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Vibration insulation of footbridges so as to reduce human discomfort

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ABSTRACT

Low frequency vibrations in footbridges is a cause of annoyance for pedestrians crossing the bridge. Bagers bro, a footbridge built in Malmö (Sweden) had several constraints in the physical design that caused the first eigenmode of the bridge to be at 1.8Hz which is a severe problem for pedestrians. Therefore the bridge was fitted with tuned mass dampers to mitigate the vibration problem. To evaluate the performance of the dampers and the accuracy in the predictions of the Finite Element (FE) Models of the bridge, an investigation trough modeling and measurements with respect to the performance of the tuned dampers fitted to the bridge has been done. The measurements were performed both with and without the mass dampers engaged. The results from the operational modal analysis of the bridge were compared with finite element simulations. The mass dampers were found to greatly improve the vibratory performance of the bridge in as much as making an otherwise almost unusable bridge acceptable.

Keywords: Vibration, Insulation, Finite Element Modelling, Operational Modal Analysis
I-INCE Classification of Subjects Number(s):47.3 72.2 75.3

1. INTRODUCTION

There is a trend towards designing slimmer and more lightweight pedestrian bridges in order to give them an aesthetically pleasing appearance. As a consequence, more care has to be taken to avoid problems with vibrations as the natural frequencies for such slim lightweight bridges tend to coincide with the walking frequencies of the pedestrians, creating accelerations of such a level that they are often regarded as annoying (1). Thus, the need for an accurate a priori dynamic analysis of pedestrian bridges become more important. As simulations of such constructions become more prevalent, assuring that these simulations with reasonable accuracy represent the reality must be ensured. The comparison between simulated and measured dynamic properties is an important task in calibrating the finite element models, which will subsequently be used in the design phase as prediction tools. If the simulations indicate that the eigenfrequencies for the bridge will coincide with the walking frequencies of the pedestrians, action has to be taken. Either in redesigning the bridge or, if the design can not be altered, by installing active or passive countermeasures such as for instance tuned mass dampers (TMD).

In this investigation the influence of such TMDs on the behavior of a footbridge Operational Modal Analysis (OMA) can be used. In OMA only the output signals are measured which means that the bridge does not need to be closed during the measurements and that the natural loads, such as pedestrians and wind, are used as the only source of excitation.

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2. TEST BRIDGE: BAGERS BRO

Bagers Bro is a bicycle and footpath bridge in the inner harbour of Malmö. The bridge is 2.4m wide and has a span of 37m. The bridge consist of a three dimensional truss with a largest height of 1.5m. The bridge has a curvature in-plane as well as in elevation as seen in figure 1

Figure 1 – Bagers Bro in Malmö.

The truss bearing the load of the bridge is constructed from three beams made from large steel pipes in a triangle formation spanning the length of the bridge with smaller pipes welded between the large ones. The diameter of the larger pipes is 323.9mm and the smaller ones have a diameter of 168.3mm. A cross-section of the bridge can be seen in figure 2. The lower beam is split in two separate beams each connecting to the two upper beams 0.5m from the ends of the bridge. This makes the height of the truss vary from 1.5m in height at the middle of the bridge to 0m at the ends of the bridge. The bridge deck is made from planks manufactured from a recycled plastic called *G9 Rustik*. The planks are fastened using screws to longitudinal beams of HEB100 profiles which in turn rest upon the truss. The railing is also fastened to the same longitudinal beams as the bridge deck. The steel quality used in the bridge is S355, whereas the railings were made of S235.

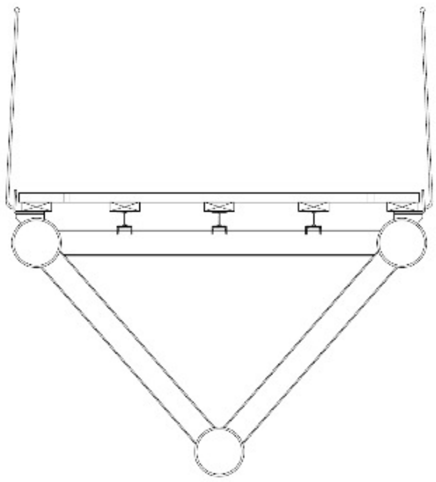


Figure 2 – Cross-section of the bridge.

