Measuring Bridge Characteristics to Predict their Response in Earthquakes

Michael Phillips[1] and Kevin McCue[2]

1. EPSO Seismic, PO Box 398, Coonabarabran, NSW 2357.
   Email: michael.andre.phillips@gmail.com

2. Adjunct Professor, Central Queensland University, Rockhampton, Qld 4701.
   Email: mccue.kevin@gmail.com

Abstract

During 2011 and 2012 we measured the response of the Sydney Harbour Bridge (SHB) to ambient vibration, and determined the natural frequencies and damping of various low-order resonance modes. These measurements were conducted using a simple triaxial MEMS acceleration sensor located at the mid-point of the road deck. The effectiveness of these measurements suggested that a full mapping of modal amplitudes along the road deck could be achieved by making many incremental measurements along the deck, then using software to integrate these data. To accommodate the briefer spot-measurements required, improved recording equipment was acquired, resulting in much improved data quality. Plotting the SHB deck motion data with 3D graphics nicely presents the modal amplitude characteristics of various low order modes, and this analysis technique was then applied to a more complex bridge structure, namely the road deck of Sydney's Cahill Expressway Viaduct. Unlike the single span of the SHB, the Cahill Expressway Viaduct (CHE) dramatically changes its modal behavior along its length, and our analysis system highlights a short section of this elevated roadway that is seismically vulnerable. On the basis of these observations, the NSW Roads & Maritime Services (RMS) indicated that they will conduct an investigation into the structure at this location.

Keywords: seismic, hazard, bridge, modal vibration, frequency, structural motion monitoring

Introduction

Structural motion monitoring technology is improving rapidly, and during the period since 2011 when we began measuring the natural motion of large NSW road and rail bridges, the Sydney

Harbour Bridge has now become well instrumented with a state-of-the-art real-time motion monitoring system. In an earlier paper we recommended that such a system could be used to compare short-term and long-term changes in a bridge's natural motion, to detect maintenance issues before they become serious, and that is precisely the main mission of the award winning 'bridge health' monitoring system developed by the NSW Roads & Maritime Services (RMS) in conjunction with National ICT Australia (NICTA)[1]. In due course this monitoring system will likely be rolled out to numerous other bridges and structures within the NSW RMS portfolio, but in the mean time there are still many structures for which there is no monitoring, and no high-quality Finite Element modelling available to check structural response to earthquake ground motion.

Method

Our 2012 AEES paper[2], along with earlier AEES papers[3], highlighted the extraordinary technical advances and cost reduction with MEMS solid-state accelerometers. These inexpensive robust devices have now found their way into practically every modern smart-phone, car, and computer disk drive. There is however an enormous range in sensor quality, with the vast majority being modest quality 'consumer' grade devices, suitable for correctly orienting a smart-phone's screen, but not suitable for detecting very weak vibration. The usual limiting specification is the internal noise generated by MEMS sensors, where weak accelerations may be detected but are masked far beneath the sensor's inherent noise floor. However in the case where very weak acceleration signals are coherent and constantly present, such as with the natural structural resonances of structures such as bridges, it is possible to detect and measure these 'buried' MEMS sensor signals by numerical analysis techniques.

During 2011 and 2012 the authors experimented with MEMS sensors placed on the road decks of large and iconic Sydney bridges, trying different sensors and loggers, and varying the sampling rate, sample size and subsequent data analysis. We eventually determined that quite satisfactory results could be obtained from an inexpensive Analog Devices ADXL-335[4] triaxial acceleration sensor (this sensor has very similar specifications to the STMicroelectronics LIS331DLH[5] sensor used in iPhone models 4 & 5).

Browsing the linked sensor data sheets below, one may see that the level of the sensor noise floor is somewhat frequency dependent (e.g. 218μg/√Hz for the LIS331DLH versus 150μg/√Hz for

[1] Bridge Deck Structural Health Monitoring System - 2012 finalist with Engineering Excellence Awards, a collaboration between the Powerhouse Museum and the Sydney Division of Engineers Australia.
[2] Phillips, McCue & Samali, (2012)
[3] Haritos, (2009), Pascale, (2009)
[4] Analog Devices ADXL335 sensor - Data Sheet
[5] STMicroelectronics LIS331DLH – Data sheet

the ADXL335, where 100µg≈1mm/s^2). This noise figure is sufficiently high that if one looks closely at many smart-phone vibration-measuring apps, one will notice that graphical recordings will jitter even when the phone is perfectly stationary. But as we determined in 2011-2012, a Fast Fourier Transform (FFT) can satisfactorily extract weak coherent signals when using a sufficiently long recording run, in our case 60-minutes sampled at 200 samples per second, with each sample itself being a many-point average conducted over the 5ms sampling interval. We found that a post-analysis spectral noise floor of less than 1mm/s^2 (at ≈1Hz) was typically achievable even when measuring the roadway of a heavily trafficked road bridge such as the SHB.

Although various low-order modes of vibration of the Sydney Harbour Bridge were clearly identified using this method, the obvious next step was to sample at many locations along the length of the road deck to positively determine the modal shapes. Acquiring 60-minute samples at each deck location is obviously impractical, so we needed to substantially shorten our sampling run time, say to a few minutes. To achieve this we required higher quality acceleration sensors with lower internal noise, and thus we acquired a triaxial acceleration board[6] based around the Model 3052[7] single-axis sensor manufactured by Measurement Specialties Inc. For nominal operation this device has a sensitivity of 7.3mV/g compared with the ADXL335's nominal sensitivity of 300mV/g. However the Model 3052 has a flat frequency-independent noise floor of 1µV.

Consider for example a modal peak amplitude one might expect to observe on a large road bridge, of frequency 1Hz and of amplitude 1mm/s^2. 1mm/s^2 is approximately equivalent to 100µg, and with the 1Hz specified noise floor of 150µg from the ADXL335 we are essentially working at the noise floor of the device. In fact our measured modal amplitudes are usually well below 1mm/s^2 so we are typically working well beneath this particular sensor's noise floor. At 1Hz & 1mm/s^2 a Model 3052 will be outputting 0.74uV with a specified noise figure of 1uV, which is comparable S/N performance to the ADXL335. But for frequencies *below* 1Hz the Model 3052 will significantly outperform the ADXL335. Tall buildings and large bridges have natural periods measured in seconds, so there is much merit in the performance of the Model 3052 sensor, and we used it for all our 2013 measurements.

