Acoustics • Shock • Vibration • Signal Processing **August 2002 Newsletter**

Shalom

I hope that you are enjoying your summer and that your projects are going well.

A few notes about my projects….

I am currently performing consulting work at Orbital Sciences Corporation in Chandler, Arizona, where I have the opportunity to perform a variety of shock and vibration tasks.

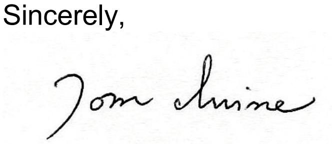
For example, I am analyzing the bending modes on a launch vehicle via the finite element method. I am also using the Rayleigh-Ritz method to verify the finite element results for both the natural frequencies and the corresponding mode shapes. This data is needed for the autopilot control algorithm.

In addition, I am performing a fretting analysis on an electrical connector for an automotive company. Fretting is related to fatigue.

Finally, I am working with a marine company to characterize the shock levels encountered by Navy Seals that must travel in high speed planing boats.

Well, I hope you enjoy this month's newsletter.

Sincerely,



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Feature Articles

Welcome to Vibrationdata Consulting Services

Vibrationdata specializes in acoustics, shock, vibration, signal processing, and modal testing. The following services are offered within these specialties:

1. Dynamic data acquisition
2. Data analysis and report writing
3. Custom software development and training
4. Test planning and support

Vibrationdata also performs finite element analysis.

Vibrationdata's Customers

Allied-Signal Fluid Systems and Turbine Engine Divisions

Boshart Automotive

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ECS Composites

Itron

Motorola Flat Panel Display

Motorola Government Electronics Group

Orbital Sciences Corporation

Prolink

SpeedFam

Sumitomo Sitix

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The London Millennium Bridge Vibration by Tom Irvine

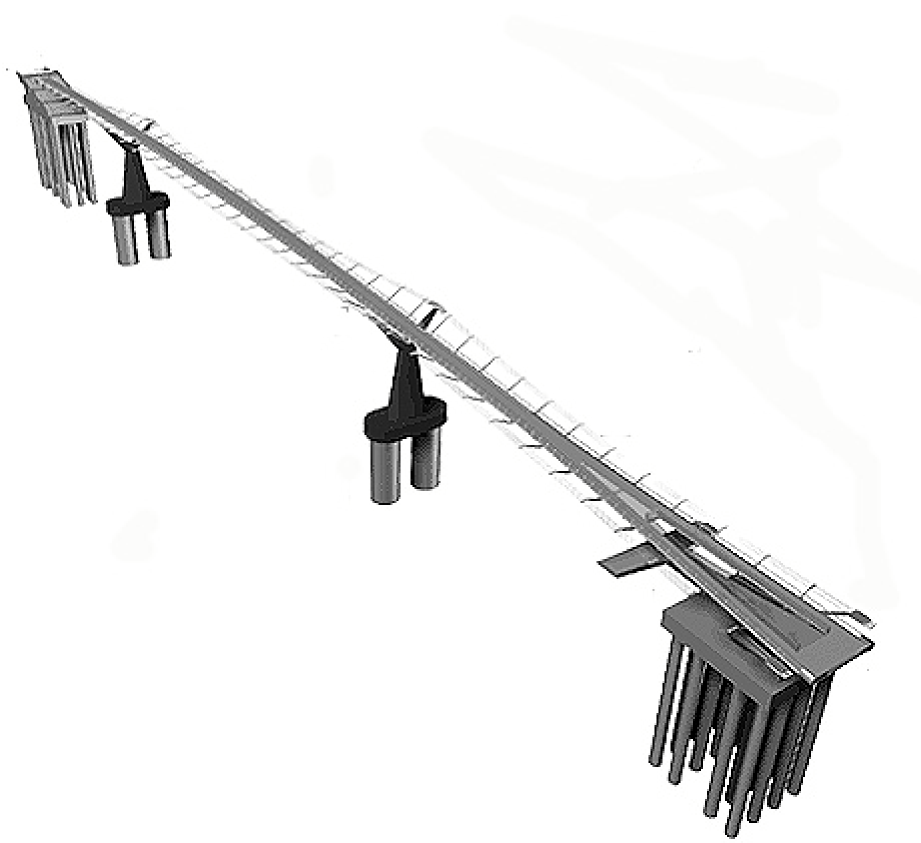

Figure 1. Computer Model of the Millennium Footbridge

Introduction

London's Millennium Bridge is the first pedestrian river crossing over the Thames in central London for more than a century.

The bridge has a unique design that was chosen to provide unimpeded views of St. Paul's Cathedral.

Design

The Millennium Bridge is a 325-meter long suspension bridge that links the City of London at St. Paul's Cathedral with the Tate Modern Gallery at Bankside.

