Modal Testing of Tamar Suspension Bridge

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ABSTRACT

The paper described modal testing of the Tamar suspension bridge by University of Sheffield in April 2006

1 INTRODUCTION

The Tamar Bridge (Fig. 1) is a vital transport link over the River Tamar carrying the A38 trunk road from Saltash in Cornwall to the city of Plymouth in Devon. The bridge is owned, operated and maintained by the two local authorities, and has relied solely on toll income to cover all capital and operating costs.

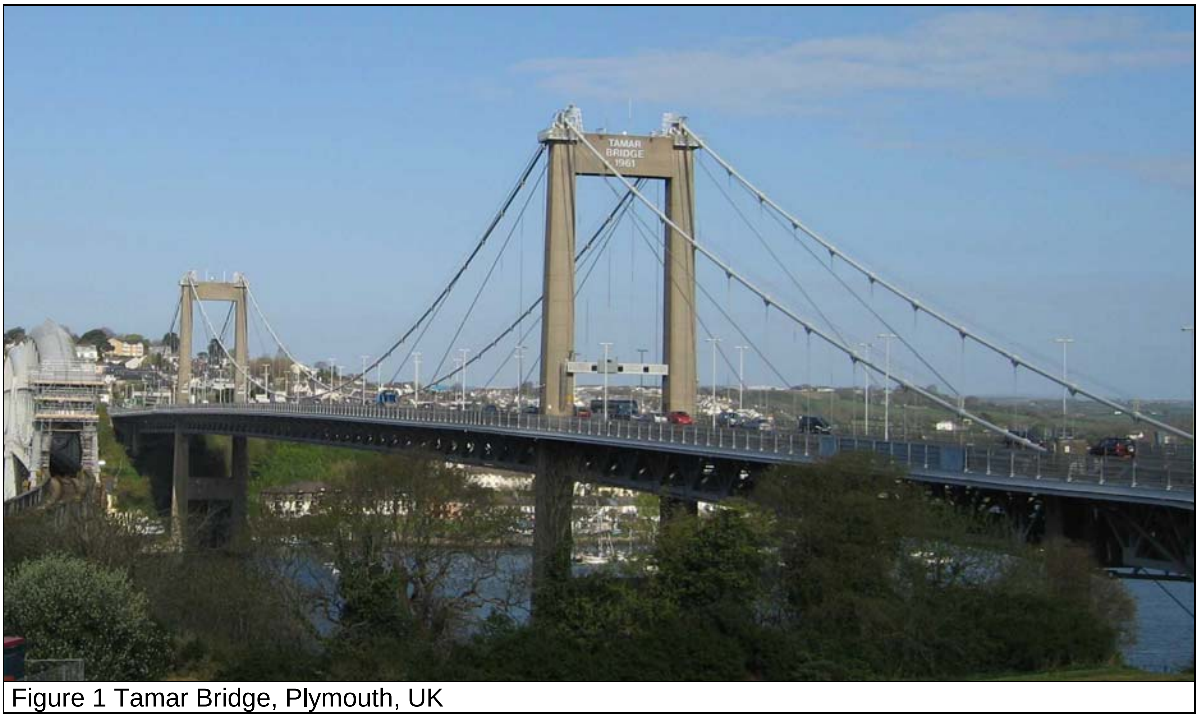


Figure 1 Tamar Bridge, Plymouth, UK

The original bridge opened in 1961, was designed by Mott Hay and Anderson as a conventional suspension bridge with symmetrical geometry, having a main span of 335m and side spans of 114m, and with anchorage and approach spans the overall length is 642m. Unusually for a suspension bridge of this era, the towers were constructed from reinforced concrete, and have a height of 73m with the deck suspended at half this height. The towers sit on caisson foundations founded on rock. Main suspension cables are 350mm in diameter and each consists of 31 locked coil wire ropes, and carries vertical locked coil hangers at 9.1m intervals. The stiffening truss is 5.5 metres deep and composed of welded hollow boxes.