As the bridge had constraints on the placement of the landing points and on the minimum free height over the water as well as on maximum elevation due to the regulations for accessibility for the disabled, It was discovered in the design phase of the bridge that the curvature of the bridge along with its relative small cross-section would result in a low first eigenfrequency of about 1.8Hz. To mitigate this a pair of TMDs were installed on the bridge as indicated in figure 3.

The TMDs consist of a mass of 340kg placed on top of springs with a stiffness of 88kN/m. The springs in turn connect to a frame attached to the beams beneath the bridge deck. Between the frame and the mass,

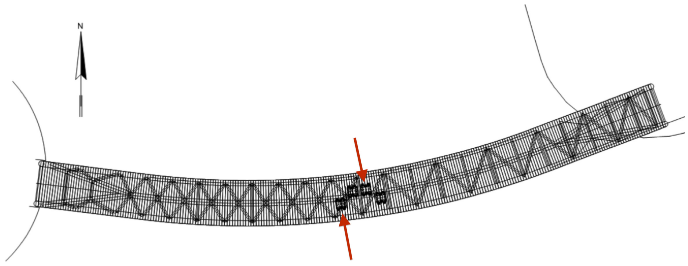


Figure 3 – Placement of the dampers on the bridge, the installed dampers are indicated with red arrows.

viscous dampers are connected with a damping coefficient of 1.39kNs/m. A drawing of a TMD can be seen in figure 4. The active frequency interval for the TMDs is between 1.6Hz and 2.15Hz and the TMDs are tuned to the eigenfrequency 1.81Hz. The total mass of a single TMD is 420kg.

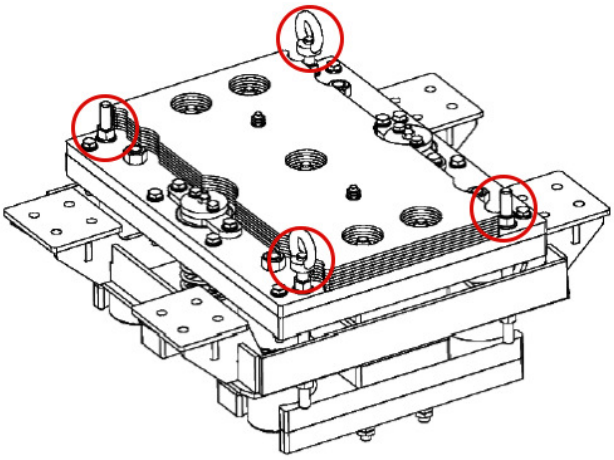


Figure 4 – Drawing of a tuned mass damper with locking pins and transportation hooks attached (marked in red).

3. FINITE ELEMENT MODEL

Eigenvalue analyses were performed in terms of Finite Element simulations. The bridge was modelled using the FEM software BRIGADE/Plus which is specifically made for bridge construction. The analysis is constrained to the first 6 eigenmodes and eigenfrequencies as the higher modes and corresponding frequencies will have little impact on the perceived comfort of the bridge for the users (2).

3.1 Geometry

The authors had access to the drawings of the bridge which greatly facilitated the construction of the model. The truss and the longitudinal beams supporting the decking were modeled using Beam elements. The railing and the decking of the bridge were assumed to marginally affect the eigenfrequency analysis and were therefore manifested as non-structural masses spread along the longitudinal beams. The two locked TMDs were represented as point loads at their respective points of attachment. The material parameters used in the model can be seen in table 1.

Table 1 – Material properties.

	Construction steel	G9 Rustik (plastic)
E-modulus	210GPa	1.2GPa
Density	7850kg/m^3	960kg/m^3
Poisson number	0.3	

3.2 Constraints

The bridge rests upon two supports at each end, the bearings are of the type TOBE Potbearing with a teflon coating to reduce friction. In the model the supports are assumed to be frictionless and the foundation is assumed to be infinitely stiff. The constraints and the direction in which they are fixed are shown in figure 5. No rotations are fixed in the model. The direction of the coordinate system for the constraints coincides with the direction of the bridge at the west landing of the bridge, hence the direction of the constraints does not follow the direction of the bridge at the east landing.

