VIBRATION PERFORMANCE OF LONDON’S MILLENNIUM FOOTBRIDGE

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The London Millennium Footbridge has an unusual low-slung suspension design, supported by steel cables anchored to piers on the opposite river banks. When opened in 2000, it was found that low-frequency lateral vibrations were excited by pedestrians. To reduce the amplitude of these swaying oscillations, modifications were made in two ways. One was to install, under the bridge deck, passive tuned-mass vibration absorbers of broadly conventional design. The other was to add damping by introducing linear viscous dampers. These modifications had to be made without altering the visual appearance of the bridge. That made the design of viscous dampers difficult because most of their only suitable locations were where the relative amplitudes of vibration were small. A key feature was therefore to deploy dampers that could work with very small amplitudes of movement. The design of both tuned-mass absorbers and viscous dampers will be reviewed. Proving tests, involving 2,000 people walking over the modified bridge, and the subsequent service experience, including the results of examinations by the manufacturers after 15 years’ service, will be described. An opportunity for IIAV members to visit the bridge is included in the ICSV24 programme.

Keywords: vibration, millennium, bridge, dampers, pedestrians

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1. Introduction

To mark the millennium, a new footbridge was built across the river Thames in London. Following a worldwide competition, the winning design team was led by architect Norman Foster, sculptor Anthony Caro and engineers Arup. Their design is a shallow suspension bridge over 300 metres long, with three spans, the longest, centre span, being 144 metres. The bridge’s suspension cables sag only 2.3 metres and carry a high tensile load of approximately 2,000 tonnes. Detailed computational studies of the bridge dynamics were made, supported by wind tunnel tests on a 1:16 scale model, but the potential severity of human-induced vibration was not anticipated and what became known as the “Fujino effect” was not incorporated in relevant bridge design codes at the time.

Figure 1: the London Millennium Footbridge

When the bridge was opened, it was found to sway noticeably when crowded with walking pedestrians. The amplitude of this crowd-induced lateral vibration was large enough to cause concern that injuries might result, and immediately a decision was made to modify the bridge so as to reduce the amplitude as far as practicable. A very important proviso for all modifications was that, so far as possible, the much-praised elegant appearance of the bridge should remain unchanged. A two-fold approach was therefore adopted.

First, to increase the structural damping of the bridge for lateral movements, a total of 37 viscous dampers were installed. A complication was that connections to the ground could only be made over the south bank, and had little effect on the middle and north spans. Furthermore, there were few adjacent places where sufficient relative lateral motion occurred for dampers to be useful. To overcome the latter problem, Arup introduced an ingenious A-frame design that amplified the available relative motion. Even so, this led to a challenging design specification for the dampers. They were supplied by the US firm Taylor Devices Inc.

Secondly, in addition to the added viscous damping, tuned-mass vibration absorbers were installed under the bridge deck. Their action effectively reduces the amplitude of lateral movement by exerting a counteracting force at the lateral resonant frequency (and for this reason we use the term ‘absorber’, rather than ‘damper’, to distinguish between the two devices). For the centre span, four pairs of laterally-acting absorbers were installed. Also, to guard against the possibility, however unlikely, that synchronous vertical vibration might occur when the lateral problem had been resolved, 26 more pairs of vertically-acting absorbers were distributed across the complete span, all out-of-sight under the bridge deck. All these tuned-mass absorbers were supplied by the German firm GERB Schwingungsisolierungen GmbH.

In order to understand the design requirements for these modifications to the bridge, a detailed research programme was carried out, most of the work being done by Arup, but with contributions from Professors Fujino in Japan, and Bachmann in Switzerland, as well as experts in the UK. This has been reported in detail already. A complete bibliography would be lengthy, but some of the contemporary papers are listed and include references to most of the salient publications within them.

The focus of the present paper is on the design of the viscous dampers and tuned-mass absorbers that were installed, how they were tested in situ, and how well they have performed during the 15-year period since the bridge was reopened to the public in early 2002.

