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Real-time performance monitoring of a TMD for a 183m reinforced concrete chimney

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ABSTRACT: Since February 2007, a 183m reinforced concrete chimney at a conventional power station in England has been monitored due to concerns about in-wind vibration levels due to interference effects following the construction of a new chimney in the upstream direction of prevailing winds. A 40-tonne tuned mass damper (TMD) was later installed to reduce response levels and the monitoring system was adjusted to track the resulting mode frequency and damping ratios.

The system implements the stochastic subspace identification procedure directly in the LabVIEW environment, performs automated identification and mode quality assessment, then reports mode properties via daily emails and an internet viewer.

The system has confirmed the operation of the TMD, which has been able to increase damping from 0.7% to 4% in the strongest winds. The mode tracking has also been able to show some interesting temporary operational effects on chimney modal properties.

1 EXPERIMENTAL STUDIES OF TALL REINFORCED CONCRETE CHIMNEYS

Performance of tall reinforced concrete chimneys due to both along-wind and cross-wind loading has long been a concern for operators of industrial facilities such as conventional power stations. Although not well reported in academic literature, a particular problem is the effect of upstream structures that cause interference effects and enhanced crosswind response.

Even for isolated chimneys, prediction of response levels requires accurate estimates of modal parameters, in particular damping ratio, and some of the earliest studies on accurate assessment of damping were carried out as long as half a century ago on such structures. Novel experimental techniques for modal parameter identification that would these days be ruled out due to safety concerns included use of rocket thrusters and installation of massive shakers.

New developments in system identification procedures are such that accurate modal parameter estimation only requires measurement of response to random wind-buffeting.

2 RUGELEY STACK, NEW CHIMNEY AND TUNED MASS DAMPER

The 183m tall original flue gas chimney at Rugeley power station (near Birmingham, UK) operated without incident since it was built in 1968 until construction, in late 2006, of a replacement chimney in the upstream direction of the prevailing wind. The two chimneys, shown in Figure 1, were intended to coexist for approximately two years until demolition of the original chimney. However, during the construction of the new chimney, the old chimney was observed to sway significantly. Following an investigation [1] into the anticipated across wind interference effects and a structural analysis of the reinforced concrete windshield, a vibration monitoring system was installed, followed rapidly by the installation of the world's largest tuned mass damper for a concrete chimney.

No experimental values of modal properties were available for the response calculations undertaken in the investigation, which were based on analytical models and previous studies (for damping). In fact obtaining reliable estimates of modal properties of the chimney to validate the calculations presented a challenge: access to upper levels of the chimney was possible only by steeplejacks, and suitable 'point and shoot' response measurement technology (such as laser vibrometer) was not available.

The wind effect investigation concluded that, with the new chimney present, maximum response of the existing chimney, at a level depending on the existing damping capacity, would occur with free-stream wind speed of 31m/sec. Given historical wind conditions, it was found that there was a significant probability of design capacity being exceeded over the remaining lifetime for a damping ratio of 1%, a credible upper bound value for this type of structure. Hence the decision was made to install the tuned mass damper (TMD) as well as a monitoring system to first confirm the structure modal properties (for design of the TMD) and subsequently to confirm the effectiveness of the additional damping and monitor the performance of the damped system.

Installation of the monitoring system by University of Sheffield and of the TMD by Multitech (France) ran in parallel during the first four months of 2007. The TMD, shown under construction in Figure 2 and in final configuration in Figure 3 comprises 4.2×10^4kg of moving mass in a ring suspended from brackets so as to act as a pendulum, with five viscous damper units connecting the ring to the chimney. In the first mode of the chimney (at around 0.3Hz) the TMD/chimney mass ratio is 3.9%, with up to 450 mm relative displacement between chimney and moving mass accommodated by the suspension and dampers.

