Dynamic Response of Recessed Balcony Facades to Wind Loading

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ABSTRACT

Modern high-rise tower designs incorporating recessed balcony cavity spaces can be prone to high-frequency and narrow-band Rossiter aerodynamic excitations under glancing incident winds that can harmonize and compete with recessed balcony volume acoustic Helmholtz modes and facade elastic responses. Recessed balcony cavities with single orifice type openings and located within curved façade tower geometries appear particularly prone. Resulting resonant inertial wind loading to balcony facades responding to these excitations is additive to the peak design wind pressures currently allowed for in wind codes and can present as excessive facade vibrations and sub-audible throbbing in the serviceability range of wind speeds. A Cavity Amplification Factor methodology to account for façade resonant inertial wind loads resulting from balcony cavity dynamic-resonant-elastic amplifications is described drawing upon field observations and the results of full-scale monitoring, model-scale wind tunnel tests and literature review. Balcony façade and tower design implications are discussed, and mitigation recommendations provided.

INTRODUCTION

In recent years, high frequency narrow-band wind pressure fluctuations have been observed in several recessed balcony configurations within high-rise towers. Recessed balcony cavities with single orifice type openings located within curved façade tower geometries, as indicatively represented in Fig.1, appear particularly prone. These wind pressure fluctuations can produce excessive balcony façade vibration amplitudes in the serviceability range of wind speeds, with disturbing levels of vibration and noise reported by residents on some recently completed tower projects. Anecdotally, this is known to have led to whole tower repairs.

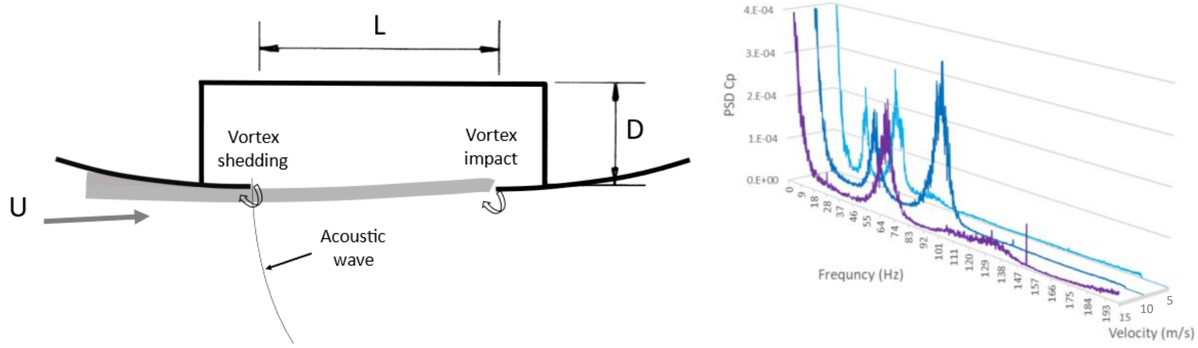

Figure 1. Simplified model of flow over a balcony cavity in plan (L) and spectra of fluctuating pressure coefficient plotted against velocity in a model-scale balcony cavity (R)

A 'Cavity Amplification Factor' (CAF) methodology for predicting the occurrence and magnitude of these high frequency narrow-band wind pressure fluctuations within balcony cavities has been proposed by (Glanville and Holmes 2024) and introduces a significant aero-acoustic-elastic inertial wind loading component. The work is based upon field observations and results from full-scale monitoring (Glanville and Bourke 2022) and wind tunnel model scale measurements conducted on various recessed cavity configurations, as well as cavity oscillation studies by researchers in the fields of hydrodynamics, aeronautical engineering, and acoustics. Resonant inertial wind loading quantified by the CAF is additive to the peak façade wind pressures currently allowed for in wind codes such as (AS/NZS1170.2 2021). This paper will recap on some key findings of this previous work.

FLUID DYNAMIC-RESONANT-ELASTIC AMPLIFICATIONS

(Rockwell and Naudascher 1978 and 1994) and (Lee 2010) have described fluid-dynamic, fluid-resonant and fluid-elastic amplification mechanisms.

Amplification by Fluid Dynamic Feedback

(Rossiter 1964) described strong periodic fluctuations in the flow over bomb-bay cavities of aircraft. An ‘edge tone’ is established being a fluid-dynamic connection between periodic vortex shedding at the opening upstream end and reflected acoustic radiation following the impact of vortices at the downstream end. Acoustic waves can traverse back across the opening with energy to shed another vortex from the upstream end, and this loop can occur in recessed balcony cavities such as the balcony configuration illustrated in Fig. 1(L).

