Dynamic Results

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When it opened to the public in June of 2000, London's Millennium Bridge experienced lateral sway as large numbers of pedestrians crossed. The installation of damping devices changed this wobbly bridge into a rock-solid one.

On June 10, 2000, the Millennium Footbridge was opened to the public—the first new bridge in more than a century across the River Thames in historic London. In its first day of operation, nearly 100,000 people used the new bridge, but on June 12, the bridge was ordered closed due to hazardous deck motions. Seemingly random pedestrian footfalls were causing resonance of the bridge deck, with lateral accelerations measuring up to 0.25 g. The selected method of retrofit was to add fluid damping to the bridge and test the structure with groups of up to 2,000 people.

BRIDGE OPENS

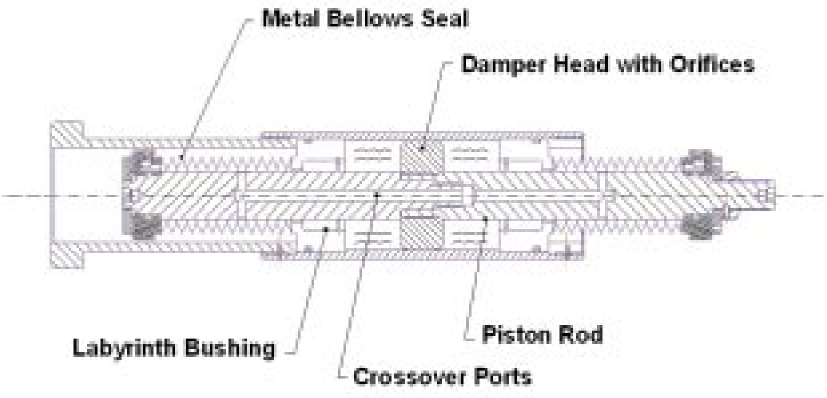
Because the modern bridge was constructed in a historic area, its design had to accept the latest design codes and ordinances while maintaining the historic context of the site. The bridge design team elected to use lateral suspension cables, where the cables are located at the level of the bridge deck. Two piers are located in the river, with a main span of 144 m (474′) between piers and end spans of 81 m (266′) on the north and 108 m (350′) on the south. The bridge deck is 4 m (13′) wide and uses articulated sliding joints spaced at regular intervals along its length. The architectural design theme for the Millennium Bridge is that of a "Blade of Light," expressed and exemplified by the slender, ribbon-like cross section of the structure.

The Millennium Bridge was officially opened to the public on June 10, 2000, and immediate problems were noted. Maximum pedestrian loads of 2,000 people filled the entire bridge deck to capacity, with a resulting loading density of approximately 1.5 people per square meter. Under these conditions, the bridge exhibited severe lateral sway in a frequency band of 0.5 to 1.1 Hz, with lateral accelerations of up to 0.25 g. As many as five separate structural modes were being excited, and pedestrians found it virtually impossible to walk across; many held on to the hand rails for support. On June 11, the number of people allowed on the bridge at one time was reduced, but the lateral shaking periodically reoccurred. On June 12, 2000, the bridge was closed and an extensive analysis and study of the vibration phenomena began.

A UNIQUE PROBLEM

The phenomena of forced harmonic excitation of bridges are not new. What was unique about the Millennium Bridge was that resonance was occurring without any expected forced motion or marching. In fact, the pedestrian motion appeared to be purely random in nature. After extensive review of available video footage during the period the bridge was open, a series of tests were performed to study the observed pedestrian-induced motion. These identified unique biodynamic feedback phenomena, later called "synchronous lateral footfall," which resulted in seemingly random walking motions becoming synchronized over time among members of an unrelated group of people on the bridge.

In essence, when groups of more than 200 people were on the bridge the loadings induced by their footfalls were indeed random up until the point when a significant number of the people would, by pure chance, step in unison. This would produce a tiny but still perceptible lateral motion at the first lateral mode frequency of the bridge. Depending on group size and location on the bridge, this first lateral mode was in the range of 0.5 Hz to 1.0 Hz. Frequencies in this bandwidth are coincident with a normal walking pace, and the bridge structure would respond at the same frequency, thus providing positive feedback to the pedestrians. This positive feedback would cause other group members to also begin walking in phase with the motion, giving an amplified input to the bridge structure with the resultant amplified feedback. Since the bridge structure was essentially undamped, the amplification would continue until a large number of people either stopped walking or were unable to walk due to the excessive motion. During the amplification process, the large induced lateral motions also excited higher modes in the bridge structure, causing even more discomfort to the occupants. Clearly, the solution to the problem involved finding a means to completely eliminate the biodynamic feedback between pedestrians and the bridge.