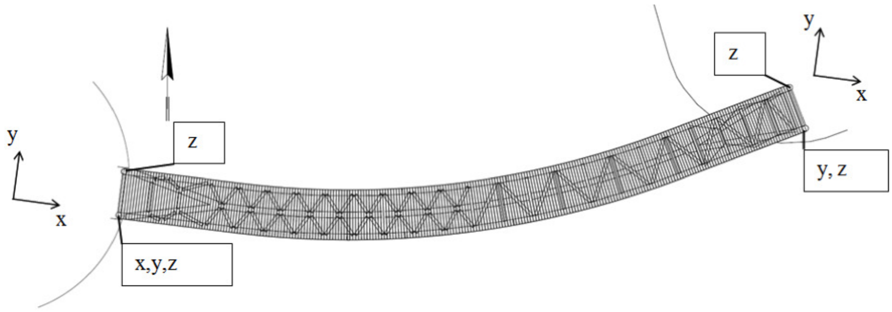


Figure 5 – Constraints in the model.

3.3 Active damping, TMD

The bridge is fitted with two active dampers which in the model are simplified to a single one located between the actual placing of the TMDs so as to avoid problems if the TMDs were not in phase. The TMDs are modelled as a spring-damper system with the mass as a point load. The total mass of the TMDs is 840 kg of which 680 kg is moving mass. Therefore 680 kg is placed in the spring-damper system while the remaining weight is placed in the actual attachment points of the TMDs. The total mass of the brigade is 44479kg.

3.4 Simulation results

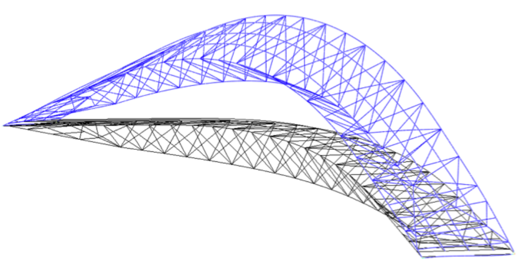
In figure 6 the first four eigenmodes and their respective frequencies with the TMDs inactive can be seen. In table 2 the eigenfrequencies for the first six modes can be seen. Note that the first mode as expected from the theory for TMDs (3) is split into two for the first mode in the case of active TMDs. Also note that the eigenfrequency for the first mode in the case of inactive TMDs is 1.53Hz and in the case of active TMDs the corresponding frequencies are 1.42Hz and 1.68Hz respectively. This is lower than what was calculated in the design of the bridge and is most likely due to the simplifications made in the model.

Table 2 – Simulated eigenfrequencies.

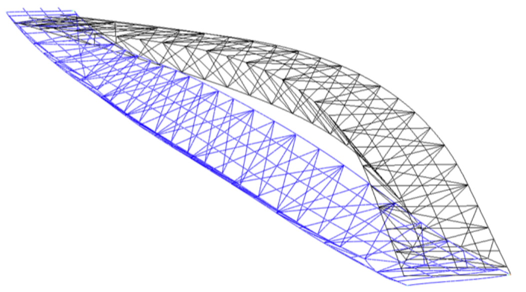
Mode	locked TMDs (Hz)	unlocked TMDs (Hz)
1 Vertical	1.53	1.42 1.68
2 Horizontal	3.09	3.15
3 Vertical	6.28	6.29
4 Torsional	9.13	9.16
5 Horizontal	10.40	10.40
6 Vertical	12.25	12.25

4. MEASUREMENTS

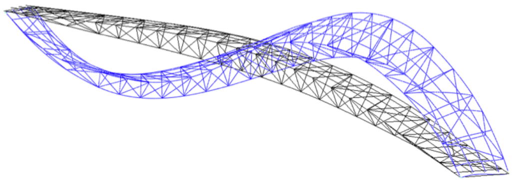
The measurement method used is Operational Modal Analysis (OMA) which enables measurements to be performed on a structure while in use. The measurements were performed on two separate occasions at the first occasion the bridge was closed for traffic as the TMDs were disabled, on the second occasion the bridge was open for pedestrian traffic. The equipment used was four 1-axial, and two 3-axial accelerometers from Brüel & Kjær. The measurement points were decided from the simulations so as to catch the first mode