Fluctuating Rossiter pressures associated with this process have been measured in a full-scale tall-building balcony of similar configuration to Fig. 1(L) and reproduced at wind tunnel model scale (Glanville and Bourke 2022). Spectra of fluctuating pressures within the scale model balcony are plotted with wind approach velocity in Fig. 1(R). There are typically multiple spectral humps of narrow-band energy resulting from the Rossiter process, with the highest energy occurring at near glancing incident wind yaw angles between parallel and 30° off parallel to the facade. (Rossiter 1964) describes a continuous feedback loop associated with this process whereby the Rossiter frequency can be modelled through the relationship:

$$f_{Ross} = \frac{U}{L}\frac{(m-\Upsilon)}{(\frac{1}{k}+M)} \tag{1}$$

Where k is the proportion of free stream speed the vortices travel over the cavity, M is the flow Mach number, L window slot opening width, U the local approach velocity (adjacent façade), and m-Υ modes describe periodic components of cavity pressure fluctuations (in atmospheric sub-Mach number wind flows $\Upsilon \rightarrow 0$). The process can be established at low ambient wind speeds, particularly over curved facades where converging streamlines can accelerate and smooth the flow. Hence, as velocity U increases, so too will the frequencies of the edge tone, demonstrating a Strouhal number dependency, but may break up or down to a different mode m at any given wind speed depending on the stability of the wavelength associated with the vortex modulated airstream.

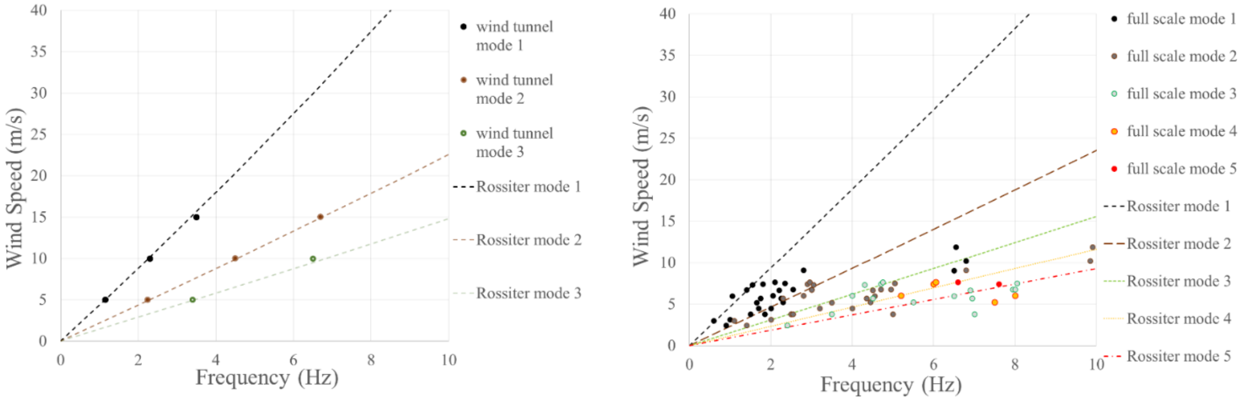

Figure 2. Wind speed versus frequency of spectral density peaks obtained from scaled wind tunnel testing (L) and full-scale monitoring (R)

This intermittent steadiness, one vortex structure at any given time, is observed more generally in the field of fluid mechanics, e.g., (Naudascher and Rockwell 1994) and (Ma et al. 2019). Wind speed versus full scale frequency associated with each spectral density peak is plotted in Fig. 2(L) based on scaled wind tunnel test results. (Rossiter 1964) predictions using Eq. (1) are overlayed for $L = 3.3$ m, $\Upsilon = 0.01$ and $k = 0.7$ with close agreement found.

The Strouhal number, St, for the vortex generation in Fig. 1(R) and Fig. 2 are seen to increase in multiples of the first mode, with similar observations made in scale model tests by (Rockwell and Naudascher et al. 1978), (Chatellier et al. 2004) and (Malone et al. 2009). Halving the window width L in wind tunnel tests was found to double the frequency of the spectral peaks as would be expected from Eq. (1) (Glanville and Bourke 2022).