Transverse arms flank the 4-meter wide aluminum deck. The steel arms are configured in a very shallow V pattern. They are spaced at 8-meter intervals, as shown in Figure 2.

The arms are clamped onto stainless steel cables. There are four cables on each side of the bridge that span from bank to bank. The arms transfer the bridge load to these cables.

The four cables on each side of the deck are anchored at each abutment and propped by two river supports.

Figure 2. Transverse Arms and Cables

Opening

The bridge opened to the public on June 10, 2000. An estimated 80,000 to 100,000 people crossed it on this day. The maximum number of pedestrians at any given time was about 2000.

The bridge underwent lateral swaying motion due to the foot traffic. The swaying was severe enough that some people had to grab hold of the handrails in order to maintain balance.

A decision was made to close the bridge two days after the opening in order to investigate and resolve the swaying problem.

The concern was the safety of individuals, rather than any risk of structural failure of the bridge itself.

Vibration Response

The amplitude of the oscillation varied along the length of the bridge.

The south span, between Bankside and the first river pier, experienced both horizontal and torsional (twisting) oscillations. The maximum displacement was 50-mm, depending on the number people walking. The frequency of the movement was about 0.77 Hz. This was the "first south lateral mode."

The center span moved up to 70-mm, mainly in the horizontal direction. This motion was a combination of the first and second lateral modes, with frequencies of 0.49 Hz and 0.95 Hz, respectively.

The north span did not move substantially.

The bridge natural frequencies are taken from Reference 1.

Note that humans are more sensitive to horizontal motion than vertical motion below 3 Hz.

Excitation Source

The candidate vibration sources were the wind and the pedestrian traffic.

Wind tunnel tests were performed on 1:16 scale sectional models. The test data showed that the bridge was aerodynamically stable. The slim depth and round edges of the cross section contribute to this stability. Furthermore, the data showed no significant vortex shedding.

The excitation source was determined to be a substantial lateral loading effect by the pedestrians. This loading condition had been unanticipated during the design process.

Specifically, the pedestrians had been synchronizing their steps with the bridge motion and with one another. This behavior was instinctive rather than deliberate.

Pedestrians find that walking in synchronization with the natural swaying of the bridge is more comfortable, even if the degree of swaying is initially very small. This cadence makes their interaction with the movement of the bridge more predictable and helps them maintain their lateral balance.

This behavior ensures that footfall forces are applied at the resonant frequency of the bridge, and with a phase that increases the motion of the bridge.

As the amplitude of the motion increases, the lateral force imparted by individual pedestrians increases, as does the degree of correlation between individuals.

Thus, resonance excitation occurred.

Footfall Frequency

A pedestrian creates a repeating pattern of forces as his mass rises and falls against the ground. The force has a vertical, lateral, and torsional component.

Pedestrian vertical forces correspond to each footfall, and typically occur at 2.0 Hz.

The bridge modes at 0.49, 0.77, and 0.95 Hz were separated from the vertical footfall frequency by more than on octave. Thus, vertical footfall forces did not drive the bridge resonance.

Lateral and torsional forces, occur at the "half walking frequency," typically 1.0 Hz. Thus, the pedestrians' lateral and torsional footfall forces provoked resonant excitation of the bridge's second lateral mode, which was 0.95 Hz. The same forces also induced excitation of the lower modes, although to a lesser extent.

Force Amplitude

Again, a pedestrian creates a repeating pattern of forces as his mass rises and falls against the ground. This creates a vertical fluctuating force of around 250 to 280 N (55 to 63 lbf), which repeats with each step. The exact value depends on the individual's weight and gait.

In addition, the pedestrian creates a small sideways force caused by the sway of his mass, as his legs are slightly apart. This force, approximately 25 N (5.5 lbf), is directed to the left when he is on his left foot and to the right when he is on his right foot and repeats with every second step. These force values are taken from Reference 1.

Design Modifications

Three options were considered for modifying the bridge to reduce the oscillations.

The first was to stiffen the bridge. This would increase the natural frequencies. The displacement would thus be reduced. The specific goal would be to raise the 0.49 Hz lateral frequency by a factor of three, to 1.5 Hz. This would require increasing the stiffness by a factor of nine, however, assuming constant mass.

The second option was to limit the number of people on the bridge or modify their walking patterns artificially using obstructions such as street furniture, for instance.

The third option was to increase the damping of the bridge structure. This would reduce the dynamic response by absorbing energy in each cycle of movement.

The engineers investigating the problem chose the damping solution. Both passive damping and a "tuned mass damper" were chosen for the modification. One of the design modification goals was to achieve 15% to 20% of critical damping for the lateral modes.

Passive Damping

Each passive damper is a "low friction viscous damper," that is somewhat similar to a shock absorber. Each damper dissipates energy by the movement of a piston passing back and forth through a fluid.