The bridge was the subject of a strengthening and widening exercise [1], completed in December 2001, necessary because after nearly four decades of use, it was found that the Tamar Bridge would not be able to meet a new European Union Directive that bridges should be capable of carrying lorries up to 40 tonnes. Since restricting use by such vehicles would damage the local economy, the bridge needed to be strengthened or replaced. The upgrading included the following major components:

- Eighteen new nominally 100mm diameter locked-coil cables were installed and stressed to supplement the original suspension system, primarily to help carry the additional dead load of the new cantilever lanes and associated temporary works.
- The composite main deck was replaced by a three-lane orthotropic steel deck.
- Single lane cantilevers were added each side of the truss
- Continuity of the main span with the Plymouth side span via an articulated link at the Plymouth Tower was replaced by continuity of the cantilevers around the Plymouth tower. The main span and Saltash side spans remain disconnected.

2 SYSTEM IDENTIFICATION FOR STRUCTURAL HEALTH MONITORING

A structural health monitoring (SHM) system is being installed and operated on the bridge, comprising a set of three accelerometers close to midspan to measure vertical, lateral and torsional response of the deck, and eight accelerometers on the additional stays. Other instrumentation includes sensors installed during the upgrading and comprising load cells in line with the additional stays and anemometers. These have been supplemented with extensometers installed at Saltash Tower to track relative motion between deck sections and tower.

Data from these sensors are collected and tracked automatically, with online automatic mode parameter extraction from the accelerometer signals using a procedure based on the Stochastic Subspace Identification (SSI) procedure. Slowly sampled static data and modal parameters extracted from the accelerometers are tracked using time series data mining procedures, with additional diagnosis to be provided using a validated structural model of the bridge.

This ‘validated model’ is under construction and development using ANSYS, with manual tuning and automated model updating based on modal information available from a modal test of the bridge carried out in April 2006.

3 MODAL TESTING FACILITIES AND PLANNING

Facilities and staff from the Vibration Engineering Section (vibration.shef.ac.uk) were used for the ambient vibration survey on 28th April 2006, preceding two days of forced vibration testing on floor systems for a new retail development in Plymouth. Testing facilities comprised:

- A set of 16 QA700 and QA750 Quartz-flex servo accelerometers
- Data Physics Mobilyzer multi-channel data acquisition/spectrum analyzer system
- Cabling system with six 100m and two 50m four-channel cable drums, 2 50m and multiple 10m and 20m single channel colour-coded cables
- MODAL and Artemis operational modal analysis (OMA) software

Figure 2 shows the test grid; as planned, measurement positions on the deck were located at every 2nd hanger.

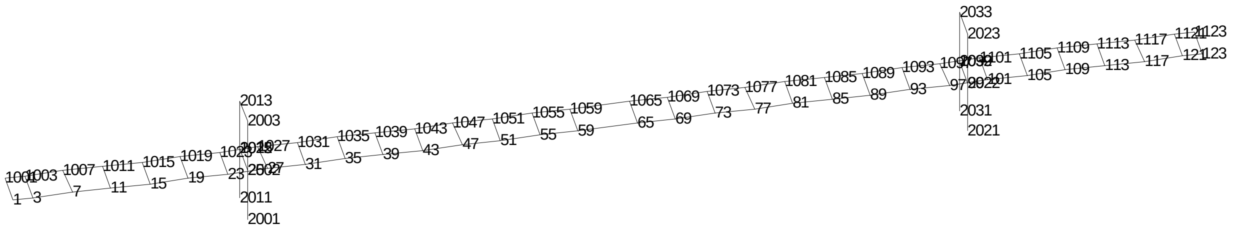


Figure 2 Test measurement grid

As the hangers are attached to main crossbeams of the truss, these provided ideal locations for the accelerometers. The hanger attachment points such as shown in Fig. 3 are in a walkway between the cantilever walkway (south side) or vehicle lane (north side) and the three-lane main deck. All except two measurement points were located on the south side of the deck; two biaxial accelerometer arrangements involving four channels such as shown in Fig. 4 were left at positions 1081 and 1085. Due to the limited cabling and the troublesome access between north and south sides of the deck no further measurements could be made on the north side of the deck. The measurement and acquisition station were planned to be located on a platform created by the widening of the cantilever around the Plymouth Tower where mains power was available.