Various rectangular cavity configurations tested at comparable velocities in water tunnels (e.g., Ethembabaoglu (1978) at Reynolds Number 6.3×10^5), or at Mach-number air flows (e.g., Rossiter (1964) at Reynolds Number 1.9×10^6), have same order Reynolds numbers to full-scale balcony wind flows. Full-scale measurements by (Glanville and Bourke 2022) utilized differential pressure transducers within tower balcony volumes and sliding door mounted accelerometers, with measured data logged remotely over 6 months. Wind speed and direction correlating to each sample was referenced to an upstream Bureau of Meteorology anemometer. Full-scale wind speed versus frequency associated with each spectral density peak obtained from the differential pressure transducer data is plotted in Fig. 2(R). The same (Rossiter 1964) predictions using Equation 3 are overlayed for $L = 3.3$ m, $\Upsilon = 0.01$ and $k = 0.7$. Available results are provided only for samples with glancing incident wind direction angles between 0-30° off parallel to the façade. Several data points display up to 3rd, 4th and 5th Rossiter modes and some deviation from the Rossiter equation is observed. Here it is considered higher Rossiter fluid-dynamic modes find alignment with Helmholtz and elastic modes.

Amplification by Fluid Resonant Feedback

Helmholtz resonance is commonly experienced as a sub-audible 'throbbing' when driving a car with one side window open. A Helmholtz resonator model assumes a slug of air mass at a smaller opening acting on the stiffness of compressible air already within the body volume, and with damping losses through the orifice opening as depicted in the resonator model of Fig. 3(L). A recessed balcony cavity can act as a Helmholtz resonator particularly when there is a single restricted orifice type opening, creating a contained air volume needed for air compressibility to generate fluctuating pressures. In this scenario, Rossiter fluid-dynamic excitations at glancing incident wind angles can excite and harmonize with the recessed balcony volume Helmholtz modes and other internal building volumes. This is analogous to edge tones associated with the sounding of a flute or organ pipe being coupled with an air column.

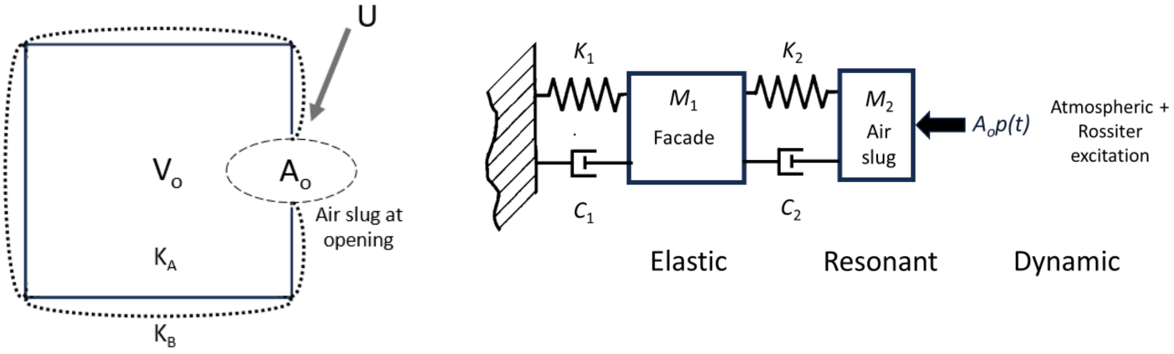

Figure 3. Basic Helmholtz resonator model (L) and a 2 degree-of-freedom (d-o-f) mass-spring-damper model proposed to represent the façade wall / air slug interaction (R)

High correlation of internal Rossiter pressure fluctuations has been observed throughout the whole interior volume of Helmholtz type cavities by (Cooper and Fitzsimmons 2008), and by (Glanville and Bourke 2022).

Many acoustic wind tunnel experiments have been conducted investigating the fluid interaction with Helmholtz resonance, e.g., (Anderson 1977), (Ma et al. 2009), (Tang 2017) and (Sergeev et al. 2024). Less attention is often given to wall stiffness important in many building applications, however (Vickery and Bloxham 1992), and (Holmes and Bekele 2021) provided a formulation to estimate the Helmholtz frequency for internal pressure fluctuations within enclosed buildings with wall flexibility:

$$f_{\mathrm{HH}} = \frac{1}{2\pi}\sqrt{\frac{\gamma A_0 p_0}{\rho_a V_0 l_e\left[1+{}^{K_A}/_{K_B}\right]}} \tag{2}$$

Here p_0 is atmospheric pressure and γ the ratio of specific heats of air, ρ_a density of air, A_o the area of opening and V_o cavity volume. The effective length l_e is a function of the opening area $\left(\sqrt{A_o}\right)$ and a measure of an ‘air slug’ dimension. K_A is the bulk modulus of air and in real buildings wall flexibility associated with building volume stiffness K_B can be significant and can be determined using load deflection tests.

