18th Australasian Wind Engineering Society Workshop
McLaren Vale, South Australia
6-8 July 2016

Dynamic response of structures with frequencies greater than 1 Hz

G.S.Wood[1], P.A.Bourke[1], and D.Banks[2]

[1]Cermak Peterka Petersen Pty. Ltd.
Unit 2/500 Princes Highway, St. Peters, NSW 2044, Australia
[2]Cermak Peterka Petersen Inc.
2400 Midpoint Drive, Suite 190, Fort Collins, Colorado 80525, USA

Abstract

The design Standards suggest that a dynamic resonant response will only occur on buildings and structures with a natural frequency below 1 Hz. This paper presents a series of case studies on relatively straightforward structures that illustrated a significant resonant response with natural frequencies in excess of the arbitrary limit. CFD has been used to illustrate the dynamic forcing mechanism.

Introduction

Vortex shedding occurs when vortices are shed alternately from opposite sides of a structure. This action gives rise to a fluctuating load perpendicular to the wind flow direction. Resonance will occur if the vortex shedding frequency is the same as the natural frequency of the structure. This occurs at the critical wind speed for vortex shedding. If the critical wind speed occurs regularly, the structure may be susceptible to fatigue with the number and magnitude of the load cycles becoming relevant.

Various wind loading design standards provide guidance for when the dynamic response of structures to be of concern. For convenience, the relevant clauses are presented below.

<u>AS/NZS1170.2:2011, Standards Australia (2011)</u>

Clause 1.1 note 2.

Where structures have natural frequencies less than 1 Hz, Section 6 requires dynamic analysis to be carried out (see Section 6).

Clause 6.1

The dynamic response factor (Cdyn) shall be determined for structures or elements of structures with natural first-mode fundamental frequencies as follows:

(a) Greater than 1 Hz, Cdyn = 1.0.

<u>ASCE 7-10, American Society of Civil Engineers (2010)</u>

Clause 26.2

BUILDING AND OTHER STRUCTURE, FLEXIBLE: Slender buildings and other structures that have a fundamental natural frequency less than 1 Hz.

<u>BS6399, British Standard (2002)</u>

Clause 1.1

NOTE 2 Wind tunnel tests are recommended when the form of the building is not covered by the data in this standard, when the form of the building can be changed in response to the test results in order to give an optimized design, or when loading data are required in more detail than is given in this standard.

Specialist advice should be sought for building shapes and site locations that are not covered by this standard.

The methods given in this Part of BS 6399 do not apply to buildings which, by virtue of the structural properties, e.g. mass, stiffness, natural frequency or damping, are particularly susceptible to dynamic excitation. These should be assessed using established dynamic methods or wind tunnel tests.

NOTE 3 See references [1] to [4] for examples of established dynamic methods.

NOTE 4 If a building is susceptible to excitation by vortex shedding or other aeroelastic instability, the maximum dynamic response may occur at wind speeds lower than the maximum.

<u>Eurocode EN1991-1-4, European Standard (2005)</u>

Clause 6.3.3

Wake buffeting effects may be assumed to be negligible if at least one of the following conditions applies

- The distance between two buildings or chimneys is larger than 25 times the cross-wind dimension of the upstream building or chimney
- The natural frequency of the downstream building or chimney is higher than 1 Hz.

NOTE: If none of the conditions in 6.3.2(2) is fulfilled wind tunnel tests or specialist advice is recommended.

It is evident from the above that a natural frequency limit of 1 Hz is prevalent across the various Standards. However, it is not clear whether this is associated with turbulence buffeting, vortex shedding, or other aeroelastic instability.

Generally, the primary mechanism for dynamic excitation is vortex shedding, the regular pattern developed by shear layers interacting from either side of a structure. These can be from individual elements, or from interference between neighbouring structures.

Case Studies

<u>Chimney</u>

The natural frequency of a 30 m tall, lightweight metal stack, Figure 1 (L), was estimated at about 1.3 Hz. This was in excess of the 1 Hz suggested limit in Standards Australia (2011) and therefore no dynamic assessment was conducted. The critical mean wind speed for the stack was about 9 m/s. This wind speed occurred within about 1 week of erection. Recorded observations showed a natural frequency of about 1.4 Hz and a peak to peak displacements of about 0.5D. For safety reason, the stack was lowered to the ground and a damper solution developed, Figure 1(R).

After installation of the damper, field measurements were taken to measure the response with and without the damper activated. A summary of the results are presented in Table 1 and Figure 2.