Figure 3 Hanger connection, shear box and cabling

Figure 4 Hanger termination and biaxial accelerometers

Figure 5 acquisition and control station adjacent to Plymouth tower

With the available cabling and the intention to measure the numbered locations on the south side of the deck as well as three locations in each of the two tower legs on the south side and one at the upper portal level in each of the tower legs on the north side, eight setups of accelerometer locations were planned, alternating between vertical and lateral measurements and in the final two setup, including tower measurements in the lateral and longitudinal directions.

Table 1 give an example of arrangement for the first setup to measure vertical response. Setups 1-4 were 30 minute duration, setups 5-8 were 15 minute duration, all sampled originally at 64Hz and decimated by four to speed analysis after checking that the main modes were in the range 0-8Hz.

Table 1: typical measurement setup

	ch1	**ch2**	**ch3**	**ch4**	drum at
setup 1_3					
c1	81NL	85NL	81NV	85NV	
short cable	**20**	-	**2x10**	-	85N
c2	73SV	77SV	81SV	85SV	
short cable	**3X10**	**10**	**10**	**3X10**	79S
EXT+c3+c5	55SV	59SV	65SV	69SV	
short cable	**2X20**	**2x10**	-	**20**	65S
EXT+c4+c6	39SV	43SV	47SV	51SV	
short cable	**3X10**	**10**	**10**	**3X10**	45S

S/N=South/North L/V=lateral/Vertical

For this setup, Fig. 6 shows auto-spectra from channels 2 and 4 and their coherence, also relative phase between channels 4 and 8, both as indicators of torsional modes. Fig. 7 shows the resulting piece of mode shape for the first torsional mode obtained using NExT/ERA implemented in MODAL.