A 2 d-o-f mass-spring-damper model is proposed in Fig. 3R to represent the facade/air slug interactions with Rossiter pressure excitation whereby M_2 represents the air slug mass ($\rho_a A_o l_e$), air volume stiffness K_2 is determined from the Helmholtz frequency and damping C_2 is associated with energy dissipation at the orifice. The volumetric stiffness of recessed balcony walls, in many apartments, is governed by a large proportional area of flexible doors rather than the relatively stiff reinforced concrete floors/ceilings and therefore balcony wall mass M_1, stiffness K_1 and damping C_1 approach the governing modal properties of the façade spans themselves, noting it is the collective properties of the balcony facade and walls responding volumetrically as indicated in Fig. 3(L).

Amplification by Fluid Elastic Feedback

The 2 d-o-f system has two different high and low coupled natural frequencies, described in further detail by (Glanville and Holmes 2024), where it is demonstrated at lower façade stiffness there can be close alignment between the elastic façade frequency and Helmholtz cavity air slug frequency such that the façade and cavity air slug oscillate as one at the same low coupled frequency. Furthermore, the ratio of air slug mass to facade modal mass will often be low in typical residential balconies and Helmholtz amplification may not be problematic beyond serviceability range wind speeds, justifying a 1 d-o-f façade model simplification. Frequency domain analysis can then be used by applying the Rossiter excitation in addition to atmospheric turbulence directly to the façade elastic system. This methodology was found to predict façade (sliding door) acceleration amplitudes with glancing wind speeds in agreement with the full-scale measurements conducted by (Glanville and Bourke 2022).

Boundary layer wind tunnel testing of large-scale cavity balcony models can be used to measure Rossiter excitation spectra over several Rossiter modes which can then be combined numerically with mechanical admittance functions of the elastic façade. Multiple Rossiter humps corresponding to modes m=1, 2, 3 etc. occur whereby Strouhal number (St) of each Rossiter mode increases in multiples of the first mode such that $\mathrm{St}_{m2}=2\mathrm{St}_{m1}$, $\mathrm{St}_{m3}=3\mathrm{St}_{m1}$, etc. A methodology to then obtain a ‘Cavity Amplification Factor’ (CAF) is described by (Glanville and Holmes 2024) whereby:

$$\text{Cavity Amplification Factor} = \frac{\check{C}_p'}{\check{C}_p} \tag{3}$$

Where $\check{C}_p'$ is the peak pressure acting on a façade accounting for aero-acoustic-elastic resonances within a balcony cavity and $\check{C}_p$ is the peak suction pressure on a façade in the absence of a balcony cavity. CAF was calculated over a typical design wind speed range of 1000 years based on wind tunnel measurements of a recessed balcony cavity like Fig. 1(L) (Glanville and Holmes 2024). At a serviceability wind speed with ARI 0.5 years, the Rossiter second mode (m=2) excitation aligned with the façade first natural frequency assumed to be 8 Hz, producing a CAF just over 1.8 suggesting serviceability vibration and material fatigue should be checked. The first Rossiter mode (m=1) excites the first façade mode at wind speeds around ARI 300 years with the CAF estimated to be approximately 1.5 and should be checked as a governing load case for ultimate limit state design.

In many tower balcony volumes, the façade natural frequency f_1 will couple with the Helmholtz resonance frequency f_{HH} as described above, particularly when balcony facades are relatively soft. For a balcony cavity volume $V_o = 25\text{m}^3$ in the Fig. 1(L) example, f_{HH} was calculated as 7.3Hz which is close to the first mode façade frequency and should be checked in the CAF analysis but substituting f_1 with f_{HH}. Stiffening and/or damping adjustments to the façade can then be calculated to reduce the CAF.