For incremental measurements along road bridges we adopted a standard measurement period of 10 minutes, sampling triaxially at 200 samples per second, with a 20-bit dynamic range. We measured the Sydney Harbour Bridge at locations as indicated in Figure 1, and the Cahill Expressway Viaduct as indicated in Figure 2.

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[6] PSN 4-Channel Strong Motion Accelerometer Sensor Board

[7] Model 3052 acceleration sensor manufactured by Measurement Specialties, Inc.

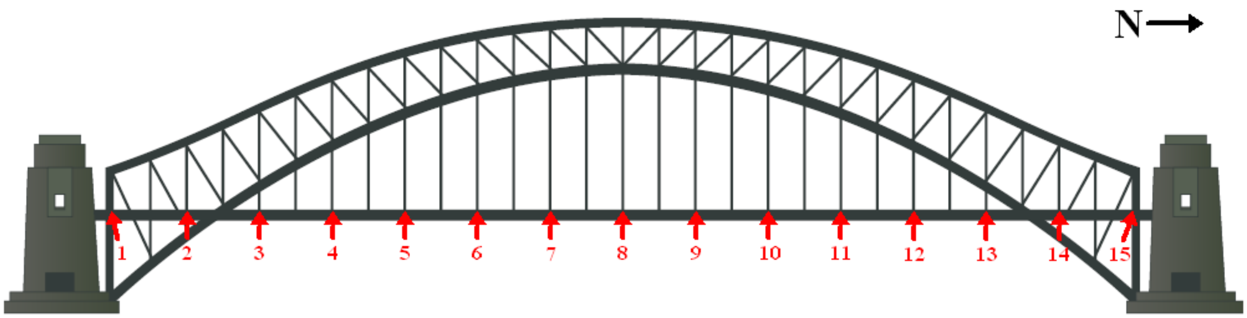

Figure 1 - Sampling locations across the Sydney Harbour Bridge. The total length of the arch span is 503m, therefore the separation between sampling locations was around 36 metres. Location 8 is the mid-point of the bridge.

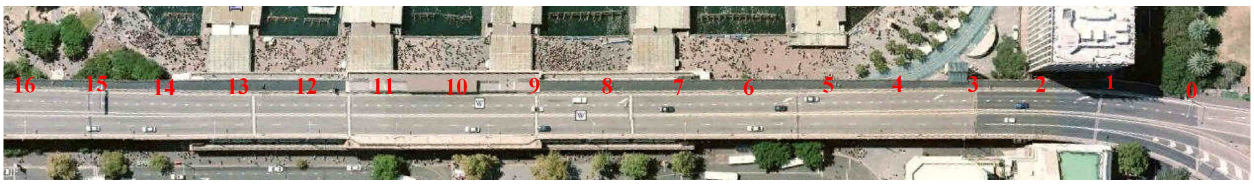

Figure 2 - Cahill Expressway with sampling locations indicated in red. Measurements were conducted along the northern side pedestrian walkway at intervals of 20 metres.

Results

Measurements at both the SHB and CHE were conducted during periods of medium-light road traffic, during calm weather. Both road deck locations were 'noisy' and traffic induced vibration could be clearly felt through one's feet. Sampling the 15 locations on the SHB and the 17 locations on the CHE took around one day to complete for each bridge. Even as the individual 10-minute samples were being acquired it became clear that the spectral composition of the data was significantly changing as one moved stepwise along the road decks. Although our data can produce motion spectra in the range 0-100Hz, our interest is focused on typical earthquake ground motion frequencies of 0-5Hz. But if one briefly considers broader bandwidth motion (0-20Hz) at these two bridges, Figure 3 presents typical spectra we measured.

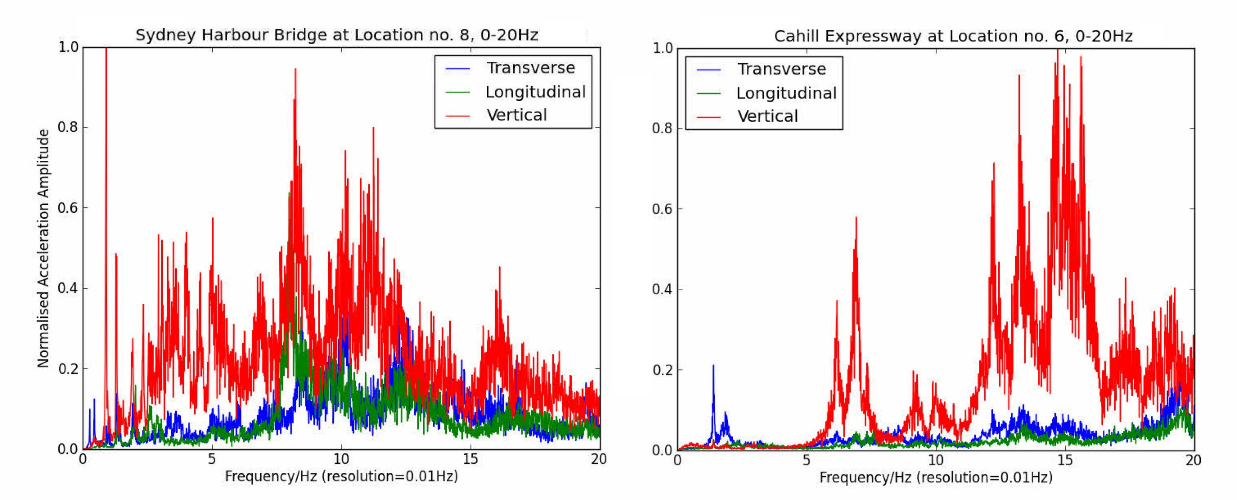

Figure 3 - Examples of normalised acceleration spectra measured at the road decks of Sydney Harbour Bridge (left) and Cahill Expressway (right).

