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CONTROL OF WIND-INDUCED MOTION OF TALL BUILDINGS USING SMART FAÇADE SYSTEMS

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ABSTRACT

The development of non-load bearing curtain walling technology around the turn of the 20th centre along with an effort to reduce the energy consumption of the building and dependence on artificial lightening, the development of high performance glass and efficient building system has seen architectural trends move toward maximising glass surface areas in order to optimise natural light. This presents an opportunity to also investigate the façade system potential to become a filter for wind-induced vibration. The façade has been rarely considered or designed as a potential wind-induced vibration absorber for tall buildings. In this paper the potential of utilizing a moveable exterior façade in a double-skin façade system is investigated and shown that with optimal choices of materials for stiffness and damping of brackets connecting the two skins, a substantial portion of wind-induced vibration energy can be dissipated which leads to avoiding expensive lateral stiffening systems and/or space consuming large damper systems such as tuned mass or liquid dampers. The works have demonstrated that up to 50% of response caused by winds can be absorbed by a smart and efficient façade design, including purely passive systems with constant stiffness and damping or better, by a smart system possessing variable stiffness for different phases of façade movement.

KEYWORDS

Curtain wall, tall building, double skin facade, damper.

INTRODUCTION

In recent decades, buildings with significant usage of glass are becoming common. The development of non-load bearing curtain walling technology around the turn of the 20th century along with double skin façade (DSF) system, which have substantial cavity space between the inner and outer façade layers, have received increased interest. Building façades generally perform as environmental mediators between the controlled interior and harsh exterior as well as building identifiers through their aesthetic design.

On the other hand an increasing emphasis has been placed on controlling structural dynamic response. The use of space frame and mega-frame concepts, outrigger trusses, belt trusses and band aid type stiffening systems can offer additional resistance to wind loads (Kareem 1992). Other alternatives

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include modification of the structural mode shapes to increase the mass participating in the dynamics of building in the fundamental mode.

Kareem (1992) proposed the concept of isolation in the mountings of the cladding to the structural system. Buildings are isolated from earthquake excitation by employing isolator bearings between the building and the foundations and a similar concept is proposed for cladding. The integrated effects of the unsteady aerodynamic loads acting on cladding are transferred to the frame which results in building motion. If the cladding is connected to the frame by an isolation mounting, then the aerodynamic loads transferred to the frame will be reduced and consequently the building motion will decrease. In order for this mounting to be effective, the ratio of excitation frequency to the natural frequency of the cladding should be greater than square root of two (Kareem 1992). In this situation the mounting system is more effective without any damping.

The proposed system can be materialized by dividing the cladding on the building envelope into several segments. The preliminary calculations (Kareem (1992) suggest that such a mounting system will be quite soft and pneumatic mounts may be an appropriate choice. Such an installation may cause the cost of a cladding system to be very high. This can be overcome by using these systems in staggered configurations and the remaining portions of the building envelope may utilize conventional cladding. The staggered arrangement has been proposed to help reduce the correlation of wind-induced pressure which in turn would result in lessening the integrated loads.

Moon (2005) shows that dynamic motion of tall buildings can be reduced, for example, by more than 50% when the DSF façade connectors are designed to have about half of the primary structure frequency. However, there exists a design challenge: the excessive motion of the DSF outer skins, which would disturb occupants through visible cues, and potentially undermine the ventilation system intended by DSF systems through pumping cavity air around the building.

SYSTEM MODELING

A simplified model is used in order to understand the behaviour of the proposed system. Complex primary structure with an outer skin facade could be modelled as two degrees of freedom shown in Figure 1 where primary mass represents the structure and secondary mass represent the outer skin. Usually this kind of modelling is used to represent a tuned mass damper (TMD) system, although there is a different way to apply the load in these cases. Loads on the tuned mass damper system, are applied to the primary mass and then transfer to the secondary mass. In this way, connection between primary and secondary masses should be tuned to make the TMD mass frequency similar to structural frequency (Den Hartog (1956, (Connor 2003)); however, in the proposed system, wind loads are applied to the secondary mass and then, through the proposed connection will transfer to the primary mass. This difference in load transfer makes tuned mass damper formulations inapplicable.

