Patterning Airflow: Qualitative Analysis and Design for Thermal Comfort

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Abstract
Natural wind movement is impeded by dense urban fabric in the tropics causing thermal discomfort and aggravating pollution. Research suggests that if average wind velocity cannot be improved, the airflow fluctuation frequency can be used as a control factor to provide a sensation of thermal cooling for pedestrians. Therefore, this paper introduces the novel application of actuated travelling waves as a façade retrofit that alters the fluctuation frequency of the stagnant airflow field to improve thermal comfort. Nine case studies were simulated to optimise the movement of the travelling wave, and the best-case scenario had a 72% improvement in velocity values compared to the initial base case. This combination of travelling wave with 34.85m wavelength and wave speed of 18m/s produced a consistent air velocity with a targeted frequency of 0.22 Hz, which is within the range of frequencies that provides a strong cooling sensation.

Introduction
More than half of the world’s population lives in urban areas, and most rapidly developing megacities are in hot and humid tropical regions. Low diurnal temperature differences and high humidity make this type of climate one of the hardest to design passive environments (Givoni, 1998). Typically, under such climatic conditions, air movement is one of the most useful and inexpensive methods to achieve a comfortable environment. However, densely built urban areas impede urban ventilation which in turn causes thermal discomfort. There are no clear counter measures to this issue as its effects are not obviously dangerous like high wind speeds in cities (Kato and Hiyama, 2012). This study presents a novel solution to this issue by retrofitting building facades and urban spaces with textured surfaces. Discrete surfaces are actuated in order to control airflow separation in bluff bodies (e.g. building structures) and pattern the air to provide cooling sensations and optimised thermal comfort. The project involved cross disciplinary work in building physics, fluid mechanics, and bio-inspired design. The first phase of the research (Yogiaman, 2018) studied the effects of various surface textures on airflow through a prototypical exterior urban canopy (Figure 1a). The canopy designs were evaluated in simulation and the most promising designs (Figure 1b) were prototyped and physically tested to confirm their performance. The results show that surface features can change the airflow patterns of velocity within and outside of the structure (Figure 1c, 1d). The airflow with consistent frequencies that falls within a range of frequencies tested through experimental results by other research groups (Tanabe and Kimura, 1994) provides stronger cooling sensations when average velocity of the regular flow cannot be increased.

Figure 1: Urban canopy simulations: (a) Prototypical urban canopy outer design for the first phase of the research project. (b) Canopy internal designs with static wave-like surface textures designed to alter flow patterns. (c) Simulations of urban canopy designs with asymmetric wave-like internal surface textures show increased vorticity (rotational flow) and flow fluctuations. (d) The velocity over time at point A has similar airflow frequency (0.1hz) in the range shown to provide cooling sensations in experiments conducted by Tanabe and Kimura (1994). Building on this first step, this paper presents the second phase of the project where the effects of actuated surface...
Textures on airflow are studied. To do this, travelling waves of various parameters were simulated on a selected building façade in a congested urban area in the Central Business District (CBD) of Singapore. Computational fluid dynamic (CFD) simulations were performed to examine the resulting flow structures (i.e. airflow patterns). This paper focuses on the discussion of CFD simulations to demonstrate that specific travelling waves moving along a building façade can change airflow frequency as well as improve overall wind speed in an urban context.