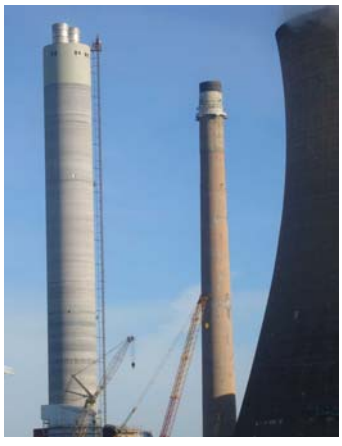

Figure 1 Rugeley chimneys

Figure 2 TMD installation and lower accelerometer box (circled)

Figure 3 TMD

3 MONITORING SYSTEM DESIGN AND OPERATION

The original concern of the operator was the level of vibration, in terms of displacement, directly derived from the expected capacity of the structure. The original specification for the monitoring required monitoring of biaxial movement at the highest possible position on the chimney, indicating and reporting of peak response and triggering of alarms at three alert levels, the largest at 0.3m displacement. Optical systems were ruled out for several reasons and a four channel accelerometer system was designed and installed in early February 2007.

The system comprises four Honeywell QA750 quartz-flex servo-accelerometers oriented in 'tangential' and 'radial' directions on the chimney in watertight enclosures at two levels (180m and 40m), and a simple 4-channel National Instruments data acquisition (DAQ) system, described later. Installation of the boxes required a team of steeplejacks installing an access ladder the full height of the chimney and anchoring the cables to existing cables for aircraft warning lights. Hence the accelerometer axes differ by 11° from crosswind and alongwind axes with respect to wind coming from the direction of the new chimney. The lower enclosure is shown circled in Figure 2.

A few minutes of response data were retrieved on the calm day of the installation, then the system was left to run unsupervised until an ADSL internet connection was installed. When returning to check the system, it was found that signals from the top pair of accelerometers were lost due to abrasion failure of the instrument cables. Further, the acquisition computer had failed and no more data were available. While the TMD was being installed (making use of the temporary hoist), a more robust cabling system was installed. From 15th March data were available remotely via ADSL connection.

4 ACQUISITION, SIGNAL PROCESSING AND PARAMETER ESTIMATION

From the initial six minutes of response data it was possible to estimate the first mode frequencies as 0.33 Hz and 0.34 Hz. Damping was estimated at 2% and 1% for the two modes, but the values were not expected to be reliable due to the extremely short recording duration.

During the March visit to fix the cables a little over two hours of data were recorded from the bottom set of accelerometers (this cable was still intact). These data were enough to provide better parameter estimates for the first two bending mode damping ratios of 0.5 % to 0.7 %, below the 1% damping level used in the wind study. These values were used in the final design of the TMD.

The ADSL internet connection was operational from 20th March and cables had been replaced (while a hoist was still in place for the TMD installation) so this marked the start of continuous remote monitoring.

To minimize costs, a relatively simple acquisition system was designed. A NI-USB-6251 16-bit National Instruments data acquisition (DAQ) chassis fitted with two SCC-AI13 low pass filter modules with 4Hz cut off frequency was installed but unfortunately, being only 2-pole filters, a substantial amount of energy was being aliased making the first 4Hz band very noisy. To mitigate the weak filtering and skew of the multiplexer, signals were over-sampled, at 64 Hz and digitally decimating by a factor of eight (incorporating an eight pole Chebyshev filter in the decimation). A LabVIEW virtual instrument (VI) was written to collect 180-second frames saved on the DAQ laptop computer. The same stored data are also transmitted over the broadband line using LabVIEW's datasocket protocol allowing for viewing at any computer equipped with a standalone executable client application.

The alarm trigger levels for the top set of accelerometer responses were set to correspond with three levels of displacement associated with the strength capacity of the concrete windshield. The highest response level represents 25cm displacement amplitude with excedence requiring site evacuation for personal safety. The bottom set of accelerometers were installed as a backup in case of failure of the top set. Comparing acceleration data to a displacement threshold requires response to be pure first mode (which it practically is in strong winds) and at a constant frequency (which in fact it isn't). Trigger levels for the lower set were obtained via mode shape ordinate measurements from analysis of data from 21st March to the 10th April, resulting in an estimated value of 0.07 for mode shape normalised to 1.0 at the top accelerometer.

