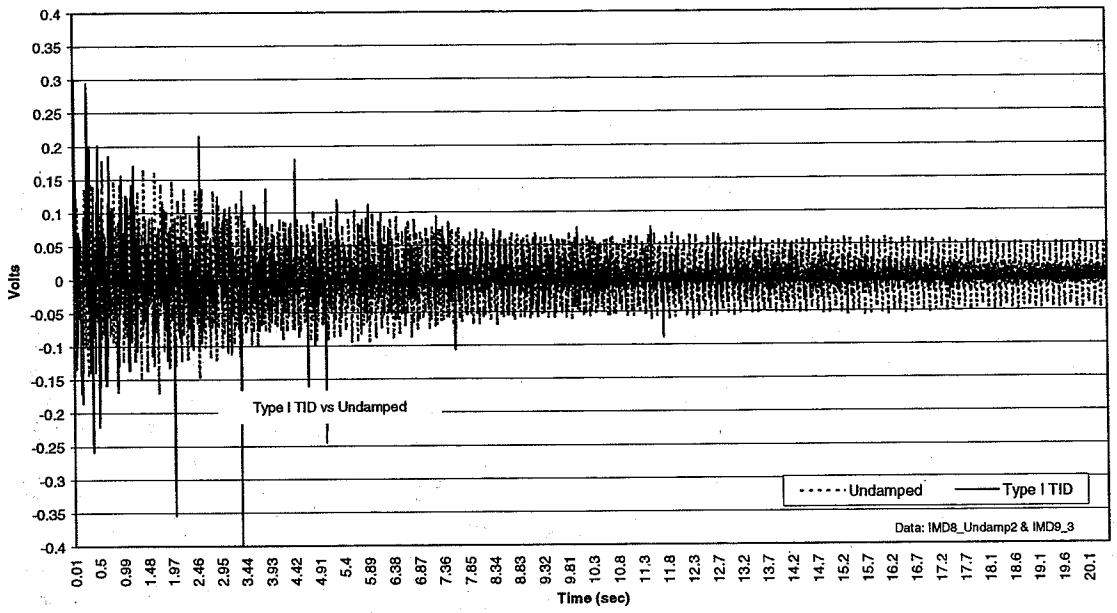


Figure 7 - Type I TID Data

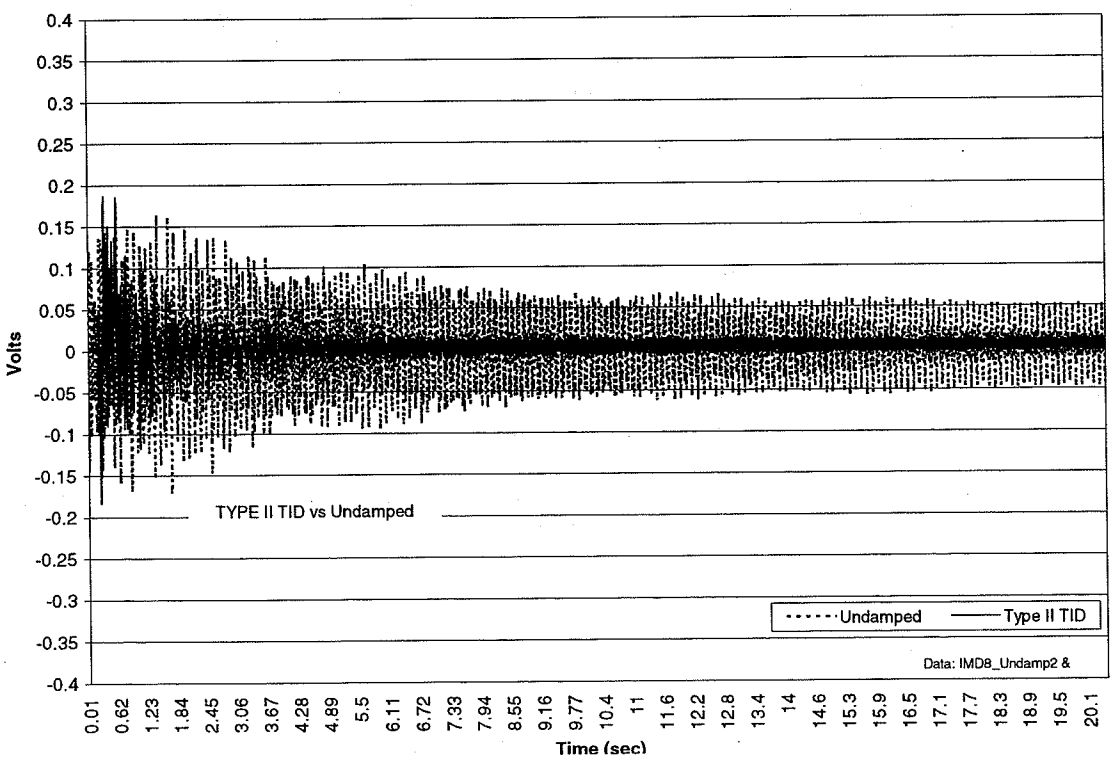


Figure 8 - Type II TID Data

Laboratory Tests to Check Functionality of TIDs at Low Frequency

The effectiveness of the TID in damping the vibration of the primary vibrating body is based on free vibrations of the TID with periodic impact of the TID with the primary vibrating body. The free vibration of the TID is entirely based on the vibration of the primary body, and consequently, if the vibration frequency of the primary body is low, the resultant acceleration imparted to the TID may not be adequate to create enough motion in the TID to be effective in damping the vibrations of the primary vibrating body. In addition, if the TID is initially seated, then the acceleration of the TID in the vertical direction due to the low frequency vibration of the primary body may not be adequate to sufficiently oppose the acceleration due to gravity, and hence allow free vibrations of the TID.

The low frequency test consisted of testing the effectiveness of the TIDs on a prismatic steel cantilever vibrating at approximately 1 Hz. The cantilever consisted of a prismatic steel cross-section 2 inch x 3/8 inch with a length of 106 inches setup on the laboratory floor by clamping one end between load blocks. The frequency of vibration of the cantilever was 1.07 Hz. The TID models were clamped on the cantilever to align their free ends with that of the cantilever, and an accelerometer was attached at the free end of the cantilever to record the vibration response. The tip of the cantilever was deflected approximately 2 inches downwards and released, and the subsequent free vibrations were recorded via the accelerometer. (See Figure 9.)

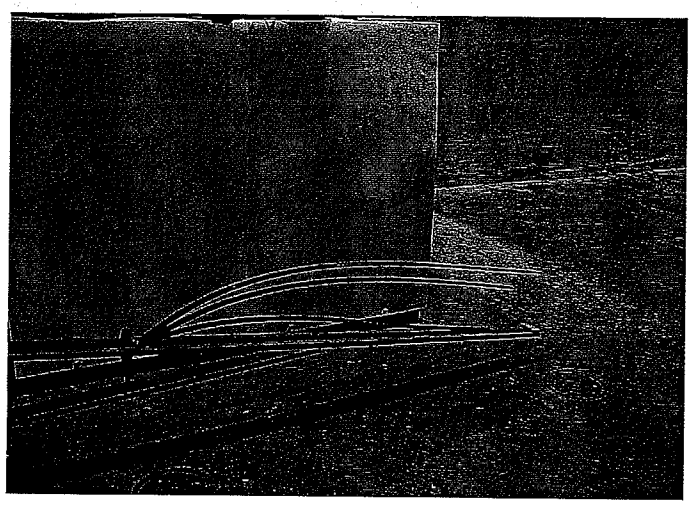


Figure 9 - Low Frequency Test of Type d TID

Several alternative TID configurations were tested. The TIDs were similar in their make up as the Type II TIDs tested on the model cable, and consisted of different numbers of cantilevered thin steel strips. Although various TID configurations were tested, they could be divided into the following four categories:

a) One to three tuned strips.

b) One to three over-tuned strips, each with the same tuning.

c) Three strips, one under-tuned, one tuned, and one over-tuned.

d) Three strips, all three over-tuned, each with a different tuning.

The results were encouraging, and proved that the TIDs were effective also in damping at lower frequency vibrations. The observations from the low frequency tests are as summarized below:

1. Impact of the strips with each other and with the prismatic steel cantilever was essential for the TID to be effective in attenuating the vibrations.

2. The effectiveness of the TID increased with increase in the number of strips.

3. TIDs consisting of over-tuned strips ($f_{cable}/f_{damper} > 1$) were more effective than those with perfectly tuned strips.

4. TID type d were the most effective, followed by type c and then by TIDs with strips of the same frequency. See Figure 10.

Based on the experiments on the model cable and low frequency tests, it appears that dampers utilizing the semi-tuned impact dampers should give satisfactory results on real bridge stay cables.