The most conspicuous similarity between the SHB and CHE spectra presented in Figure 3, is that the vertical motion amplitude generally strongly dominates the horizontal. This is undoubtedly due to the vertical forcing from passing road traffic, where normal sized car tyres are rotating and pounding the deck at around 10Hz, and truck/bus tyres at around 7Hz (given the speed limit during sampling, of 70km/h). Although the spectra change their appearance significantly along the length of these bridges, there remain conspicuous amplitude peaks in the 7-10Hz range. The plot above also shows the SHB has a strong lowest-order vertical resonance at 0.92Hz, whose amplitude dominates even the considerable broadband spectral noise induced by road and rail traffic.

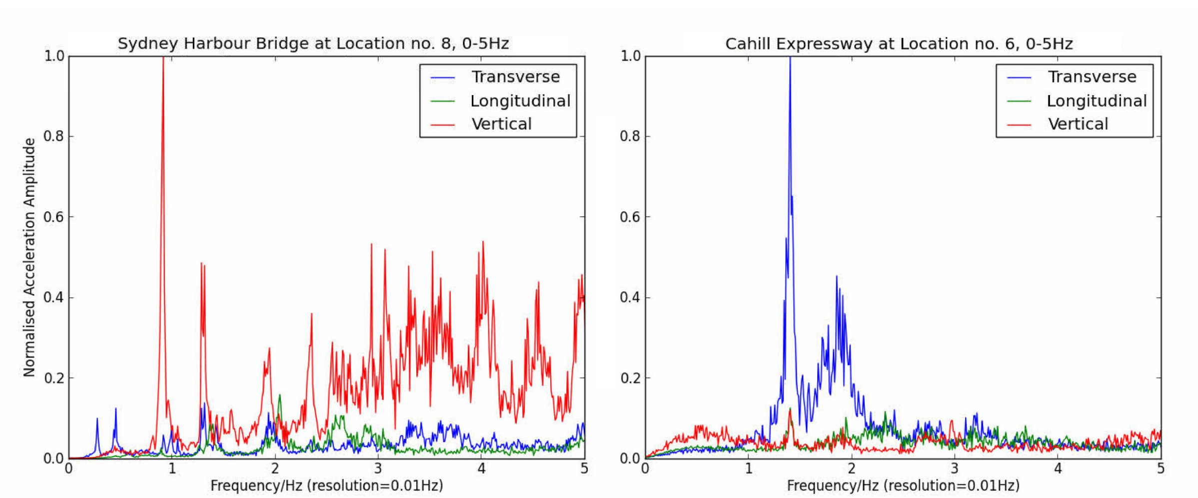

Figure 4 - Normalised acceleration spectra of Sydney Harbour Bridge (left) and Cahill Expressway (right) for the frequency range 0-5Hz, showing the lowest frequency modal motions.

FFTs of data acquired from 10-minute spot-measurements sampled at 200 samples per second permit good frequency resolution of any coherent monochromatic signals. For our desired frequency resolution of 0.01Hz such a FFT is actually oversampled by a factor of around six times, but this oversampling may be utilised by forming average FFT figures for each 0.01Hz frequency step. Applying this averaging process delivers cleaner looking spectra than when plotting every single point in the raw FFT. A frequency resolution of 0.01Hz permits the detailed plotting of individual spectral lines and from the shape of these line profiles an estimation of the 'Q-factor' (f/Δf) may be formed, where Δf is the spectral line width at 0.71× the peak line amplitude. Structural engineers are more familiar with expressing structural resonance in terms of damping ratio (damping/critical damping = ζ), which is related to Q-factor by ζ = 1/2Q, and which is normally expressed as a percentage of critical damping. An example of this analysis is shown in Figure 5.

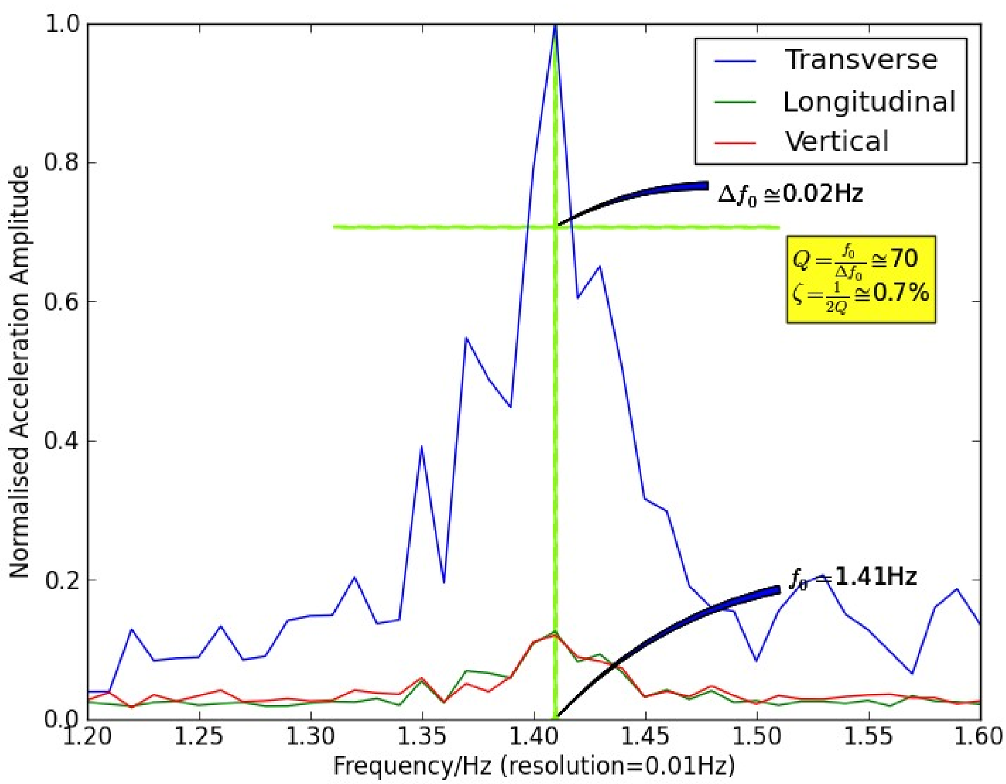

Figure 5 - An example of graphical measurement of damping factor based on measuring spectral line width at 0.71× the peak amplitude, in this case for the 1st transverse mode of the Cahill Expressway at Location 6.

