Downstream interference effect of low-Scruton-number high-rise buildings under turbulent boundary layer flow

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ABSTRACT

This paper investigates the variation of root-mean-square values of acceleration responses and corresponding aerodynamic dampings of two square cross-sectional high-rise buildings with low Scruton numbers due to interference effects caused by neighboring identical buildings. Aero-elastic vibration test is adopted for displacement and acceleration measurements of a rigid, base-pivoted aero-elastic principal building model by a two-directional sway gimbals system. The principal building is manufactured in the shape of a square prism model with an aspect ratio of eight. Twenty close interference locations are of interest, with a special focus on the across-wind responses. Results show that the variations of interfered acceleration responses and estimated damping ratios exhibit different tendencies for different interference locations at different reduced velocities. For the typical upstream interfered effect, the interfering building located at the oblique-upwind locations in this study, the acceleration response with lower Scruton number is suppressed at lower reduced velocities and is amplified at higher reduced velocities. On the other hand, for the secondary downstream interference effect, i.e., the interfering building located at downwind locations, the amplification or reduction in acceleration response is less sensitive to Scruton number but is related to the gap between two buildings. The corresponding response spectra and resultant damping ratios are then calculated to enhance the understanding of different interference mechanisms. Finally, an idealized two-dimensional CFD simulation technique is adopted to further explain the differences between the upstream and downstream interference mechanisms from the viewpoint of the vortex movement between two buildings.

1. Introduction

In practice, wind load resistant design of a target building is usually estimated based on the condition of an isolated building. However, the real-life surrounding environment of a building may make it much more complicated because of those various interference effects from existing neighboring buildings. Interference effects are considered very difficult to be integrated into design regulations or standard codes due to their complex nature. In some codifications, descriptive explanations or phrases are contained to remind the designers of the interference concern, such as AIJ Recommendation 2015, GB-2015, and so on. The issue with interference effects remains one of the most difficult research topics in the wind engineering field.

In previous works, researchers have adopted various methodologies to examine potential factors to cause interference effects, including approaching flow characteristics, wind directions, relative location of neighboring buildings, cross-sectional shapes and aspect ratios, Scruton numbers, Strouhal numbers, modal frequencies, and mode shapes (Saunders and Melbourne, 1979; Surry and Mallais, 1983; Bailey and Kwok, 1985; Blessmann and Riera, 1985; Kareem, 1987; Taniike and Inaoka, 1988; Sakamoto and Haniu, 1988; Taniike, 1991, 1992; Yahyai et al., 1992; Sun and Gu, 1995; Hui et al., 2012, 2013a, 2013b; Fang et al., 2013; Kim et al., 2011, 2013, 2015; Mara et al., 2014; Yu et al., 2015; Lo et al., 2016). Among these methodologies, square or rectangular prisms, as well as cylindrical prisms, chimneys, storage tanks, or cladding structures, are common choices for discussions (Kareem et al., 1998; Niemann and Kasperski, 1999; Wang et al., 2014; Uematsu et al., 2015). In most references,
Fig. 1. Characteristic profiles of simulated turbulent boundary layer flow.

Fig. 2. Configurations of the principal building model.

Fig. 3. Scheme of the interfering building model.

Fig. 4. Scheme of the aero-elastic vibration test.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Principal</td>
<td>Interfering</td>
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<tr>
<td>Height (H)</td>
<td>0.56</td>
<td></td>
</tr>
<tr>
<td>Depth (D)</td>
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<td>Rigid</td>
</tr>
<tr>
<td>Width (B)</td>
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</tr>
<tr>
<td>( f_0 ) (Hz)</td>
<td>5.95</td>
<td>6.30</td>
</tr>
<tr>
<td>( \zeta ) (%)</td>
<td>0.50</td>
<td>0.80</td>
</tr>
<tr>
<td>( M' ) (kg)</td>
<td>0.11</td>
<td>0.15</td>
</tr>
<tr>
<td>( S_c )</td>
<td>1.05</td>
<td>1.31</td>
</tr>
<tr>
<td>( U_r = \frac{U_L}{f_0 B} )</td>
<td>6.7, 7.5, 8.3, 9.0, 9.7, 10.5, 11.0, 11.5, 12.2, 13.1, 13.8, 14.6</td>
<td>7.22, 7.94, 8.66, 9.38, 10.11, 10.83, 11.55, 12.27, 12.99, 13.71, 14.44, 15.18</td>
</tr>
</tbody>
</table>

The damping ratio is identified based on the logarithmic decrement method via the free vibration test under no winds. The 2nd – 11th peaks in large amplitudes are selected for damping estimation.
interference effects are discussed based on distorted wind pressures/forces measured by a high-frequency force balancer or pressure scanning devices. Comparisons are focused on how interference effects alternate the mean, background and resonant components in terms of gust loading methods.