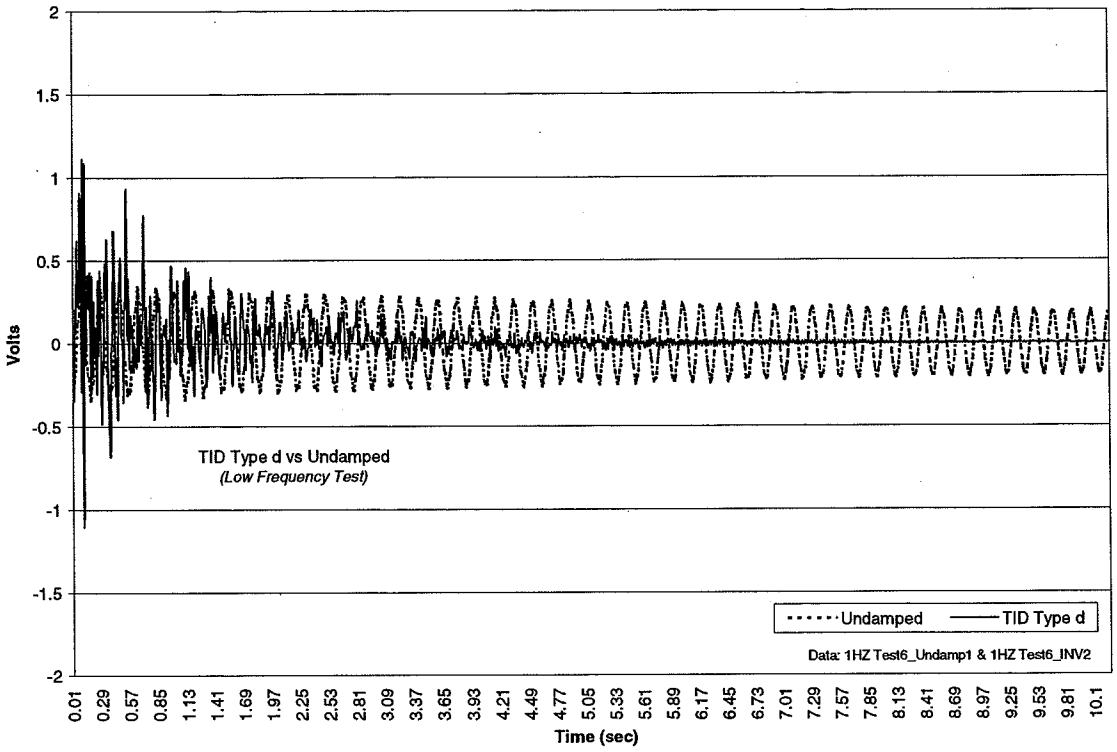


Figure 10 - Type d TID Data

The experiments proved that the TIDs were effective in damping a vibrating body (cable) in a wide range of frequencies. It was observed that the impact of the strips with each other and with the vibrating body was essential for the performance of the TID. The effectiveness increased with increase in the number of strips, and TIDs consisting of over-tuned strips ($f_{cable}/f_{damper} > 1$) were more effective than those with perfectly tuned strips.

Expert Panel Meeting

The expert panel meeting was organized and conducted at the CTL offices on May 25, 2001. The presentation of research results and minutes of the expert panel meeting were sent to all project members on June 1, 2001.

For the purpose of presentation to the panel members, a sample prototype TID system was designed and discussed at the meeting. An average stay cable was selected for the initial fabrication of the prototype, and tuning calculations were performed to determine the ideal tuning for the various TID bars. Based on the ideal tuning, required frequencies of the six TID bars were computed. The cross section and dimensional properties for the different bars were determined based on the required frequencies. A structural stress and curvature analysis was conducted for the six TID bars to verify the stresses in the TID bars and to obtain curvature of the bars under self-load. The curvature data was then used for providing a reverse curvature to the TID bars during fabrication such that they will return to a straight profile under self-weight.

The prototype design of the TID was refined based on the comments and recommendations of the expert panel members. Further studies were conducted on the material type, layout, connection details, and fabrication requirements for the full-scale prototype. Subsequently, a refined model of the full-scale prototype was designed and detailed, and is presented in Figures 11 and 12.

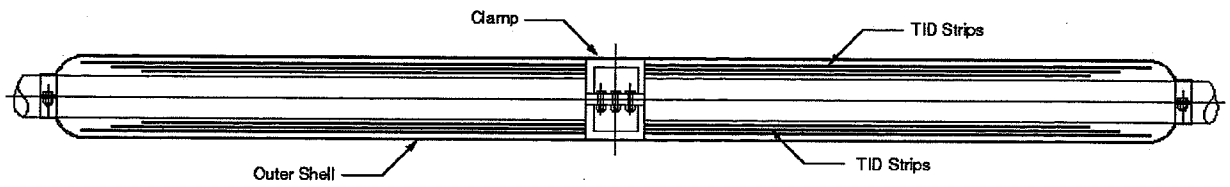


Figure 11 - Prototype TID: Alternate 1

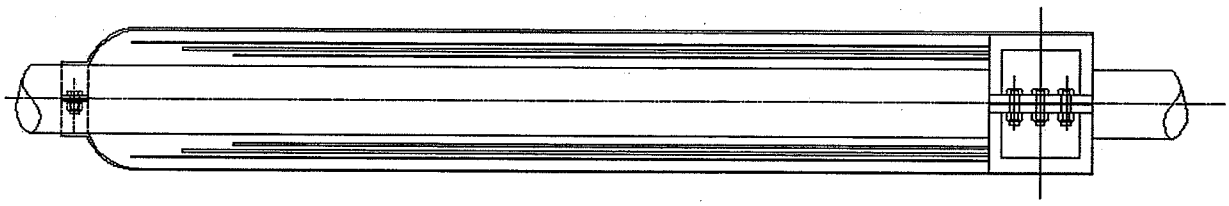


Figure 12 - Prototype TID: Alternate 2

A concern shared by panel members was the fatigue performance of the vibrating strips in the TID. The expert panel felt that the TID strips could be prone to fatigue related problems due to the repeated cyclic loading effects on the strips during cable vibrations. It was suggested that additional research be conducted to estimate the effect fatigue loading on the TID strips. CTL devised an experimental setup to investigate the fatigue resistance of the TID strips, and the details from this test are presented later in this report.

STAGE 2 RESEARCH – FIELD TESTING AND EVALUATION OF FULL-SCALE PROTOTYPE TID

The stage 2 research consisted of design and fabrication of a full-scale prototype TID, installation of this TID on a representative bridge, and monitoring and testing the effectiveness of the TID on this representative bridge. Several bridges were identified for potential field installation, and eventually, the Talmadge Bridge was selected based on its availability for the installation and testing. Short-term monitoring was considered as a viable option in evaluating the feasibility and effectiveness of the TID, and tests were conducted to determine the effect of the prototype TID on several cables of the bridge.

Prototype Material Research

After finalizing the configuration of the TID, research was conducted to identify the range of steel based materials that could be used for fabricating the TID. The research indicated that stainless steels with a varying range of significant properties were available in the market. Based on evaluation of the TID model mechanics and expert panel comments, the two main properties that were considered as beneficial for better application of TID strips were high ultimate bending strength and high fatigue resistance. It was found that stainless steel material with bending strength of as high as 120 ksi with fatigue resistance of up to 90 ksi (e.g. Carpenter Custom 450® and 455® Stainless Steel, Condition H900; Allegheny Ludlum Stainless Steel Type 301, Full Hardened, UNS S30100) would be available in the market.

However, in an effort to produce a full-scale TID at a reasonable cost, it was decided to fabricate the TID using Grade A36 carbon steel and to experimentally evaluate the fatigue resistance of the TID strip in the laboratory. Grade A36 steel is the most common steel material used for structural application, and is available in the market with the least price amongst other steel grades. The fatigue test of the prototype TID strip made of Grade A36 steel in presented in succeeding sections.

Fatigue Testing of TID Strips

Based on the expert panel recommendations, the manufactured TID bars were tested in the CTL laboratory for evaluating the resistance of the bar to fatigue loading. The fatigue test was conducted on a TID bar identical to the one used for the TID field test assembly. For the fatigue resistance testing, the TID bar was clamped in the test setup at one end and free at the other end, similar to the end conditions when used in the TID assembly (Figure 13). A minor excitation at the clamped end of the strip resulted in an oscillation of the free end at an amplitude of approximately ±1 inch and frequency of 1 Hz to mimic the motion of the TID in the field. The test was conducted for over 2 million cycles, and on culmination of the test, the TID bar was visually evaluated for any signs of fatigue or stress related damage.

