Spectral analysis of pressures measured on two high-rise building models in side-by-side arrangement

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Abstract

Pressure measurements on an isolated square plan form high-rise building model and two square high-rise building models in side-by-side arrangement were analysed using the Fast Fourier Transform (FFT) to define peak frequencies resulting from interference. For the isolated building model, a peak in the power spectrum was determined on the side face at a reduced frequency of $f_{\text{red}} = fB/U_{\infty} = 0.08$. This value corresponds with $St = 0.09$, which is a typical value for the vortex shedding process for this type of model. In the side-by-side arrangement, spectral peaks were observed at $f_{\text{red}} = 0.03$, 0.09, and 0.12 on the face inside the passage. The first peak is related to vortex shedding of the combination of two models, the second peak to vortex shedding of the single model. The last peak is caused by reattachment of the shear layer. Analysis of the reduced power ($fS_{pp}/q_{\infty}^2$) in three frequency bands, $f_{\text{red}} = 0.01 – 0.06$, 0.06 – 0.11 and 0.11 – 0.16, shows an increase in power near the entrance and a decrease near the exit of the passage in all bands with decreasing separation distance. These changes in the spectral power distribution indicate the processes related to the determined spectral peaks ($f_{\text{red}} = 0.03, 0.09,$ and 0.12) increase in intensity, but their region of influence in the passage decreases.

1 Introduction

Local wind loads on building facades in the urban environment can deviate significantly from the loads on an isolated building. These deviations can result from interference of neighbouring buildings, which change the flow characteristics around and the resulting pressure distribution on the building of interest. Kim et al. (2009) showed that for two buildings in side-by-side arrangement the magnitude of the peak pressures measured on the face inside the passage increase with decreasing separation distance ($S$). To obtain a better understanding of this increase in relation to the behaviour of the flow, this study analyses the spectral characteristics of the pressure time series determined for two square cylinders in side-by-side arrangement.

Most of the research on the side-by-side arrangement was performed on ‘infinite’ circular cylinders in low-turbulence approach-flow (e.g. Ohya, 1989; Sumner, 2010). For this configuration, the behaviour of the wake for increasing Reynolds number and separation distance is quite well understood. Figure 1 illustrates the flow modes which are most likely to be observed in the specified $Re$-regimes for separation distances smaller than $S/B < 1.2$ ($B$ is the model width). For $Re < 1700$ (Brun et al, 2004), a stable biased flow pattern is observed. In this flow mode, different Strouhal numbers have been determined in the wide ($St \approx 0.13$) and narrow wake ($St \approx 0.35$), indicating different vortex shedding processes in both wakes. For $Re > 1700$, the biased flow pattern becomes bi-stable (Kim and Durbin, 1988), switching random between the two flow patterns.
Re; the first Strouhal number corresponds with the vortex shedding frequency of a rectangular
The same flow patterns determined for circular cylinders were also observed for square (Kolar et al, 1997) and triangular cylinders (Roshko et al, 1975), and flat plates (Miau et al, 1996). Miau et al determined that an increase in turbulence in the oncoming flow influences the switching behaviour. For increasing turbulence, they first \((I_u = 0.01 - 0.02)\) observed an increase in the number of switching events, followed \((I_u = 0.02 - 0.08)\) by a decrease in switching events. Their statistical analysis suggests that the decrease corresponds with an increase in occurrence of the coupled vortex shedding mode.

For infinite square cylinders in homogeneous flow \((Re = 4.7 \times 10^4)\), Alam et al (2011) determined two Strouhal numbers \((St = 0.07\) and \(St = 0.19\)) for \(0.2 < S/B < 1.1\); and three Strouhal numbers \((St = 0.08, 0.13\) and \(0.19\)) for \(S/B < 1.8\). For two square prisms in a turbulent boundary layer \((Re = 1.52 \times 10^5)\), Sakamoto and Haniu (1988) found \(St = 0.04\) and \(0.09\) for \(S/B < 0.9\). Measurements at \(S/B = 0\) showed that the first Strouhal number corresponds with the vortex shedding frequency of a rectangular cylinder with a width-depth ratio \(B/D = 2\). The second Strouhal number corresponds with the vortex shedding frequency of the single cylinder. For \(0.9 < S/B < 1.5\) they determined \(St = 0.09\) and \(St = 0.11 - 0.12\). They related the third Strouhal number to a small vortex street in the narrow wake side.

Most of these studies determined the peak frequencies using hot-wire measurements in the wakes of the models. To the author’s knowledge, the spectral characteristics of the flow inside the passage have not been investigated in much detail.

The objectives of this paper are:

1. To identify the peak frequencies in the spectrum at the pressure tap locations along the circumference of the reference model.
2. To assess the influence of separation distance on these frequencies and the reduced power distribution along the circumference of the reference model.
3. To clarify the flow behaviour responsible for the determined spectral peaks.