Figure 4 shows a screen shot from the client application at the time of a low level alarm. The system also emails a daily log file of minimum and maximum response values for every 3-minute frame in the preceding 24 hours.

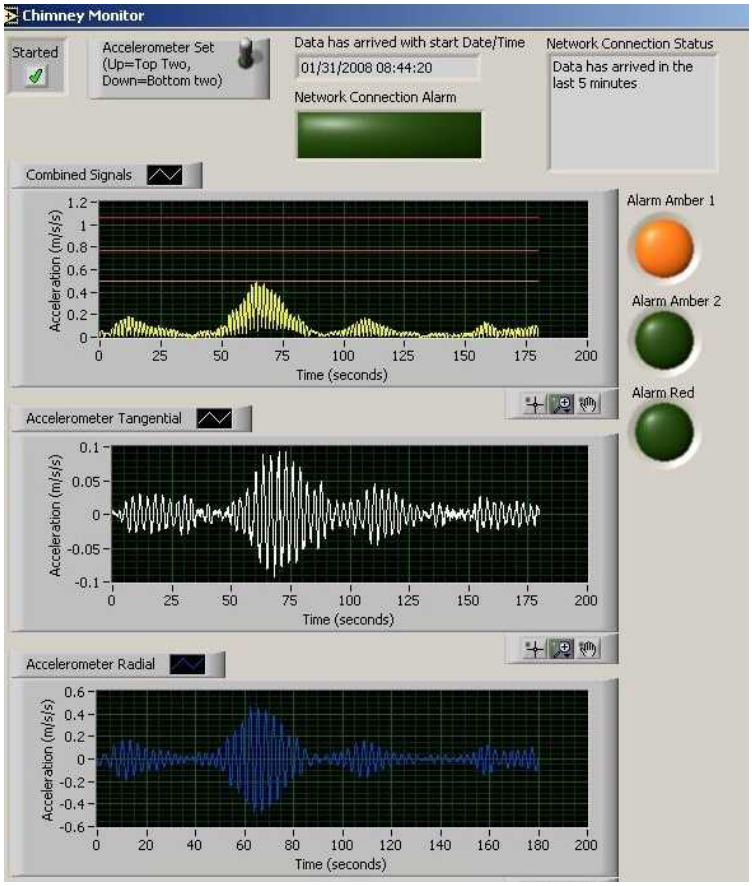

Figure 4 Client application with alert level 1, 31/01/2008

5 VERIFICATION OF THE TMD

With the installation of the TMD, the instrumentation system was adapted to check its correct functioning. Since the purpose of the TMD was to enhance damping, procedures were implemented to extract the damping parameters of the first two bending modes automatically online using a procedure based on a previous implementation at the Tamar suspension bridge [2]. The system batch-processes data to extract modal parameters using reference based covariance-driven stochastic subspace identification (SSI-COV) [3] implemented using the Mathscript language of LabVIEW, to avoid the expense of a MATLAB commercial license.

In the LabVIEW version (8.2) for the original implementation the linear algebra functions of the Mathscript language were far slower and inefficient compared the MATLAB equivalents. To provide reliable parameter estimates without overloading the processor and compromising the DAQ operation a second VI was written which operated in tandem with the acquisition VI on a timed loop analyzing two-hour sequences of concatenated 3-minute data files resampled at 2Hz.

SSI usually requires user intervention with the interpretation of 'stability diagrams', although in recent years several procedures have been proposed for their automatic interpretation. Stability diagrams show vibration modes identified as the order (or number of mathematical poles, related to the number of modes) of the estimated system is increased. Further issue not normally considered are the choice of 'reference' channel(s), the way in which the covariance function functions are constructed and how many data points from them are used. Figure 5 shows the stability plot for 8Hz sampled data recovered for September 2007. Around 0.32Hz is a cluster of modes (four would be expected) that boils down to two modes that are clearly identifiable, with two second mode(s) around 1.4Hz. The chimney is not quite symmetric; the flue ducts pass through flanking buttresses shown in Figure 6 hence there is an expected stiffer ('tangential') direction.