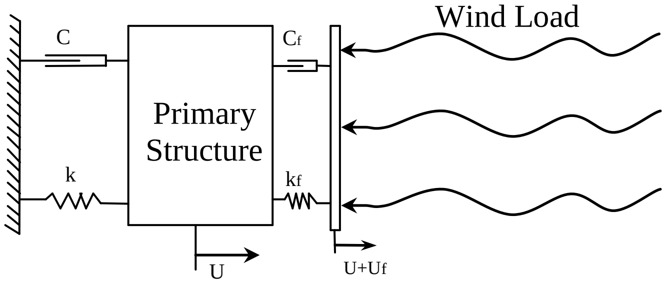


Figure 1. Simplified model of the primary structure and façade system connected by movable brackets

Connection properties concerning stiffness and damping have been modelled and varied to achieve the appropriate response. For achieving optimal performance of the proposed system, the connection frequency is tuned to the primary mass frequency. Dynamic force is applied to the secondary mass and through the connections, between the primary mass and the secondary mass, is transferred to main frames. The outer skin mass is assumed to be around 1% of the primary structure mass.

DYNAMIC RESPONSES OF THE SYSTEM

Below are the governing equations of the system shown in Figure 1.

$$m\ddot{u}+c\dot{u}+ku=\mathrm{c}_f\dot{u}_f+k_f u_f \tag{1}$$

$$m_f(\ddot{u}_f+\ddot{u})+c_f\dot{u}_f+k_f u_f=p \tag{2}$$

where $m=$ primary structure mass; $m_f=$ DSF outer skin mass; $k=$ primary structure stiffness; $k_f=$DSF connector stiffness; $c=$primary structure viscous damping parameter; $c_f=$DSF connector viscous damping parameter; $p=$ applied loading; $u=$ primary structure maximum lateral displacement; and $u_f=$DSF outer skin maximum lateral displacement. It is convenient to work with the solution expressed in terms of complex quantities. The force is expressed as

$$p=\hat{p}e^{i\Omega t} \tag{3}$$

where $\Omega=$forcing frequency and $\hat{p}$ is a real quantity. The response is taken as

$$u=\bar{u}e^{i\Omega t} \tag{4}$$

$$u_d=\bar{u}_d e^{i\Omega t} \tag{5}$$

where the response amplitudes, $\bar{u}$ and $\bar{u}_f$, are considered to be complex quantities. Then the corresponding solution is given by either the real or imaginary parts of u and u_f. Substituting Eqs. (3)–(5) into the set of governing Eqs. (1) and (2) results in

$$-\Omega^2 m\bar{u}+i\Omega c\bar{u}+k\bar{u}=i\Omega \mathrm{c}_f\bar{u}_f+k_f\bar{u}_f \tag{6}$$

$$-\Omega^2 m_f(\bar{u}_f+\bar{u})+i\Omega c_f\bar{u}_f+k_f\bar{u}_f=\hat{p} \tag{7}$$

Considering the following relations:

$$\omega^2=\frac{k}{m} \tag{8}$$

where $\omega=$natural frequency of the primary structure, and

$$c=2\xi\omega m \tag{9}$$

where $\xi =$ primary structure damping ratio, and

$$\omega_f^{\,2} = \frac{k_f}{m_f} \tag{10}$$

where $\omega_f =$ natural frequency of the DSF outer skin. $k_f =$ stiffness of the brackets which is a variable relating to the input frequency, and

$$c_f = 2\xi_f \omega_f m_f \tag{11}$$

where $\xi_f =$ façade connector damping ratio. Defining $\overline{m}$ as the DSF outer skin to primary mass ratio, then

$$\overline{m} = \frac{m_f}{m} \tag{12}$$

Defining f as the DSF outer skin frequency to primary structure frequency ratio, then

$$f = \frac{\omega_f}{\omega} \tag{13}$$

and defining ρ as the ratio of forcing frequency to primary structure frequency ratio, then

$$\rho = \frac{\Omega}{\omega} \tag{14}$$

The dynamic amplification factor can then be obtained from the equations of motion.