Figure 1: Flow modes most likely to be observed for two circular cylinders in side-by-side arrangement \((S/B < 1.2)\) for increasing Reynolds number; (a) biased mode, (b1 and b2) bi-stable mode (switching of the biased mode), (c1) anti-phase and (c2) in-phase vortex shedding (coupled vortex shedding mode). The Reynolds numbers for the three states are indications based on previous studies; however these values depend on \(S/B\) and oncoming flow conditions (after Zhou et al, 2009).
2 Materials and Methods

Wind tunnel experiments were carried out in the open circuit atmospheric boundary layer (ABL) wind tunnel of TNO in the Netherlands. It has a working section of approximately 13.5 m in length; the test section has a 3 m width and 2 m height. The boundary layer applied in this study had an aerodynamic roughness length \( z_0 = 3.2 \) mm at wind tunnel scale. The turbulence intensity at building height \( (H = 0.48 \) m) was \( I_u,H = 0.12 \) and the turbulence intensity at \( 2/3H \) was \( I_u,2/3H = 0.14 \). Measurements were performed with a reference velocity at building height \( U_H = 14.2 \) m/s \((Re \approx 100.000)\). The instrumented model had a height \( H = 0.48 \) m and width \( B = 0.12 \) m; the interfering model had the same dimensions. More details of the measurement set up are given in Bronkhorst et al (2011).

Figure 2(a) shows the pressure tap distribution, pressure taps are indicated by face specification (A, B, C or D) and row \( (i) \) and column \( (j) \) number. For example, pressure tap A41 is positioned on face A, row 4 and column 1.

The sampled pressures series (400 Hz) were divided in 32 intervals of 0.64 s. The Fast Fourier Transform was applied on each interval to obtain spectral power densities \((S_{pp})\). An average spectral density was determined for each pressure series through ensemble averaging of the 32 intervals; frequency averaging was applied to smooth the spectra in the high frequency range. Results will be presented for the reduced power and reduced frequency, \( fS_{pp}/q_H^2 \) and \( fB/U_H \), in which \( q_H \) and \( U_H \) are the undisturbed mean dynamic pressure and mean velocity at building height.

Figure 2(b) illustrates the side-by-side configurations that will be discussed in this paper. Besides the isolated configuration, side-by-side configurations with an identical interfering model with separation distances \( S/B = 1, 0.75, 0.5, \) and \( 0.25 \) were analysed.

Figure 2: (a) Pressure tap distribution on one of the model faces; (b) top view of investigated arrangements and designation of faces.
3 Results and Discussion

Figure 3 illustrates spectra determined at three pressure taps on face A for two configurations. In the isolated configuration, illustrated in Figure 3(a), a spectral peak is observed at a reduced frequency $f_{\text{red}} = f_B/U_H = 0.08$ at tap A41, A43 and A47. This frequency corresponds with $St = fB/U_{2/3H} = 0.09$, which is a typical value for the vortex shedding process for this type of model. Similar values were described by Sakamoto and Haniu (1988) and Surry and Djakovich (1995) for a square platform high-rise building model in suburban terrain.

At tap A47, an increase in power is observed in the reduced frequency range $f_{\text{red}} = 0.09 - 0.23$; a similar increase was observed by Surry and Djakovich (1995). This increase is caused by the transverse motion of the point of reattachment of the shear layer. The slight increase in power at $f_{\text{red}} = 0.6 - 1.5$ is a result of the fluctuations inside the shear layer, due to Kelvin-Helmholtz instabilities which are caused by the large velocity gradient in the shear layer (Prasad and Williamson, 1997).

![Figure 3: Power spectral densities on face A at $\frac{2}{3}H$ for building taps A41, A43 and A47 for (a) the isolated model and (b) side-by-side configuration ($S = 0.5B$).](image_url)
In the side-by-side configuration with two square cylinders at $S = 0.5B$, illustrated in Figure 3(b), the spectral peak observed at tap A41 has reduced significantly compared to the peak observed in the isolated configuration. The power is distributed over a larger frequency range ($f_{red} = 0.01 – 0.15$). At tap A43, an overall increase is observed in the same frequency range with peaks at $f_{red} = 0.03$, 0.09, and 0.12. These frequencies correspond well with the frequencies determined by Sakamoto and Haniu (1988); they performed spectral analysis on pressure time series measured at a tap in the middle of the passage face. The first frequency ($f_{red} = 0.03$) can be related to the characteristic width of the two buildings ($2B + S$), which gives a Strouhal number of approximately 0.08 – 0.09 (depending on $S/B$). This value corresponds with the Strouhal number of a 2:1 rectangular plan form building model (Sakamoto and Haniu, 1988). This suggests the spectral peak at this frequency is a result of the vortex shedding process of the combination of the two building models. The second frequency ($f_{red} = 0.09$) is caused by vortex shedding of the single buildings. The third frequency ($f_{red} = 0.12$) is most likely associated with reattachment of the shear layer. This is supported by the peak observed in the range $f_{red} = 0.6 – 1.5$, which is caused by the Kelvin-Helmholtz instabilities in the shear layer. At tap A47, the power has reduced to very low values over the complete frequency range; no clear peaks are visible at any frequency, suggesting a stable, low-turbulent flow.