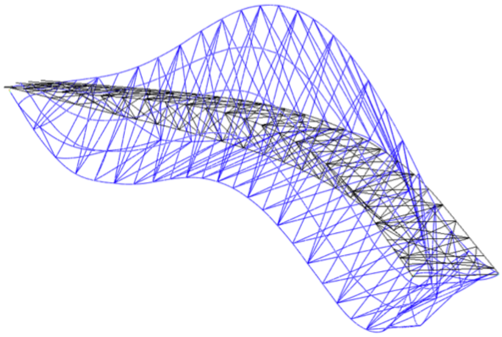
(a) First mode, first vertical 1.53 Hz



(b) Second mode, first horizontal 3.09 Hz



(c) Third mode, second vertical 6.28 Hz



(d) Fourth mode, first torsional 9.13 Hz

Figure 6 – The first four eigenmodes of the bridge, the position of the bridge at rest is depicted in black.

shapes. The placement of the measurement points can be seen in figure 7. Due to a lack of channels in the measurement system, roving measurements had to be performed, to this end measurement point 3 was chosen as the reference point.

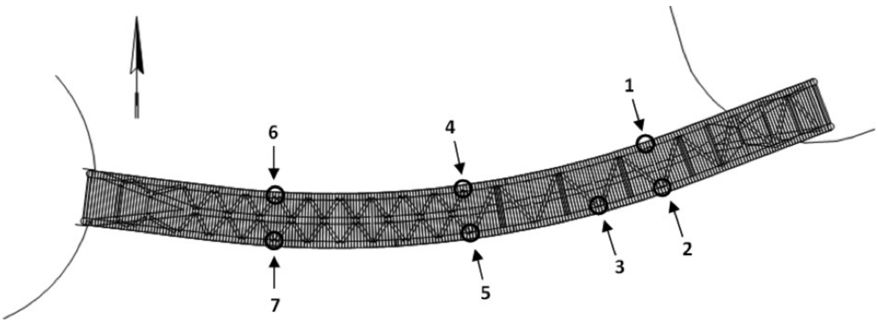


Figure 7 – Measurement points on the bridge, point 3 is the reference point.

As all handling of measurement equipment was done from the top of the bridge, all placements of the measurement equipment were constrained to what was reachable from that position. As the 1-axial sensors were to measure the vertical movement and due to their construction only one option of orientation is possible, their placement had to be on a surface that was as horizontal as possible. For the 3-axial sensors more options of placement was available. A can be seen in figure 8 the single-axis sensors are placed on the bean supporting the decking and the tri-axial sensors are placed on the truss.

4.1 Effect of the TMDs

In table 3 the resulting eigenfrequencies and corresponding damping from measurements with unlocked and locked TMDs are shown. The values are mean values from measurement series for all modes. Note however that the number of measurement series can vary as not all modes were detected in all measurement series due to technical difficulties. Note also the increased damping from 0.96% to 2.51% for the first eigenmode when the TMDs are active.

To compare the identified modes in the two measurement cases the Modal Assurance Criterion (MAC) was used. In table 4 the diagonal values, in red, are close to 1 indicating that the measured and simulated modes are coincident. However, some off-diagonal values, marked in blue, are quite high most notably between the

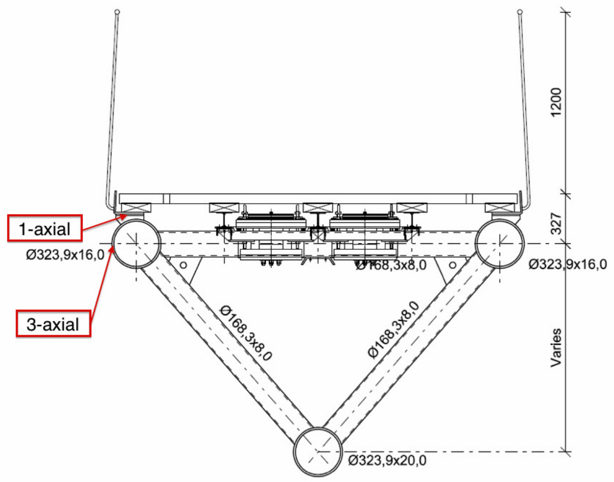


Figure 8 – Placement of the accelerometers.