Space Satellite Damper

A cutaway of a typical Frictionless Hermetic Damper is shown in Figure 5. Two metal bellows seals are used to seal fluid in the damper. As the damper moves, the two metal bellows alternately extend and retract, by flexure of the individual bellows segments. Since the seal element elastically flexes rather than slides, seal hysteresis is nearly zero. The volume displaced by the compressing bellows passes through the crossover ports to the extending bellows at the opposite end of the damper. While this is occurring, damping forces are being produced by orifices in the damping head, and the pressures generated are kept isolated from the metal bellows by high restriction hydrodynamic labyrinth bushings. Because hydrodynamic bushings are used, no sliding contact with the piston rod occurs, assuring frictionless performance.

POTENTIAL SOLUTIONS

The project team evaluated numerous concepts that would reduce or eliminate the feedback response and offered some promising solutions.

Stiffening the bridge. Stiffening of the bridge structure could be accomplished by adding bracing or additional piers. Since the stiffening approach would have to shift frequencies as low as 0.50 Hz to values well above 1.0 Hz, a substantial amount of structural modifications would be required. The resultant changes would be exceedingly heavy and costly. More importantly, the unique architecture of the bridge would essentially be destroyed.

The concept of adding additional support piers would not only have a negative architectural impact, but also would impede ship traffic in a waterway with high velocity tidal currents, conceivably even causing the bridge to become a hazard to navigation.

Limiting the permissible number of people allowed on the bridge. This concept was unacceptable to the owner, even as an interim solution to the problem.

Active control. The use of controllable actuators to continuously oppose the cycling input of the pedestrians is theoretically possible for structures of

There are 16 pier dampers with a stroke of 60 mm (2.4").

this size and is within the present state of the art. However, it is generally accepted that control of only one or two vibratory modes is possible at large scale with current technology, far short of the number of modes being excited. In addition, the required actuator response frequencies and forces at any point on the bridge must be able to vary with both the localized and macroscopic crowd sizes. Thus, a robust control solution was required, even if only one or two modes were to be suppressed by active methods. A further issue was raised with respect to the amount of control power required, and the need for a continuous guaranteed power supply. These issues could not be resolved, and the concept of active control was discarded.

Supplemental passive damping. One of the most direct solutions to the problem utilized supplemental viscous damping devices to elevate total structural damping levels to the 20% critical range. This was compared to approximately 0.5% critical damping for the as-built structure. The design concept was based on the premise that added damping would reduce resonant deflections to a low level, such that the bridge would no longer provide any appreciable feedback to the pedestrians.

The advantage of added damping in a structure undergoing forced resonance is well understood, although used more often by mechanical engineers in the technology fields of mechanisms and machinery. For a simple spring-mass-damper system, amplitude under steady-state forced resonance is:

$$X = \frac{X_0}{2\delta}, \text{or } \frac{X}{X_0} = \frac{1}{2\delta}$$

where X = resonant amplitude, X_0 = zero frequency deflection of the spring-mass system under the action of a steady force, δ = critical damping factor

$\frac{X}{X_0}$ = by definition, the magnification factor of the resonant response

Thus, if a simple first order system with 0.5% critical damping is excited by forced resonance, the magnification factor is:

$$\frac{X}{X_0} = \frac{1}{2 \times (.005)} = 100$$

If damping in the system is elevated to 20% critical, then the magnification substantially reduces to:

$$\frac{X}{X_0} = \frac{1}{2 \times (0.2)} = 2.5$$

Constaninou and Symans (1992) and Kasalanati and Constaninou (1999) have conducted previous studies and tests on scaled structural models with added supplemental damping. This research revealed that the addition of viscous damping to a structure tends to suppress the response not only of the damped mode but also of higher order modes. Thus, added viscous damping appeared to be a viable means to suppress the motions observed on the Millennium Bridge.

