Real-time performance tracking on a 183m concrete chimney and tuned mass damper system

J.M.W. Brownjohn
Vibration Engineering Section, University of Sheffield, UK

E. P. Carden
Lloyds Register, UK

R. C. Goddard
Bierrum International, UK

G. Oudin
Multitech, France

K. Koo
Vibration Engineering Section, University of Sheffield, UK

ABSTRACT: Since February 2007, a 183m reinforced concrete chimney at a conventional power station in England has been monitored due to concerns about across-wind vibration levels arising from 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 is an implementation of the stochastic subspace identification procedure directly in the LabVIEW environment which 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. The paper describes the system and its evolution, as well as observations on the structure performance.

1 INTRODUCTION: LARGE-AMPLITUDE OSCILLATIONS AND EXPERIMENTAL STUDIES OF 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. As well as public failures e.g. at Ferrybridge Power Station in 1965 when three cooling towers collapsed due to wind effects, there have been concerns with other structures, including those affected by upstream structures such as at West Burton Power Station (Goddard 2007).

Prediction of wind-induced structural response levels requires accurate estimates of modal parameters, in particular damping ratio, and their evaluation at full-scale has led to some novel experimental methods, including use of rocket thrusters, and cumbersome inertial force generators. Being (almost) symmetric, modes of circular chimneys appear in tight pairs that lead to problems when using simple techniques such as random decrement and autocorrelation functions. Technology for system identification procedures is now such that time series of multi-mode chimney response to random wind-buffeting are sufficient for recovering reasonable parameter estimates. This paper describes an application of such technology for structural health monitoring of an ageing structure.

2 RUGELEY STACK AND NEW CHIMNEY

The chimney at Rugeley Power Station, north of Birmingham, was constructed around 1968 and consists of a 183m high reinforced concrete windshield, internally protected by a sectional, acid resisting brickwork lining. The windshield tapers from an external diameter of 9.4m at the
top to 15.7 m at the base. Its outer surface has suffered from environmental actions and external reinforced concrete cladding was added in 1998 over the top 24 m.

Due to the installation of a new flue gas desulphurisation (FGD) plant a replacement chimney of the same height was constructed beginning in 2006, at a distance of 110 m and a bearing of 218°, which is in the southwest direction of the prevailing winds in the UK. The two chimneys, in September 2008, are shown in Fig. 1.

Construction of the replacement chimney prompted the designers (Bierrum International) to commission an investigation (Galsworthy & Vickery 2006) into cross-wind interference effects on the old chimney and a structural analysis of its reinforced concrete windshield. The findings of this study are more accessibly reported in (Goddard 2007). The investigation concluded that ‘interference effects associated with the construction of the new chimney would significantly increase loads on the existing chimney’ and that maximum response of the existing chimney, at a level depending on the damping capacity, would occur with free-stream wind speed of 31 m/sec. Mild steel reinforcement was used in the original chimney and given historical wind conditions, it was found that there was a significant probability of design capacity being exceeded during the period of coexistence for a damping ratio of 1%. The designers recommended installation of a monitoring system to track possible large amplitude response and if necessary a tuned mass damper to control response. The operators decided to act on both recommendations.

Creation and installation of the monitoring system by University of Sheffield and of the TMD designed by Multitech ran in parallel during the first four months of 2007, with early data from the monitoring system being used to fine-tune the TMD, hence the TMD itself is first described, briefly.

3 INSTALLATION AND OPERATION OF TUNED MASS DAMPER (TMD)

The TMD, provided by Multitech (France) comprises 4.2\times10^4 kg of moving mass (steel ring with concrete elements) and five viscous damper units. The damper is believed to be the largest of its type installed on a concrete chimney and compared to the analytically estimated 1.07\times10^6 kg modal mass of the chimney in the first vibration mode (around 0.3 Hz), this is a mass ratio of 3.9%.

The damper was designed to have the smallest moving mass possible to generate sufficient damping with maximum relative movement of 450 mm while being constrained by logistics of the erection process, seen in progress in Fig. 2. These included the limitations of the hoisting equipment and the use of post-drill anchors for the pendulum brackets. The steel structure had to be such as to allow all site adjustments without site welding as the perimeter of the stack is not a perfect circle.