Figure 1:Photo of stack before (L) and after installation of damper (R)

Table 1: Summary of results

	First translational mode		**Second mode**
Damper state	**Natural frequency /Hz**	**Damping /% of critical**	**Natural frequency /Hz**
Active	1.61	5.2	7.4
Chocked	1.61	0.13	

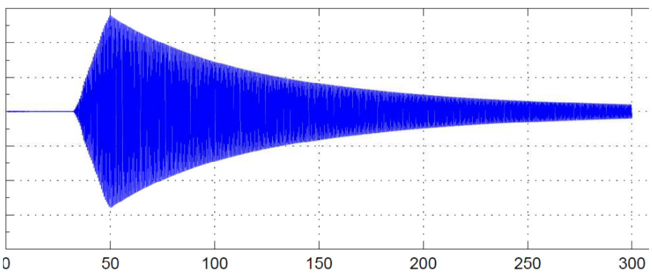

Figure 2: Decay trace with the chocked damper

An estimation of the cross-wind dynamic response of the stack in various configurations was estimated using the procedure outlined in ESDU (1989), Figure 3. The predicted peak cross-wind deflection agrees reasonably well with the observations and Bureau of Meteorology weather data measured nearby.

It would be recommended to include a sentence to the end of Note 2 in Clause 1.1, that regardless of natural frequency, all lightweight circular hollow sections such as masts and chimneys should be assessed in accordance with Clause 6.3.3.

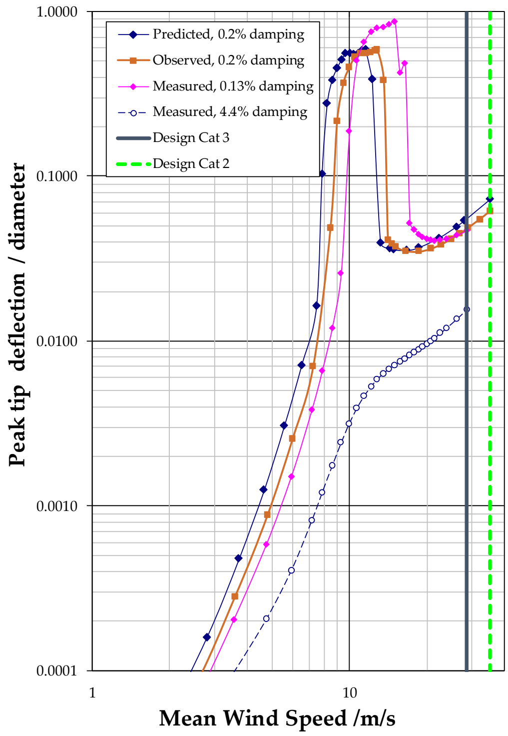

Figure 3: Comparison between the cross-wind response of the original stack design and with damper active and chocked

Fence

A 2 m high fully welded fence suffered fatigue failure after 3 months installation. The fence palings are circular in section, with a 25 mm diameter, and have a natural frequency of about 22 Hz.

Figure 4: 2 m high full-scale fence in the wind-tunnel

The wind-induced dynamic response was assessed through qualitative visual observations for a range of sample orientations and wind speeds. Observations include all potential excitation mechanisms associated with the wind passing between the individual elements as well as interference between elements. The rigidity of the entire assembly allows vibration energy to be transferred throughout the system. As all the vertical palings have essentially the same natural frequency in all directions, there is the potential for vibrational energy transfer between modes as was observed.

The observed vibration was categorised into four categories with approximate peak to peak displacements: S(mall) (<1/16D deflection), Mi(ld) (1/16-1/4D deflection), Mo(derate) (1/4-3/4D deflection), and E(xtreme) (>3/4 D deflection), where D is the diameter of the vertical element (25 mm). The results for the three configurations are presented in Table 2, where 3 sets of data under each wind speed refer to a 2 m tall fence, the 2 m tall fence with additional angle, and the 1.4 m tall fence. Incident wind of 0° is for the wind parallel to the fence.

Table 2: Qualitative results for all tests

		Wind direction /°					
Wind speed /m/s	Fence	0	10	20	30	60	90
3	2	S	S	S	S	S	S
	2A	S	S	S	S	S	S
	1.4	S	S	S	S	S	S
5	2	S	Mi	Mo	Mo	Mo	S
	2A	S	S	S	S	S	S
	1.4	S	S	S	S	S	S
7	2	S	Mo	E	E	Mo	S
	2A	S	S	S	S	Mo	S
	1.4	S	S	Mi	Mi	Mi	Mi
10	2	S	Mi	Mi	Mi	Mi	S
	2A	S	S	S	S	S	S
	1.4	S	Mi	Mo	Mo	Mo	Mo
13	2	S	S	S	S	S	S
	2A	S	S	S	S	S	S
	1.4	S	S	S	S	S	S
16	2	S	S	S	S	S	S
	2A	S	S	S	S	Mi	S
	1.4	S	S	S	S	S	S

The extreme responses were caused by interference effects between elements. The upwind elements generated vortices that shed from the cylinder in an oscillating pattern. The frequency of shedding is a function of the geometry of the element and the approach wind speed. At a critical wind speed, these vortices in turn generate a fluctuating load on the next element at the natural frequency of the element therefore causing resonance. The magnitude of the loading is small, but with such a low level of structural damping at about 0.2% of critical, and the near identical natural frequencies of the elements in all directions the entire array of elements stores vibrational energy over time and eventually becomes excited. The movement of the vertical elements has a beating characteristic where the element vibrates in one direction, then transfers the vibration to the orthogonal mode. The mode switching takes place over a duration of about 2 s.