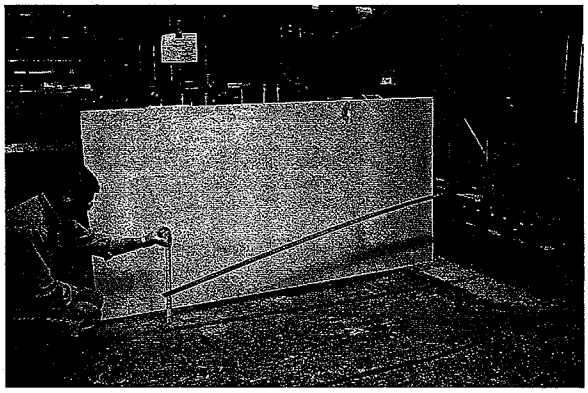


Figure 13 - Fatigue Experiment of TID Strip

The evaluation indicated no signs of damage or distress, and showed that a typical TID bar made of standard A36 steel was not affected by fatigue in the test condition that is similar to the actual TID application. In addition, the useful life of the TID strips could be increased further if special and more robust fatigue resistant materials are used for fabrication of the TID strips. The corrosion of the strips can be prevented using two layers of barriers. An internal barrier could be formed by priming and painting the strips while an encasement of strips with a waterproof covering will act as external barrier. It should be noted that the stress range for each specific design should be calculated and made certain that fatigue would not be an issue for the TID system.

The Prototype TID

A full-scale prototype TID was fabricated for field installation and monitoring by scaling laboratory models to actual cable dimensions. The prototype (Figure 14) consisted of a steel bracket with attachments for the TID strips. The bracket was made of two semicircular halves that were placed around the cable over a thin sheet of neoprene rubber, and bolted tightly together to clamp the cable without creating any damage to the cable surface. Up to four tuned TID strips, 4 inches wide, ¼ inch thick, and varying in length were attached to the bracket. Typically, two TID strips were attached to the top, and two to the bottom of the bracket. The length of the TID strips ranged from 94 inches to 100 inches. The strips were reverse curved to the self-weight deflected shape to avoid excessive deformation under its own weight and to allow impact between strips themselves and between the strips and the cable cover pipe. The dimensional and other pertinent details of the prototype TID are given in Table 1.

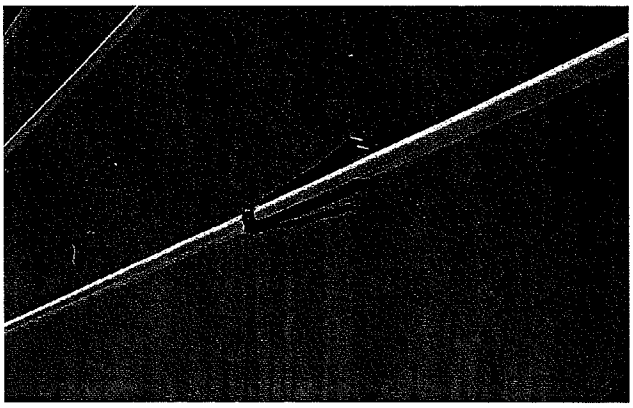


Figure 14 - Prototype TID Installed on Stay Cable

Table 1 - Prototype TID Data

TID Component	Length	Diameter (OD) or Width	Thickness	Weight	1st Mode Frequency	Tuning (Freq. of Cable/Freq. of TID)
	inches	inches	inches	lb	Hz	
Bracket	12	6.625	0.69	43.64	-	
Tid Strip 1	94	4	0.25	26.66	0.91	1.19
TID Strip 2	100	4	0.25	28.36	0.80	1.34
Total Weight (4 TID Strips + Bracket + Connection Hardware)					153.66	pounds
Ratio of Weight of TID strips to Weight of Cable (Avg. 11219.60 lb)					0.98%	
Avg Freq of all three cables = (1.044+1.083+1.102)/3 =					1.0763	Hz

The TID bracket had an inside diameter of 5-3/4 inches, and was approximately 1 foot long. The diameter of the TID bracket was chosen to fit the intermediate length cables on the Talmadge Bridge in Savannah, Georgia. The prototype TID was attached to several cables of the Talmadge Bridge, and the acceleration or velocity time history of the cable vibration was recorded using a portable data acquisition system. The recorded data was analyzed to determine the effectiveness of the TID system.

Field Test Procedure

The prototype test was conducted on several of the Talmadge Bridge cables. The Talmadge Bridge (Figure 15) is a twin-pylon cable-stayed bridge with a main span of 1100 ft and two side spans of 470 ft. The pylons are H-shaped. The deck cross section is composed of two concrete edge girders with floor-beams and a concrete deck. The stay cables are anchored in the edge-girders at the floor-beam to edge-girder joint. There are two planes of cables at each pylon with a semi-harp arrangement. Seventy-two cables are anchored at each pylon for a total of 144 stay cables on the bridge. Each pylon has two towers that anchor 36 cables each. The cable nomenclature consists of a two-letter designation for the specific pylon tower and a numerical designation for the cable number. The two-letter designation can be NE, NW, SE, or SW for the northeast, northwest, southeast, and southwest towers respectively. All the cables anchoring into a particular pylon tower are numbered from one for the longest side span cable to eighteen for the shortest side-span cable and nineteen for the shortest main span cable to thirty-six for the longest main span cable.

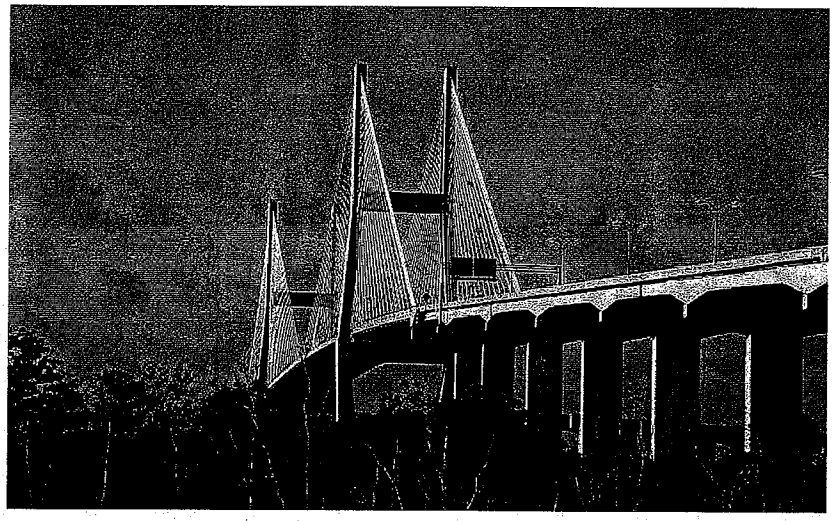


Figure 15 - Talmadge Bridge

The stay cables consist of parallel 0.6 in., 270 ksi seven-wire strands inside a polyethylene pipe filled with cement grout. The entire cable free length is wrapped with a PVF tape. As per design and shop drawings, each cable consists of between 19 to 61 strands. The anchorage is "Stronghold" type, consisting of a conical steel socket filled with epoxy-steel ball compound. Each strand is also anchored with wedges at a wedge plate behind the socket. According to the shop drawings, the end caps behind the anchorages at the deck level are fully grouted while those at the pylon level are filled with grease. Inspection of the guide pipes indicated some damage to few of the guide pipes, possibly due to stay-cable vibrations. Based on the condition inspection of the guide-pipes (Figure 16), the condition of the washers and keeper rings, and the visual signs of cable vibration susceptibility, it can be inferred that the intermediate to longer length cables on this bridge were prone to wind induced vibration effects.

Figure 16 - Guide Pipe Damage

The TID was initially installed near the quarter span-length on selected cables using a 60-foot lift truck (Figure 17). A rope with a quick release system (Figure 18) and a sensitive accelerometer was attached on the stay cable around the vicinity of the TID. The other end of the rope was anchored to the bridge deck, and the rope was tensioned using a manual winch to deflect the cable approximately at right angles to the axis of the cable (Figure 19). Each cable was winched using the rope to a calibrated magnitude, and the rope was released instantaneously using the quick release mechanism. The ensuing vibration of the stay cable was recorded by the accelerometer and the attached data acquisition system (Figure 20). This process was repeated several times for each stay cable. The vibration of the stay cables was recorded as acceleration time history for a duration ranging from a few seconds to a few minutes. Sets of vibration readings were also obtained for each cable without TID. The time-history readings without TID were used as a datum for comparison purposes and in determining the effectiveness of the TID. The time-history files were then filtered and analyzed to evaluate the effect of the TID on the vibration of the cables.