Final verification of the performance of the TMD via site measurement, described in the next section, showed that it has provided total damping up to 4% and that it has continued to be effective throughout its operational life.

4 MONITORING SYSTEM DESIGN AND OPERATION

The original requirement for the monitoring system was simply to provide an alarm on occurrence of large amplitude response so that safety measures (including evacuation in extreme conditions) could be taken. Alarm thresholds were specified in terms of peak displacements and while optics-based technology is conventionally optimal for displacement tracking it was ruled out in this case for logistical and operational reasons. Since first mode response was expected to dominate in strong winds and in effect only the resonant component of dynamic displacement was required, displacement levels could be derived from acceleration signal amplitudes.

Hence a simple acceleration monitoring system was designed comprising four Honeywell QA750 quartz-flex servo-accelerometers oriented in ‘tangential’ and ‘radial’ directions on the chimney in watertight enclosures at two levels (180 m and 40 m), and a simple 4-channel National Instruments data acquisition (DAQ) system, described later. The system was installed
on 2\textsuperscript{nd} February 2007. Installation of the boxes required a team of steeplejacks installing an access ladder the full height of the chimney and anchoring the cables alongside existing cables for aircraft warning lights. Hence the orientation of accelerometer axes could not be preset and differ by 11° from crosswind and along-wind axes with respect to wind coming from the direction of the new chimney. Fig. 2 shows the TMD under construction, with the lower accelerometer box visible at the level of the access rungs.

To minimize costs, a relatively simple acquisition system was installed comprising a NI-USB 6251 16-bit National Instruments DAQ chassis fitted with two SCC-AI13 low pass filter modules having 4Hz cut off frequency. Being only 2-pole filters, a substantial amount of energy was being aliased making the first 4 Hz band very noisy. This, and the lack of simultaneous sample and hold facility, were managed by over-sampling at 64 Hz and digitally decimating the signal by a factor of eight (incorporating an eight pole Chebyshev filter). A LabVIEW virtual instrument (VI) was written to record 180-second length frames on the local DAQ laptop computer (Panasonic Toughbook T4). Recently the DAQ has been replaced by a NI-USB 9239 which due to higher specification has several advantages (and a few disadvantages) compared to the original device.

During the initial commissioning very short recordings were made purely to check system operation before leaving the system to run unsupervised until installation of an ADSL internet connection. In this interim period, which predated installation of the TMD, the system halted due to failure of instrument cable sheathing and resulting water ingress. The cables were replaced with more robust alternatives fixed to the chimney at short intervals, and from 15\textsuperscript{th} March data were available remotely via the internet connection.

5 PARAMETER ESTIMATION

At the start of the monitoring modal parameters were required for validating the response prediction investigation and for fine tuning the design of the TMD. Only six minutes of data from the February recordings were available due to the ‘technical’ problem. These very limited data provided an interesting challenge to estimating modal properties, reported briefly at the previous IOMAC conference (2007).

Fig. 3 shows the results of applying eigensystem realization algorithm (ERA) to the cross-covariances of the four response channels and taking a range of lags to form the Hankel matrix.
The data were originally sampled at 128Hz and the cross-covariances involving the upper accelerometer channels shown in the left are re-sampled at 32Hz. This proved to be still too high a frequency for ERA to identify the lowest modes so further decimation to 8Hz was used for the final process with 200 lags representing about eight cycles of the fundamental mode. The figure shows, among estimates for different numbers of lags, values of 0.324Hz and 0.94% damping and 0.341Hz and 0.28% damping at d=100 lags for the 8Hz sampling rate.

![Figure 3 Cross-covariance functions and convergence diagram for 6 minutes of response data](image)

Stochastic subspace identification (SSI) was also applied to the data providing estimates of 0.328Hz with 1.94% damping and 0.342Hz with 1.31% damping. Clearly the six minutes of data were too few to provide reliable estimates of damping, although frequency estimates corresponded.