Although some studies have introduced interference effects via aeroelastic vibration testing results, only a few of them mentioned the different interfering phenomena in the process of interference occurrences. Kareem (1987) mentioned that if the wake characteristics of the upstream building can be described as an oscillator model, the generated interference is analogous to the addition damping and therefore dampens the wake fluctuations. Zhang et al. (1994, 1995) discussed the torsional aerodynamic damping when the maximum interference effect occurs. Results showed that even under resonant buffeting caused by
Fig. 7. Root-mean-square values of across-wind displacements at different interference locations (v: vibrating interfering building; r: rigid-mounted interfering building).
interference effect, the aerodynamic damping was positive resulting in little aero-elastic effect as expected. Huang and Gu (2005) explained that as long as the variation of aerodynamic damping is concerned, the results from the HFFB test and aero-elastic vibration test should be less different. Fang et al. (2013) examined the interfered dynamic response of a square cross-sectional principal building with three Scruton numbers and concluded empirical models of aerodynamic damping in terms of reduced velocity.

According to Bailey and Kwok (1985), Yahyai et al. (1992) and Lo et al. (2016), the downstream interference phenomenon can occur when the interfering building locates very close to the principal building at high reduced velocities. This interference mechanism depends on the vortex movement existing in the rhythmically narrowing space between two buildings. Therefore, the aero-elastic vibration test is preferred to the commonly adopted force balancer tests. Previously, Fang et al. (2013) suggested aerodynamic damping models for high and mediate Scruton numbers from upstream interfered displacement responses. However, the downstream interference mainly due to low Scruton numbers has not been explained clearly. With this concern, this research attempts to investigate the interference effects from either of both the upstream or the downstream for high-rise buildings with low Scruton numbers.

To remit the confusion whether the interference effect is affected by the vibrating interfering building or not, the interfering model is manufactured to be rigidly mounted and base-pivoted mounted for validation. Then the principal building is adjusted to two low Scruton numbers for subsequent investigations. To better estimate resultant damping ratios to enhance the understanding of the interference mechanisms, accelerometers are installed at the rooftop of the principal building model. Acceleration response spectra are calculated and the resultant damping ratios are estimated by the random decrement technique. Finally, a two-dimensional idealized CFD simulation is adopted to explain more clearly the downstream interference mechanism.

2. Experimental setup

The aero-elastic vibration test is conducted in the 18.0 × 1.8 × 2.2 m atmospheric boundary layer wind tunnel at Wind Engineering Research Center at Tokyo Polytechnic University. A 1/394 scale turbulent flow over a sub-urban terrain with a power-law index of 0.2 for the mean velocity profile is simulated with properly equipped spires, saw barriers, and roughness blocks. The vertical flow characteristics of the mean wind speed profile and the turbulent intensity profile are shown with the velocity spectrum at the model height in Fig. 1.

A rigid, base-pivoted aero-elastic square prism model is made to play
the role of the principal building as shown in Fig. 2. The square prism model has a size of 0.07 m in width (B) and depth (D) and 0.56 m in height (H), which makes it a slender model with the aspect ratio (H/B) of 8. The interfering building is made in the same size as the principal building model in order to simplify the interfering source. In the first phase of the experiments, the interfering building model is firstly made rigid-pivoted and aero-elastic. It is artificially tuned to vibrate with the same fundamental frequency as the principal building model. In the second phase, the interfering building model is rigidly mounted to the ground and fixed Fig. 3 shows the scheme of the interfering building model. The interfering building model is intended to be made similar to the principal building model. The modeled Scruton number is 1.05 for the principal building model and 1.31 for the interfering building model, showing that the manufacturing of both models is quite consistent and should behave in similar aerodynamic characteristics in motion. In this study, all the models are made in the low Scruton number range in simplicity.