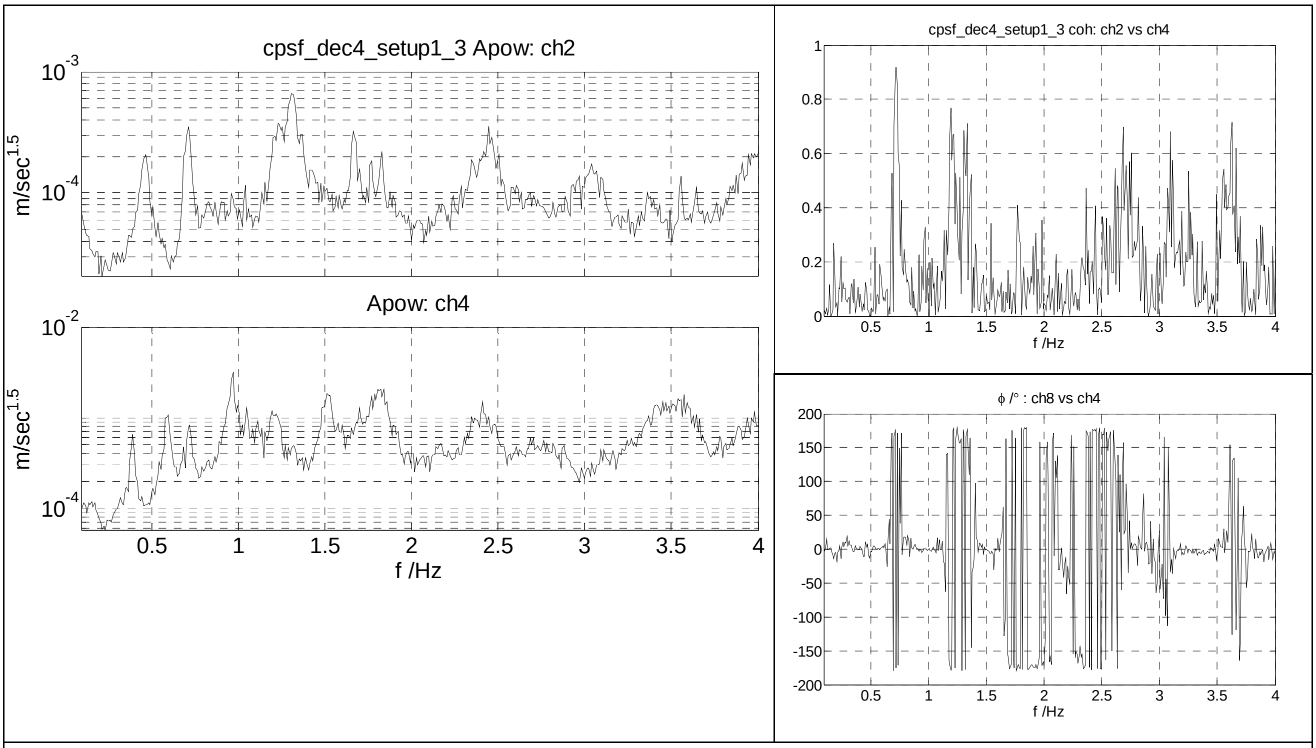


Figure 6 Auto power of lateral (ch2) and vertical (ch4) response at hanger 85, also torsional indication from (right, upper) lateral/vertical ch2/ch4 coherence