During the March visit to deliver the new cables (attached with the aid of the hoist employed for TMD erection) and connect the ADSL, a little over two hours of data were recorded from the bottom set of accelerometers, still attached by an original undamaged cable. These data were enough to provide better parameter estimates for the first two bending modes of 0.33 Hz with 0.6% to 0.7% damping and 0.34 Hz with 0.5% to 0.6% damping.

The alarm trigger levels for the top set of accelerometer responses were determined so as 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 exceedence requiring site evacuation for personal safety. Trigger levels were also determined for the lower set of accelerometers based on a mode shape ordinate of 0.07 (compared to unity at the top accelerometer). This values was determined from analysis of data from the first month or remote (and internet accessible) operation.

6 CLIENT VIEWER

The client viewer is an essential part of the system. It is a standalone executable that needs only the LabVIEW runtime engine to be installed on the client PC. Data are transmitted over the internet using LabVIEW’s Datasocket Transfer Protocol (DSTP). The VI running on the DAQ PC bundles each 180-second frame of data along with the alarm thresholds and transmits them for viewing on any PC running the client VI. Fig. 4 shows a screen shot from the client viewer at the time of a low level alarm. The DAQ PC also emails a daily log file of minimum and maximum response values for every 3-minute frame in the preceding 24 hours. All data are archived on the DAQ PC and selected datafiles are downloaded conveniently using Skype. Skype also provides a helpful means of communication during site visits for maintenance, as mobile phone signals are weak inside the chimney base.
7 VERIFICATION OF THE TMD BY AUTOMATED OPERATIONAL MODAL ANALYSIS (OMA)

As the TMD was being constructed, Bierrum extended the specification of the monitoring system to check the correct functioning of the TMD immediately after installation and during the remainder of its operational life. Hence it was decided to extract the damping parameters of the first two bending modes automatically online and report them immediately using a procedure based on a previous implementation at the Tamar suspension bridge (Brownjohn & Carden 2007). The system batch processes large amounts of data to extract modal parameters using reference based covariance-driven Stochastic Subspace Identification (SSI-COV) (Peeters & De Roeck 1999) implemented using the Mathscript language of Labview, rather than MATLAB, which would have required a costly commercial license. SSI was chosen instead of ERA due to the good experience at Tamar and the better developed procedures for interpretation of results as described below.

Speed of computation is an important issue for real-time operation hence the choice of SSI-COV over data-driven SSI. SSI is a well documented procedure which usually requires a significant amount of user intervention, including the interpretation of stability diagrams. Interpretation of stability diagrams can be automated up to a point using various quality measures, while the choice of ‘reference’ channel(s) and the way in which the covariance function functions are constructed and how many data points from them are used also affect the results.

At the time of the original implementation the linear algebra functions of the Mathscript language were significantly slower than the equivalent MATLAB functions used at Tamar. To provide more reliable parameter estimates without overloading the processor and compromising the DAQ operation a second VI was written which operates in tandem with the original acquisition VI on a timed loop. This loop was set to up so that at two-hourly intervals, the
preceding two hours of data would be concatenated, re-sampled at 2Hz and then analysed using the Mathscript SSI routines, while collecting the next two hours of data.

For the SSI implementation, all channels are used as references, the maximum order is 20 and 20 lines of the covariance functions are used. Tolerances of 1%, 5% and 2% are placed on variation of frequency damping ratio and modal assurance criterion between estimations at successive orders. The tolerances have to be observed for a minimum number of successive orders.

Such coarse sampling of modal parameter values is as near real-time as required given expected slow changes in performance of the TMD. The crucial parameter for the system is the modal damping: in principle the TMD should increase the damping to well above the 1% level. In practice for small amplitudes of chimney movement there may be no relative motion of the TMD so its full effectiveness is likely to be revealed in the strongest wind conditions, that generate significant response amplitudes. Hence the extra information from the updated VI should indicate that the TMD is working correctly or otherwise. In essence this is a rather pure form of structural health monitoring: timely and reliable information on which operational/maintenance decisions can be based.