The viscous dampers were mounted under the bridge deck and around the piers and the south landing to control the lateral motions. A distinctive new chevron steelwork transfers the bridge movements to the viscous dampers beneath the deck, as shown in Figures 3 and 4.

Tuned Mass Damper

The tuned mass dampers are simple weights mounted on compression springs, as shown in Figure 5. Their purpose is to reduce vertical movements. They were added to the solution as a precaution.

The tuned mass dampers are installed on top of the transverse arms beneath the deck. They are positioned along the length so that they are at or close to the modes that they are damping.

The weight of each mass varies from 1 to 3 tons.

Bridge Reopening

The Millennium Bridge was successfully reopened on February 22, 2002.

Jonathan Duffy wrote in a BBC article:

> But the bridge doesn't wobble. Despite the blasts of wind, which seem to come barreling down with ever greater ferocity as we lose the cover of surrounding buildings, it stays firm.
>
> There is an ever so slight bounce under foot, but this almost seems reassuring. Even when the crowds are as thick as Oxford Street on a Saturday afternoon, there is no hint of sway.
>
> No one is gripping on to the side barriers for dear life. In fact the atmosphere is relaxed and a little festive. Parents trundle over with pushchairs, a cyclist pedals hurriedly, betraying not an ounce of ceremony.

References

1. P. Dallard, et al, The London Millennium Footbridge, The Structural Engineer, November 2001.

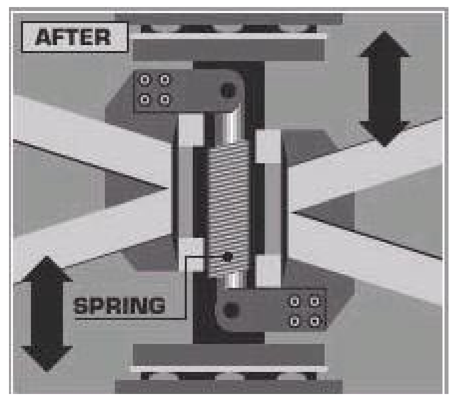

Figure 3. Viscous Damper (Courtesy of BBC)

This viscous damper is located at the position where the two chevron points meet.