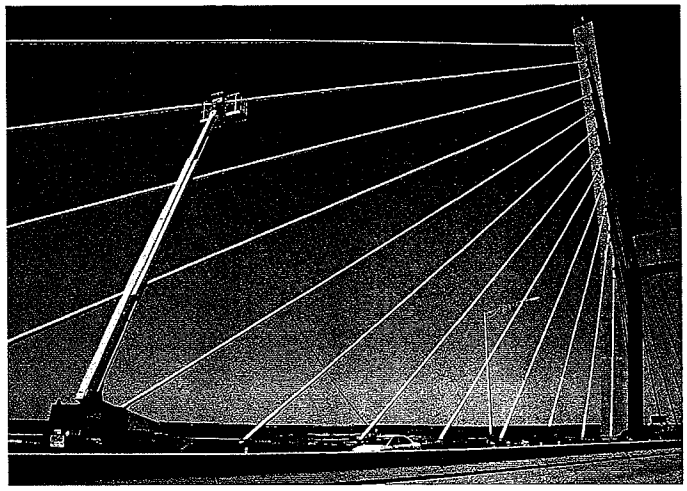


Figure 17 – TID Installation

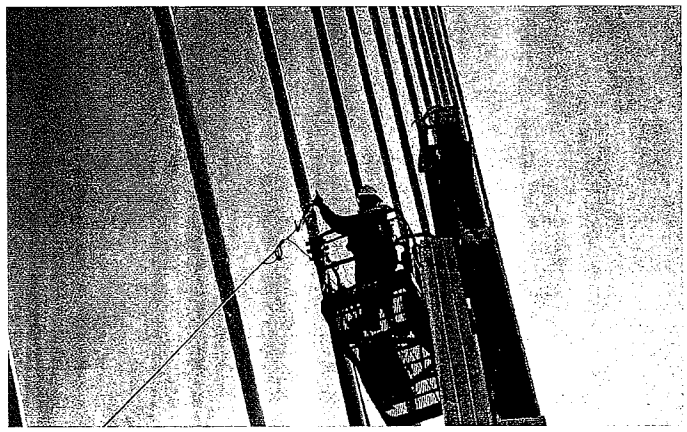
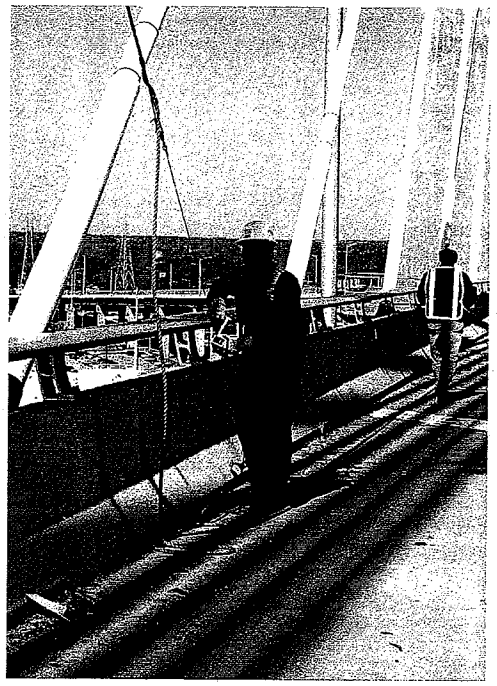


Figure 18 – Quick Release System



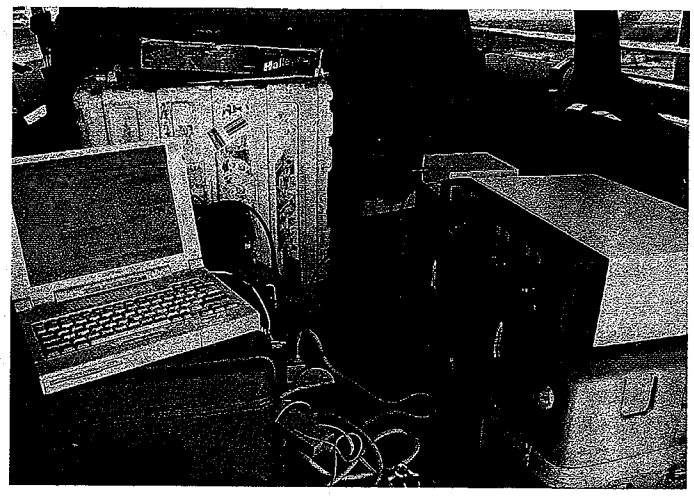


Figure 19 – Winch Mechanism

Analysis of Field Instrumentation Data

To evaluate the effect of TID on different modes of vibration, the field recorded time-histories were filtered in the frequency domain to obtain separate first and second mode vibration time-histories. The intent of the TID was to suppress the lower vibration modes of the cables, especially the second mode, and therefore the effectiveness of the TID was evaluated for the first two frequencies. A program filtered the raw time-history in the frequency domain to obtain the first and second mode time histories. The filtered time histories for each cable and for both conditions, i.e. with and without TID, were then evaluated in an excel spreadsheet. The analysis and evaluation of filtered time histories from a few representative cables is presented in the following sections, and the dimensions and other salient features of these cables is given in Table 2.

Table 2 – Test Cable Data

Cable Number	Length	Outside Diameter	Number of Strands	Measured 1st Mode Frequency	TID Location	Ratio of TID Location to Span
	feet	inches		Hz	feet (approx.)	
NE8	383.33	5.56	28	1.044	100.50	0.26
NE9	355.74	5.56	27	1.083	100.58	0.28
NW28	355.19	5.56	28	1.102	92.00	0.26

The effect of the TID on the vibration of the cable is visually analyzed to identify any change in the damping trend. In order to facilitate this comparison, the filtered time histories with and without the TID are superimposed onto one another in a single chart. These charts for the NE8 cable are shown in Figures 21 through 23.