State of the art
Thermal comfort studies have been a prevalent area of research in the past decades, and a rich body of research exists that examines the effects of air movement on human comfort. Although mean velocity was considered the main parameter contributing to comfort, more recent studies indicate that turbulent intensity, air flow direction and fluctuation frequency are also important parameters for the perception of thermal comfort. Most experimental research in this area involves documenting subjective responses in a controlled climate chamber and comparing these responses against the PMV (predicted mean vote). PMV is the average response of a large number of people calculated using P O Fanger’s equation involving 6 environmental and physiological parameters (Fanger, 1972). Comparative studies of past experimental data indicate different preferences for air flow frequency in cold and warm climates. Experiment results for flow fluctuation frequency by Fanger and Pederson (1977) showed that maximum discomfort was experienced when air velocity fluctuated at 0.3-0.5 Hz in a temperature range of 20-26°C. However, in warm and humid conditions of 30°C, a higher air velocity fluctuation of 0.2-2Hz is accepted and is expected as a cooling measure (Huang et al, 2012). Tanabe and Kimura (1994) conducted similar experiments in warm and humid conditions at a temperature range of 27-31°C. They looked at the different patterns of airflow over time and concluded that sine waves with cycles of 10, 30 and 60 seconds (0.0167, 0.033 and 0.1Hz) produced significantly cooler thermal sensations.

This was also confirmed by Zhou et al (2006) from experiments carried out with simulated natural flow and sinusoidal waves at cycles of 10 seconds. Figure 2 illustrates a combined graph of airflow fluctuation experiment results in warm and humid conditions. This shows that although similar environmental input parameters like air velocity, operative temperature, and relative humidity produce almost similar PMV results, varying just the airflow pattern can strongly affect the subjective cooling sensation (TSV) of test subjects.

Collectively, these studies indicate that specific airflow patterns with a particular dominant frequency distribution can improve thermal comfort in conditions where average airflow velocity is limited and cannot be increased. Currently, airflow fluctuation frequency is a criterion that remains unaccounted for in empirical models of thermal comfort. The comparative studies from past experiments suggest air flow patterns can be considered as another control factor to offset increased temperature in warm indoor environments and dense, stuffy outdoor environments.

Figure 2: Summary of physiological experiment results: sinusoidal patterned flows provide higher subjective cooling sensations (based on Tanabe and Kimura, 1994).
Outdoor airflow research on an urban scale is currently limited to understanding airflow behaviour in existing urban environments or by manipulating different generic urban configurations for optimised natural ventilation for building, urban and pedestrian comfort. This is illustrated by Toparlar (2017) in an exhaustive review on the use of CFD for urban microclimate analysis. This review calls for changes in urban geometry and the inclusion of open spaces like courtyards and parks. These solutions may not be applicable to existing cityscapes such as old downtown areas. Hence, alternative novel methods are required to address urban ventilation. Dash et al (2017) studied the fluid dynamic effects of both static and moving surface features of an isolated bluff body to control air flow separation. The simulation results showed that active movements on the surface of the bluff body were able to create a turbulent boundary layer region which enabled drag reduction on the body by more than 40% and delayed air flow separation (similar to the well-known phenomenon of airflow around a golf ball) (Chear and Dol, 2015).

Controlling the airflow field on an urban scale through the actuated movement of façade features has not been explored yet. If this technique of controlling air flow movement around bluff bodies (like a building) can be extrapolated to urban conditions, it would enable better airflow in congested urban spaces, facilitating the possibility of airflow patterning and improved pedestrian thermal comfort. Starting from this hypothesis, this study analyses the flows produced by simulating textures that replicate continuous moving sinusoidal waveforms on a building façade. To analyse the effective of the hypothesis, a test region shall be carefully selected and applied. Their ability to produce air flow patterns that improve thermal comfort are also investigated.
Methodology

Site selection:
Singapore, like other major cities in the tropics, faces the issue of high urban density and low horizontal wind speeds. This is especially true in the Central Business District (CBD) which consists of closely spaced high-rise buildings. A test area of 374,000 m² from the CBD was modelled to understand the urban flow behaviour in such dense urban areas. 3D steady state CFD simulations (Figure 3) were done for all four prevailing wind directions of S, SE, N and NE as per BCA guidelines (2017) with the corresponding power law wind speed profile as input boundary conditions. Problem areas with stagnant air pockets throughout the site were identified for the four wind directions. Stagnant air velocity wake regions around Lau Pa Sat, a historic open-air market and food centre featuring heavy crowds and pedestrian movement, were a common flow feature in all four cases. The research then focused on mitigating this specific problem region. The south wind direction was chosen as the base case as it represented the largest area of wake amongst all the 4 cases. The urban context was therefore narrowed down to Lau Pa Sat and its surroundings as the test region.