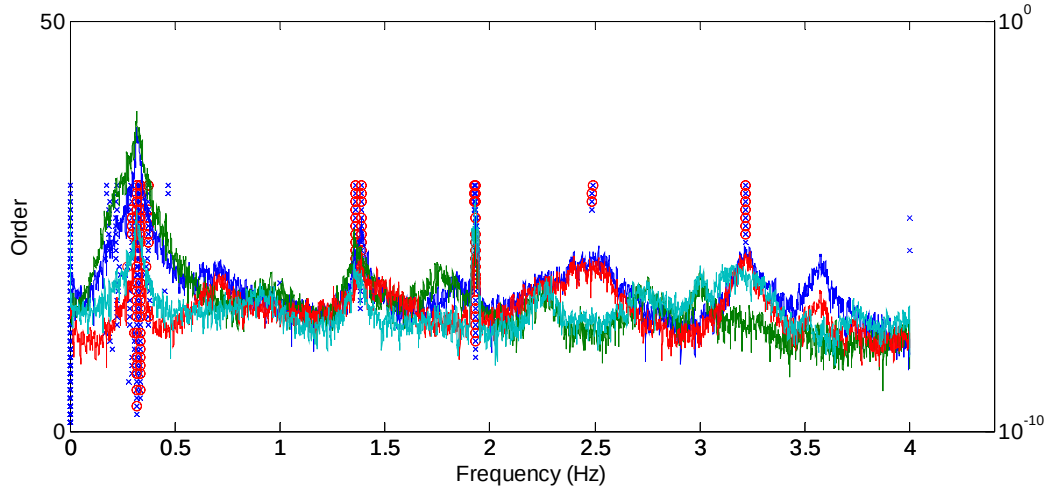

Figure 5 stability diagram during normal operation

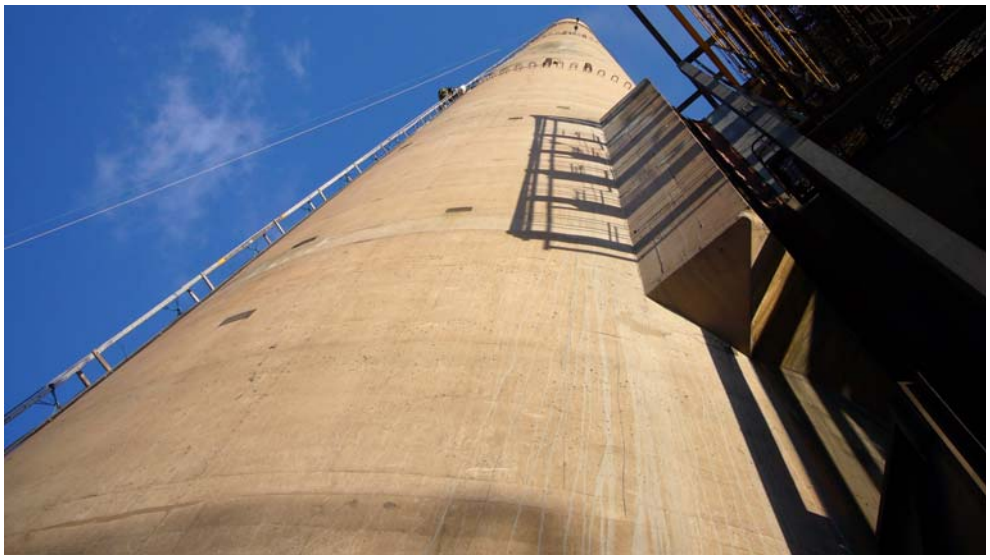

Figure 6 Flue ducts flanking chimney (and steeplejack installing sensors)

The client monitoring software graphically displays the previous few days of estimated damping (and more recently also frequency) parameters giving a medium-term trend used for monitoring the performance of the TMD. As expected the TMD performance proved to be amplitude dependent; apparently it was not engaged substantially during periods of weak wind. Moreover the damping parameters were identified with a higher (poorer) variance when the modes were weakly excited. Observing the TMD performance (through damping ratios) is aimed not at identifying sudden failure of the TMD but rather to show slower degradation of effectiveness, giving due warning for maintenance.