The purpose of the first phase test is to confirm the differences between when the interfering building model is made rigid-pivoted and aero-elastic or rigidly mounted. In the second phase of the experiments, the principal building model is tuned to have similar fundamental frequencies (same generalized masses and same stiffness) with two different systematic damping ratios. The setup of the aero-elastic vibration test is illustrated in Fig. 4. The gimbal system provides two sway degree-of-freedom motions. The displacement signals of both directions are recorded by two laser sensors at the sampling rate of 550 Hz. The sampling length is 16,384 for one sample record. Ten samples are collected to maintain stable statistical results. For the second-phase test, accelerometers are installed at the rooftop of the principal building model to compare it with the displacement measurements and also to better estimate the resultant damping ratios. Table 1 shows the information of the principal building model and the interfering building model at the two phases. The wind speed is varied to cover enough reduced velocity range for investigation. The Scruton number is also calculated by the related generalized mass and the identified damping ratio with the model’s geometric parameters in Table 1.

The interference locations of interest are those considered significant in the surrounding area shown in Fig. 5. The principal and interfering building models are orientated with one face normal to the wind when the tests are carried out. Five location series including the upward series, the oblique-upwind series, the side series, the oblique-downwind series and the downwind series are selected to be compared with the isolated case.

3. Results and discussions

3.1. Effect of vibrating interfering building

The differences caused by a vibrating or rigidly mounted interfering building model is examined based on the results from the first-phase test. Figs. 6 and 7 show the comparisons in terms of root-square-mean values of along-wind and across-wind displacements.

For the along-wind displacements in Fig. 6, small amplification is indicated at upwind and oblique-upwind locations. The small amplification is presumed due to the upstream vortex separated from the interfering building model. The series of side locations, oblique-downwind locations, and downwind locations are different from the isolated case. As for the across-wind displacements in Fig. 7, five series of interference locations express different tendencies under different reduced velocities. Among them, the figures/results of the series of upwind locations, the side locations, and the oblique-downwind locations are similar. The existence of the interfering building model generally suppresses the responses at all reduced velocities. For the oblique-upwind locations, which are commonly discussed in previous works, the interfering building model amplifies the principal building model’s responses at almost all reduced velocities. Particularly, as locations get closer to the principal building model, the amplification increases rapidly in proportion to the reduced velocity. On the other hand, for the downwind locations, the principal building’s response is first suppressed at lower reduced velocities and then amplified at higher reduced velocities. It is noticed that, in this study, the reduced velocity ranges in the along-wind and across-wind figures are different simply because the...
Fig. 14. Acceleration response spectra for upwind location series.
along-wind displacement signal fail to be recorded. Such measurement failure is found due to the large across-wind vibration which causes the laser to miss (Lo et al., 2016).

Comparing the cases with the vibrating interfering building model to those with the rigidly mounted interfering building model, only the upwind locations in the across-wind figures show differences, regardless of the distance of the location. The cases with the vibrating interfering building model show slightly larger responses than the rigidly mounted one. However, when comparing to the isolated case, the responses are suppressed significantly when there is an interfering building. Although the manufacture of the vibrating interfering building model in such tests is more practical, the vibrating interfering building model is considered less sensitive to the subsequent investigations. Therefore, for the second phase test, the interfering building model is rigidly mounted for experimental saving.

3.2. Effects induced by Scruton numbers

In the second-phase test, displacement and acceleration signals are recorded. Comparing to other isolated principal buildings in references (Bailey and Kwok, 1985; Kawai, 1992; Huang and Gu, 2005), the normalized across-wind responses in this study are quite consistent with those of previous works shown in Fig. 8. Even though their aspect ratios and surrounding terrains are slightly different from this study, the responses with respect to reduced velocities are considered to be in the same pattern for small Scruton numbers. From the comparison in Fig. 8, the setting of flow condition and the manufacture of the principal building models in this study shall be considered acceptable for the research motivation. Furthermore, from the comparison of displacement and acceleration records shown in Fig. 9, both tendencies with respect to reduced velocity recorded by different sensors are quite similar. Both indicate a clear deviation induced by Scruton number effect. To avoid the duplication of results and to ensure a better damping ratio identification from acceleration responses, the subsequent analysis is explained in acceleration records.

3.2.1. Damping ratio identification

Referring to Tamura (2012), there are several methodologies proposed to identify the damping ratio from vibration signals. Among these methodologies, the traditional random decrement (RD) technique (Cole, 1973) with certain requirements is still widely adopted in many signal identification examples, although newly developed techniques may improve the precision. The process adopted to identify the damping ratio in this study is briefly introduced here.