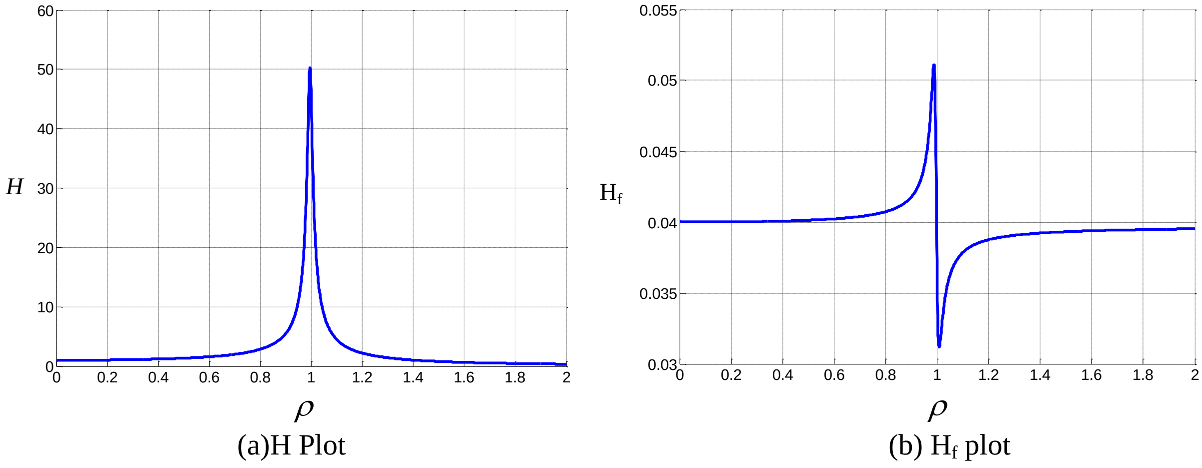
$$H = \frac{\sqrt{f^4 + 4f^2\zeta_f^2\rho^2}}{\sqrt{(f^2\overline{m}\rho^2 - \rho^4 + \rho^2 + f^2\rho^2 - f^2 + 4\zeta\rho^2\zeta_f f)^2 + (2\rho^3\zeta_f f + 2\zeta\rho^3 - 2\zeta\rho f^2 - 2f\zeta_f\rho + 2\overline{m}\rho^3\zeta_f f)^2}} \tag{15}$$

$$H_f = \frac{\sqrt{(\rho^2 - 1)^2 + 4\zeta^2\rho^2}}{m\sqrt{(f^2\overline{m}\rho^2 - \rho^4 + \rho^2 + f^2\rho^2 - f^2 + 4\zeta\rho^2\zeta_f f)^2 + (2\rho^3\zeta_f f + 2\zeta\rho^3 - 2\zeta\rho f^2 - 2f\zeta_f\rho + 2\overline{m}\rho^3\zeta_f f)^2}} \tag{16}$$

CASE STUDY

To illustrate the performance of the system, dynamic amplification factor is plotted with values ranging from 0 to 2. The mass ratio between DSF and primary structure is assumed to be 1% and also DSF frequently to primary structure, frequency is assumed to be 50, 0.5 and 0.1, which represent the system from Conventional Façade to low stiffness connectors. In this study, a frequency ratio of about 50 represents a system with rigid connector or conventional façade. For a damped single degree of freedom (SDOF) system subjected to harmonic load, dynamic amplification factor could be obtained as follows:

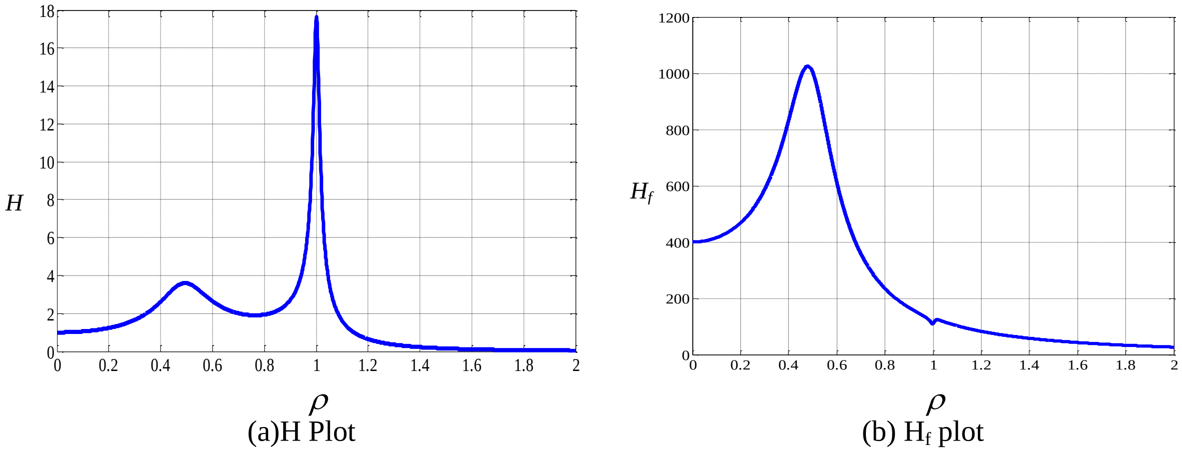
$$H_{SDOF} = \frac{1}{2\xi\sqrt{1-\xi^2}} \tag{17}$$



(a)H Plot (b) H_f plot

Figure 1. Dynamic amplification factors for the primary structure (*H*) and DSF outer skin (H_f) with ρ (DSF outer skin frequency/primary structure frequency) =50

Solving Eq.17 leads to the maximum dynamic amplification with the value of 50 which is exactly the same as the system with stiff connector as shown in figure 2a. In Figure 2b, dynamic amplification factor is less than 1 which means that there is no dynamic amplification for the DSF in this case.