The target level of additional damping was between 15% and 20% of critical for all lateral and lateral/torsional modes below 1.5 Hz, and between 5% and 10% of critical for vertical and vertical/torsional modes below 3 Hz. The most important target, for the main lateral mode that is excited by walking pedestrians, was 20% of critical. These values compare with original measured values of 1% of critical or less. The required increase in damping was therefore effectively unachievable with typical solutions, such as tuned-mass absorbers or viscous/frictional elements acting alone.

2. Tuned-mass absorber layout and design

The idea of tuned–mass vibration absorbers is over 90 years old and has been applied practically in structural engineering over the last 35 years or so. The governing parameter for an absorber and its efficacy – besides an optimum tuning frequency and damping ratio – is the ratio between the effective mass of the absorber and the modal mass of the relevant structural vibration mode. Figure 2(a) illustrates the additional structural damping that can be achieved in theory based on this mass ratio.


(a) (b) (c)

Figure 2: (a) typical additional damping vs. mass ratio achieved for random and harmonic excitation; and installation of (b) laterally- and (c) vertically-acting tuned-mass absorbers on the Millennium Footbridge.

The proposed solution for the Millennium Footbridge included 26 pairs of vertically-acting absorbers, each with an effective mass of between 1 t and 3 t (mass ratio 3-5%) and four pairs of laterally-acting absorbers with an effective mass of 2.5 t (mass ratio 15%). The 11 different types of vertical absorbers are addressing vibration modes between 1.1 Hz and 2.2 Hz, with the lateral absorbers addressing the fundamental lateral mode at 0.48 Hz. The main challenge for the absorber design was to incorporate the devices aesthetically into the overall bridge design, and to keep the additional supporting steelwork at the bridge deck to a minimum. Several design approaches were considered, including a bi-directional absorber (vertically and laterally effective) but the final design was based on uni-directional units that could be attached directly to the main lateral members of the deck (see Fig. 2(b-c)).

The key components of the absorbers – the springs and damping units – were tested separately at the factory, as well as the fully-assembled units. See Figure 3. The springs were tested for stiffness, and endurance tests were performed to ensure adequate fatigue life. Force-deflection tests were performed with the damping devices to verify the required damping ratio for a specified temperature range, and to verify that this ratio remains constant during long-term cyclic loading.

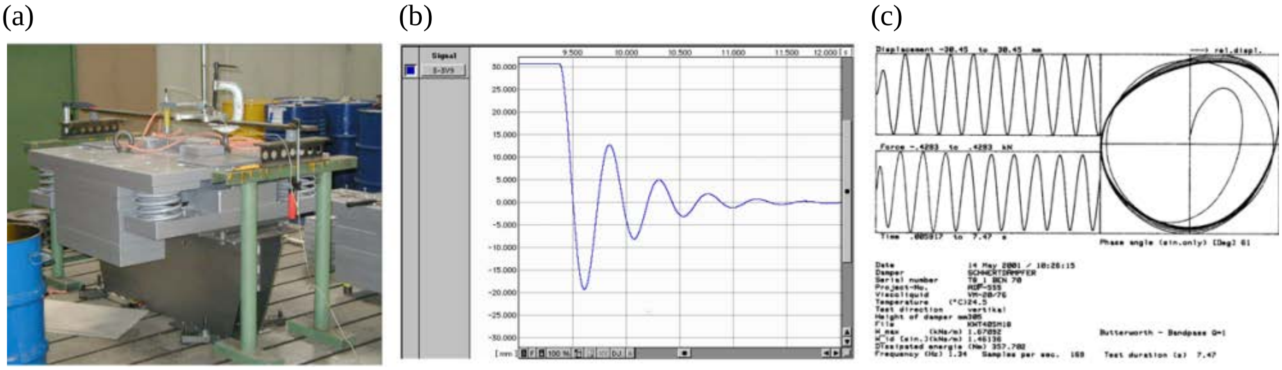
(a) (b) (c)

Figure 3: (a) workshop testing of a vertically-acting tuned-mass absorber, showing (b) the amplitude-time decay curves of the step response and (c) the force-deflection diagrams of the frequency response.