8 REAL TIME MODAL DAMPING DISPLAY

The second VI adds to the data bundle the set of damping and frequency values identified from the previous but one two-hour data set i.e. the values are updated at the same time as new SSI calculations begin. These values (typically between zero and four sets of damping/frequency values) are retrieved by the updated viewer and damping values displayed for up to the last ten. This provides a very graphical and immediate view of the performance of the TMD; it is possible to watch the damping values change as storms pass through.

Fig. 5 is a screenshot of the damping plot soon after the updated viewer was installed. The plot is for June 2007, two months into TMD operation and it shows a number of features. The damping values appear to have been stable below 1% up to 25th June 2007 when the values rose progressively to around 3% due to strong winds which were associated with the heavy downpours and flooding throughout the UK at that time.

![Figure 5 Damping values from seven days of monitoring, varying from 0.5% to 3%](image)

Some zero values are presented showing that no mode met the criteria for a stable identified mode, likewise some outlying values are present. Such occurrences have usually accompanied either the weakest response or the fastest changing weather conditions (and presumably least stationary response), and some minor adjustments were made to the automated stability diagram interpretation to minimize such occurrences.

One interesting observation is that there are usually exactly two modes identified around 0.3Hz, never more, unless the SSI procedure is coerced by using a higher maximum order, in
which case spurious modes pop up at several frequencies. When attached to a single degree of freedom system (as the first mode of the chimney in each principal axis is considered), a TMD would be expected to generate an extra mode, which does not appear. Nevertheless the system tracks the damping for the dominant mode of the system that comprises both the chimney and the TMD, which has implications when considering variations in natural frequency.

In fact since late 2008 a third version of the viewer has been in operation which adds a display of the modal frequencies to the four existing plots. Variations in modal frequency have been even more interesting to track as they are driven by several factors.

9 CHARACTERISTICS OF RESPONSE DURING AND AFTER INSTALLATION OF TMD

Because of the loss of signals from the upper accelerometer box until the TMD was installed, there are no useable data describing the wind-induced response of the bare unmodified chimney. The TMD installation was begun on completed on 5th April 2007 and modal analysis of data recorded from March 21st to April 20th and retrieved from the DAQ PC for post-processing is presented in Fig. 6. The condition of the TMD on 21st March is shown in Fig. 2, i.e. some mass units were already installed so the data represent a slightly modified structural system with inert TMD until 5th April.

Figure 6 Variation of fundamental mode frequency and damping and of chimney response levels over 18-minute frames during 31 days of operation spanning commissioning of the TMD

Modal damping levels were below 1% until about a week after the TMD installation was completed, when damping levels began to increase noticeably. Close inspection of modal frequency variation appears to show a changed pattern, but the reliability of the estimates is reduced due to the calm conditions indicated by relatively low response levels.

10 SYSTEM PERFORMANCE IN NORMAL SERVICE

10.1 Response characteristics –time histories

The monitoring system has operated with a few hiccups since installation in 2007. Major hiccups were due to failure of power supply of accelerometer power supplies and of the original
NI DAQ unit. Minor hiccups included broadband disconnection and ‘clogging’ of the datasocket that required periodic resetting of the DAQ PC.

The monitoring system has, however, been operational in the most relevant wind conditions, fulfilling the original requirements for informing the power station operators (and the consultant) and has provided a fascinating view of the performance of the TMD and the chimney. The emailed daily log files can be viewed collectively to identify trends using standard viewing tools in MATLAB or Excel.

Data available from the monitoring system include time series of response continuously recorded (with short breaks due to period maintenance resets), daily summary files of maxima and minima for each channel during each three-minute frame and daily summaries of frequency and damping values for two-hour frames. The only useful wind data were one-hour average values obtained via http://weather.noaa.gov/ for the weather station at Birmingham Airport at a distance of 37km to the south, and East Midlands Airport at a similar distance of 40km, to the east. These wind data have been used only as general indicators of prevailing conditions, although recently an automated procedure has been developed to retrieve the hourly wind speeds for correlation with response and modal parameters.