The spectral profile in Figure 5 is approximately Gaussian in shape, and a more rigorous analysis would have numerically fitted a Gaussian curve to this jagged profile, but if one-significant-figure accuracy is all that is required, one may simply measure the width of the profile at 0.71× the peak amplitude, and in this case arrive at a Q-factor estimate of 70, implying a damping factor of around 0.7%.

By applying this analysis to various fundamental modes of the SHB, the figures in Table 1 were computed.

	1		**2**		**3**		**4**	
	f_0(Hz)	Damping Factor ζ (%)	f_0(Hz)	Damping Factor ζ (%)	f_0(Hz)	Damping Factor ζ (%)	f_0(Hz)	Damping Factor ζ (%)
Transverse	0.28	1.8	0.45/0.46	1.8	0.62	2.0	1.31	-
Longitudinal	1.38	1.6	2.04	-				
Vertical	0.92	1.0	1.28/1.32	-	1.92	1.0		

Table 1 - Fundamental resonance modes of the Sydney Harbour Bridge measured along the road deck. Frequency measurements are ±0.005Hz, and damping factor estimate ±50%. Clicking on the Web links above will direct the reader to the particular spectral plot that was used to make the damping factor estimate.

The above frequencies are consistent with our 2011-2012 observations of SHB modes measured at centre-span of the SHB except for the 0.62Hz transverse mode which (we were to discover later) is at an amplitude node at centre-span.

Measuring at 15 locations along the length of the SHB road deck and conducting detailed analysis of the spectra at each point generates a large amount of information that is difficult to interpret by viewing the many individual spectral plots. So many spectra were combined into 3-dimensional 'surface plot' graphics[8], such as that presented in Figure 6. In this example, showing the SHB's longitudinal component of motion, one can identify modal motion as a series of long narrow hills separated by long valleys. Moreover one can see at a glance that in this case the overall peak amplitude occurs at a frequency of around 10Hz and is located toward the centre of the bridge. If one then considers an individual modal 'hill' and then focuses on a narrow frequency band either side of the hill, a more detailed picture emerges such as that shown in Figure 7. Here one may observe how the amplitude of the SHB's 0.92Hz vertical mode varies along the length of the road deck, and in this case it is fairly clear that this is characteristic of a fundamental Mode 1 oscillation.

[8] Utilising the graphics library of matplotlib

Earlier measurements of the SHB natural motion conducted by the authors in 2011 & 2012 failed to detect a conspicuous transverse mode at 0.62Hz, and Figure 8 which presents the transverse amplitudes around this frequency, shows why. Earlier measurements were conducted at the

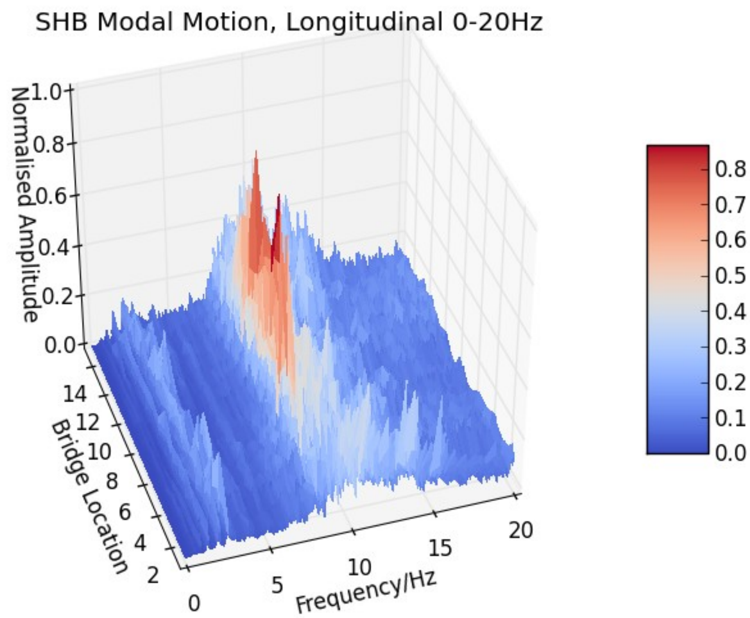

Figure 6 - Normalised spectral amplitude of longitudinal motion on Sydney Harbour Bridge, presented as a function of frequency and location along the road deck.

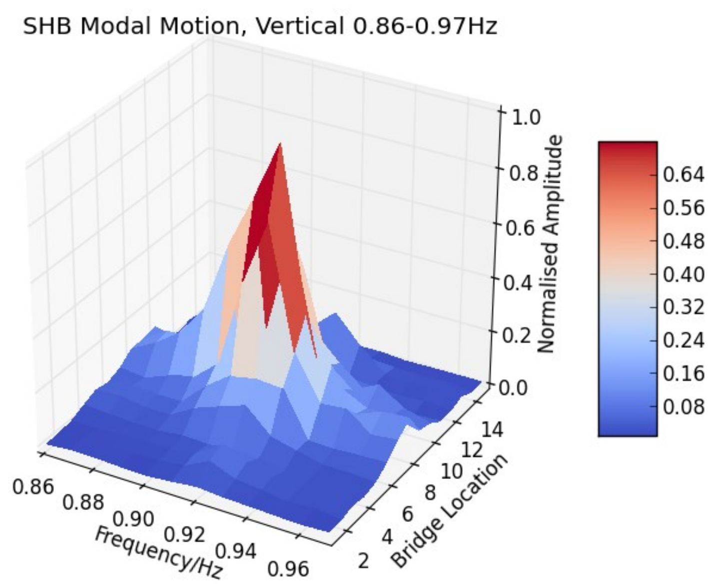

Figure 7 - Normalised spectral amplitude of vertical motion on Sydney Harbour Bridge, presented as a function of frequency and location along the road deck.