In addition, both the step response (Fig. 3(b)) and frequency response (Fig. 3(c)) of the fully assembled absorbers were measured to obtain the tuning frequency and damping ratio. The former involved measuring the amplitude-time decay of an absorber released from its position of maximum travel; the latter involved measuring the response to base excitation on a shake table.

3. Viscous damper layout and design

A total of 37 viscous dampers are employed on the bridge, arranged as shown in Figure 4. Four ‘vertical dampers’ are located in two pairs on the south bank (see Fig. 4(a)), connected between the ground and a structural arm on the bridge.

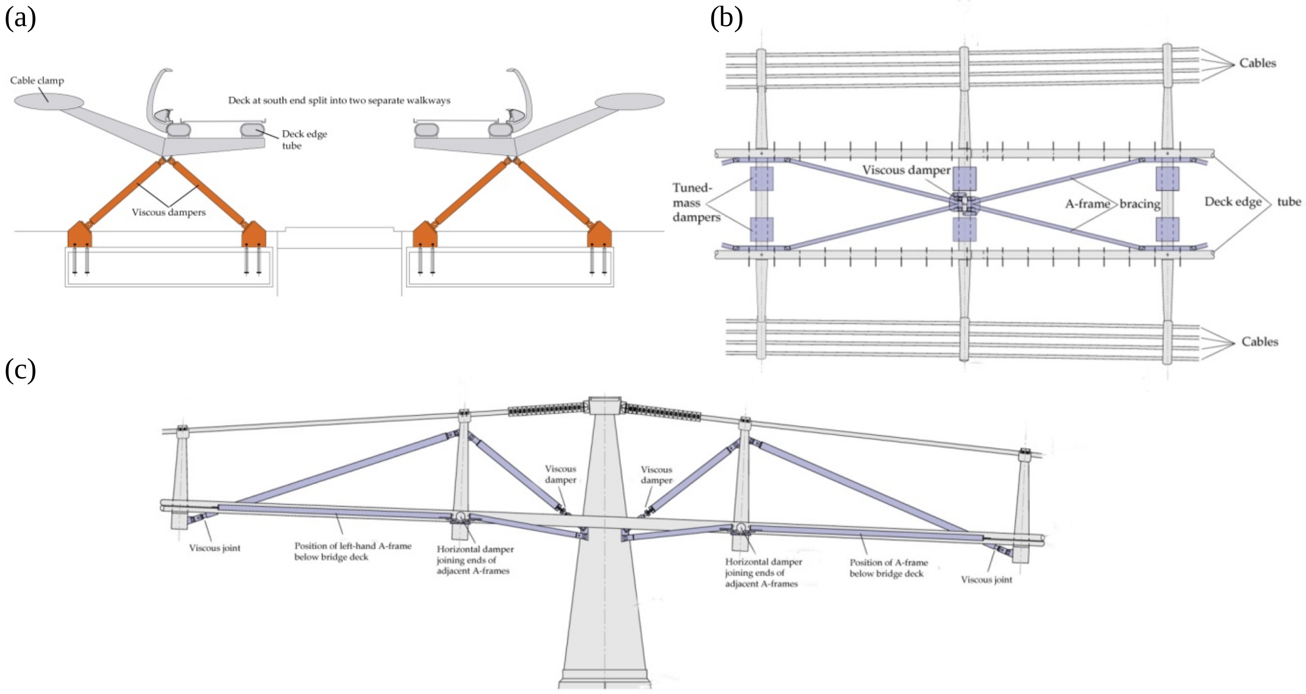

Figure 4: the viscous damper arrangement, showing (a) the ‘vertical dampers’ connected to the south bank, (b) the A-frame arrangement connecting the horizontal ‘deck dampers’ and (c) a side elevation showing two pairs of ‘pier damper’. Based on similar figures in Dallard et al. [3, 4].