and (right, lower) ch4/ch8 phase angle

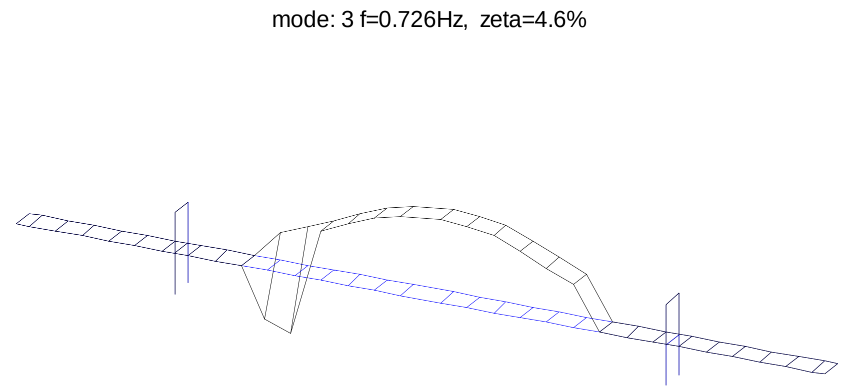


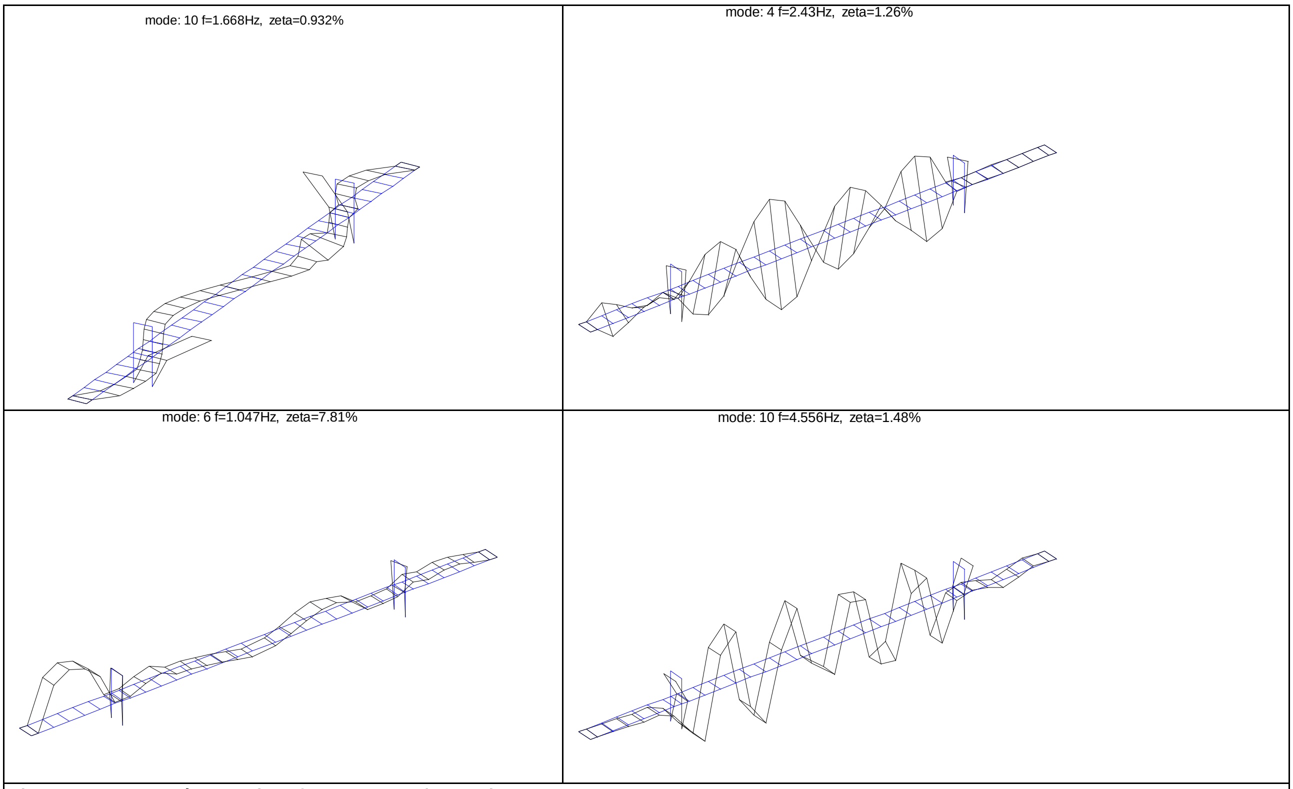
Figure 7 piece of first torsional mode TS1 from setup 1 using NExT/ERA