Lau Pa Sat is a one-storey octagonal structure that is surrounded by high rise buildings that block most of the airflow movement in and around it for all prevailing wind directions. Figure 3a shows the final area with the minimum surrounding urban context required to maintain the original flow field. 2D transient simulations were carried out for this new model with wind from the south. Due to constraints in computational costs needed for 3D CFD, this project studied the factors by conducting simulations in 2D CFD and validating the results in scaled 3D PIV experiments (Yogiaman et al., 2017). The previous phase of the research showed a clear correlation between surface texture and periodic air flow velocity fluctuations. This second phase builds on that concept as well as the research done by Dash et al (2017). Sinusoidal wavelike surface textures are actuated to create travelling waves. These waves are meant to be externally retrofitted to buildings to alter and pattern the airflow field around them.

Analysing the base case (i.e. no façade actuation), it was observed that the areas A and B (dotted red ovals in Figure 3a) are in the wake region. Adding travelling waves on buildings 2 and 3 would not be useful as the strong stream of air passing in front of them, marked as C, would negate the impact on the wake region B behind Lau Pa Sat (Figure 3a). Based on these observations, travelling waves were added on the façade of building 1 (yellow line in Figure 3a) to modify stagnant areas A and B. These travelling waves are actuated sinusoidal waves moving unidirectionally from right to left (i.e. towards the direction of building 3) and the shape and size of the travelling waves are governed by three input parameters: wave amplitude (A) fixed at 20cm, wavelength (λ), and wave speed (V) as shown in Figure 3c. For this study, wavelength (λ) and wave speed (V) were altered three times, resulting in 9 different test cases as shown in Table 1. The wavelength is referenced to the length of the façade (L).

Table 1 - Combination of parameters for the resultant 9 test cases highlighted in blue.

<table>
<thead>
<tr>
<th>Names of the test cases</th>
<th>V = 18m/s</th>
<th>V/3 = 6m/s</th>
<th>V/7.5 = 2.4m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ = L = 34.85m</td>
<td>Case 1 (λ, 18)</td>
<td>Case 2 (λ, 6)</td>
<td>Case 3 (λ, 2.4)</td>
</tr>
<tr>
<td>λ2 = L/2 = 17.425m</td>
<td>Case 4 (λ_2, 18)</td>
<td>Case 5 (λ_2, 6)</td>
<td>Case 6 (λ_2, 2.4)</td>
</tr>
<tr>
<td>λ8 = L/8 = 4.35 m</td>
<td>Case 7 (λ_8, 18)</td>
<td>Case 8 (λ_8, 6)</td>
<td>Case 9 (λ_8, 2.4)</td>
</tr>
</tbody>
</table>

Figure 3b shows the 6 check points selected in areas with high pedestrian and eatery activities for further analysis. The analysis will investigate the variation of velocity and airflow frequency over time at the check points and compare the results to the original base case scenario.

Model setup:
The computational domain is shown in Figure 4; the centre of Lau Pa Sat is placed at [0, 0] and L is the length of the façade (34.85m) of building 1. Two meshes are used for CFD, one Eulerian mesh for the flow field and one Lagrangian mesh for the surface of the building. The Eulerian mesh, which only contains rectangular cells, is generated using an in-house code and the Lagrangian mesh is obtained through the ANSYS Fluent software (2018). The grid size for the meshing is 1000 x 1224.

The solver used for the Fluid Structure Interaction simulations is an immersed boundary-lattice Boltzmann flux solver (Wang et al, 2015). Laminar flow is studied in these simulations at a Reynold’s number of 1000. No-slip boundary conditions are applied on the sides. Inlet boundary condition is a free stream velocity of 1.2m/s which is the average wind speed experienced for south prevailing winds at a human height of 1.1m in Singapore. The outlet is zero gradient under natural condition.