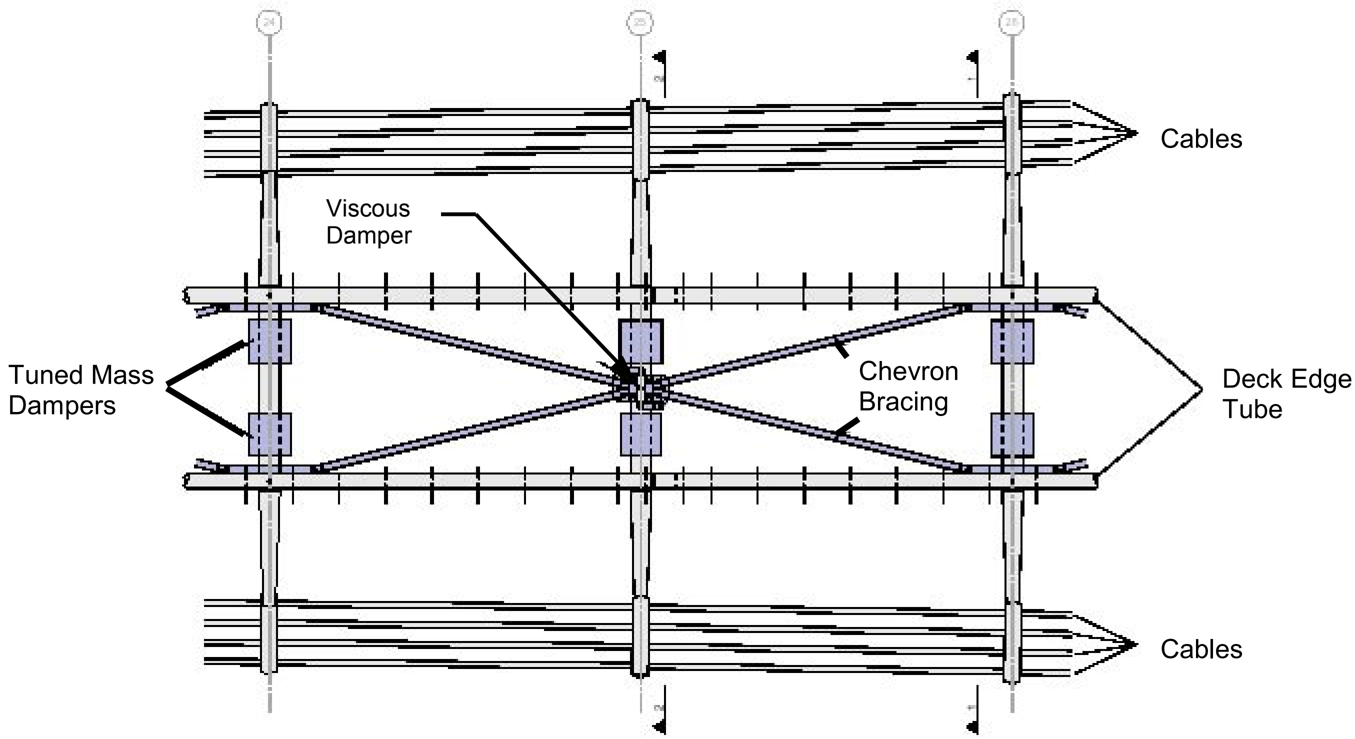

Figure 4. Viscous and Tuned Mass Dampers (from Reference 1)

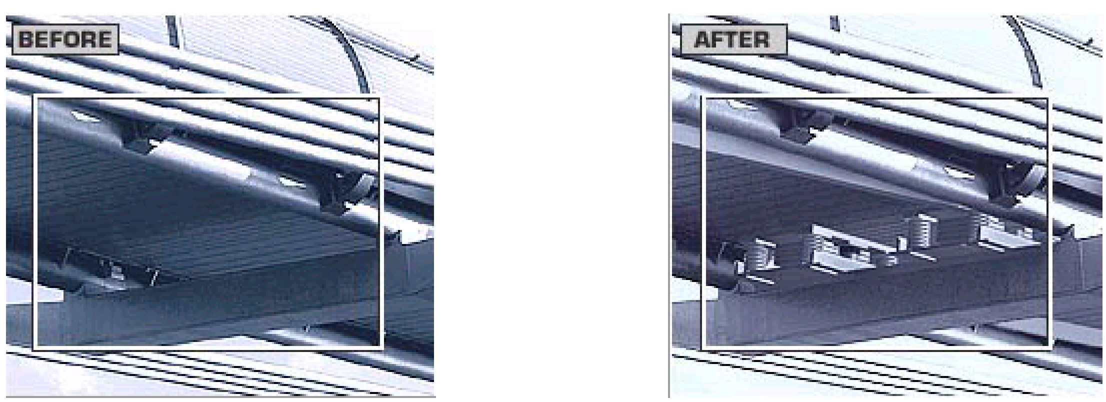

Figure 5. Addition of Tuned Mass Dampers (Courtesy of BBC)

VIBRATION OF THE HUMAN EYE

By Tom Irvine

Figure 1. Head-up Display

Image courtesy of Rockwell Collins

Introduction

Sound and vibration can effect human vision. The body has reflex mechanisms which attempt to compensate for these effects.

Vibration Sources

Either the target object or the observer may undergo vibration. An example where both effects could occur is in the cockpit of a fighter aircraft.

Many fighter aircraft have a "head-up" display, as shown in Figure 1. This display is a system which projects data onto the windshield just below the pilot's line of sight. Note that a fighter aircraft can undergo substantial vibration, particularly if it is flying near the transonic velocity. The resulting vibration can cause the blurring of the data image.

Passive Vibration

Eye resonant frequencies are highly variable between individuals. The fundamental frequency tends to occur between 20 and 70 Hz, according to Reference 1. Some individuals experience blurring caused by the excitation of the eye resonance when humming or playing a musical instrument. Resonance may also occur in a few vehicles and near some industrial machinery.

Pupil Dilation

Sound can cause dilation of the pupil, according to Reference 2. Dilation can begin at a sound pressure of 75 dB. This level corresponds to busy traffic or a noisy restaurant. Laboratory studies show that a rapid resumption of the normal pupil diameter occurs when the noise source is suddenly removed.

Psychological Effects

The effects of sound and vibration can be psychological as well as physiological.

For example, building vibration may cause suspended light fixtures to oscillate. This could be an annoyance to the occupants, who might feel less secure in the building.

Reflexes

The eye is part of control system, as discussed in Reference 1. There are several reflex mechanisms which are part of the control loop. These reflexes attempt to compensate for the target object vibration or for the observer's own vibration.

One reflex is the "vestibulo-ocular" reflex. Head rotation is sensed by the semicircular canals in the ear. This reflex attempts to maintain a stable line of sight.

Another is the "pursuit reflex." The eye rotates to follow the moving object. This reflex is only useful for target vibration below 2.5 Hz for sinusoidal vibration and 1 Hz for random vibration. The exact frequency limits also depend on amplitude.

References

1. M.J. Griffin, Handbook of Human Vibration, Academic Press, London, 1990.

2. C. Harris, Handbook of Acoustical Measurements and Noise Control, McGraw-Hill, New York, 1991.