Table 3 – Measured eigenfrequencies and damping for locked and unlocked TMDs.

		Unlocked TMDs		Locked TMDs	
Mode number	Mode type	Eigenfrequency (Hz)	Damping (%)	Eigenfrequency (Hz)	Damping (%)
1	Vertical	1.84	2.51	1.85	0.96
2	Horizontal	5.05	2.80	4.89	4.12
3	Vertical	6.82	0.40	6.81	1.76
4	Torsional	9.70	0.56	9.65	0.63
5	Horizontal	10.02	1.87	9.95	2.09
6	Vertical	13.95	0.65	13.73	0.99

second and fourth and the fourth and second modes. This most likely is due to too few measurement points having been used in the case with locked TMDs.

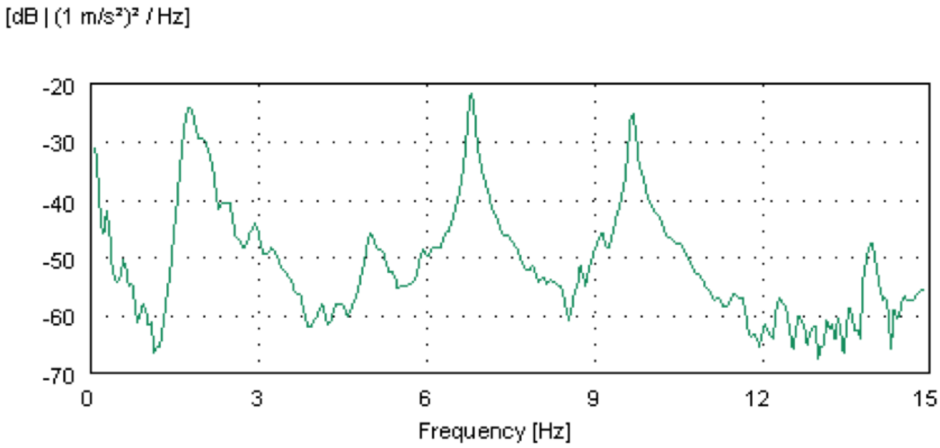
Table 4 – Cross MAC between Active and inactive TMDs.

	Inactive TMDs						
	Eigenfrequency [Hz]	1.802	4.889	6.812	9.672	10.019	13.746
Active TMDs	1.834	0.974	0.271	0.202	0.239	0.071	0.010
	5.047	0.312	0.961	0.013	0.457	0.017	0.101
	6.822	0.210	0.010	0.997	0.048	0.055	0.229
	9.702	0.192	0.444	0.059	0.995	0.019	0.307
	10.089	0.086	0.023	0.039	0.033	0.964	0.071
	13.943	0.002	0.155	0.210	0.299	0.023	0.997

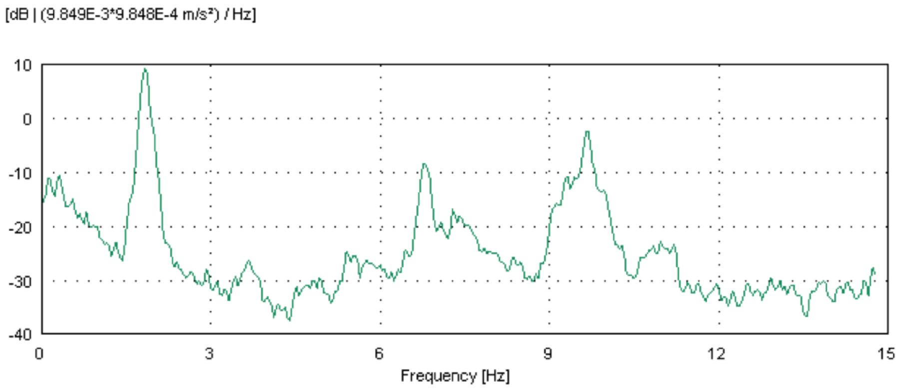
Figure 9 shows the magnitude of the spectral densities for the cases with active and inactive TMDs respectively. Note that since the measurements have been performed with an unknown load and they have different reference points no statement can be made with regards to the absolute values. However, the shape of the graphs can be compared which gives information on the damping of the system. Comparing the two graphs it is clear that the first peak is narrower for the case of inactive TMDs than for the case of active TMDs.