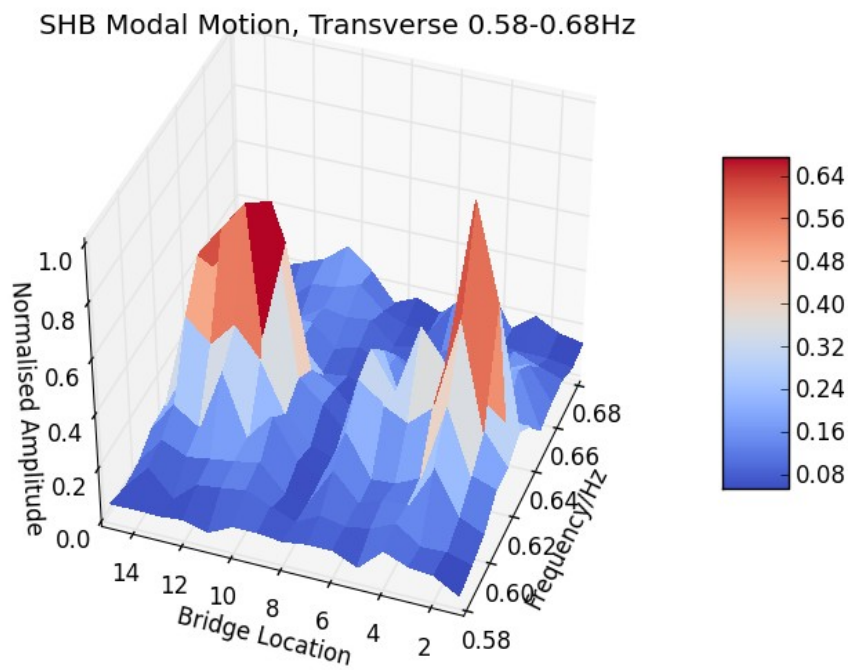

Figure 8 - Normalised spectral amplitude of transverse motion on Sydney Harbour Bridge, presented as a function of frequency and location along the road deck.

the bridge centre span (i.e. Location 8), and Figure 8 demonstrates a nodal valley at this location.

When plotting out these modal shapes, the highest mode one can clearly show using just 15 measurements along the length of the road deck is Mode 3, a good example being provided by the 1.31Hz transverse mode. The 3D surface plots shown in Figures 6-8 present only one fixed view of a 3D object, which can sometimes limit the observation of all surface features when viewed from all angles. To address this limitation Table 2 lists many of the significant low frequency modes of the SHB, and if the reader is viewing this document on an internet-linked device, clicking on one of the Web links will load an animated graphic similar in appearance to Figures 6-8, but rotating in azimuth to show the reader all aspects of the surface plot.

	Band	Frequency (Hz)
Transverse	0-2Hz	0.28, 0.45, 0.62, 0.90, 1.31
Longitudinal	0-4Hz	1.38, 1.93, 2.04, 2.55-2.70, 2.91
Vertical	0-2Hz	0.92, 1.28/1.32, 1.58, 1.92

Table 2 - Noteworthy low order modal oscillations of the Sydney Harbour Bridge road deck. Clicking on Web links above will load the related animated 3D graphics.

When viewing the linked graphics in Table 2, although one can usually clearly identify the modal structure of a particular frequency, the 3D surfaces are often not as smooth as they could be. An example is provided in Figure 9 showing the SHB's first transverse mode at 0.28Hz.

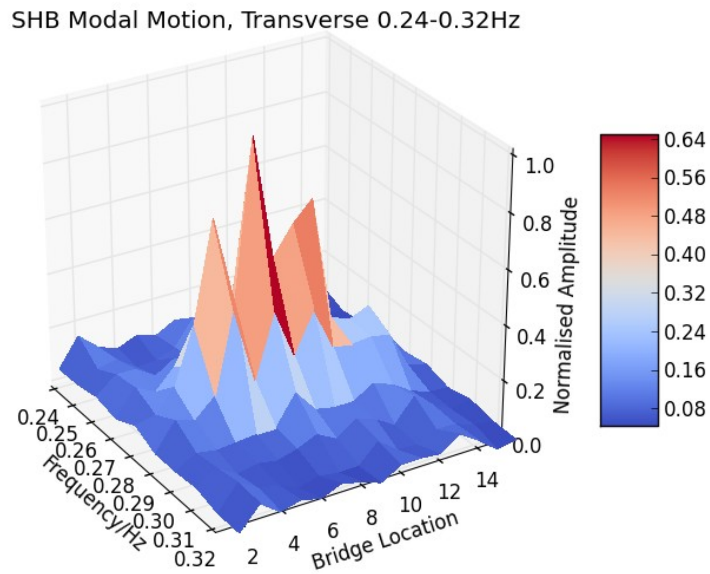

Figure 9 – SHB first transverse mode centred at 0.28Hz.

Although we believe 0.28Hz to be a Mode 1 oscillation, the single 'hill' presented in Figure 9 is unexpectedly 'pointy'. The simple explanation (we believe) is that the modal amplitude was continuously changing during the several-hour measurement session. We were able to check whether this might be the case by investigating SHB data we acquired during a 60-minute observing run at SHB centre-span on 5th July 2012. By breaking that observation into four 15-minute records, and by comparing FFT spectra from each record, one could clearly see that the *relative* amplitudes of the low frequency modes changed with respect to each other by factors of 20-30%. Hence this temporal variation in modal amplitude presents a major limitation with obtaining unambiguous smooth 3D modal amplitude plots. Since the road traffic and weather were fairly calm and consistent during our observing run, we suspect that the passage of heavy commuter trains[9] across the SHB likely had a significant bearing on the modal amplitudes during our 10-minute spot-measurements.

Measuring the Sydney Harbour Bridge's natural motion provided a good test platform for our measuring equipment and analysis, and since we had worked with SHB data previously we had a good idea of what to expect by way of road and rail traffic vibration and the detectability of modal motion. But now we wished to test our equipment on a more complex structure and at the informal suggestion of a NSW RMS engineer, we chose the elevated steel road/rail viaduct which forms part of the Cahill Expressway[10], (CHE) and which connects to the southern end of the SHB. The underlying support structure of the CHE's road deck changes continuously along the length of the roadway, both with the height and separation of the vertical support trestles, as well as by interposition of the Circular Quay Railway Station which is built into the viaduct about half way along its length.