Figure 4: Dimensions of the computational domain.
The code has been verified and validated by simulating various test cases (Yan Wang, 2015). The resolution is sufficient for experimental grade simulation results according to our previous experience (Wang et al, 2016; Wang et al 2017).

**Results and Discussion**

**Overall velocity flow field structures:** Nine test cases detailed in Table 1 were simulated using the above-mentioned method and model setup. Each test case took about 72 hours to be simulated. Out of the nine cases the paper will discuss three most significant ones: Case 1 ($\lambda_{18}$), Case 7 ($\lambda_{8_{18}}$) and Case 6 ($\lambda_{2_{2.4}}$). These cases exhibit the largest variation in the flow field structures in comparison to the base case. Figure 5 illustrates the velocity and vorticity flow field structures for these 3 cases in addition to the base case with no travelling wave retrofitted on the façade of building 1 (the base case highlights the standard case of wake regions A and B with very low wind speeds). In order to mitigate the wake region areas, travelling waves with varying wavelengths and wave speeds were set up to investigate for any improvement.

In Case 7, the travelling wave which has a wavelength of 4.35m ($L/8$) moving at a speed of 18m/s generates the most significant identifiable air flow structure amongst all cases. The velocity builds on the existing strong air current in front of buildings 2 and 3 and then bifurcates when incident on building, thereby reducing the stagnant region ‘B’ behind Lau Pa Sat. The vorticity plot highlights the Von Karman vortex wake formed (region C) with intense vortex shedding seen across the whole urban context as an impact of this specific wavelength and wave speed. The wake region ‘A’ in front of Lau Pa Sat is also greatly reduced.

In Case 1, the travelling wave with a wavelength of 34.85m ($L$) and moving at the speed of 18m/s results in a different impact on the velocity flow field. It does not strengthen the existing air flow in front of buildings 2 and 3 (region C) but instead it periodically releases large vortices in the wake region A between building 1 and Lau Pa Sat. This allows for better air mixing, resulting in a much higher variation in wind speeds ranging from 0.7-1.1m/s in the wake region A. Evidently, not all combination of traveling wave parameters had a positive impact on the flow field.

Case 6 with a wavelength of 17.425m and lower wave speed of 2.4m/s increases the area of the wake regions A and B. There is no significant shedding of vortexes and hence no variation in the windspeed either.

Therefore, Case 7 exhibits the largest variation in the flow field structures around Lau Pa Sat with the Von Karman vortex wake region. The next best scenario is case 1, which releases large slow shedding vortexes allowing dynamic variation in velocity. Case 6 was the worst-case scenario with larger stagnant zones formed around Lau Pa Sat when compared to the base case.

**Velocity and flow frequency analysis over time at selected check points:** Average velocity values and Fast Fourier Transform (FFT) analysis were carried out at the 6 points selected in region A and B to better understand the impact that air flow structures have on velocity and frequency at localised points. These points indicate areas which experience high pedestrian and market related activity throughout the day. Finally, the study will focus on one selected point in each of the regions A and B around Lau Pa Sat to further analyse the air velocity over a period of 100 seconds.

![Figure 5: Velocity and vorticity plots for selected cases.](image_url)
Figure 6: (a). Average velocity over time at selected points. (b) Fluctuation frequencies at selected points. Note that points 1-3 are in region A and points 4-6 are in region B

1. **Average velocity analysis for all cases:** An overall increase of average wind speed over time can be seen for cases 1 and 7, at all points except 4 (only Case 7) and 5 where velocity values have slightly deteriorated from the base case. The highest wind speed of 3.5m/s is noted for Case 7 at point 1 (Figure 6a). Case 6 has lower velocity values than the base case at all points except for point 2. This indicates that the actuated travelling waves require specific parameter values in order to perform better than the original condition. The windspeeds have increased by 72% and 182% on an average for cases 1 and 7 respectively.