6 CHARACTERISTICS OF RESPONSE DURING AND AFTER INSTALLATION OF TMD

Because of signal loss from the upper accelerometer box, there are no useable data describing the wind-induced response of the bare unmodified chimney. The TMD installation was completed on 5th April 2007 (Figure 2, from 9th March, shows one quarter of the TMD masses installed), and modal analysis of data recorded from March 21st to April 20th is presented in Figure 7. This shows that for the majority of the time, damping levels were below 1%, until about a quiet week after the TMD installation was completed when damping levels began to increase noticeably, as if the damper had been 'run in'.

Some other features of the data are notable: the gap between frequencies varies as do the absolute values in apparent diurnal cycles of varying range. Around 1st April there is a hint that frequency might depend on amplitude, on 5th April there are jump-shifts in frequency. Around 9th April there are very large frequency drops that have little to do with amplitude and are suspected to be due to 'operational' effects on the chimney, i.e. how it was being used (or not) for flue gas emission.

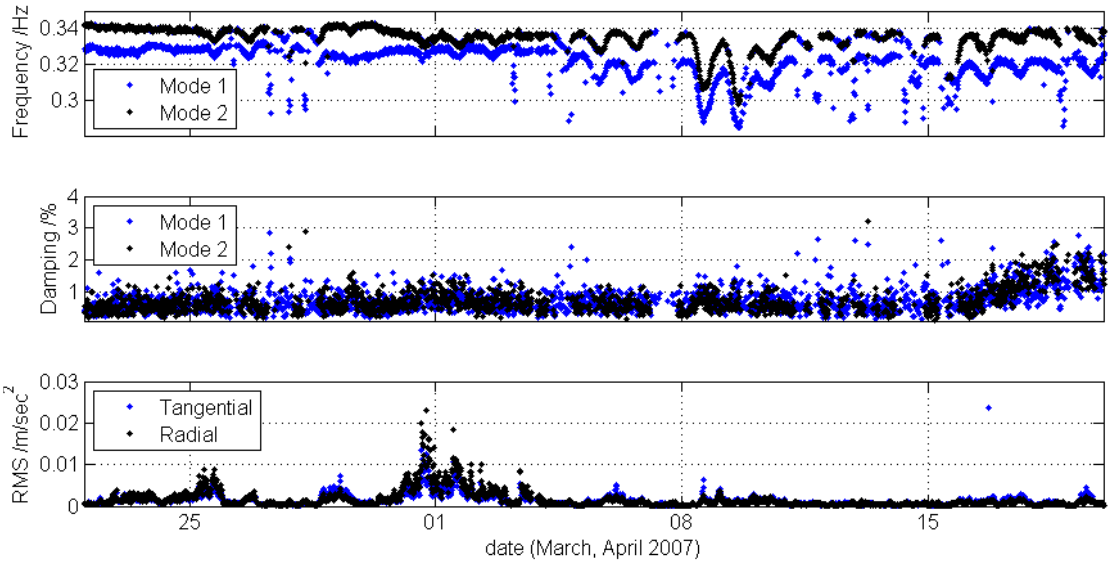

Figure 7 Chimney/TMD system performance during early days of operation (TMD engaged on 5th April)

Figure 8 is a screenshot of the damping plot for late February 2007 during strengthening south westerly winds showing the TMD at the peak of its effectiveness. Wind data were not available for the site so Meteorological Office data for stations at East Midlands and Birmingham

airports, obtained via http://weather.noaa.gov/ were used for indicative purposes. Meanwhile for graphical display of wind conditions, xcweather.co.uk (Figure 9) was used.