The procedure for gluing the pieces together using MODAL involved either one of two processes:

Assembling a combined cross-power matrix representing all the measurements normalized with respect to one or two measurement channels, then using ERA to estimate the mode frequencies, damping ratios and mode shapes.

Using singular value decomposition of setup 1 to identify the modes of interest, then performing SVD of each of the eight setups, extracting the mode shape pieces (singular vectors) at the chosen frequency as text files, before assembling in the final step.

In each case, the mode shape ordinates for the unmeasured locations on the north span were ‘guessed’ as equal in magnitude to but either in phase or out of phase with the opposite locations on the south side. South side lateral mode ordinates were mapped directly to the north side. Due to technical problems (e.g. not having the keys to access doors and facing other physical barriers) it was not possible to map the mode ordinates at all tower locations; the tower base ordinates could not be measured as planned and so were assumed to be zero representing the towers as fully fixed at water level. Sample mode shapes are shown in Fig. 8.


mode: 10 f=1.668Hz, zeta=0.932%

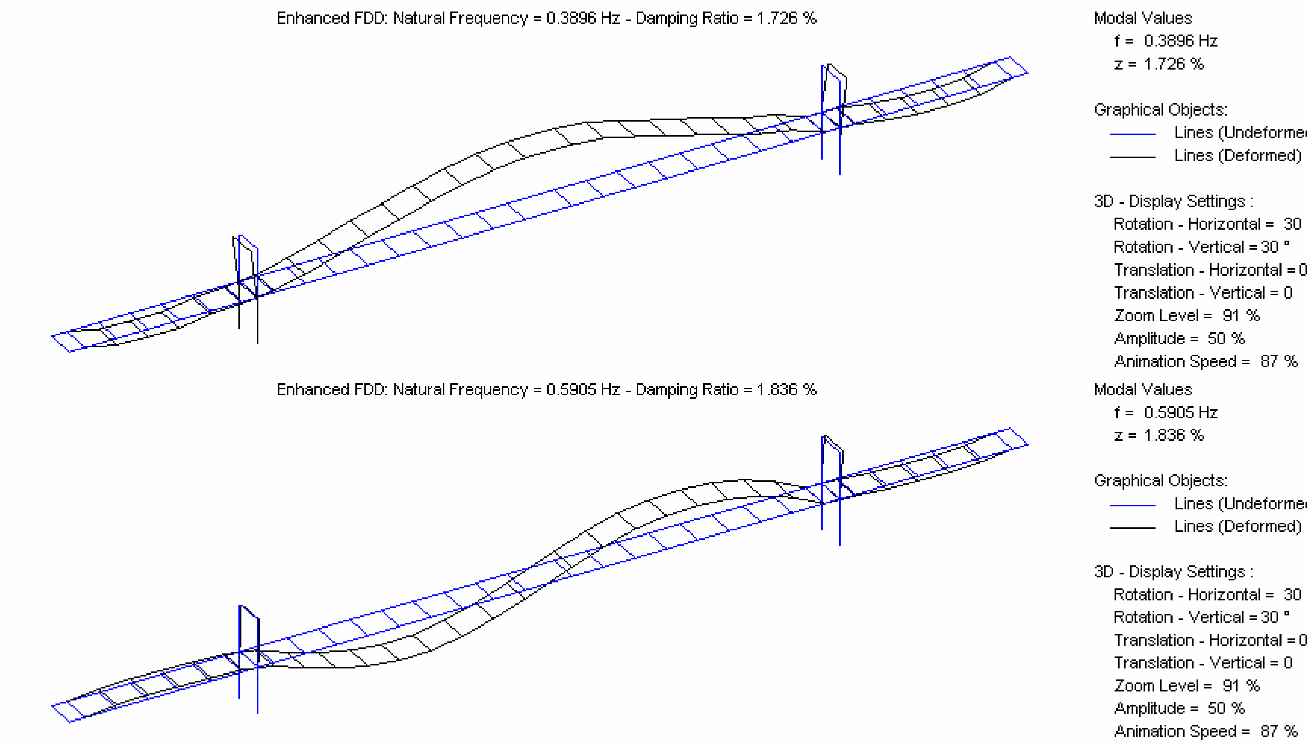
mode: 4 f=2.43Hz, zeta=1.26%

mode: 6 f=1.047Hz, zeta=7.81%

mode: 10 f=4.556Hz, zeta=1.48%

Figure 8 example modes from NExT/ERA in MODAL

To cross-check the modes ERA and SVD modes, the EFDD procedure implemented in Artemis Extractor was used; Fig. 9 shows three of the identified modes. Generally the Artemis modes compared well with the NExT/ERA modes, with the Artemis mode shapes generally looking a little ‘smoother’.


Enhanced FDD: Natural Frequency = 0.3896 Hz - Damping Ratio = 1.726 %

Modal Values
f = 0.3896 Hz
z = 1.726 %

Graphical Objects:
Lines (Undeforme
Lines (Deformed)

3D - Display Settings :
Rotation - Horizontal = 30
Rotation - Vertical = 30 °
Translation - Horizontal = 0
Translation - Vertical = 0
Zoom Level = 91 %
Amplitude = 50 %
Animation Speed = 87 %

Enhanced FDD: Natural Frequency = 0.5905 Hz - Damping Ratio = 1.836 %

Modal Values
f = 0.5905 Hz
z = 1.836 %

Graphical Objects:
Lines (Undeforme
Lines (Deformed)

3D - Display Settings :
Rotation - Horizontal = 30
Rotation - Vertical = 30 °
Translation - Horizontal = 0
Translation - Vertical = 0
Zoom Level = 91 %
Amplitude = 50 %
Animation Speed = 87 %

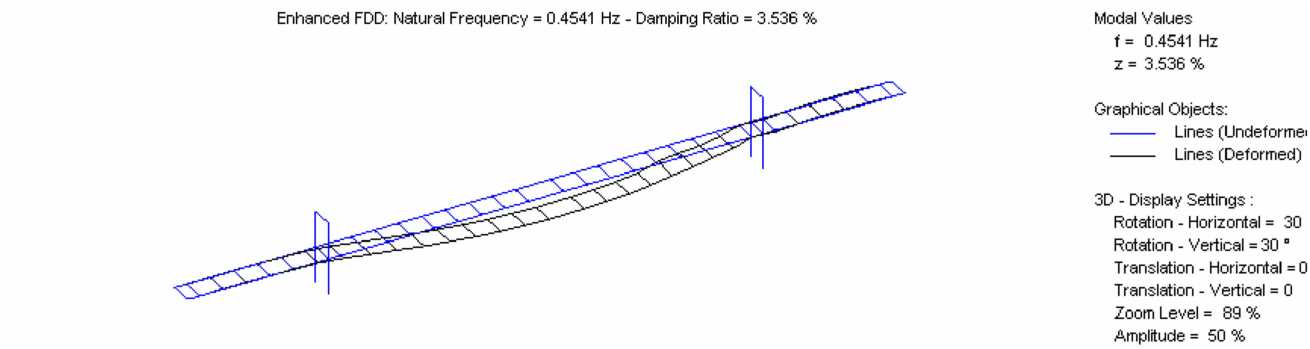


Figure 9 Three mode shapes using EFDD procedure in Artemis Extractor

From all the analyses the following set of modes was distilled. Modes up to higher frequencies were also identified (even to 5Hz as shown in Fig. 8). The best estimates of damping ratios were obtained from frequency domain SDOF curve fitting. This procedure works well enough for well separated modes but is subject to positive bias due to the limited frequency resolution and averaging available due to the limited duration of the records.