When identifying the damping ratios of all cases, the original continuous record of each case, constituted by ten 16,384 sample records, is used to accumulate enough number of decrement segments to form the decaying signature. Based on Cole (1973) and Tamura (2012), the continuous record of across-wind vibration is processed the selection of segments with a suggestive criterion, which is the standard deviation of acceleration signals multiplied by 1.44. In this study, all cases possess at least 2000 segments to form a smooth decaying signature. As shown in the isolated low-Scruton-number model under $U_t = 7.94$ in Fig. 10, more than 2000 segments are selected from Fig. 10(a) to form the decrement signature in Fig. 10(b).

Damping ratio is calculated based on the following Equation (1). By taking the mean value of all the identified damping ratios from the same decrement signature, the resultant damping ratio, including the systematic damping and the aerodynamic damping, for this very case is obtained. However, in this study, in order to improve the estimation precision, the original time history is negated by multiplying a minus sign and processed the same procedure to obtain the second resultant damping ratio. Averaging these two resultant values gives the final estimation value.

$$\xi(\%) = \frac{1}{2\pi j} \ln \left( \frac{S_{y_{th \_ peak}}}{S_{y_{jth \_ peak}}} \right) \times 100$$ (1)

When the vibration is in small amplitudes, the superpositioned number should be necessarily large; while the vibration is in resonant phenomenon, the application of Equation (1) may not be appropriate to provide good and stable estimations. Therefore, according to Tamura (2012), a bandpass filter to remove the long-term trend and the noise near the peaks is necessary once the decrement signature is formed. In this study, a bandpass filter with 0.05–15 Hz is used.

When applying the aforementioned technique to the acceleration signals from the free vibration tests under no winds, the associated amplitude-dependent systematic damping ratios of the two principal building models may be identified for the calculation of aerodynamic damping effect. Fig. 11 shows the amplitude-dependent damping ratios varying with tip accelerations. It is indicated that the systematic damping ratios are quite small in the small amplitude range. As the amplitude increases, the identified damping ratio increases until it reaches the tip drift ratio (Tamura, 2012). After the drift ratio point, the damping gradually decreases with the amplitude and eventually approaches its stable constant value, in this study 0.1 m/s² for both models. The tip drift ratio here is calculated by dividing the estimated displacement, $a_{max}/(2\pi f_0)^2$, by the model height $H$. Both ratios are in the $10^{-3}$ range, similar to the examples in Tamura (2012).

Fig. 15. Identified damping ratios for upwind location (2, 0).

Fig. 16. Normalized root-mean-square values of acceleration responses for oblique-upwind location series.
Fig. 17. Acceleration response spectra for oblique-upwind location series.
For the subsequent discussions, aerodynamic damping ratio is estimated by subtracting the amplitude-dependent systematic damping ratio from the resultant damping ratio, as shown in Equation (2):

$$
\xi_{\text{total}}(\%) = \xi_{\text{sys}}(\%) - \xi_{\text{ori}}(\%)
$$

(2)

The resultant damping ratio, $\xi_{\text{total}}$, is estimated based on Equation (1) for each case under winds and the amplitude-dependent systematic damping is as shown in Fig. 11. However, in this study, it is essential to notice that in Fig. 12, the smallest root-mean-square value of acceleration response among all cases is larger than the criterion, after which the systematic damping can be considered constant.

3.2.2. Upwind interfering effect

To avoid duplicate discussion with previous references, the along-wind acceleration responses are not discussed in this section and only the across-wind acceleration responses are discussed. Furthermore, to clarify the interfering effect leading to amplification or reduction, normalization with the isolated principal building model is conducted by the root-mean-square values of acceleration responses with respect to reduced velocities.

Fig. 13 shows the normalized root-mean-square (RMS) values of acceleration responses for the interfering building model located in the upwind locations of the principal building model. Two marker colors are selected to indicate the differences caused by two Scruton numbers. As indicated in the figure, the normalized RMS values are generally smaller than 1, which confirms the reduction effect in this series. When reduced velocity $U_r (= U_p/f_n B)$ is smaller than 10, the Scruton number effect is not clear; however, when it is larger than 10, low Scruton number (hereafter: Scr1.6) cases have lower normalized RMS values than high Scruton number (hereafter: Scr4.0) ones in general.