As noted in the Introduction, to enable the effective use of dampers laterally, an ingenious A-frame design was employed (Fig. 4(b)), which was incorporated directly under the deck panels of the bridge. Rigid A-frames were attached to alternate load-bearing transoms of the deck so that relative yaw of the transoms would be translated into lateral motion of the tips of the A-frames. By connecting a total of 17 horizontal ‘deck dampers’ between the tips of adjacent A-frames, it was demonstrated that sufficient damping could be introduced. Even so, the target limit of the span acceleration response, of less than 0.02 g r.m.s. at about 1 Hz, corresponds to a span lateral amplitude of the order of 10 mm and relative movement of the A-frame tips of 1 mm, so that it was necessary for the dampers to operate at working amplitudes of the order of 0.5 mm and below.

Sixteen ‘pier dampers’ complete the arrangement, with eight dampers per pier arranged in pairs either side of each of the two piers, on both the east and west side of the bridge.

A significant design challenge was the requirement for a permanent, maintenance-free solution that would last throughout the life of the bridge. It was necessary to specify a minimum life of 2×10^9 cycles, based on a design life of 50 years continuous cycling of the dampers at 1.3 Hz (the maximum frequency at which synchronous pedestrian excitation is believed to be possible). Due to this long-life, low-maintenance requirement, Taylor Devices proposed the use of specialised viscous dampers that employ flexing metal bellows seals, rather than traditional sliding seals that are elastomeric in nature and therefore subject to wear and degradation over long-term environmental and cyclic conditions. Figure 5 illustrates the design, known as a Frictionless Hermetic Damper. Two metal bellows seals are used to seal fluid in chambers at each end of the damper. As the damper moves, the two bellows alternately extend and retract by flexure of the individual bellows segments. Since the seal element flexes elastically, 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 near-frictionless performance.

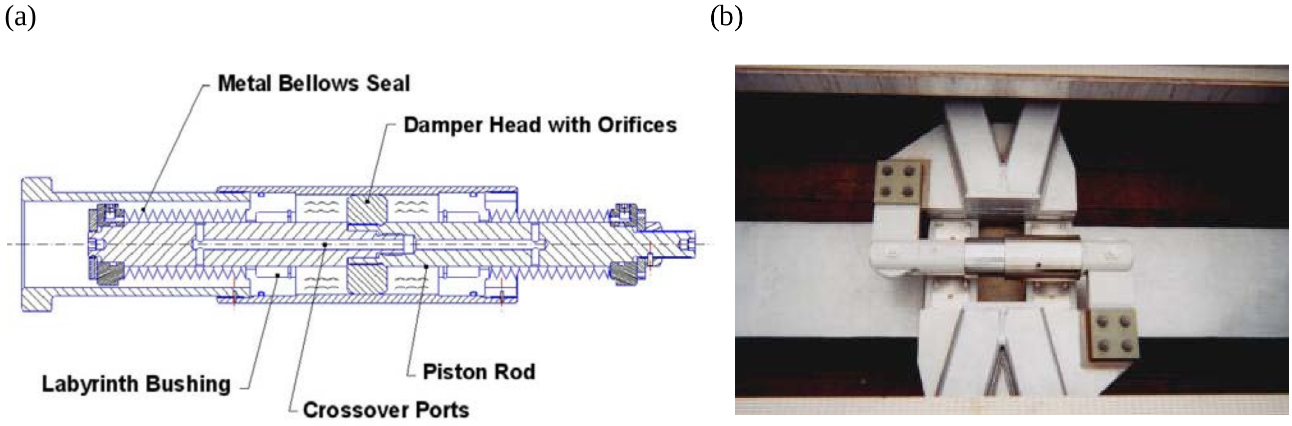

Figure 5: the Frictionless Hermetic Damper, showing (a) the design details and (b) an example deck-damper in position on the bridge.