On the 25th May 2013, the senior authors made a series of 17 measurements along the pedestrian walkway of the CHE elevated roadway (see Figure 2 for measurement locations). These spot-measurements commenced at the eastern end, eastwards of the road deck abutment (i.e. location '0') and from this place spot-measurements were repeated every 20 metres. All spot-measurements were of 10 minutes duration. Between the viaduct's eastern abutment and the railway station the roadway is supported by two-leg steel trestles placed at intervals of 20 metres, whereas on the western side of the railway station this trestle separation distance increases to around 25 metres (since the road deck is lower at the western end). Within the railway station structure itself, the road deck is supported by three-leg steel trestles separated by 15.5 metres. Natural motion measured on the road deck eastwards of the railway station is strongly characterised by the first transverse mode at ≈ 1.4Hz (analysis of this spectral feature is shown in Figure 5). As one approaches the railway station from the east the low frequency modes (i.e. <5Hz) fall away and essentially disappear at the railway station's concrete-frame building, but they resume again westward of the station with the first transverse mode now at a frequency ≈ 1.25Hz.

This spectral behaviour is summarized in Figures 10 and 11, where Figure 10 presents frequencies in the range 0-5Hz and shows that the most significant transverse motion occurs on the eastern side of the railway station. Figure 11 is the same as Figure 10 but highlighting just the 1.0-1.6Hz frequency range. These plots clearly show how the first transverse mode on the eastern side of the railway station is relatively large and centred at a frequency of 1.4Hz, whereas on the western side it is relatively weak with a frequency of around 1.25Hz.

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[9] Sydney commuter trains weigh 40-60 tonnes per carriage.

[10] Cahill Expressway Wikipedia Page

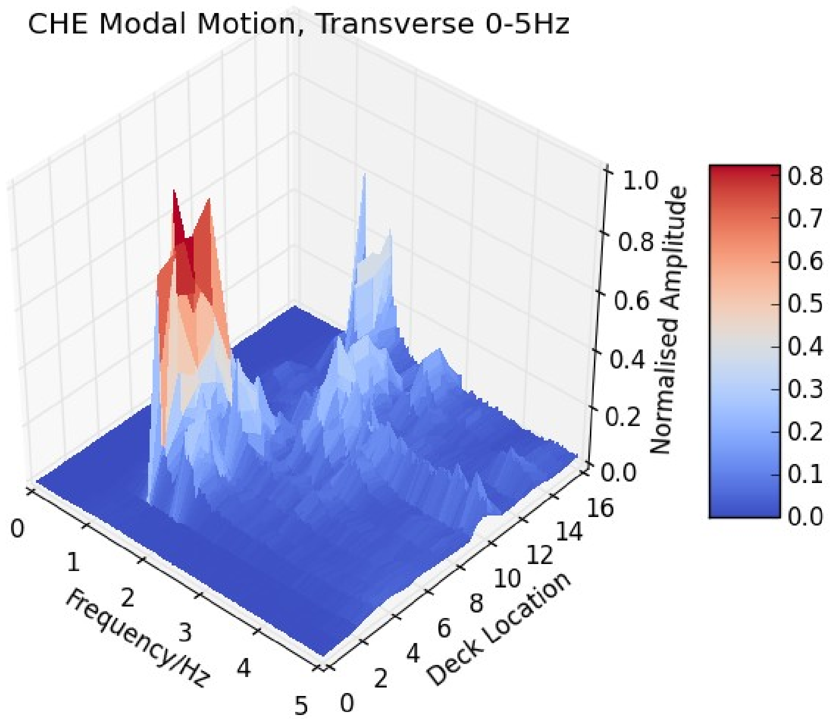

Figure 10 – Normalised amplitude of the transverse acceleration measured on the Cahill Expressway Viaduct elevated roadway, for frequencies 0-5Hz.

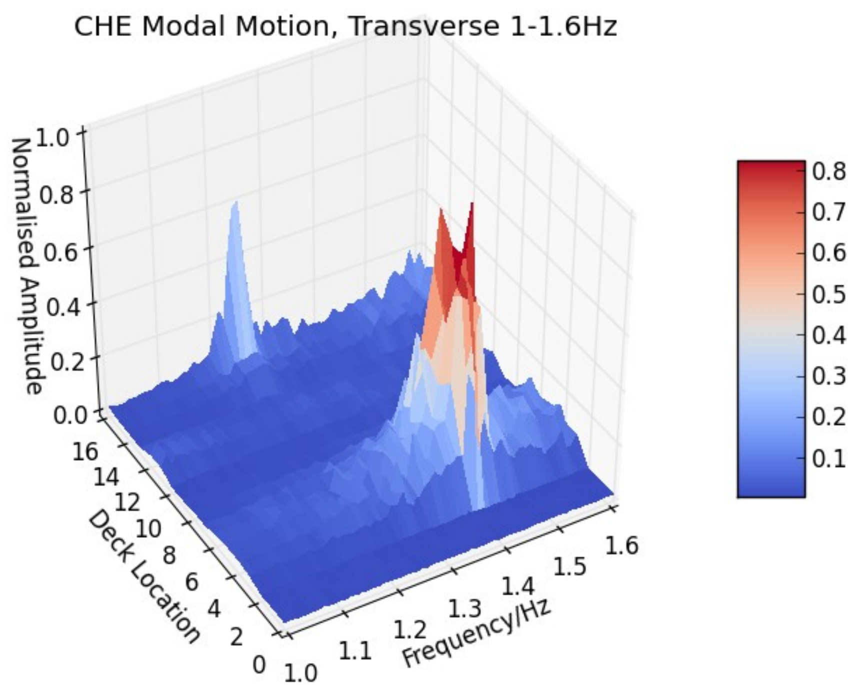

Figure 11 – As for figure 10, but highlighting the 1st transverse mode located at 1.25Hz (western end) and 1.4Hz (eastern end).

Discussion

The technology of real-time structural motion monitoring is advancing rapidly and during the brief time that the authors have been developing their own structural monitoring techniques, the Sydney Harbour Bridge has advanced from never having had any structural motion measurements conducted on it[11], to now having a state-of-the-art real-time monitoring system running beneath its road deck that sends automated warnings to bridge maintenance personnel if any monitored structural element abruptly changes its normal motion. On February 28th, 2013 train services across the SHB had to be suspended for several hours when several steel plates detached from the bridge and were found hanging over the train lines[12]. Although it does not appear that the detached steel plates were structural or particularly critical in this case, it does perhaps indicate that after 80 years of fine service the Bridge is starting to show its age and installation of a 'bridge health' monitoring system is a timely and wise precaution.