The bridge design team noted several major design issues for the dampers, and all of these needed to be satisfied before added damping could be considered as a viable solution.

DAMPER DESIGN REQUIREMENTS

The application of damping devices to the bridge resulted in five major design issues, some of which are unique to this particular structure.

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

The second issue was that the damper must respond to tiny deflections as low as .025 mm with high resolution, otherwise the suppression of feedback would not be possible until the bridge was already well into resonance. Damper frequency response requirements were defined as D.C.–2 Hz with a high fidelity output over this entire bandwidth. This issue was compounded by the fact that due to wind, thermal and static loadings, total damper deflections of up to plus or minus 275 mm were required.

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

The fourth issue was that several distinct designs of dampers were required, each of which had different output forces, deflections, component equations and envelope dimensions.

The final design issue was environmental in nature. The dampers are located outdoors over a brackish waterway with tidal flows. The design life was such that all major operating elements of the dampers needed to be constructed from inherently corrosion resistant metals that would not degrade over time.

A total of 17 chevron dampers were installed. These dampers are 0.7 m (2.3') long, with a stroke of 25 mm (1").

FRICTIONLESS HERMETIC DAMPER

Taylor Devices, a 50-year-old manufacturer of damping products, proposed a unique solution to the damper design requirements for the Millennium Bridge. To address the various design issues, a unique and patented damper was proposed, previously used exclusively by NASA and other U.S. government agencies for space based optical systems. These former applications had similar requirements for long life and high resolution at low amplitudes but required relatively low damper forces from small, lightweight design envelopes. These dampers have been used in space on more than 70 satellites to protect delicate solar array panels. The most unique element of this design, a frictionless seal made from a welded metal bellows, does not slide, but rather flexes without hysteresis as the damper moves.

To adapt this basic design to the Millennium Bridge largely involved simply scaling the small satellite dampers to the required size range. All parts, including the metal bellows, were designed with low stress levels to provide an endurance life in excess of 2×10^9 cycles. The metal bellows and other moving parts were constructed from stainless steel for corrosion resistance. To assure a high resolution output, it was required that all damper attachment clevises be fabricated with fitted spherical bearings and fitted mounting pins, such that zero net end play existed in the attachment brackets. All dampers were fabricated and delivered to the bridge site in 2001, and testing of the structure with groups of pedestrians began in January 2002.

PUT TO THE TEST

The bridge was subjected to three separate series of tests during the month of January 2002: two scheduled, one unexpected.

The first test series used a group of 700 people as subjects, statically loading the bridge to approximately one-third capacity. The testing involved walking the test subjects across the deck at various metered speeds with variable group sizes. Maximum local loading density was one person per square meter. This first test series was essentially for preliminary assessment of the modified bridge, and no anomalies were noted.

The second test series was totally unplanned and occurred during the period of January 27 through January 29, 2002, when severe windstorms swept the entire United Kingdom. The overall event was categorized as a ten-year return period windstorm, with peak gusts at the bridge in the 120 km/hour (74.56 mph) range. Again, no anomalies were noted.

The third and final series took place on January 30, 2002, with a total of 2,000 people. The test began at 6:00 P.M., using office workers exiting from businesses near the bridge as test subjects. Crowd control was maintained by stationing the test subjects within fenced compounds at each end of the bridge.

Testing consisted of three well-regulated crossings on the bridge by the

Four vertical dampers (two are shown in this photo) connect the bridge to the ground. They are 2.3 m (7.5') long, with a stroke of 275 mm (10.8").

entire crowd at three different walking speeds with a fourth and final crossing essentially at random. All of these four final tests proved to be totally anticlimactic—the bridge behavior being generally described as "rock solid" by the crowd. More importantly to the engineering team, the damped bridge structure performed superbly:

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

FINAL OBSERVATIONS

The use of supplemental fluid dampers providing 20% critical damping to a suspension-style pedestrian bridge will dramatically reduce or eliminate the potential for biodynamic feedback occurring between the pedestrians and the bridge structure. This level of supplemental damping allows the use of unique bridge architecture, even when the bridge has modal frequencies coincident with normal walking motions of pedestrians.

The Millennium Bridge was officially re-opened to the public on February 22, 2002, without problems or difficulties of any type. Up to four million people each year are expected to visit the bridge while in London.

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