Such dampers had been used previously by NASA, and other U.S. Government agencies, for space-based optical systems, which have similar requirements for low-amplitude operation and long life but require relatively low damper forces. Adapting this design for use on the Millennium Footbridge largely involved scaling the small satellite dampers to the required size range. All parts, including the metal bellows seals, were designed with low stress levels to provide an endurance life in excess of the required 2×10^9 cycles. The metal bellows and other moving parts were constructed from stainless steel for corrosion resistance. To assure low-amplitude operation, 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.

4. Acceptance test

Because of the negative publicity that occurred when the bridge ‘wobbled’ on its opening day, its funding body, the London Millennium Bridge Trust, wished to make sure that, whatever calculations suggested, the modified bridge would perform satisfactorily when carrying a full load of walking pedestrians. It was therefore determined to carry out a full-scale test. For this purpose, some 2,000 people were assembled under cover of darkness one January evening in 2002. Starting from the south bank, they walked across to the north side of the bridge, where they reassembled before walking back to the south bank. Meanwhile the response of the bridge was monitored by numerous transducers whose output was logged. It was immediately seen that the target vibration limit of 0.02g r.m.s. below 1 Hz was being achieved.

Subsequent calculations for crowd-induced lateral vibration, focussed on a non-dimensional “Pedestrian Scruton Number” S_{cp} which, for each mode, is the product of the modal damping ratio and the ratio of bridge mass/length to pedestrian mass/length [7, 8]. These calculations indicated that maintaining S_{cp} above 1.0 would ensure stability under all realistic conditions. Having originally been approximately 0.1, the modifications to the bridge have been shown to increase S_{cp} to approximately 2.3. The safety factor is therefore high.

Figure 6: pedestrian acceptance tests demonstrated the success of the bridge modifications.

5. Tuned-mass absorber long-term performance

The tuned-mass absorbers are also designed to be maintenance free. The vertical masses are supported on springs that centralise automatically, whilst the lateral units are designed as a folded pendulum device, thereby minimizing the number of bearings and sliding contacts. The VISCODAMPER® damping element is based on a piston plunging in a viscous fluid, the resulting damping ratio being a function of the fluid's viscosity and the shear area. The design avoids any joints or seals, and the piston does not have to be guided, again avoiding any sliding contact.

A random selection of the absorbers has been inspected regularly for corrosion and mobility since the reopening of the bridge, the last inspection being in October 2012 (see Fig. 7). In particular, the protective sleeves of the damping elements are checked for degradation and water ingress. All inspected absorbers have shown no significant corrosion, and the visual inspections of the damping elements have revealed no degradation, leakages or water ingress.

Figure 7: the inspection of the installed tuned-mass absorbers in 2012, showing (above) vertically-acting and (below) laterally-acting absorbers.

In addition to the visual inspections, the absorber parameters (i.e. the tuning frequency and damping ratio) of the inspected units have been determined from in-situ vibration tests (see Fig. 8). To do this, it is not sufficient to analyse the response of the absorber mass alone, since the absorber interacts with the structure of the bridge. Instead, transfer functions are measured between the acceleration of the absorber mass and that of the bridge, which may then be compared to a single-degree-of-freedom response curve and the parameters derived. Either the response following direct manual excitation of the absorber mass or that under ambient wind excitation may be used, the latter providing more accurate values of damping ratio. In this way, it has been verified that the absorber parameters remain unchanged from their original 2001 values.