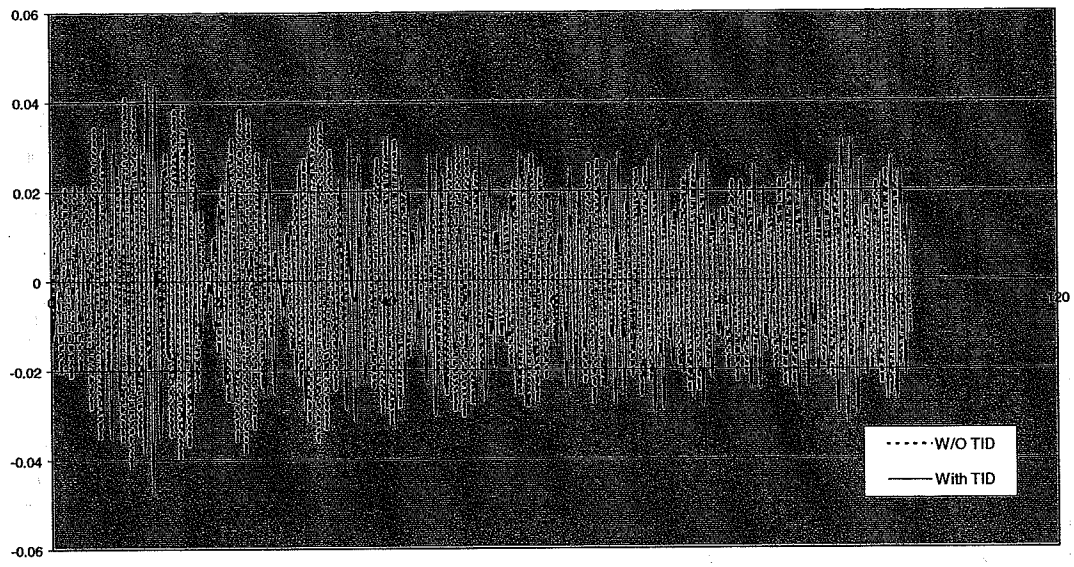


Figure 21 – First Mode Time History of Cable NE8

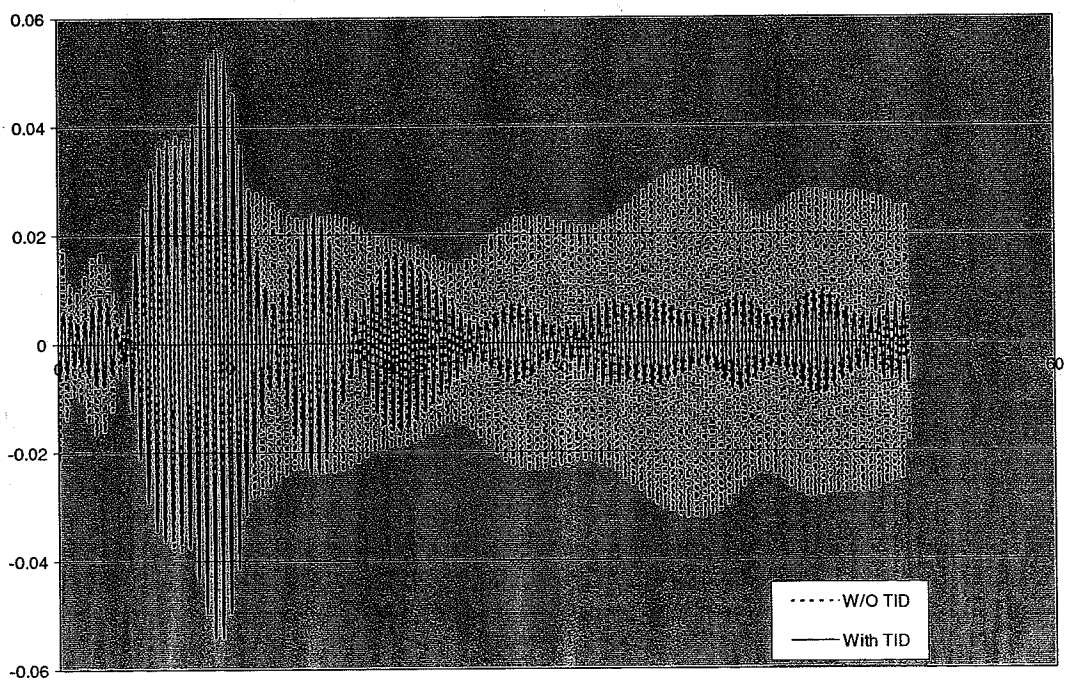


Figure 22 - Second Mode Time History of Cable NE8

Figure 21 shows the filtered first mode time history for the NE8 cable with and without The TID. Although the figure does not show significant difference between the two conditions, it is apparent that there is a light damping effect of the TID on the cable. Figure 22 shows that the TID is highly effective in mitigating the second mode cable vibrations. The higher effectiveness of the TID for the second mode of vibration can be attributed to the fact that the TID was attached near the quarter length of the cable. Figure 23 shows the comparison of the cable frequency spectrum with and without the TID, and conclusively shows the marked effect of the TID in reducing the amplitude of vibration for the second mode. This figure indicates that the acceleration amplitude of cable has been suppressed by TID to about 30% of the undamped condition. From the charts, it can be concluded that the TID has been effective in reducing the cable vibration by providing substantial damping.

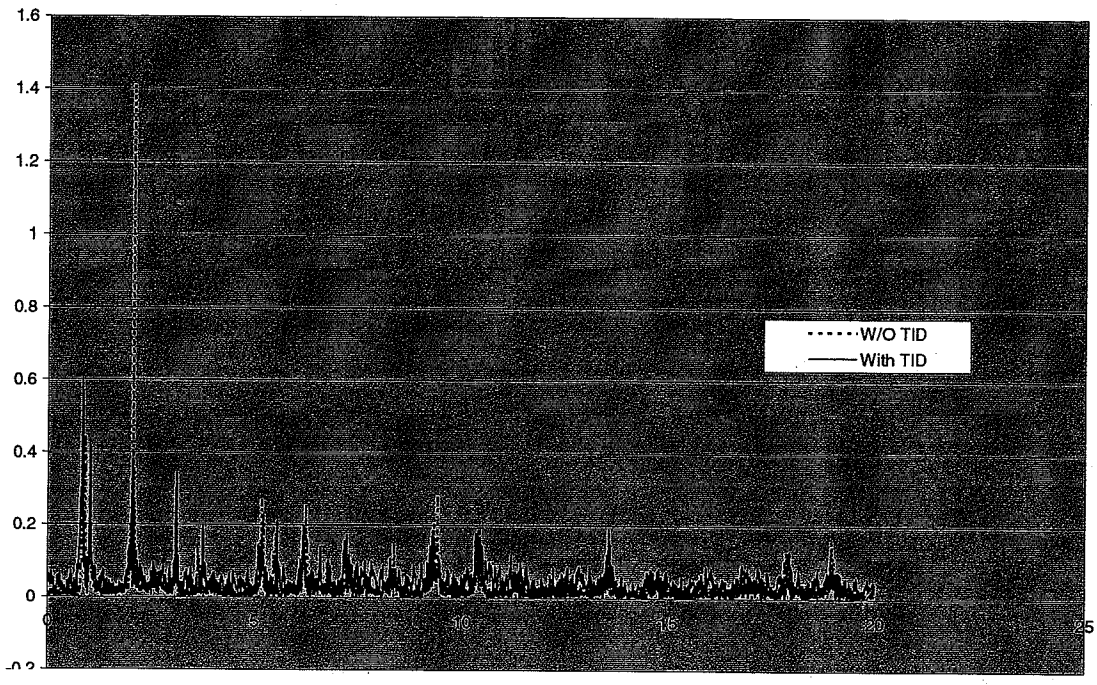


Figure 23 - Frequency Spectrum of Cable NE8

TID Effects on Cable NE9

The charts for the NE9 cable are shown in Figures 24 through 26. Figure 24 shows the filtered first mode time history of the cable with and without TID. It is apparent from the figure that there is some damping effect of the TID on the cable. Figure 25 shows that the TID is highly effective in mitigating the second mode cable vibrations. The higher effectiveness of the TID for the second mode of vibration can be attributed to the fact that the TID was attached near the quarter length of the cable. Figure 26 shows the comparison of the cable frequency spectrum with and without TID, and conclusively shows the marked effect of the TID in reducing the amplitude of vibration for the second mode. This figure indicates that the acceleration amplitude of cable has been suppressed by TID to about 65% of the undamped condition. From the charts, it can be concluded that the TID has been effective in reducing the cable vibration by providing substantial damping.

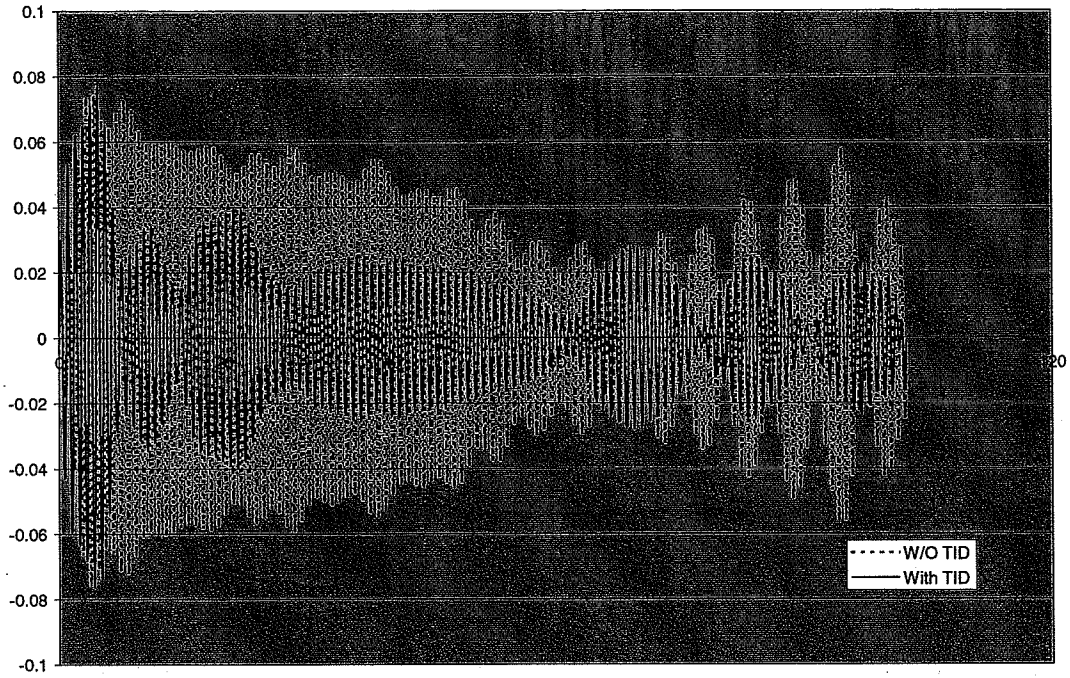


Figure 24 – First Mode Time History of Cable NE9 (W/O TID Data Normalized)