2. **FFT analysis for all cases:** Further analysis of the prominent frequencies obtained through FFT analysis show that the dominant frequency values at all points have improved from an average of 0.004Hz for the base case to a range of 0.02 - 0.2Hz for rest of the test cases. Case 1 has the highest frequency (0.2Hz) which falls within the comfort experiments done by Fanger and Pederson (1977), followed by Case 7 with an overall FFT value of 0.07Hz which is also within the established range of 0.05-0.1 Hz by Tanabe and Kimura (Figure 6b). Case 6, although marginally better than the base case, has an average frequency of 0.02Hz which do not fall within the comfort range as per the literature review.

Case 1 is selected for further study, plotting the raw velocity magnitude over a period of 100 seconds. Figure 7 illustrates that velocity values for Case 1 and base case through points 1 and 6 which are situated in front of the travelling wave mechanism and within wake region B respectively. It can be inferred that not only do the velocity values improve from the base case situation at both the points, but the velocity magnitudes also fluctuate in a consistently patterned manner. This patterned air velocity yields a dominant frequency of 0.2 Hz for the point directly in front of the travelling wave mechanism and at the wake region B behind Lau Pa Sat. The consistency of the resultant frequencies at both regions is significant to our study, as it presents the possibility of creating a consistent desired air flow frequency over longer distances around or behind buildings and other urban structures.

Case 6 performed poorly for all selected points with a 10% decrease in velocity values and a frequency range beyond comfort limits. This indicates that the selection of appropriate values for wavelength and travelling wave speed is important.

**Conclusion**

The test results present the possibility of controlling resultant air velocity, magnitude and frequency over long distances in outdoor urban environment by retrofitting an active surface mechanism on building facades. The parameters of the travelling wave of this active surface mechanism can be tailored to produce air flow structures that effectively produce a resultant air velocity frequency within the range that induces a strong cooling sensation. From our study, Case 1, with a traveling wave of 0.2m amplitude, 34.85m wavelength and at a speed of 18m/s
produces the best overall results. It increased wind speed by an average of 72% compared to the base case and produced a consistent air flow frequency of 0.2Hz on five out of the six points sampled around Lau Pa Sat. Previous literature reviews were based on velocity values within the perceptible range for humans with values ranging greater than 0.5m/s. Although Point 6 in case 1 have been patterned to a desired frequency range, the velocity values are still in the imperceptible range (<0.5m/s). Thus, the effect of the improved frequency for point 6 is unknown.

**Future Works**

**Validation of base case**

The research is currently working on a wind tunnel experiment of a 1:2000 scaled 3D model of the test site to validate the base case data. While keeping the Reynolds number consistent, the base case shall be verified through comparing the flow structure of the physical experiment and the CFD simulated base case.

**Fabrication of moving façade assembly**

Currently, the research has fabricated a 1:300 scale travelling wave vertical surface assembly that consist of an undulating cast silicon surface that moves along a motorised mechanical track. Subsequently, the research aims to test the travelling wave mechanism in a wind tunnel experiment to study the flow behaviour at and around the standing wave. The 1:300 scale model would be able to run standing wave parameters as seen in simulation cases 1, 6 and 7. The 1:300 scale moving mechanism is a step forward to develop and materialise a potential 1:1 scale moving façade assembly.

**Urban configuration study**

The research studied the site-specific remedy for urban ventilation around Lau Pa Sat, an area situated in closely spaced high-rise commercial buildings. This specific area of study is a prototypical urban configuration of an 85m by 85m city block with streets width ranging from 15m to 20m. In the future, the research intends to review other typical urban configurations in Singapore that are poorly ventilated. The planned study on the general urban conditions shall unveil the typical wake regions, and the subsequent airflow analysis shall help to identify guidelines for potential retrofits of an acted surface mechanism on building surfaces to introduce pattern airflow.

With the ability of controlling the resultant urban airflow parameters and coupled with actuated facade technology, this research projects future potential of a real-time control mechanism which responds to the changing ambient conditions to induce a fluctuating airflow optimised for the comfort of pedestrians.

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