Our improved measuring equipment incorporating lower-noise MEMS sensors worked as expected, permitting accurate identification of bridge fundamental modal frequencies. Although for practical reasons we chose a spot-measurement time interval of 10 minutes, ideally a much longer sampling period would be preferable, permitting improved spectral signal-to-noise, and the improved FFT spectral resolution. This would improve the accuracy of the spectral profile shapes of modal resonances, permitting improved accuracy with estimating the damping factors of the various modes.

By use of a modest triaxial sensor stepped across a bridge, we are now able to promptly plot structural modal behaviour, best displayed with animated 3D graphics. Using our new software this analysis may be conducted within minutes of the completion of an on-site bridge measuring session, perhaps over a coffee at the nearest café. However a major limitation with stepping a single sensor about a structure, is that modal amplitudes are likely to change during the several hours that a measurement session is in progress. The next step for us will be to develop an array of autonomous sensor/loggers whose measurements will be synchronised via a precision real time clock on each sensor. With many loggers recording in parallel it will become practical to increase the logging interval substantially, with benefits mentioned above. Recent advances in microcontroller technology and the dramatic reduction in the cost of suitable microcontrollers, make this development a possibility.

[11] As far as we know Phillips, McCue & Samali 2012 was the first publication to enumerate the SHB lower order modal frequencies, from actual road-deck measurements.

[12] Sydney Morning Herald article, 1st March, 2013

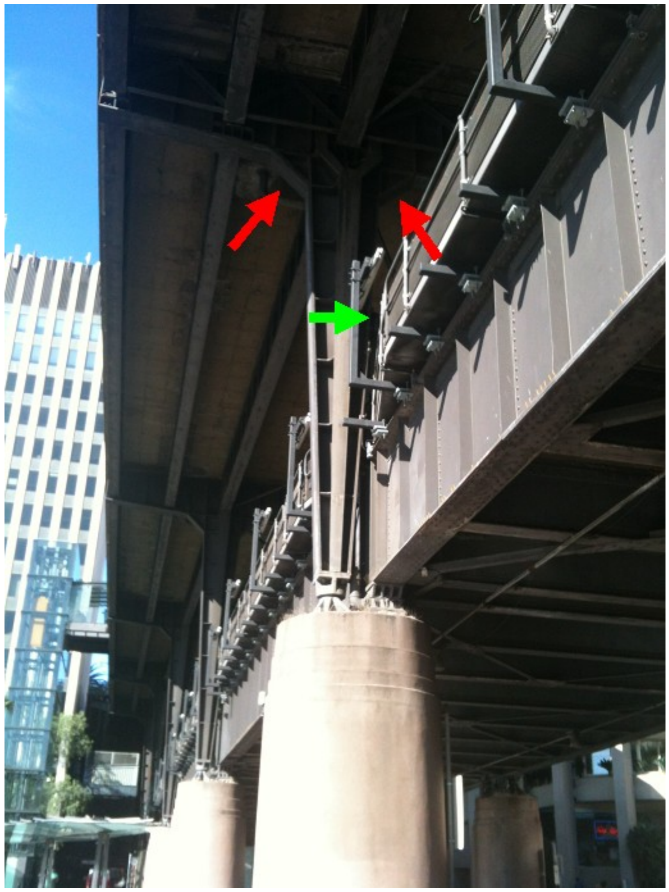

Figure 12 - Underside of the Cahill Expressway Viaduct road deck, showing a trestle leg support. Red arrows indicate welded fillets to resist transverse motion. Gross transverse deflection would be arrested by the trestle leg contacting the underlying railway line support structure at a point indicated by the green arrow.

One of the unexpected outcomes with measuring the Cahill Expressway Viaduct was identifying one stretch of the roadway whose transverse modal motion was substantially greater than anywhere else along the viaduct, and very poorly damped. An inspection was made of the trestle supports underneath this section of the roadway, one of which is shown in Figure 12. Here we see the tapered trestles extending upwards from the concrete pier that also supports the train line. Moderate transverse loads on the road deck will be resisted by the welded fillets located at the top of the trestles (indicated by red arrows) whereas gross transverse deflections will be additionally resisted by the trestle legs contacting the railway support structure (green arrow). But given the natural transverse motion strongly favouring the first transverse mode at 1.4Hz, and the low damping of this mode ($\zeta \approx 1\%$), we wondered if this particular section of roadway might present a seismic hazard, so we informally contacted the NSW RMS with our observations, querying if their CHE Finite Element model for this section of roadway might also show the same enhanced transverse motion that we observed.

The NSW RMS have created many detailed Finite Elements (FE) models for the historical bridges in their portfolio, but at this time they don't have one for the Cahill Expressway Viaduct. But they did informally agree that our observations were interesting and advised that the original engineering drawings for this section of roadway would now be reviewed to assess if a hazard exists and what might be done to address it. However we know this section of roadway is not at especially high seismic risk as a significant NSW earthquake actually tested it shortly after construction. The elevated roadway section of the Viaduct was opened in March 1958, in time for the Magnitude 5.6 Robertson-Bowral earthquake[13] of 22nd May, 1961 (whose epicentre location was around 110km due South West of CHE). This earthquake did a lot of superficial damage around Sydney and contemporary newspaper reports stated that the Sydney Harbour Bridge "shuddered". It is probable that the SHB and CHE were inspected by engineers in the wake of this earthquake, but as far as we know no written reports exist[14] indicating if any inspections were done, or damage noted.

To assist a NSW RMS structural engineer with her current FE modeling work of Stockton Bridge[15], NSW, on the 13th July 2013 we made another series of measurements along the Stockton Bridge's pedestrian walkway. This large bridge was damaged[16] by the nearby Magnitude 5.6 Newcastle Earthquake of 28th December 1989, when one of the bridge's abutments settled (epicentre location ≈ 18km WSW of the bridge). This tall and wide-span concrete bridge has quite different spectral behaviour when compared with the SHB and CHE, with an example presented in Figure 13.

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[13] Cooney (1961)

[14] NSW RMS, private communication.