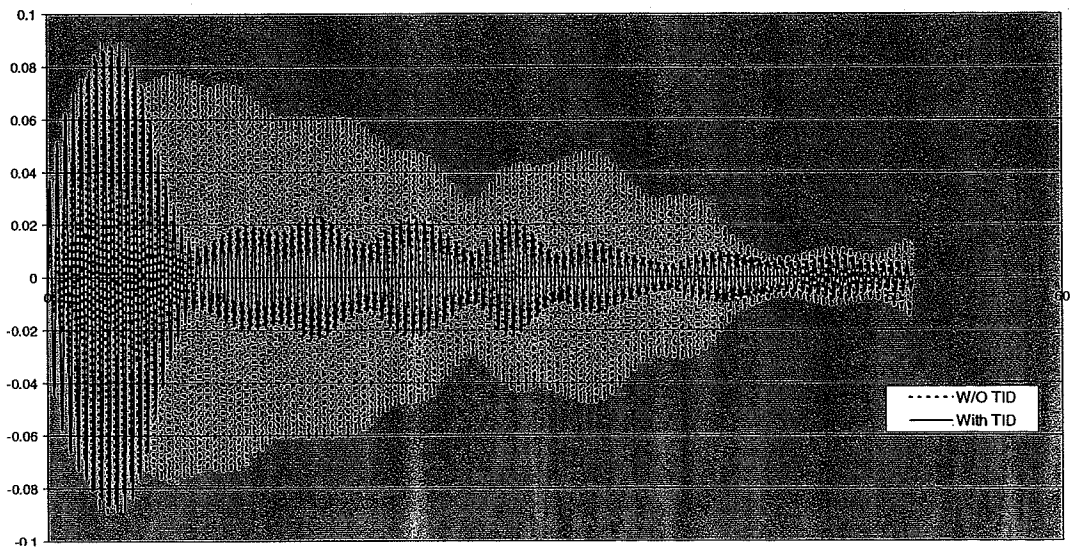


Figure 25 – Second Mode Time History of Cable NE9 (W/O TID Data Normalized)

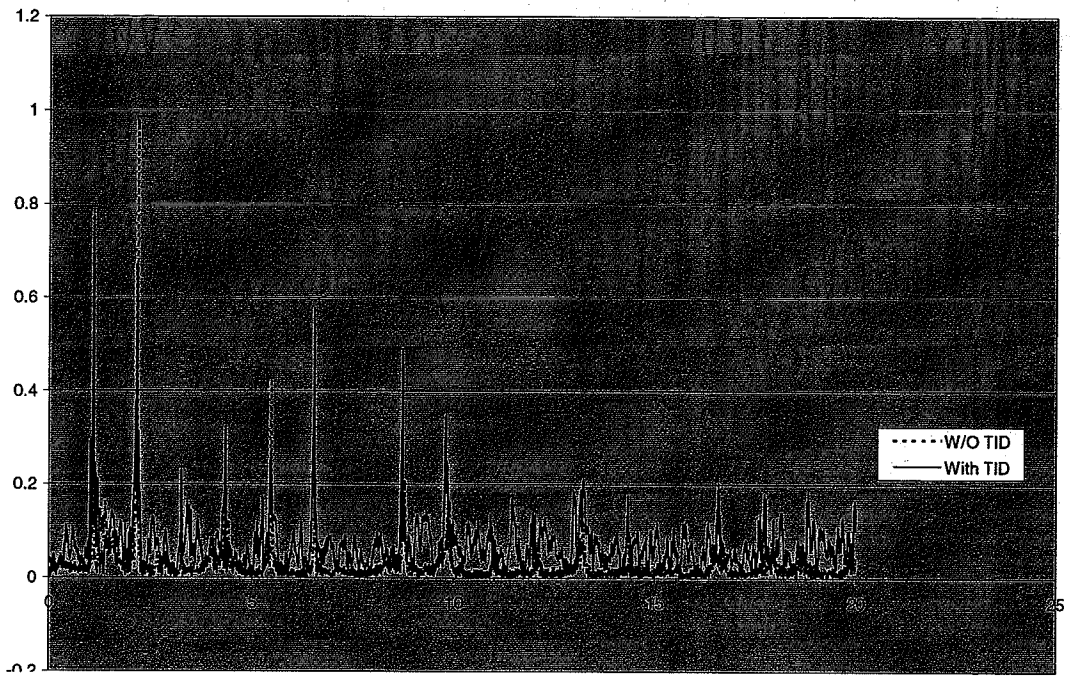


Figure 26 – Frequency Spectrum of Cable NE9

TID Effects on Cable NW28

The charts for the NE9 cable are shown in Figures 27 through 29. Figure 27 shows the filtered first mode time history and Figure 28 shows the second mode time history of the cable with and without TID. The figures show that the TID is highly effective in mitigating the first and second mode cable vibrations for this cable. Figure 29 shows the comparison of the cable frequency spectrum with and without TID, and conclusively shows the marked effect of the TID in reducing the magnitude of the frequency spectrum for the first and second modes. The higher effectiveness of the TID on the first mode vibration of NW28 when compared to the previous two cables may be due to a better match between frequency of TID and cable. Figure 29 indicates that the acceleration amplitude of cable has been suppressed by TID to about 50% of the undamped condition. From the charts, it can be concluded that the TID has been effective in reducing the cable vibration by providing substantial damping.