From the selected acceleration spectra in Fig. 14, two selected $U_r$ values (nearly 8 and 14) generally show the lower spectrum values than the isolated cases. At $U_r = 14-15$ cases, the Scr1.6 case has similar approaching peaks as the Scr4.0 one; however, the isolated cases of Scr1.6 and Scr4.0 are essentially different at peaks and humps, where the vortex shed from the principal building. Therefore, the normalized RMS values of Scr1.6 cases are generally lower than the values of Scr4.0 cases in Fig. 13.

Resultant and aerodynamic damping ratios of selected cases at the location of $(x/B, y/B) = (2, 0)$ are plotted against reduced velocities in Fig. 15. For the isolated buildings, the aerodynamic damping is observed to be positive at low reduced velocities and then becomes negative when the reduced velocity is larger than 10. For the interfered cases, the aerodynamic damping ratios at all reduced velocities are positive to suppress the vibration, indicating the consistent observation in Fig. 13. However, when at low reduced velocity of near 7, both the Scr1.6 and Scr4.0 cases show inconsistent values with their corresponding RMS responses in Fig. 13. This is considered to be an identification bias caused by the identification technique when the response is in mild vibration motion.

3.2.3. Oblique-upwind interfering effect

Fig. 16 shows the variation of normalized RMS acceleration values at oblique-upwind locations in a complex nature consisting of the effects from location, Scruton number, and reduced velocity. When the interfering building model is far at $(x/B, y/B) = (3, 3)$, both Scr1.6 and Scr4.0 cases are amplified slightly at all reduced velocities, which indicates that the amplification comes from the vortices shed from the upstream interfering building model solely and it is less sensitive to vortex shedding frequency. When the location of the interference moves to $(x/B, y/B) = (2.5, 2.5)$, the vibration becomes more sensitive to the shedding frequency but is still less sensitive to the Scruton number. At the reduced velocity range lower than 11, the RMS values are reduced by the interfering building; at the range higher than 11, the values are amplified. When the location moves to $(x/B, y/B) = (2, 2)$, the same tendency of $(x/B, y/B) = (2.5, 2.5)$ remains and the Scruton number effect begins to take place at reduced velocity larger than 12. Finally, when the interfering building approaches the principal building, at the location of $(x/B, y/B) = (1.5, 1.5)$, the variations become dramatic and the Scruton number effect changes the timing when the reduction in response turns to the amplification in response.

Two reduced velocities are selected for spectrum examination in Fig. 17. Scr1.6 and Scr4.0 cases have inverse trends when their reduced velocities are low or high. When the reduced velocity is low, the spectrum peaks move to lower frequency and deviate from the structural frequency. This is considered to be the vortex shedding frequency from the upstream interfering building. When the reduced velocity is high and the location is close, the structural frequency dominates the vibration; when the interfering building gets farther from the principal building, the vortex from the principal building itself gradually forms and the peak at the structural frequency decreases slightly.

The resultant and aerodynamic damping ratios at the location of $(x/B, y/B) = (1.5, 1.5)$ in Fig. 18 generally reflect the overall tendencies in Fig. 16. Significant variations of aerodynamic damping indicate that the vibration of the principal building is strongly suppressed at lower reduced velocities and then greatly amplified after the reduced velocity of 12. It is also found that the point when the positive aerodynamic damping ratio turns to negative is different for two Scruton numbers.

Fig. 18. Identified damping ratios for oblique-upwind location (1.5, 1.5).

Fig. 19. Normalized root-mean-square values of acceleration responses for side location series.
Fig. 20. Acceleration response spectra for side location series.
3.2.4. Side and oblique-downwind interfering effects