5. COMPARISON BETWEEN FE-MODEL AND MEASUREMENTS

The comparison of the measured values with the results from the simulations was done using the modal assurance criterion. In table 5 and 6 the MAC values between simulated and measured modes for the case with inactive and active TMDs in the simulations are shown. In the case of inactive simulated TMDs the vertical modes (1.834Hz, 6.822Hz and 13.943Hz) and the torsional mode (9.702Hz) have a high degree of correlation whereas the correlation for the horizontal modes (5.047Hz and 10.089Hz) is to low to definitely



(a) Magnitude of spectral densities for accelerometer with unlocked TMDs.



(b) Magnitude of spectral densities for accelerometer with locked TMDs.

Figure 9 – Magnitude of spectral densities for the cases of active versus inactive TMDs.

say that they are the same modes. In the case of active TMDs in the simulation, the two first eigenmodes from the simulation correspond to a high degree to the first eigenmode in the measurements. This indicates that the two first modes in the simulations are close to each other which is hardly surprising as they stem from the first eigenmode in the case with the inactive TMDs. The horizontal modes still have a low degree of correlation between the measurement and the simulation something that most likely is due to the fact that there were only three sensors all placed on the northern side of the bridge that could pick up the horizontal movement.

Table 5 – MAC-values comparing simulated inactive TMDs and measured active TMDs.

		Measured active TMDs					
inactive simulated TMDs	Eigenfrequency [Hz]	1.802	4.889	6.812	9.672	10.019	13.746
	1.531	0.915	0.278	0.041	0.066	0.016	0.011
	3.094	0.020	0.435	0.001	0.010	0.002	0.001
	6.283	0.031	0.020	0.977	0,005	0.040	0.016
	9.129	0.076	0.044	0.050	0.960	0.033	0.096
	10,398	0.013	0.012	0.008	0.007	0.506	0.001
	12.253	0.022	0.048	0.008	0.163	0.070	0.927

6. CONCLUSIONS

The tuned mass dampers fitted to the bridge increased the damping of the first eigenmode from 0.96% to 2.51%. No comparison could be made between the magnitudes of the accelerations in the measured two cases due to the absence of a well defined input force. However, the widening of the peak for the first eigenmode

Table 6 – MAC-values comparing simulated inactive TMDs and measured active TMDs.

	Measured active TMDs				
inactive simulated TMDs: Eigenfrequency [Hz]	1.802	4.889	6.812	9.672	10.019
1.418	0.921	0.289	0.041	0.065	0.016
1.678	0.910	0.267	0.041	0.066	0.016
3.149	0.020	0.434	0.001	0,010	0.002
6.285	0.030	0.019	0.977	0.005	0.040
9.159	0.080	0.044	0.050	0.961	0.033
10.403	0.014	0.012	0.008	0.008	0.508

in the spectral densities indicate that the TMDs have the desired effect. Looking at the MAC-values, the differences between the case of active versus inactive TMDs are not large with respect to the eigenfrequencies. Indeed this is to be expected as the mode shapes for the first eigenmode in the case of inactive TMDs and the two first eigenmodes for the case of active TMDs should be similar according to theory (3).

All six mode shapes and eigenfrequencies from the measurements with active TMDs can be determined with good credibility with the exception of the second mode (5.05Hz). The measurement of the second mode is more uncertain as it is not possible to find in all of the measurement series.

The eigenfrequencies and mode shapes for the case of measurements with inactive TMDs are uncertain. This is due to too short measurement times for the measurement series, and due to the fact that the number of measurement points are too few.

There is no clear split of the first eigenfrequency when the TMDs are active, this may be due to the TMDs not being tuned exactly to the bridges eigenfrequency as they shift a bit due to seasonal variations and also due to the fact that the mass of the TMDs is small compared to the mass of the bridge.

The correspondence between the results of the simulated bridge and the measured values is good. The difference in the first eigenfrequencies is likely due to the simplifications in the model. There is good correlation between the identified modes in the measurements and the simulated modes.

OMA has been shown to be a good method to test the performance of an existing structure. However, care has to be taken when planning the measurements so as to ensure the quality of the measured data.

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