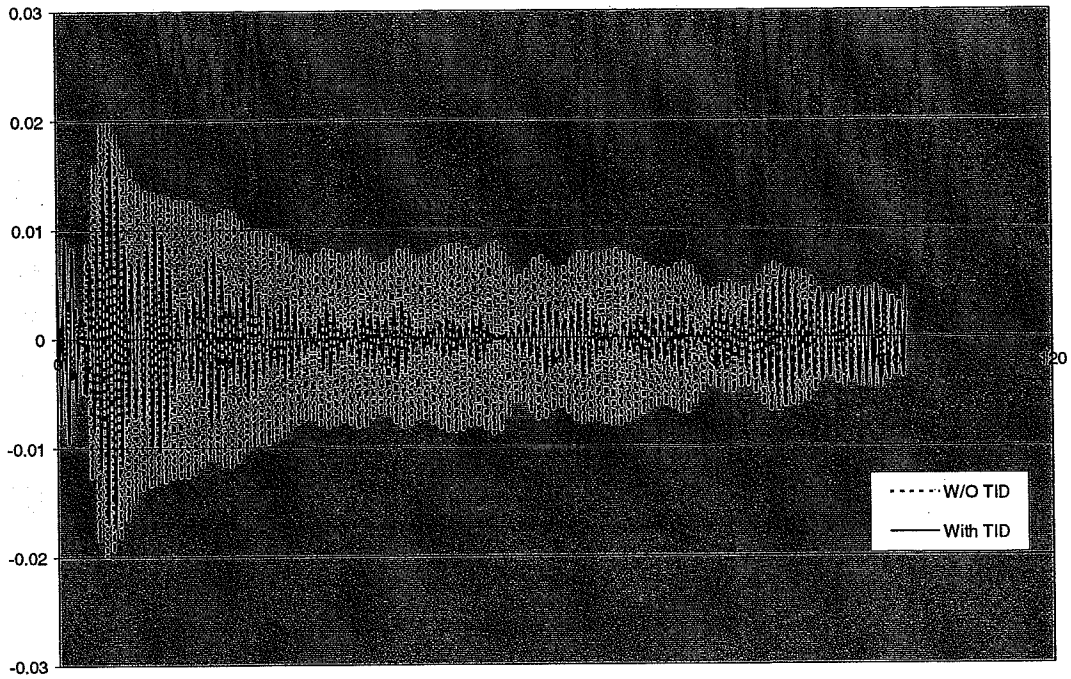


Figure 27 - First Mode Time History of Cable NW28

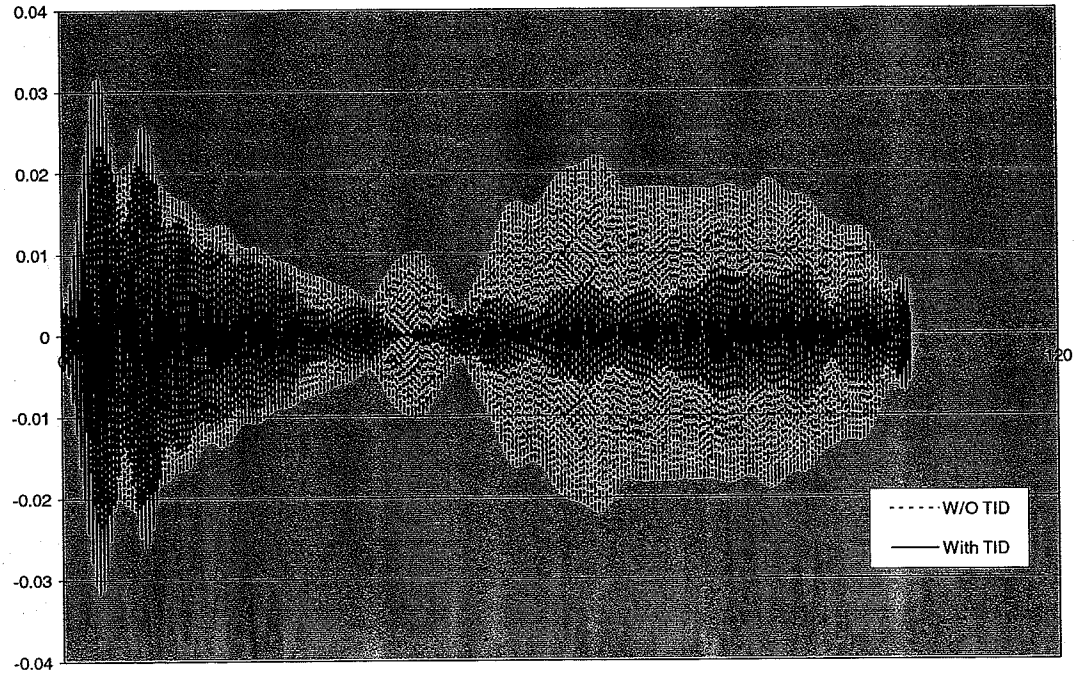


Figure 28 - Second Mode Time History of Cable NW28

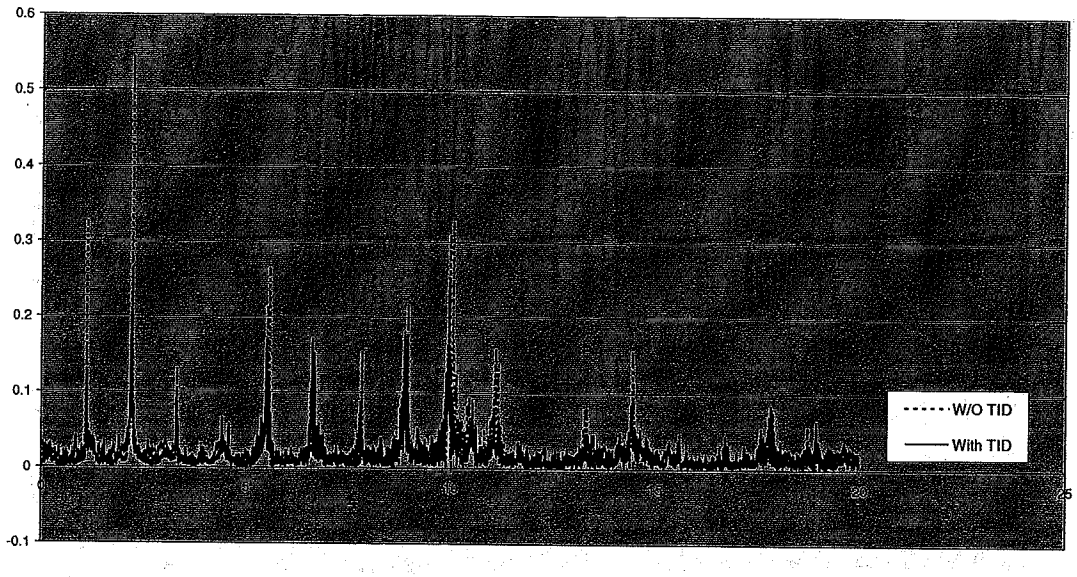


Figure 29 - Frequency Spectrum of Cable NW28

FIELD OBSERVATIONS AND DISCUSSIONS

The prototype test was conducted on several of the Talmadge Bridge cables. The Talmadge Bridge is a twin-pylon cable-stayed bridge with a main span of 1100 ft and two side spans of 470 ft. The TID was installed near the quarter length of selected cables using a 60-foot lift truck. Each cable was winched using a rope to a calibrated magnitude, and the rope was released instantaneously using the quick release mechanism. The test results were discussed in previous sections. The results indicated the effectiveness of the system in vibration suppression and increasing the apparent damping ratios.

Although it was being done for the first time, the installation of TID on cable and assembly of the system was quite easy. The curvature of the strips in some cases required minor adjustment to create the desirable gap distances between strips and between strips and cable cover pipe. The adjustments were necessary since cables of various inclination angle were installed with the same system. For a predefined rehabilitation project, each system will be pre-bent for specific cable inclination angle thus avoiding field adjustments. The installed TID system is shown in Figure14. The profile of the system was barely noticeable from the deck level as can be seen in Figure 30.

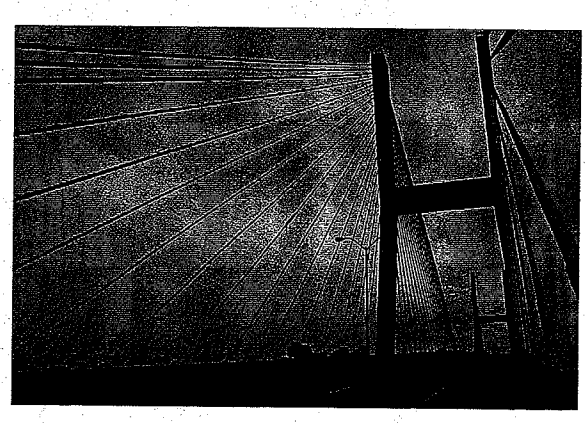


Figure 30 – Profile of TID System

Various combinations of four steel strips were used for trial purposes. Two strips on top, two on top and two on the bottom, and four strips all attached to the top of the cables were three different configurations used in this experimentation. In all cases, the pull and release of cable with TID created high amplitude oscillation in the beginning that was suppressed shortly due to interaction between the TID and the cable. The TID

performed as anticipated. With the release of the cable, the strips began vibrating and at the same time impacting each other and onto the cable. After suppressing the initial large amplitude movements of the cable, the impacting action of the TID stopped. The strips, however, continued oscillating long after with amplitude often greater than that of the cable resulting higher efficiency for the TID. Videos of the TID performance were shot during this operation and are available for viewing.

The TMD concept proved to be successful in raising the apparent damping ratios of cables beyond the threshold of vulnerability to the rain-wind induced vibrations. As an example, the damping ratio for the second mode of vibration of Cable NE9 before installation of TID was 0.31%. The TID raised the damping ratio to 1.22%, an increase of about 295%, that is higher than threshold of damping required for suppression of rain-wind induced vibration.

Table 3 – Measured Damping for Talmadge Bridge Cables with and without TID

Cable No	Damping					
	1st Mode			2nd Mode		
	Without TID	With TID	% Change	Without TID	With TID	% Change
NE8	0.14%	0.18%	28%	0.69%	1.39%	102%
NE9	0.42%	0.48%	13%	0.31%	1.22%	295%
NW28	0.47%	0.71%	52%	0.68%	0.93%	36%

It should be pointed out that the TID used for field verification was originally designed to suppress the first mode of vibration of the cables. The natural frequency of the TID was in the vicinity of the first mode vibration frequency of the cables. However, the limited reach of the available lift did not allow the installation of TID at its optimum location that is at the mid-length of the cable. As it was discussed earlier, the TID was installed near the quarter length of cable. In spite of this unfavorable condition, the TID performed successfully. However, the effectiveness of the system would be several times higher (at least for the first mode of vibration) if it was installed at the mid-length. Also, for the second mode of vibration, the effectiveness would be higher than recorded if the frequency of the TID was tuned to the second mode vibration frequency of the cable.

TID is also a low-cost, low maintenance vibration control option that can be applied to both existing and new stay cables. The advantages of TID compared to conventional viscous dampers or other alternatives can be described as follows:

- Easy to design and manufacture
- Relatively high apparent cable damping ratios achievable.
- Reasonable cost and low maintenance (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 and/or distributed to target specific modes).
- Relatively small size and mass.
- Aesthetically more pleasing. In fact the positioning of dampers in different cables can be used to highlight a specific pattern.

DESIGN CONSIDERATIONS AND GUIDELINES

Design and implementation of vibration suppression measures for stay cables of cable-stayed bridges are normally a part of an overall evaluation and mitigation program. Incidences of large-amplitude vibrations of stay cables of cable-

stayed bridges have been reported worldwide and are known to be a result of "rain-wind induced vibration" phenomenon. An effective way of addressing various types of cable vibration problems including rain-wind induced vibrations is to increase cable damping. This solution has been considered for several bridges in the recent years. Owing to the awareness of the bridge owners and bridge engineering community generated in recent years by publicity surrounding this problem, more bridges are now designed taking into consideration the cable vibration problems. However, there exist bridges for which the cable vibration problems have been only been recognized after significant damage has occurred due to excessive vibration in cables.

The process of evaluation and mitigation of the vibration problems in stay cables in general should include:

1- Diagnosis of problem and identification of the cables that require vibration suppression measures

2- Determination of cable parameters to be used in vibration suppression design

3- Design of vibration suppression measure(s)

4- Manufacturing process

5- Installation of vibration suppression measure(s) on cables

Diagnosis- The need for TID or any other vibration suppression measure should be verified first by an analytical and field investigation or observation records. The CTL research team compiled valuable databases for determining the susceptibility of stay cables to rain-wind induced and galloping vibrations through analytical investigations. Visual observations normally originate from the users of the bridges or maintenance crews. The analytical approach to diagnose is conservative and reliable. This method determines the level of damping that a cable requires for suppressing rain-wind induced vibrations. Using the analytical method, CTL helped to identify, before construction, those cables in the Charles River Bridge that would require additional vibration suppression measures against rain-wind induced and/or galloping oscillation. CTL used the same procedure to identify the cables in need of damper installation for the Cochrane Bridge in Alabama and the Talmadge Bridge in Georgia. In the latter cases, the analytical method was supplemented by a field measurement of existing cable damping prior to damper installation.