The variations of normalized RMS values are plotted in Fig. 19 for the interfering building models located at the side positions. The distribution patterns of two Scruton numbers seem to be similar to those at the upwind locations in Fig. 13. However, the distinction at low reduced velocities for those farther locations can be found. Examining the spectrum figures in Fig. 20, the tendency in the location of the $S_{cr}1.6$ case does not have a similar regularity as the tendency of the $S_{cr}4.0$ case. The spectrum peak at the structural frequency decreases as the location gets closer to the principal building. Although the spectrum area of the $S_{cr}1.6$ case decreases when the location gets closer, the spectrum peak seems not to stick to the structural frequency and is strongly affected by the surrounding interfered flow. On the contrary, the two Scruton cases are quite consistent at high reduced velocities. Resultant and aerodynamic damping ratios at the location of $(x/B, y/B) = (0, 2)$ are plotted in Fig. 21. They show similar variations as those in Fig. 15 with even stronger suppression in vibration at most reduced velocities. The same mismatch between damping ratios at the location of $(x/B, y/B)$ is quite consistent at high reduced velocities. Resultant and aerodynamic damping ratios are similar to those at the upwind location series. The distributions of this series are similar to those of the side location series. The special case of the oblique-downwind location, indicated by Bailey and Kwok (1985) and Lo et al. (2016), is the rhythmic resonant vibration near the location $(x/B, y/B) = (-2, 2) - (-3, 3)$ at near $U_r = 6$. As can be observed from Figs. 22 and 24, at reduced velocity around 7, the vibration is slightly amplified and the aerodynamic damping of the $S_{cr}1.6$ case turns negative. However, it may not be sufficiently considered to be the rhythmic resonant vibration since its reduced velocity is over 7, higher than values indicated in Bailey and Kwok (1985) and Lo et al. (2016). And it is hard to distinguish the difference of the RMS responses from Fig. 19 because they share a very similar variation tendency.

3.2.5. Downwind interfering effect

The variations of normalized RMS values at the downwind locations are different from the aforementioned series. As shown in Fig. 25, the reduction in RMS values increases with the reduced velocity until $U_r = 9$ and then the reduction decreases and turns to amplification in RMS values near $U_r = 11-12$. As the reduced velocity increases even higher, the amplification becomes higher if the location is also getting closer to the principal building. Comparing to Fig. 16, the location effect may not be significant in this series; however, a slight gradual variation can still be indicated. The $S_{cr}4.0$ cases have a lower reduction at low reduced velocities and lower amplification at high reduced velocities than the $S_{cr}1.6$ cases. As the distance shortens between the interfering building and the principal building, the reduction or the amplification increases. Comparing spectrum figures in Figs. 17 and 26 for two location series, the downwind location series does not have a clear decaying spectrum area at both selected reduced velocities; nevertheless, the reduction at low reduced velocity and the amplification at high reduced velocity are confirmed.

An interesting point is that when at either low or high reduced velocity, the spectrum peak adhere to the structural frequency despite whether the interfering building is close or far. This is because the vibration in this series is only dominant at structural frequency, which corresponds to the interference mechanism mentioned by Lo et al. (2016). The downstream interference depends on the wake structure existing between the principal building and the interfering building. When the existing space between the principal building and the interfering building is small, the two buildings are considered as a coherent rectangular whole. The wake structure behind this pseudo rectangular cylinder is weak when the reduced velocity is low and is strong when the reduced velocity is high. When the existing space widens, the individual behavior of the principal building becomes clearer. In this study, all the downwind locations are considered to be sensitive to downstream interference effects, which is the same distance mentioned by Yahyai et al. (1992). The tendencies of damping ratios at the location $(x/B, y/B) = (-1.5, 0)$ in Fig. 27 are similar to those in Fig. 18; however, the positive aerodynamic damping is generally smaller so that the reduction at lower reduced velocities is less significant. It would be interesting to conclude a potential decaying curve model with reduced velocity if more different Scruton numbers are tested.

3.3. CFD simulation for downstream interference effects

3.3.1. CFD setting

A simplified numerical simulation is conducted by computational fluid dynamic (CFD) technology to enhance the understanding of the aforementioned downstream interference mechanism. The CFD environment is idealized to be a 2D analysis with those identified structural characteristics and the flow condition at model height. The 2D LES model had been worked successfully on vortex shedding from a bluff body flow (Bouris and Bergeles, 1999; Noda and Nakayama, 2003; Vikram et al., 2011). This study follows the simulation technique in Lo et al. (2016) to further examine the downstream interference effect for two Scruton numbers. The following part briefly introduces the CFD setting algorithm.

For an efficient calculation, a partitioned procedure is chosen. The fluid-structure interaction algorithm is similar to the conventional sequential staggered procedure. In this study, the response of the principal building model is calculated based on a forced mass-spring-damper algorithm.