To investigate the influence of the separation distance on the flow behaviour in more detail, three frequency bands were defined which correspond with the spectral peaks at $f_{red} = 0.03$, 0.09, and 0.12. These frequency bands range from $f_{red} = 0.01 – 0.06$, 0.06 – 0.11 and 0.11 – 0.16 with central frequencies at $f_1 = 0.03, f_2 = 0.09$ and $f_3 = 0.14$.

Figure 4 shows the distribution of the reduced power in these bands along the circumference of the reference building model at $2/3H$. In the first frequency band ($f_1 = 0.03$), illustrated in Figure 4(a), an increase in power is observed near the entrance of the passage (face B) with decreasing separation distance. A small increase in power is observed on face D; this corresponds with a strengthening of the vortex shedding process related to the combination of the two models. The large peak in the passage indicates this process has its largest intensity near the inlet.

Figure 4(b) shows the reduced power in the second frequency band ($f_2 = 0.09$). Similar to Figure 4(a), a decrease in separation distance results in an increase in reduced power near the inlet of the passage. Only for $S/B = 0.5$, the reduced power does not follow this trend, this appears to be related to the limited resolution of the pressure tap distribution. The reduced power on face D diminishes with decreasing separation distance, suggesting a weakening of the vortex shedding process of the single model. This observation in combination with the small increase in the low frequency band ($f_1 = 0.03$), suggests a transition from a vortex shedding process related to the separate single building models, to a lower frequency vortex shedding process related to the combination of building models.

The reduced power in the third frequency band, $f_3 = 0.14$, is illustrated in Figure 4(c). For the isolated building model, peaks are observed near the leeward side of both side faces (face B and D), which are related to the reattachment of the shear layer. With decreasing separation distance, this peak moves towards the inlet of the passage, which indicates a decrease in average reattachment length.
Figure 4: Reduced power $P_{\text{red}}(f)/q_H^2$ versus the distance $c$ along the circumference of the model at $\frac{2}{3}H$ (320 mm) for three reduced frequency bands with central frequencies: (a) $f_1 = 0.03$, (b) $f_2 = 0.09$, and (c) $f_3 = 0.14$. 
4 Conclusion and Recommendations

Pressure measurements were performed on an isolated high-rise building model and four side-by-side configurations in a turbulent boundary layer. Spectral analysis of the pressure time series resulted in the following observations:

1. On the side face of the isolated model, peaks were observed in the reduced power spectrum at a reduced frequency $f_{\text{red}} = 0.08$, in the range $f_{\text{red}} = 0.09 - 0.23$, and in the high frequency range $f_{\text{red}} = 0.6 - 1.5$.
2. An additional peak in the side-by-side configuration in the passage at a reduced frequency of $f_{\text{red}} = 0.03$.
3. A decrease in separation distance results in an increase of power in all frequency bands near the entrance and a decrease near the exit of the passage.
4. On the side face opposite to the passage face, a decrease in separation distance results in a decrease in power in the frequency band $f_{\text{red}} = 0.07 - 0.11$ and a slight increase in the band $f_{\text{red}} = 0.01 - 0.05$.

A comparison of these observations with findings from other literature sources, allowed for some clarification of the frequency peaks in relation with the behaviour of the flow:

1. The observed peaks on the single high-rise building model are related to vortex shedding ($f_{\text{red}} = 0.08$), transverse motion of the point of reattachment of the shear layer ($f_{\text{red}} = 0.09 - 0.23$) and Kelvin-Helmholtz instabilities inside the shear layer ($f_{\text{red}} = 0.6 - 1.5$).
2. The additional peak in the side-by-side configuration ($f_{\text{red}} = 0.03$) is related to the vortex shedding process of the combination of the two models.
3. The increase in power near the entrance of the passage and the decrease near the exit with decreasing separation distance indicate the described processes increase in intensity, but their region of influence in the passage decreases.
4. The decrease in reduced power in the frequency band $f_{\text{red}} = 0.07 - 0.11$ on the side face opposite of the passage face combined with the slight increase in the frequency band $f_{\text{red}} = 0.01 - 0.05$ suggests a transition from the vortex shedding process of the single cylinders to a vortex shedding process of the combination of cylinders with decreasing separation distance.

In the current study, the pressure time series were analysed with the Fast Fourier Transform. Under the assumption that the processes responsible for these pressures have a stationary character, this analysis method is very suitable. However, previous studies (e.g., Kim and Durbin, 1988) have already observed that the switching behaviour of the jet at the outlet of the passage is random. It is likely that the flow behaviour inside the passage also has a random character. Future work will investigate this aspect in more detail. A time series analysis of the pressure distribution in the passage can establish whether and to what extent the assumption of a stationary character is valid. The flow processes suggested in this study to be responsible for the observed spectral peaks will be investigated in more detail through analysis of Particle Image Velocimetry measurements, which were performed on the same configurations described in the current work.
References