DISCUSSION

(Rockwell and Naudascher 1978 and 1994) describe flow field cases in which fluid-dynamic, fluid-resonant and fluid-elastic feedback mechanisms compete for control. An analogy is the air column resonance of an organ pipe tending to alter the free edge tone to match the resonant frequency of the pipe (Coltman 1976). Helmholtz cavity laboratory studies including (Chatellier et al. 2004), (Cooper 2008), (Ma et al. 2009), (Verdugo 2011) and field observations and measurements by (Glanville and Bourke 2022) support analogous aero-acoustic-elastic feedback mechanisms competing for control in some recessed balcony configurations.

In a balcony configuration similar to Fig. 1(L), low-frequency Rossiter excitation $f_{RossLow}$ can establish at low wind speeds and with the highest Rossiter mode excitations most likely first harmonizing with large-volume whole-of-building low frequency Helmholtz resonance f_{HHlow} and standing wave harmonics. This can occur in poorly sealed buildings and is potentially felt as a subaudible 'throbbing' and may manifest itself in vibrations and rattling of internal partitions and lobby doors. As wind speeds increase, so too will the Rossiter excitation frequencies $f_{RossMed}$ aligning with increasingly smaller building volumes such as recessed balcony cavities i.e., fluid dynamic and resonance feedback amplification harmonising and competing for control and sometimes producing visible and audible façade vibrations at low serviceability wind speeds.

At intermediate serviceability design wind speeds there can be vibrational alignment between the increasing frequencies of the Rossiter mode excitations $f_{RossMed}$, medium volume recessed balcony cavity Helmholtz frequency f_{HHmed}, and balcony wall natural frequency f_1, i.e., fluid dynamic, resonance and elastic feedback amplifications all harmonising and competing for control. This was observed in the deviation of Rossiter modes to align with Helmholtz modes and façade elastic modes in Fig. 2(R). High amplitude vibrations may manifest in some balcony facade elements such as sliding doors if insufficiently stiffened, then potentially leading to serviceability and fatigue issues.

At higher serviceability to design level wind speeds the lowest mode Rossiter frequencies f_{RossHi} are often beyond the Helmholtz frequencies of typical balcony cavity volumes. Balcony facades depending upon their stiffness can resonate at their natural frequency (suitably modelled as a 1 d-o-f. system) with competing higher volume displacing façade amplitudes, also responding to increasing atmospheric turbulence buffeting energy, in turn disrupting the Rossiter excitation process intermittently, i.e., fluid dynamic and elastic feedback amplifications competing for control.

DESIGN IMPLICATIONS AND MITIGATION

These aero-acoustic-elastic interactions have more recently been observed in modern tower balcony designs and hence there is limited mitigation guidance available. The designer should recognise recessed balcony cavities with smaller single orifice type openings and located within curved façade tower geometries appear particularly prone to aero-acoustic-elastic cavity resonances.

A contained air volume is needed for air compressibility to generate significant fluctuation of pressures within the cavity, and introducing additional exterior façade openings has been demonstrated to reduce the overall excitation energy on an example corner balcony configuration (Glanville and Holmes 2024). Further work could investigate the effectiveness of a second exterior opening on single sided balcony configurations. Several other mitigation options are discussed in (Glanville and Holmes 2024), including balcony geometric modifications, the use of external spoilers and baffles and partial sealing of single façade openings.

Adjusting facade stiffness K_1 to alter f_1 and increasing structural damping ζ can reduce façade vibration amplitudes to meet codified deflection criteria. Measuring the CAF through wind tunnel testing can assist in making these façade design adjustments and further parametric studies over a range of balcony geometric configurations and façade dynamic properties may justify future codification of some indicative CAF values. Designers and manufacturers should note potential limitations of static-load prototype façade test procedures when determining façade dynamic properties. Mock-up tests may not capture the loss of stiffness to some façade systems under dynamic wind loading, e.g., breaking stile connections of interlocking balcony sliding doors whereby the vibrating door system assumes the much lower stiffness and frequency of a disconnected sliding door leaf.

A well-sealed façade and internal partition design at key locations is particularly important to prevent penetration and harmonisation of fluctuating balcony cavity pressures into the building interior. Balcony sliding doors adjoining apartment volumes need to maintain a full seal during resonant response to aero-acoustic-elastic excitation, e.g., prevent breaking seals of interlocking sliding door stiles under sinusoidal resonant oscillations. Any fluctuating pressure within an apartment must be prevented from further permeating into tower lobby volumes requiring full seals to lobby/apartment door perimeters. Similarly, any fluctuating pressure penetrating a tower lobby level must be sealed from building lift shafts, stairwells and risers linking to other building levels and potentially the whole tower internal volume.

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