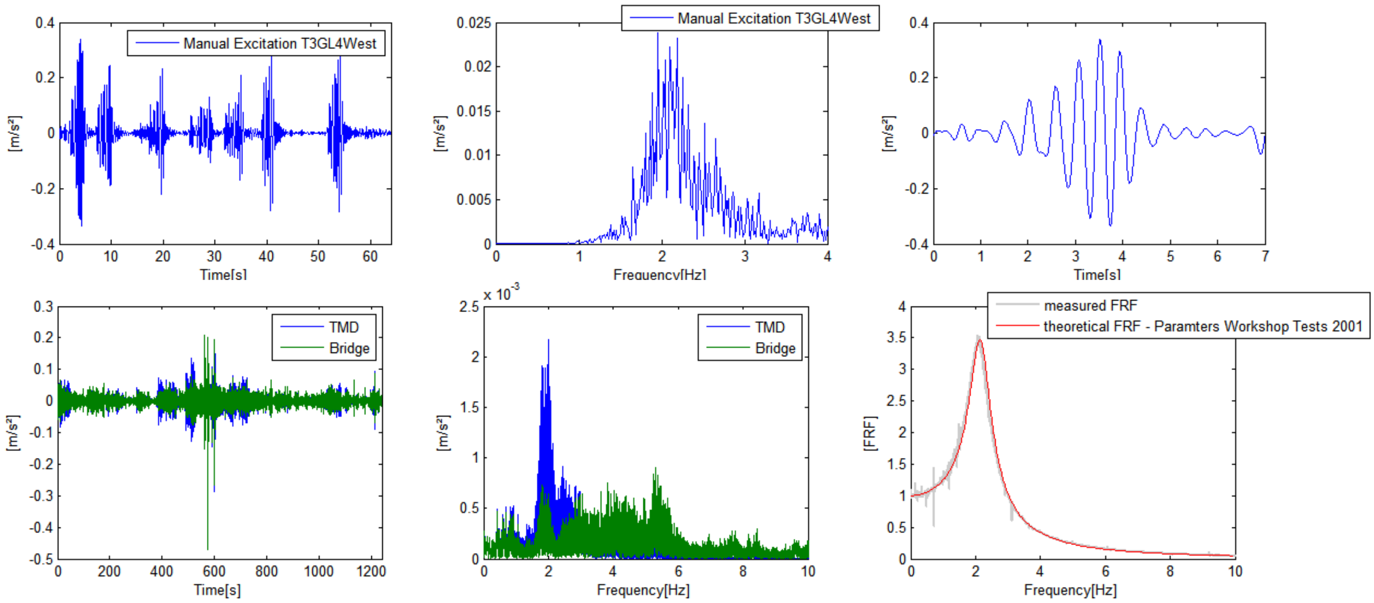

Figure 8: in-situ test results from the 2012 inspections, illustrating (above) the response of the absorber mass under direct manual excitation (time record, FFT spectrum and amplitude-time decay curve) and (below) ambient vibration records (time record, FFT spectrum and frequency-response function).

6. Viscous damper long-term performance

Taylor Devices have performed two inspections of the viscous dampers following their installation: an intermediate inspection after approximately 7 years' service (amounting to ~2.0 x 10^8 cycles), followed by a more comprehensive inspection after a total of 11 years (~3.1 x 10^8 cycles).

A visual inspection of each damper was performed as part of the intermediate inspection, looking for corrosion, service damage to the unit and for fluid leakage. The units were all found to be in working condition, with minimal signs of physical damage or deterioration, and no signs of fluid leakage. Only minor signs of corrosion and some external contamination were noted.

In 2012, a second visual inspection was performed, which examined all pier dampers, the vertical dampers and a sample of five of the deck dampers (to minimize deck panel removal costs). Again, only minor signs of corrosion and some external contamination were noted. This appears to have been caused by the corrosive action of exhaust fumes from passing river traffic, since dampers located near to, or over, the river banks exhibited nearly new appearance.

Following this inspection, two deck dampers and one vertical damper were temporarily removed from the bridge for dynamic testing at the Taylor Devices facility in North Tonawanda, New York. These tests followed the original acceptance test procedure, and used the original test machine (with force and velocity measurement accuracy of approximately ±2%), such that the results could be compared directly with the original test results from 2001. The procedure involved two types of test: a 'force vs velocity' test, in which the dampers were cycled sinusoidally throughout the specified velocity range; and a 'low amplitude' test, performed at approximately 0.5 mm amplitude to confirm the low-amplitude operation of each damper and verify that there had been no loss of fluid, which proved to be the case.