Cable Parameters- The cable parameters required for design of a vibration damping system are the geometry and mechanical properties, end conditions, cable mass, and finally the cable vibration frequencies. Among these, three parameters are the most important for designing TID systems; cable length, cable weight, and cable vibration frequencies. This information is usually available from design and/or shop drawings. The vibration frequencies of the cables, however, may need to be verified using field measurements.

Design of TID- General design of the TID system follows three simple relationships. The **mass** of the impact strips should be in the range of 0.4 to 1.2 percent of the total mass of the cable, the **frequency** of vibration of the strips should be in the vicinity of vibration frequency of the cable, and the installation **location(s)** should target the intended mode(s) of vibration of the cable. With this information, the length, thickness, and number of the strips can be determined. Hence, the TID can be designed for manufacturing. It should be pointed out that the preliminary design may require certain refinement according to bridge and site specific consideration.

Normally, in a rain-wind induced vibration of stay cables, lower modes of vibration are dominant. It is understood that a suppression measure targeting one mode of vibration of a cable suppresses also (with lower efficiency) other modes of vibration. This was verified in the laboratory and field verification tests conducted for this study. It is also believed that targeting modes beyond the third mode of vibration of cable will not be effective. As an approximate rule, the mass of TID strips can vary from 0.4 to 1.2 percent of the cable mass, the lower range being for higher modes (modes with higher frequencies) and higher for lower modes (modes with lower frequencies). The number of strips may be four to six in total, two to three on the top and the bottom of the cable.

The laboratory tests showed that strips with frequencies slightly higher (e.g., 10 percent) than target frequency of cable are more effective. Also, designing strips with a slight difference in frequencies (out of phase) will raise the efficiency by inducing the impact between the strips as well as impact on the cable. Knowing the mass and frequency, the thickness, length, and width of the strips can be calculated based on the vibration of a cantilever beam concept.

To target a certain mode of vibration for a cable, the TID can be installed at the middle of two nodes of vibration on the cable. For example, for the first mode of vibration, it should be installed at the mid-length of the cable, for the second

mode, at one-quarter of the cable length, etc. TID can also be used to target more than one mode of vibration in the cable. For example, a TID location near one-third of the cable length, will be best effective on the first and second mode.

Manufacturing- The prototype TID tested in the field was made of the most common steel material available and is believed to be adequate for the purpose of the TID application. However, few requirements need to be implemented for long-term performance of the system regarding corrosion and aerodynamic effects. These could be easily applied by painting, galvanizing, or the use of stainless-steel material for the strips, and encasing the system in a shell as shown earlier in the preliminary design of the system. In the manufacturing process, the steel strips need to be rolled with a curvature matching to the self-weight curvature of the strips installed in cable inclination angle. The fabricator should relieve the residual stresses induced by bending. Clamps should be fabricated to fit easily on the cable surface with an adjustment option for cable cover pipe dimensional tolerances.

Installation- The system can be installed using a lift truck of sufficient reach in a two-man operation. Care should be taken to prevent damage to the cable sheathing. A relatively soft pad (e.g., elastomeric sheets) could be used between the clamping system and the cable. The clamp needs to be tightened adequately to prevent slipping over the cable. The impact point of strips on the cable cover pipe needs to be reinforced using a metal or HDP strip wrapped around the cable. The strip and clamp assembly should be encased within a cover. This encasement can be made of reinforced plastics and should have a cross-sectional shape preventing formation of unwanted vortices. The encasement should be made water-tight using elastomeric boots or similar at two ends and seals at the joints.

FUTURE DEVELOPMENTS

The laboratory and field test results indicate the efficiency of the TID system in suppression of stay cable vibration and improving the stay cable performance in wind and rain-wind induced oscillations. This in turn would prolong the effective life of the cables and consequently cable-stayed bridges by reducing fatigue related damage and maintenance costs. This method is believed to offer many practical and cost advantages over the use of mechanical viscous dampers or the utilization of cross-ties. Future related work for introduction of this system into the bridge market should involve inclusion of the system in a bridge rehabilitation program. TID systems would be designed and manufactured for the potential bridge and the cables will be monitored for long-term performance. In recent years, CTL bridge engineering experts have been involved directly in evaluation and rehabilitation of at least four cable-stayed bridges in the US and are in a good position to recommend the use of the TID system for installation on stay cables to be retrofitted. If realized, the design process will be performed for a group of cables. This would allow the optimization of the process for further cost reduction, implementation of refinement in the design for the bridge and site specific conditions, and development of industrial production procedure. It would also provide the opportunity for long-term monitoring of the performance of the TID system.

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. 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. He has utilized these unique capabilities for evaluation and mitigation of several cable-stayed bridges.

The co-investigator, Mr. Niket Telang, P.E., has an extensive experience in design, evaluation, and retrofit/rehabilitation of bridge structures. He has managed a variety of bridge related projects that include several historic, cable stay, and long-span bridges. He has been a team member on several research projects, including the NCHRP projects for preparing the *Manual for Inspection, Evaluation, and Maintenance of Movable Bridges* and *The Manual for Condition Evaluation and Load Rating of Highway Bridges Using Load and Resistance Factor Philosophy.* He has also published several papers on evaluation of cable vibration problems and on rehabilitation of cable stay and movable bridges. His recent involvement has been coordination and management of large and unique projects with emphasis on the behavior of stay cables in cable-stayed bridges.

The co-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.

SUMMARY AND CONCLUSIONS

In the first stage of this study, a series of laboratory tests were conducted on a model cable to evaluate Tuned Impact Damper (TID) systems. The model TID system performed very satisfactory in raising the apparent damping ratio of the model cable and absorption of the vibration energy. The tuned impact concept essentially depends on **absorbing** and **suppressing** the vibration energy by a combination of the tuned mass principle and through impact of the secondary body (damper) on the vibrating object. It was shown that in order to achieve efficient impact, the vibration of the damper must be slightly out of phase with the vibration of the cable. The general shape of the Tuned Impact Damper (TID) system consists of profiled steel strips clamped on one end to the cable and free on the other end. The number of steel strips can be varied from one on the top and bottom of the cable to up to three strips on the top and bottom. The functionality and effectiveness of TID system at lower frequencies, similar to those on actual bridge cables, were demonstrated by a series of additional laboratory tests.

In the second stage of the investigation, a prototype TID was designed and manufactured and verification tests were conducted on several of the Talmadge Bridge cables. The TID was installed near the quarter length of selected cables using a 60-foot lift truck. The cables were pulled and released using a winch and vibration of the cables were recorded with and without TID system. The comparison of results indicated the effectiveness of the system in vibration suppression and increasing the apparent damping ratios.

Although it was being done for the first time, the installation of TID and assembly of the system was quite easy. The curvature of the strips in some cases required minor adjustment to create the desirable gap distances between strips and between strips and the cable cover pipe. The adjustments were necessary since cables of various inclination angles were installed with the same system. For a predefined rehabilitation project, each system can be pre-bent for specific cable inclination angle thus avoiding field adjustments. The profile of the system was barely noticeable from the deck level. Various combinations of four steel strips were used for trial purposes. In all cases, the pull and release of cable with TID created high amplitude oscillation in the beginning that was suppressed shortly due to interaction between the TID and the cable. The TID performed as anticipated. With the release of the cable, the strips began vibrating and at the same time impacting each other and onto the cable. After suppressing the initial large amplitude movements of the cable, the impacting action of the TID stopped. The strips, however, continued oscillating long after with amplitude often greater than that of the cable resulting higher efficiency for the TID.

The TID concept proved to be successful in raising the apparent damping ratio of cable beyond the threshold of vulnerability to the rain-wind induced vibrations. As an example, the damping ratio for the second mode of vibration of Cable NE9 before installation of TID was 0.31%. The TID raised the damping ratio to 1.22%, an increase of about 295%, that is higher than threshold of damping required for suppression of rain-wind induced vibration.

TID is also a low-cost, low maintenance vibration control option that can be applied to both existing and new stay cables. The advantages of TID compared to conventional viscous dampers or other alternatives can be described as follows:

- Easy to design and manufacture
- Relatively high effective cable damping ratios achievable.
- Reasonable cost and low maintenance (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 and distributed to target specific modes).
- Relatively small size and mass.
- Aesthetically more pleasing. In fact the positioning of dampers in different cables can be used to highlight a specific pattern.

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