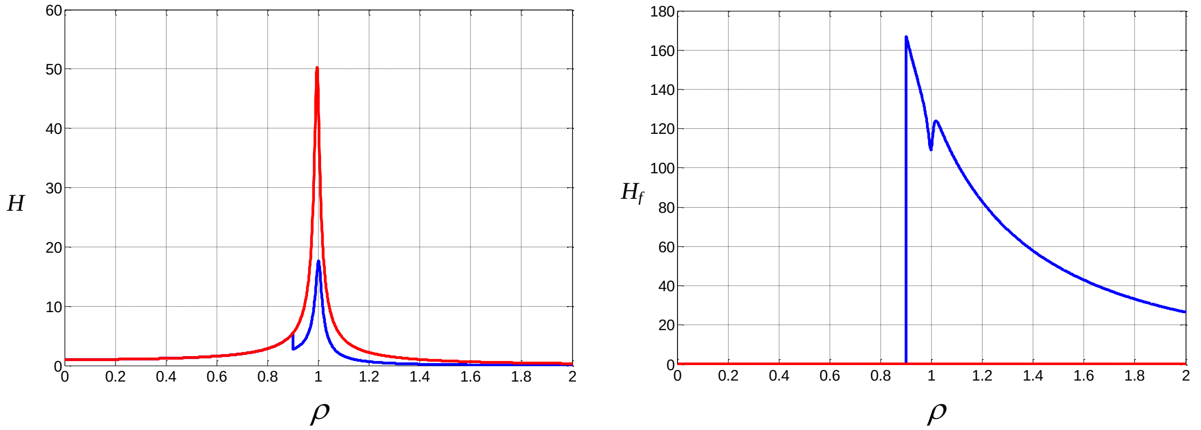


(a)H Plot (b) H_f plot

Figure 2. Dynamic amplification factors for the primary structure (*H*) and DSF outer skin (H_f) with ρ (DSF outer skin frequency/primary structure frequency) =0.5

Reducing the stiffness of connectors to the point where the DSF frequency has half the value of the primary structure, which is the frequency that leads to a noticeable reduction in a dynamic response of primary Structure, is shown in Figure 3a and shows that around $\rho = 1$, the maximum H occurs when the forcing frequency is almost the same as the DSF connector frequency. With $\rho = 0.5$, Figure 3b shows the DSF dynamic amplification factor increased to about 1000 with 20% damping. Compared to conventional case, without the proposed DSF system, the dynamic response of the primary structure is reduced by more than 35%. What needs to be considered in this case is the high dynamic amplification factor of DSF, which is not practical. To make it practical the following is presented.

The following case represents different connector stiffness based on input load frequency. Using low stiffness connector in the zone, which is critical for the structural response and at the same time having low dynamic amplification factor shows that by using smart façade, a 50% reduction is achievable.



(a)H Plot (b) H_f plot

Figure 3. Dynamic amplification factors for the primary structure (H) and DSF outer skin (H_f) with ρ (DSF outer skin frequency/primary structure frequency) =0.5.

The above equations are obtained based on a linear system and constant values for stiffness and damping ratio. However, using a low frequency could reduce the response of structure by 50%, but also it will increase the relative displacement of façade panels. Changing the DSF connector stiffness corresponding to input load could help to control excessive movement of façade panels by having a similar reduction in response of the structure.

CONCLUSIONS

Double skin façade in tall buildings is one of the most advanced forms of façade systems available today; and this study investigated another potential functional aspect of double skin façades in tall buildings as lateral motion control devices. The results of this study show that using façade as structural elements is conceivable. Using outer skins to filter input energy has significant effects on the response of the primary structure. Previous research shows that this system has potential to dissipate vibration energy, although it is far from reality. This study presents a unique solution to make movable façade practical, by controlling the connector stiffness that could reduce the primary structure response and also limit the movement of outer skin façade.

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