MODE	sidespan	MODAL ERA	Artemis EFDD	
		F/Hz	F/Hz	damping /%
VS1	strong	0.393	0.3896	1.7
LS1	neg	0.457	0.4541	3.5
VA1	weak	0.5946	0.5905	1.8
TS1	weak	0.726	0.7241	1.1
VS2	strong	0.9748	0.9692	1
VS2	out of phase	-	1.031	1.5
SSS-VS1	strong	1.039	-	1.6
VS2	out of phase	-	1.115	1.4
TA1	weak	1.227	1.222	1.7
VA2	neg	1.527	1.519	1.6
PSS-VS1	strong	-	1.695	1.1
tower lat	neg	1.697	-	0.9
TS2	weak	-	1.843	1.3
VS3	neg	2.153	2.165	1.6
TA2	neg	2.43	2.432	1.2

4 STAY CABLE PERFORMANCE

One significant concern with cable-stayed bridges is oscillations of stay-cables induced either by wind on its own or more usually by a combination of rain and wind [2]. Fig. 10 shows the additional stays for Tamar due to the upgrade; these are either 102mm or 112mm locked coil steel strands connecting tower tops (Fig. 11) to the deck (Fig. 12). According to Tamar Bridge staff'

"..A number of these cables experienced oscillations at times during the strengthening, some of the additional cables were prone to oscillation under certain winds, but always when it was raining. Eyewitnesses suggested oscillations varied from peak to peak movements of 20/30mm up to 200mm. After upgrading was complete, vibrations could still be observed on the longer cables (3 and 4), when there was a slight wind (typically 10 mph) and often when there was no rain. 'Standing waves' could be observed on the cables with peak to peak amplitudes of up to 80mm. Vibrations were always observed to take place on pairs of cables (north and south) ..'.

Simple dampers were installed on several of the cables and consist of a horizontal stainless steel disc connected to a vertical stainless steel rod clamped to the cable just above cantilever deck level. The disc is submerged in water contained within a 30-(imperial) gallon water butt.