Figs. 22–24 show the normalized RMS values, response spectra at two selected reduced velocities, and associated damping ratios at the location of $(x/B, y/B) = (-2.5, 2.5)$ for the oblique-downwind location series. The variations of normalized RMS values are plotted in Fig. 19 for the oblique-downwind location series. The distributions of this series are similar to those of the side location series. The special case of the oblique-downwind location, indicated by Bailey and Kwok (1985) and Lo et al. (2016), is the rhythmic resonant vibration near the location $(x/B, y/B) = (-2, 2) - (-3, 3)$ at near $U_r = 6$. As can be observed from Figs. 22 and 24, at reduced velocity around 7, the vibration is slightly amplified and the aerodynamic damping of the $S_{cr}1.6$ case turns negative. However, it may not be sufficiently considered to be the rhythmic resonant vibration since its reduced velocity is over 7, higher than values indicated in Bailey and Kwok (1985) and Lo et al. (2016). And it is hard to distinguish the difference of the RMS responses from Fig. 19 because they share a very similar variation tendency.
Fig. 23. Acceleration response spectra for oblique-downwind location series.
equation. The commercial package ANSYS Fluent is applied mainly for the simulation in this study, including the dynamic meshing module. The scheme of quadratic-up interpolation for convective kinematics is adopted for spatial discretization of the convective terms. A bounded central difference scheme is adopted for the diffusive terms of the momentum equations. The algorithm of pressure-implicit with splitting of operators is selected as the pressure-velocity coupling scheme for its robust convergence advantage. The time discretization is a second-order accurate and fully implicit scheme. The time duration for initializing the calculation of all cases is set to 50,000 steps and each step is 0.0001 s for computation, which satisfies the Courant-Friedrichs-Lewy and the grid Fourier criteria. The Gauss-Siedel point-by-point iterative method in conjunction with the algebraic multigrid method is used to obtain a converged solution. The dynamic Smagorinsky-Lilly model is selected for the sub-grid-scale model.

For generating the uniform turbulence inlet, modified discretizing and synthesizing random flow generation (MDSRGF; Castro et al., 2011) is adopted. Turbulence intensity and turbulence integral length scale at the 2/3 principle building height, which is 12% and 0.4 m respectively, are given to generate the anisotropic turbulence flow. Moreover, the wind spectra of the generating flow in 3 directions obey von Karman’s models.

For the simulation in this study, the dimensions of the computational domain are 45D × 24D, where D = B. Two square cylinders are arranged at 6D downstream from the inlet as the principal building model and the interfering building model. The simulation domain is discretized by a non-uniform unstructured grid with a finer grid distribution near the cylinders to capture the viscous boundary layer as well as the wake and the vortex street behind the cylinders. The structured grid near the cylinders is built with a minimum grid space of 0.05D and extruded ten layers normal to each cylinder surface. The y+ value is less than 10 on the cylinders. Grids are generated by the grid generation software POINTWISE.

3.3.2. Simulation results

In Lo et al. (2016), the trial of CFD simulation was conducted for the high reduced velocity near 14. A clear amplifying effect was indicated in both the experimental and simulation results. The amplifying effect due to the vibration-induced gap allows the merging of the vortex shed from the upstream principal building and the vortex shed from the downstream interfering building. The merged wake behind the buildings is in a good structure and therefore provides a good chance to amplify the across-wind vibration of the principal building.

In this study, the simulation results are again focused on the discussion of downstream interference effect at the location (x/B, y/B) = (−2, 0) and the discussion of upstream interference effect at the location (x/B, y/B) = (2, 2). From the aforementioned discussion in Fig. 16, the typical upstream interference effect occurs when the interfering building model is located at the oblique-upwind locations. Obviously, not only the Scruton numbers but also the interference locations have different interfered results with respect to reduced velocity. On the other hand, from Fig. 25, it is found that the amplification exists in larger reduced velocities regardless of the Scruton number effect and the interference locations. In order to distinguish and explain the mechanisms from upstream and downstream interference effects, the CFD simulation selects the Scr = 1.6 case at low (Ur = 7.9) and high (Ur = 14.4) reduced velocities for comparisons.

Fig. 28 extracts certain simulated time histories from CFD simulation results of both cases together with the isolated case. Fig. 29 shows their corresponding spectrum characteristics from wind tunnel tests. In Fig. 28, the time histories of the isolated principal building and the upstream-interfered building at Ur = 7.94 show a vibration with at least two frequencies. For the upstream-interfered building case, those two frequencies are well separated; and for the isolated one, the two frequencies are close to each other. The time history behaviors of the isolated and the upstream-interfered buildings based on CFD simulation results are well consistent with those observed spectrum characteristics from the results of the wind tunnel test in Fig. 29. The displacement spectrum of the isolated case shows a wider peak around the structural frequency which contains the energies from two frequencies; meanwhile, the spectrum of the upstream-interfered case has well-separated peaks. As for the downstream-interfered case, the spectrum hump or peak at lower frequency is not clear. Therefore, its time history vibrates in a harmonic form. The spectrum area is lower compared to the isolated one, which corresponds well to the suppressed responses in Figs. 16 and 25. On the other hand, when the reduced velocity rises to Ur = 14.44, the time histories vibrate in similar harmonic form. Among them, the upstream-interfered case has the largest amplitude and the downstream-interfered case has the second-largest amplitude. The amplified responses is also referred to those obvious spectrum peaks in Fig. 29. Their larger spectrum areas are consistent with the amplified responses in Figs. 16 and 25 as well.