Figure 9 compares the results of the force vs velocity tests conducted in 2001 and 2012. It is clear that there has been negligible change in damper characteristics over the 11 year period.

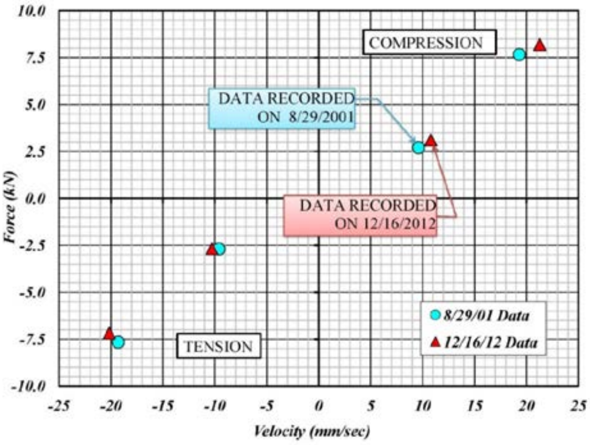

Figure 9: ‘force vs velocity’ test results for the dampers, indicating negligible change in damper characteristics over the 11 year period in service.

7. Conclusions

The London Millennium Footbridge now has an exceptionally high level of structural damping. The required amount of additional damping was between 5% and 20% of critical for vibration modes below 3 Hz, compared with original levels of 1% of critical or less. A combination of mechanical shaker tests on the unloaded bridge, and the crowd acceptance tests of 2001, have indicated that these levels of damping have been achieved by the combined action of the viscous dampers and tuned-mass absorbers described here. Furthermore, subsequent calculations for crowd-induced lateral vibration, based on the “Pedestrian Scruton Number”, indicate that the safety factor is high and that a significant reduction in performance is required before there is any significant risk that the modified bridge will wobble again.

Now that detailed inspections of the dampers and absorbers installed on the bridge have confirmed their continued satisfactory performance, after over 15 years’ service, there is no doubt that the bridge may be expected to continue to serve its purpose satisfactorily for many years to come.

8. References

1. Bachmann, R. H. Case studies of structures with man-induced vibrations, *Structural Engineering, Trans. ASCE*, 118, 631-647, (1992)
2. Bachmann, R. H. and Ammann, W. Vibrations in structures induced by man and machines, *Structural Engineering Document 3e, Int. Assoc. for Bridge and Structural Engineering (IABSE)*, Ch. 2: Man-induced vibrations, (1987)
3. Dallard, P., *et al.*, London Millennium Bridge: Pedestrian-induced lateral vibration, *J Bridge Engineering, Trans. ASCE*, 6, 412-417, (2001)
4. Dallard, P., *et al.*, The London Millennium Footbridge, *Struct Engineer*, 79, 17-33, (2001)
5. Fujino, Y., Synchronization of human walking observed during lateral vibration of a congested pedestrian bridge, *Earthquake Eng. and Struct. Dynamics*, 22, 741-758, (1993)
6. Newland, D. E., Vibration: problem and solution, in Sudjic, D. (ed), *Blade of Light: the story of London’s Millennium Bridge*, Penguin, London, 88-93, (2001)
7. Newland, D. E., Vibration of the London Millennium Bridge: cause and cure, *Int. J. Acoust. Vibr.*, 8, 9-14, (2003)
8. Newland, D. E., Pedestrian excitation of bridges, *Proc. Inst. Mech. Engrs., Part C, J. Mech. Engng. Sci.*, 218, 477-492, (2004)
9. Roberts, T. M., Synchronized pedestrian excitation of footbridges, *Bridge Engng, Proc. ICE*, 156, 155-160, (2003)
10. Taylor, D., Damper retrofit of the London Millennium Footbridge – a case study in biodynamic design, *Proc. 73rd Shock and Vibration Symposium* (2002)