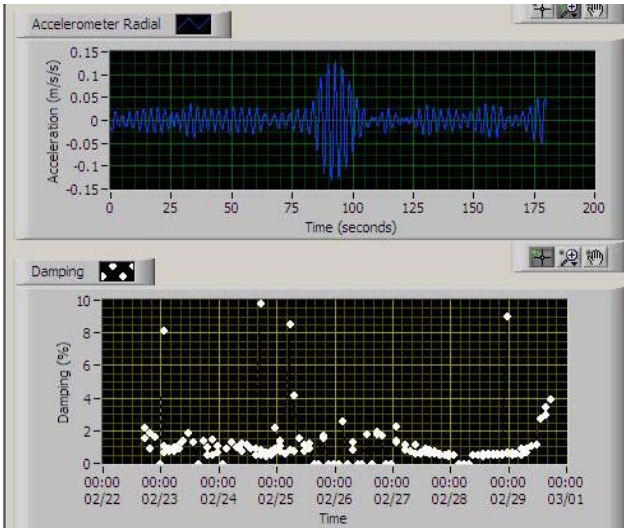

Figure 8 Response and damping in Feb 2007

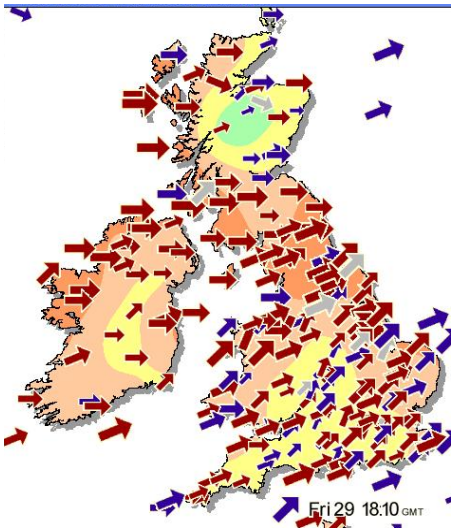

Figure 9 Corresponding wind conditions

Figure 10 shows a full year of performance data. Lowest damping (around 0.7%) corresponds to low winds with damping occasionally (as in Figure 8) rising to 4%. Occasional large frequency dips (observed in Figure 7) recurred, otherwise larger response (seen by increased damping) tended to result in reduced frequencies. Interesting effects are visible in data from April 2008, but are not discussed in this paper.

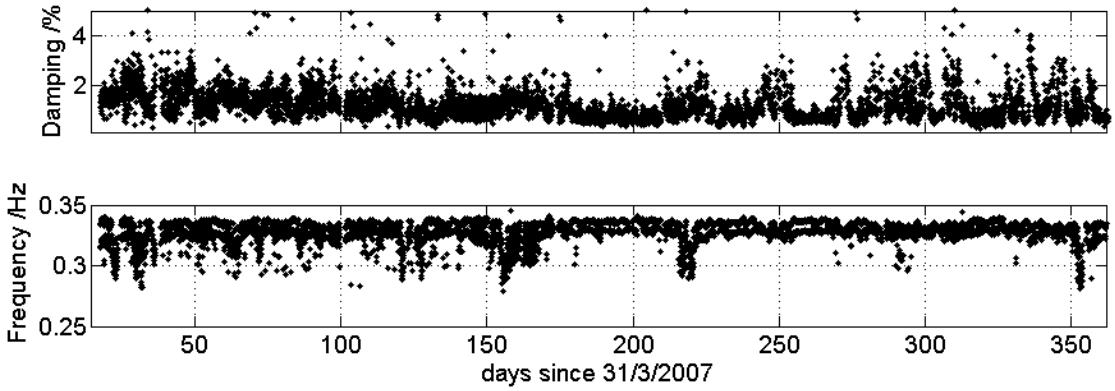

Figure 10 One year of damping and frequency estimates

7 DIRECTIONAL EFFECTS

The new chimney was constructed at a distance of 110m and a bearing of 218° from the original chimney so it would be expected that transverse response to winds from that direction would be greater than (and probably more cross-wind aligned) than similar strength winds from other directions. Without relatively fast-sampled local wind data only general observations could be made.