The wind tunnel tests and the CFD simulation results are fairly consistent with the knowledge gained from previous works for the typical upstream-interfered case at the oblique-upwind locations. The aerodynamic behavior of this effect has also been introduced in many publications. It would be interesting to investigate the secondary interference effect in this study, which is the downstream-interfered case at the downwind locations. However, it is still not clear to examine how it is different from the upstream-interfered case in Fig. 29. Vorticity patterns
Fig. 26. Acceleration response spectra for downwind location series.
given by CFD simulation may provide a clearer picture.

In Figs. 30 and 31, the downstream interference phenomenon with the vorticity patterns of one cycle is illustrated for the cases of $U_r = 7.94$ and 14.44, respectively. For the case of $U_r = 7.94$ in Fig. 30, the gap between two buildings is not wide enough so that the vortex from the upstream building is weakened by the vortex shed from the downstream building and results in a small and narrow vortex behind two buildings. The wake structure between two buildings is not strong so that the vibration is decreased a bit. For the case of $U_r = 14.44$ in Fig. 31, the gap between two buildings is wide enough to allow the vortex shed from the upside of the upstream building to roll down and merge with the vortex shed from the bottom side of the downstream building, or on the contrary, to allow the vortex shed from the bottom side of the upstream building to roll up and merge with the vortex shed from the upside of the downstream building. Comparing to Fig. 30, the wake structure in Fig. 31 is much stronger and lasts longer. Previously in Lo et al. (2016), a similar vorticity pattern within one cycle like Fig. 31 has been introduced to explain why the vibration has been amplified. This study further compares the same setting but under two different reduced velocities to further clarify the concept.

4. Conclusions

This study has conducted wind tunnel tests for interference effect investigations. The tests are conducted in two phases. The first phase is mainly for the validation of a vibrating interfering building to examine its differences from a rigid-mounted interfering building. The second phase is for examining the Scruton number effect in different interference mechanisms. Several conclusions are summarized as follows:

(1) The interfering building model is adjusted to be rigidly mounted to the ground and pivot-based elastic in the same vibrating frequency as the principal building model. Results from five location series show that there are less significant differences between the vibrating interfering building model and the rigid pivot-based model. The rigidly mounted interfering building model is then chosen for the subsequent analysis in this study for the experimental saving.

(2) Results from the five-location series show that there can be four different interference mechanisms induced by their relative locations, reduced velocities, and different Scruton numbers. Among them, the side location and the oblique-downwind location series have consistent patterns. Although the Scruton numbers manufactured in this study are few for high-rise buildings, differences due to Scruton number effect can still be noted among these four mechanisms, especially the oblique-upwind location series.

(3) Downstream interference effects are mainly caused by reduced velocities. The narrow space between two building models makes a difference in the wake structure shed from the principal building. In general, the vibration is suppressed at low reduced velocities and is amplified at high reduced velocities. Scruton number has relatively smaller effect on downstream interferences rather than the oblique-upwind interferences.

(4) The suppressed and amplified across-wind vibrations with an interfering building located in the downstream area are illustrated with CFD simulations. When the space between the principal building and the interfering building is alternated by the relative motion, the vortices shed from the two buildings behave in a different merging way. When at low reduced velocities, the vortex shed from the principal building is weakened by the vortex shed from the interfering building, resulting in a weaker wake structure. When at high reduced velocities, as mentioned in Lo et al. (2016), the vortices merged to enhance the vortex from the principal building and results in stronger wake structure.
Fig. 30. Vorticity patterns within one cycle for $U_r = 7.94$ at downwind location $(x/B, y/B) = (−2, 0)$.

Fig. 31. Vorticity patterns within one cycle for $U_r = 14.44$ at downwind location $(x/B, y/B) = (−2, 0)$. 
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