[15] Stockton Bridge, NSW, shown in Google Maps

[16] Jankulovski, Sinadinovski, & MccCue, 1996

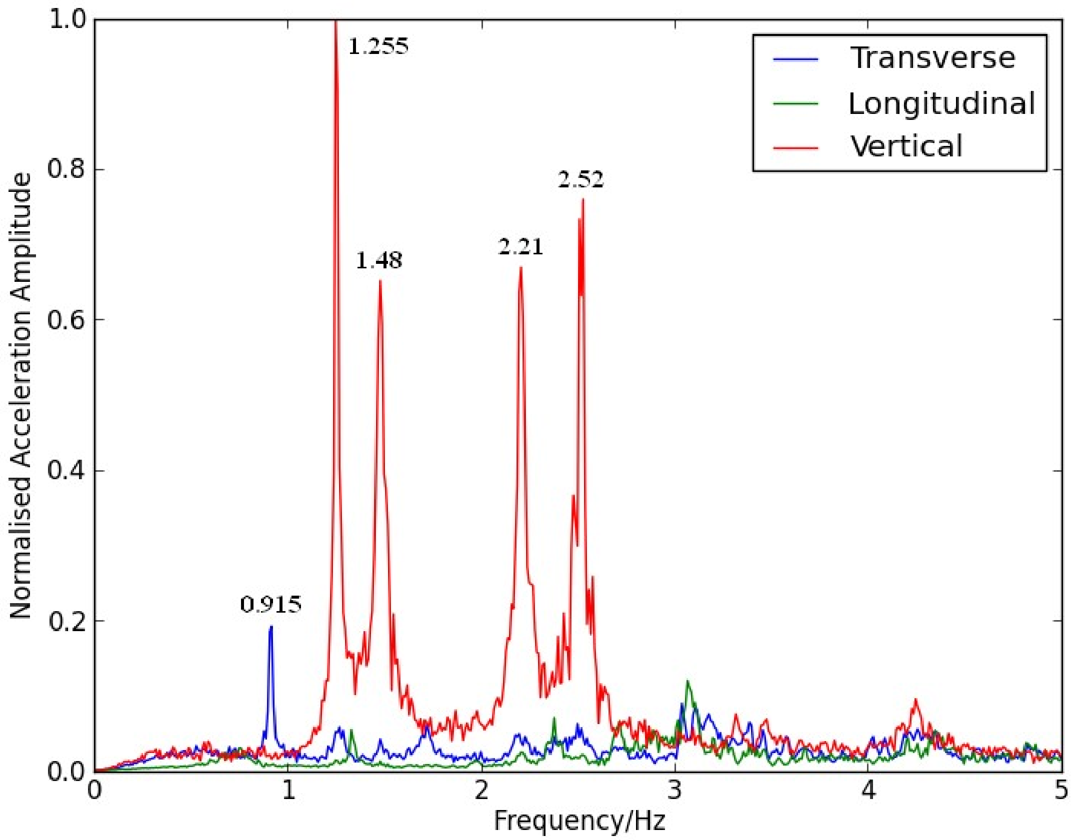

Figure 13 - Natural motion of Stockton Bridge, NSW, measured centre-span on the road deck. Frequencies of key modal motions are indicated above each spectral line.

Here vertical modes dominate in amplitude, where the only significant transverse oscillation occurs at 0.915Hz with $\zeta \approx$ 1.1%.

Perhaps the most noteworthy modern example of a new bridge with unexpectedly high amplitude natural motion is London's Millenium Footbridge, a 320m long lateral suspension bridge. Engineers called it "an absolute statement of our capabilities at the beginning of the 21st century". When it was opened in June 2000 and for the first time fully loaded with pedestrians (up to 2000 possible at any given time) an alarming transverse swaying became apparent. Curiously this motion was generated and inadvertently greatly *amplified* by the walking pedestrians, through a positive feedback cycle caused by the pedestrians *compensating* for the transverse motion they could sense. No one was trying to walk in step; pedestrians did so only to accommodate the bridge's movement under their feet.

The bridge was closed shortly after opening and reopened in February 2002, following the addition of 37 fluid-viscous dampers to arrest transverse resonance, and 52 tuned mass dampers to arrest vertical resonance. Although this curious human-generated feedback effect would have been difficult for engineers to predict in advance, and extraordinary engineering ingenuity went into the analysis and solution of the problem[17], it could perhaps have been anticipated during final construction by simple measurements of natural motion, and from these the calculation of modal fundamental frequencies and damping factors.

In fact this human induced transverse motion on bridges has been observed before, one notable example being when ≈ 2000 pedestrians marched across New Zealand's Auckland Harbour Bridge during September 1975. In this case the motion affected the bridge's steel box section extensions (known affectionately by Aucklanders as the 'Nippon Clippons') that had a natural transverse period of ≈ 0.7Hz[18]. In view of this event, it would have been most interesting to have had motion-measuring equipment installed on the SHB during the Bridge Walk for Reconciliation, May 28, 2000, when more than 300,000 people walked across the bridge.

Conclusions

Earthquakes are low risk but high consequence events. As such, for important structures like the iconic Sydney Harbour Bridge or high usage Cahill Expressway, special measures are required to reduce the risk of failure even further. In the last 50 years four moderate magnitude earthquakes at ≈ 100km distance have rattled the Sydney CBD and the prospect and consequences of a larger, closer earthquake need to be thoroughly assessed.

We have focused on measuring, for the very first time, just the basic essential parameters required for that assessment of consequences to be performed. We have shown that measurement is quick and relatively simple and allows modellers to tweak their Finite Element models of these complicated structures to better represent reality.

We recommend that as their cost decreases and sophistication of measurement systems increases, engineers should regularly upgrade their monitoring systems to get up-to-date information in near real time. This should start from completion date when the structure should be measured and compared with the structure as designed. Earthquakes will find the weakness in every structure.

Acknowledgements: Thanks are extended to the reviewers of this paper for their work and particularly helpful suggestions. Also to Mr. Peter Mann (Asset Manager, Strategic Infrastructure, NSW RMS) for organising our access to Sydney Harbour Bridge and other Sydney road bridges. Thanks are also extended NSW RMS structural engineer, Meera Mohan, for her assistance.

[17] http://www.londonmillenniumbridge.com/

[18] A Critical Analysis of the Auckland Harbour Bridge, New Zealand. Sullivan, 2009