Figure 11 shows examples of acceleration signals for comparable winds from critical and non-critical directions. These two are single samples so firm conclusions cannot be drawn but it

generally appears that, even allowing for the strongest winds coming from the southwest quarter, the responses are disproportionately higher. The diagonal straight line in Figure 11 shows the cross-wind direction for winds coming from the direction of the new chimney. The investigation of this effect [1] predicted that interference effects for winds with bearings in line with the new chimney, plus or minus a generous margin, and that with 5% damping, would result in peak tip displacement approximately 120mm at the critical wind speed of 30m/sec. The largest recorded response, which occurred on 31st January 2008 matches this value, with average winds up to 40mph (17.8m/sec, logged at EGBB) from SSW direction and certainly including gusts around the critical speed.

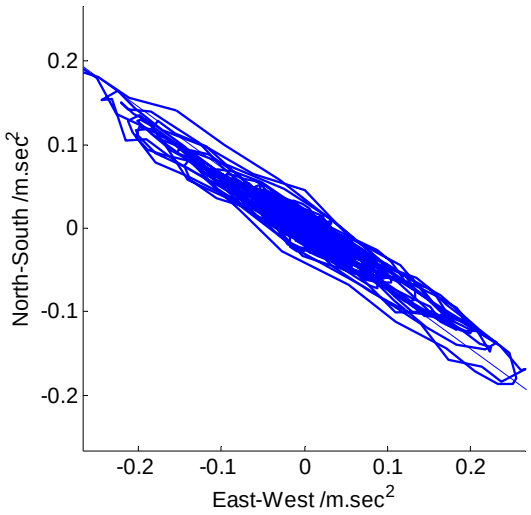

Figure 11a During SSW17-24 MPH winds

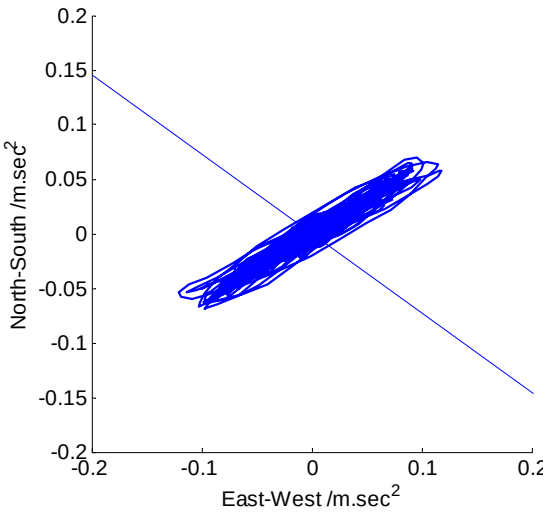

Figure 11b During SSE 22-24 MPH winds

8 REFERENCES

[1] Galsworthy, J. K., Vickery, B. J., *Wind loads and interference effects for new and existing chimneys at the Rugeley power station, UK*, Alan Davenport Wind Engineering Group, Boundary Layer Wind Tunnel Laboratory, 5-9-2006.

[2] Brownjohn, J. M. W., Carden, E. P., "Tracking the effects of changing environmental conditions on the modal parameters of Tamar Bridge", *Proceedings of the 3rd International Conference on Structural Health Monitoring and Intelligent Infrastructure*, Vancouver, Canada, 2007.

[3] Peeters, P., De Roeck, G., "Reference-Based Stochastic Subspace Identification For Output-Only Modal Analysis", *Mechanical System & Signal Processing*, Vol. 13, No. 6, pp. 855-878, 1999.