The introduction of a 25 mm equal angle screwed to each vertical element significantly reduced the dynamic response for all wind directions. The angle was connected with general roof sheeting screws, with the rubber washer placed between the angle and the vertical elements to increase the structural damping. It should be noted that as the overall geometry of the system is not changing and therefore the dynamic wind forces will remain similar, however the change in structural dynamic properties reduces the response by suppressing the transfer of energy between modes, and the incorporation of additional structural damping at the connection.

Ground-mounted solar panels

Ground mounted solar arrays, or other structures with large horizontal extent, and/or numerous repetitive structures, can be subject to vortex shedding and consequent dynamic resonance effects. The turbulence causing vortices are generated by the geometry and repetitive upwind structures, rather than coming from gust energy inherent in the wind as is the case for other situations with vortex shedding. The resulting buffeting can introduce significant dynamic resonance effects.

A Strouhal number of about 0.15 has been determined for isolated flat plates in free flow and in proximity to a surface by Fage and Johansen (1927) and Matty (1979) respectively. From studies using simultaneous pressure measurements on rigid models, Strobel and Banks, (2014) found the Strouhal number for peak excitation of the structure is between 0.05 and 0.20, where

$$St = n_1 . L/U,$$

where U is the mean wind speed, L is the vertical projected vertical height Chord length x sin(tilt), and n_1 is the structural natural frequency. This is not a single, well-defined peak in the spectrum. Instead there is a broad peak in the energy spectrum extending over this entire range. The dynamic amplification factor may not be insignificant at St = 0.30.

Vortex shedding is most evident from tilt angles from 15° to 30°, but extends down to 10° and up to 45°. To avoid excitation under such a mechanism it is recommended that in areas not prone to hurricane-force winds, the torsional natural frequency of the solar array should be greater than 5 Hz. This advice is based on the risk of modal excitation due to buffeting. It is not clear that a 5 Hz natural frequency would prevent vortex lock-in or torsional galloping as detailed in Rohr et al. (2014) and described below.

Instability in solar single axis trackers

Long ground-mounted solar racking systems that track with a single axis typically have a central drive system with the remainder of the supports along the length fixed in location, but allowed to freely rotate, Figure 5. A number of such systems with rotational natural frequencies in excess of 1 Hz have experienced significant dynamic excitation with rotations in excess of ±60° along the length. With a fixed central restraint, the dynamic response is purely torsional.

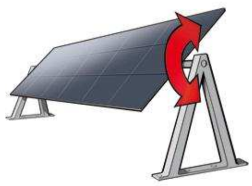

Figure 5: Typical solar tracking ground mounted array

The instigation of any dynamic response of flexible structures is highly dependent on the stability of the vortex shedding process. To instigate instability, a fixed point of separation, such as the leading edge, or the torque tube, can instigate a fluctuating differential pressure that can excite a structure with low torsional stiffness. Once the structure starts to rotate, a resonant self-exciting mechanism can develop as illustrated in Figure 6.

This instigation of this unsteady mechanism is dependent on the initial position of the solar panel, torsional stiffness, and geometry. The excitation mechanism is somewhat similar to bridge dynamics and the torsional flutter derivative.

A parametric fluid-structure CFD study has been conducted on a range of solar panel geometries with different structural dynamic properties to compare the results with flutter derivatives derived for bridges. From the initial position the response of the system can either diverge, decay, or stay in equilibrium based on the total damping of the system, mechanical and aerodynamic.

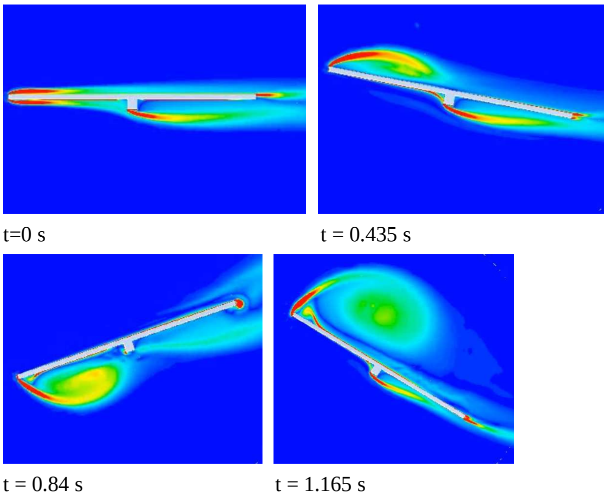

Figure 6: CFD images for flow over 2d representation of solar array

The single degree of freedom torsional bridge flutter derivative is A_2^*, defined as:

$$A_2^* = \frac{2I(\lambda + \zeta_\alpha \omega_\alpha)}{\rho b^4 \omega}$$

Where I is the mass moment of inertia, λ is overall response damping of system, ζ_α is the rotational structural damping, ω_α is the rotational natural frequency, ρ is air density, b is chord length, and ω is the response rotational natural frequency. The values of λ and ω are extracted from the results of the parametric study.

The relationship between the bridge flutter derivative and reduced velocity, V/ω·b, is shown in Figure 7 and Figure 8. It is evident that a divergent response for samples with a reduced velocity greater than 8 is prevalent, however the flutter derivative for lower reduced velocities does not allow for accurate description of whether the response of the solar panel will be stable or otherwise. The lack of collapse of data suggests that these are not the correct non-dimensional parameters for this excitation mechanism.

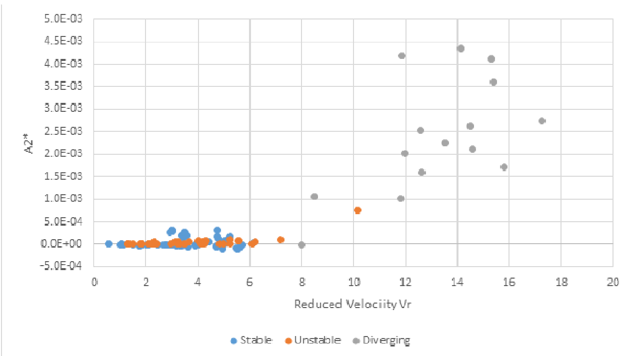

Figure 7: Flutter derivative with reduced velocity for all data

Other Cases,

As well as the above, there are other cases where failure of structural members has occurred due to resonant fatigue of isolated and groups of structural elements during relatively low wind speeds such as sun-shading pergolas.

Long truss elements with natural frequencies in excess of 1 Hz, are also sensitive to resonant excitation through vortex shedding.

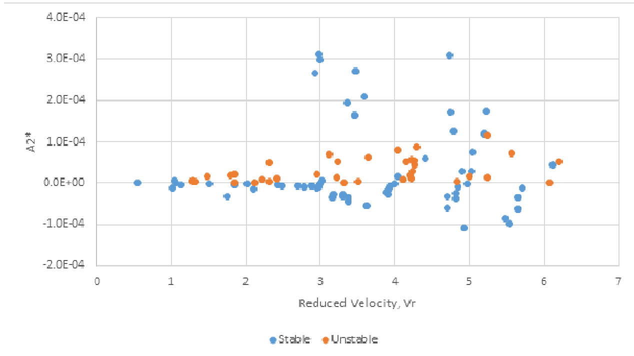

Figure 8: Flutter derivative for low reduced velocity

Conclusions

It is evident from the above that there are distinct cases where wind-induced dynamic response occurs for structures with a natural frequency greater than 1 Hz predominantly due to vortex shedding or interference effects.

It is recommended that a clause is included in the Standard to clarify to users that for lightweight structural elements, there is the potential for significant wind-induced dynamic response for relatively long prismatic elements either in isolation or in arrays of similar elements.

References

American Society of Structural Engineers (2010), Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10.

British Standard (2002), Loading for buildings — Part 2: Code of practice for wind loads, BS6399-2 1997.

European Standard (2005), Eurocode 1: Actions on structures – Part 1-4: General Actions – Wind actions, EN1991-1-4.

ESDU (1989), Response of structures to vortex shedding structures of circular or polygonal cross section, Engineering Science Data Unit 96030.

Fage,A., and Johansen, F.C., (1927).On the flow of air behind an inclined flat plate of infinite span ,Proceedings of the Royal Society of London, Vol.116, pp.170–197.

Matty, R.R., (1979). Vortex shedding from square plates near a ground plane: an experimental study, Masters thesis, Texas Tech University.

Rohr, C. Bourke, P. and Banks, D. Torsional Instability of Single-Axis Solar Tracking Systems, Proceedings of the 14th international conference on wind engineering, Porto Alegre, Brazil, 2015.

Standards Australia (2011), Australia New Zealand Standard, Structural Design Actions Part 2: Wind Actions, AS/NZS1170.2:2011.

Strobel. K., and Banks, D. (2014) Effects of vortex shedding in arrays of long inclined flat plates and ramifications for ground-mounted photovoltaic arrays, J.Wind Eng. Ind. Aero. Vol.133.