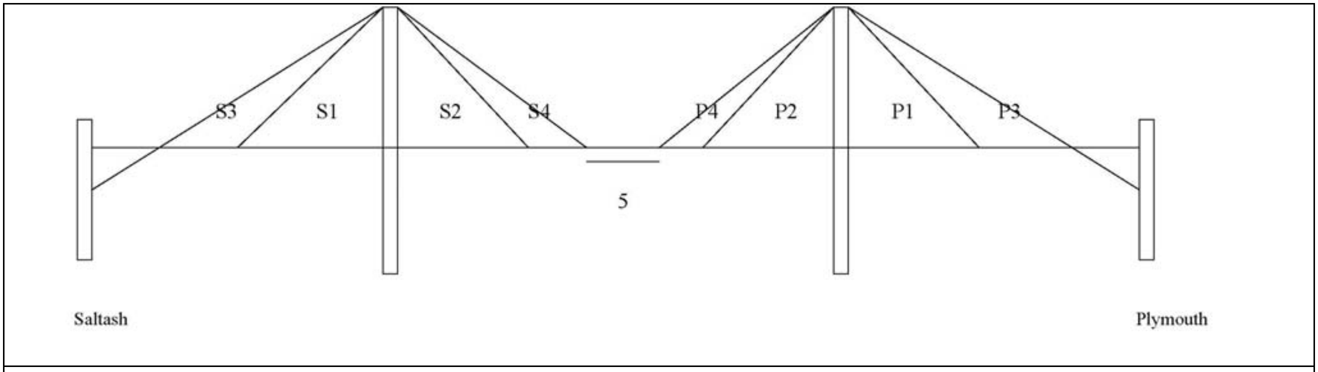


Figure 10 Additional stay cables

Figure 11 Saddle and stay anchorage points on Plymouth tower

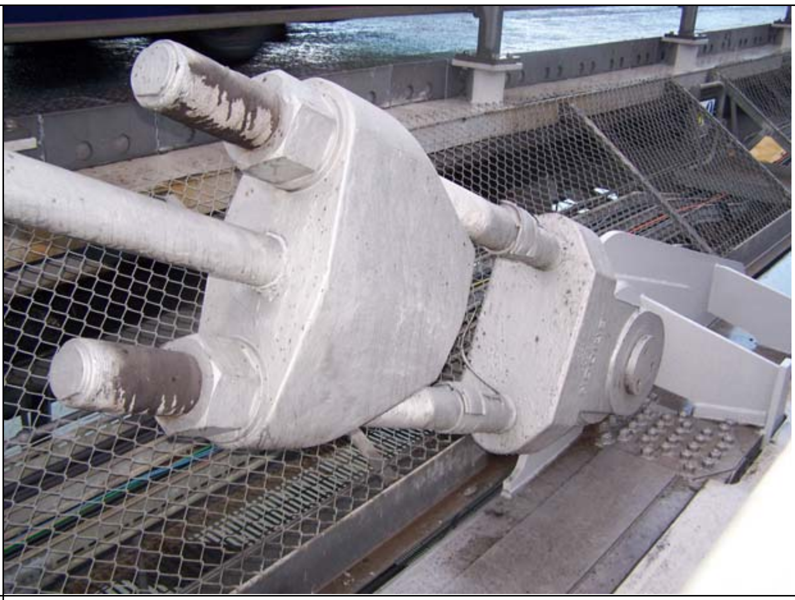


Figure 12 Stay anchorage to deck

Fig. 13 shows the arrangement for one of the cables, P3S and (Fig. 14) results from forced vibration (manually). The lateral decay visible in the time/frequency (spectrogram) plot is much slower than the vertical decay; lateral damping is 0.3% for a fundamental frequency of 0.845Hz, for vertical oscillation damping is 2.8% for a frequency of 0.852Hz.

For the monitoring program, biaxial accelerometers have been installed on four undamped cables to investigate further the nature of the oscillations, which are still observed under certain conditions.

5 REFERENCES

1. Fish R, Gill J, Tamar suspension Bridge -strengthening and capacity enhancement. In Bridge Modification 2: Stronger and Safer Bridges Thomas Telford, London, 1997, ed B Pritchard
2. Flamand O, Rain-wind induced vibration of cables Journal of Wind Engineering and Industrial Aerodynamics **57**(2-3), 1995, p353-362

Figure 13 P3S under test

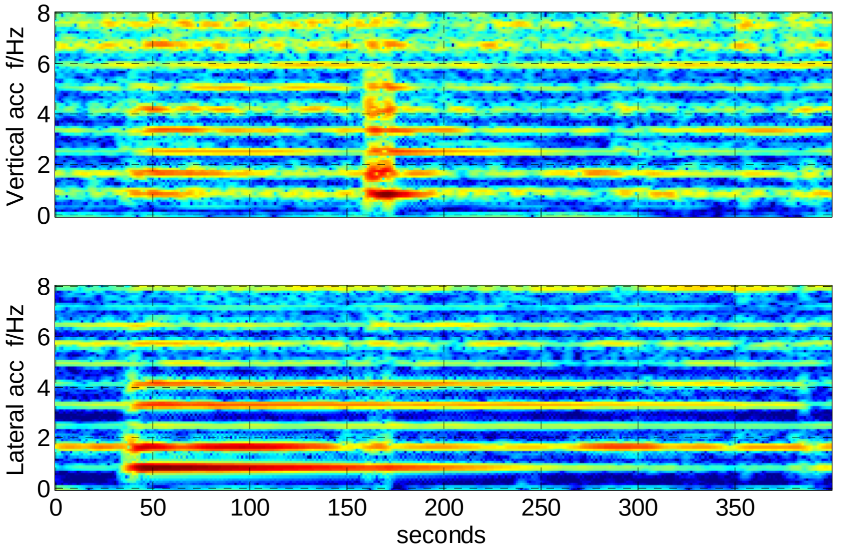


Figure 14 P3S free decay after forcing