Fig. 7 shows a selection of acceleration signals representing typical and unusual events. For the polar plots (Fig. 7a-c), the diagonal line is the cross-wind direction corresponding to wind from the direction of the new chimney, aiming to highlight any cases where response is enhanced due to the presence of the upstream structure.

The wind effect investigation (Galsworthy & Vickery 2006) predicted that interference effects for winds with bearings in line with the new chimney, plus or minus a generous margin, structural damping of 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, is illustrated in Figs. 7a and matches this value, with average winds at Birmingham airport up to 40mph (17.8m/sec) from SSW direction and certainly including gusts around the critical speed. By comparison. Fig. 7b shows highly aligned (i.e. transverse) response due to similarly strong north-westerly winds which could not cause interference effects. By contrast Fig. 7c shows response lacking any alignment for low wind speeds. Study of such traces suggests the conclusion that the mechanism is vortex shedding but that for winds in the critical SSW direction response is enhanced.

Finally Fig. 7d shows response during the M5.1 Market Rasen earthquake (strongly felt in Sheffield!). The earthquake occurred at the same time as strong winds, but the higher mode response is clear. The 8Hz sample rate was too low to capture the higher frequency content of the event, believed to be dominant around 6Hz.
10.2 Response characteristics-peak accelerations and modal parameters

For the longer term, Fig. 8 shows the variation of peak responses for 3-minute frames and damping and frequency estimates for the first of the two fundamental modes for 2-hour frames during the monitoring up to mid-March 2008. The data show clear dominance of radial response dominated, not least because that was the cross-wind alignment for prevailing strong winds. The damping values show the lower bounds for zero response at around 0.5%, rising to over 4% during periods of strong response.
The frequency estimates are particularly interesting although superficially they show no apparent relationship with the other response parameters, other than a diurnal variation. There are occasional significant drops in frequency that do not correspond with unusual weather conditions and a possible explanation is thermal effects on the structure continuity due to operation of the power station. Seasonal temperature variations (i.e. from sub-zero to mid-summer highs) are not responsible for these large excursions. As ever single frequency values reported for a structure need to be viewed with caution and in context.

The TMD was designed for two or three years of operation i.e. for the anticipated remaining life of the old chimney, and it has proved to be effective up to the time of writing. In the meantime there has been some reduction in natural frequency of the chimney and the maximum damping ratio achieved has apparently decreased slightly to about 3%. During the monitoring and TMD operation to date only one weather event has resulted in any alarm condition, although normal strong south westerly wind conditions regularly generated transfer vortex-induced responses of the order 0.1m amplitude.

11 RADAR MEASUREMENTS

In March 2008 in collaboration with researchers from IDS in Italy, measurements were made of the dynamic performance of both chimneys using a new interferometric radar sensing system (Gentile & Bernardini 2008). The system has a line of sight resolution as good as 0.01mm and can sample at frequencies e.g. 100Hz limited by data storage. Radar is reflected from a structure strongly at surface existing or artificial features that can be separately identified when more than about 1m apart. The system is shown in Fig. 9; the mode indicated in Fig. 9c, which was obtained using ERA is for the old chimney mode dominating in the line-of-sight direction of the sensor, and confirms the parameters estimated from the monitoring system, while providing additional information about mode shape. The mode shape ordinates were not resolved for the lower two-thirds of the chimney due to reflections from the various industrial hardware around the sensor and chimneys.
12 CONCLUSIONS

The monitoring exercise has in effect been a perfect example of structural health monitoring that has relied purely on vibration data. Such vibration based monitoring is generally dismissed as being unhelpful, incapable of identifying real problems and providing useful information for operators. This case is quite the opposite.

The solution is simple, elegant and reliable and has provided the operator with confidence for safe operation of the facility.

The SSI implementation has also worked very well and has provided a rich dataset of performance. There are features of the chimney performance identified by the system due to structural factors (and reflected in frequency variations) that will be presented after it has been demolished, but for damping estimates there is are clear indications on the continued functioning of the TMD to control across-wind vibration.

This appears to be the first commercial operation of an automated structural parameter identification system following probably the first research implementation (at Tamar). LabVIEW and MATLAB together provide a perfect environment to implement such technology.

13 REFERENCES


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