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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 the effects to reduce the energy consumption of the building and dependence on artificial lightening, as well as the development of high performance glass and efficient building systems has seen architectural trends to move toward maximising glass surface areas in order to optimise natural daylight. This present study shows the potential offaçade systems potential to become an energy absorber of wind-induced vibrations. The façade has been rarely considered or designed as a potential wind-induced vibration absorber for tall buildings in the past. In this paper the potential of utilizing a moveable exterior façade in a double-skin façade 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 work has 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 a system possessing variable stiffness for different phases of façade movement.

Keywords: Double-skin Façade, Tunned Mass Damper, Wind Loads, Strucutral Resposne

1 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 increased interest in these systems with the aim of fully exploiting their potential. Building façades generally perform as environmental medium between the controlled interior and harsh exterior as well as building identifiers through their aesthetic design.

Jean-Baptiste Jobard, director of the Industrial Museum in Brussels, described an early version of a mechanically ventilated multiple skin façade in 1849 (Poirazis, 2004). He mentioned how in winter, hot air should be circulated between two glazing while, in summer, it should be cold air (Saelens, Roels, & Hens, 2004). The first instance of a double skin curtain wall appeared in 1903 in the Steiff factory in Giengen/ Brenz. Priorities were to maximize day lighting while taking into account the cold weather and strong winds of the region (Saelens, Blocken, Roels, & Hens, 2005). The solution was a three-storey structure with a ground floor for storage space and two upper floors were used for work areas.

The structure of the building proved to be successful and two additions were built in 1904 and 1908 with the same double skin system but using 5 timbers instead of steel in the structure for budgetary reasons (Streicher et al., 2007). In Russia, Moisei Ginzburg made an experiment with double skin strips in the communal housing blocks of his Narkomfin building (1928) and Le Corbusier designed the Centrosoyus in Moscow (Poirazis, 2004). A year later, Le Corbusier started the design for the Cite de Refuge (1929) and the Immeuble Clarte (1930) in Paris and postulated two new features. Little or no progress was made in double skin glass construction until the late 1970s and early 1980s. During the 1980s, this type of façade started gaining momentum.

Most were designed while considering environmental concerns, like the offices of Leslie and Godwin. In other cases, the aesthetic effect of multiple layers of glass was the principal concern. In the 1990s, two factors strongly influenced the proliferation of DSFs. Environmental concerns started influencing architectural design, both from a technical standpoint and as a political influence that made 'green buildings' a good image for corporate architecture (Braham, 2005).

On the other hand an increasing emphasis has been placed on controlling structural dynamic response of wind sensitive buildings during moderate to severe winds.

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 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 foundation and a similar concept is proposed for cladding. The integrated effects of the unsteady aerodynamic loads acting on the 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 be reduced as well. 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 of suggest (Kareem, 1992) that such a mounting system will be quite soft and pneumatic mounts may be an appropriate choice here. Such an installation may cause the cost of a cladding system to be, however, 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 which is the excessive and extreme motion of the DSF outer skins, which would disturb occupants through visible cues, and would potentially undermine the ventilation system intended by DSF systems through pumping cavity air around the building.

2 SYSTEM MODELING

A simplified model is used in order to demonstrate the behavior of the proposed system. The complex primary structure with an outer skin facade could be modelled as a two degree of freedom system as shown in Figure 1, where primary mass represents the structure (including the inner skin mass) and the secondary mass represents the outer skin. Usually this kind of modelling is used to present a tuned mass damper (TMD) system, although there is a different mechanism to apply the load in these cases. Loads on the tuned mass damper system, are applied to the primary mass and then transferred to the secondary mass. The connection between the primary mass and the secondary mass should be chosen so that the TMD mass frequency is similar to structural frequency (Den Hartog (1956), (Connor, 2003)), however, in the proposed system here, the loads are applied to the secondary mass and then, through the proposed connection will be transferred to the primary mass. This difference in load transfer makes tuned mass damper formulations inapplicable.

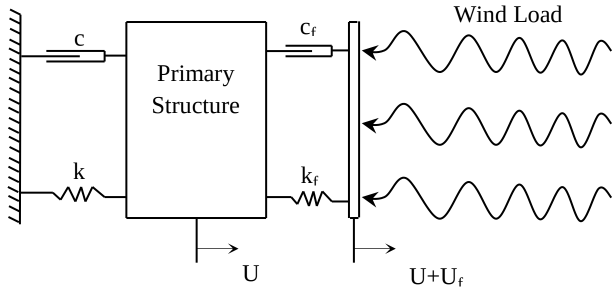


Figure 1. Simplified model of the primary structure and façade system connected by movable brackets

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

3 DYNAMIC RESPONSES OF THE SYSTEM

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

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

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

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 dynamic 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 representing the loading amplitude. The response is taken as

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

$$u_f = \bar{u}_f e^{i\Omega t} \tag{5}$$

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) in the set of governing Eqs. (1) and (2) results in

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

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

Considering the following notations:

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

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 and a function of the input frequency.

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

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

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

and defining f as the DSF outer skin frequency to primary structure frequency ratio

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

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

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

Then the dynamic amplification factors can be obtained by derivation from the equations of motion as follow,

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

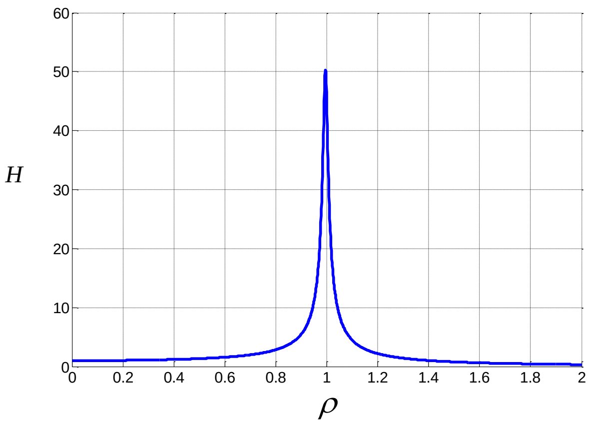
$$H_f = \frac{\sqrt{(\rho^2 - 1)^2 + 4\zeta^2\rho^2}}{m\sqrt{(f^2\bar{m}\rho^2 - \rho^4 + \rho^2 + f^2\rho^2 - f^2 + 4\zeta\rho^2\zeta_f f)^2 + (2\rho^3\zeta_f f + 2\zeta\rho^3 - 2\zeta\rho f^2 - 2f\zeta_f\rho + 2\bar{m}\rho^3\zeta_f f)^2}} \tag{16}$$

4 CASE STUDY

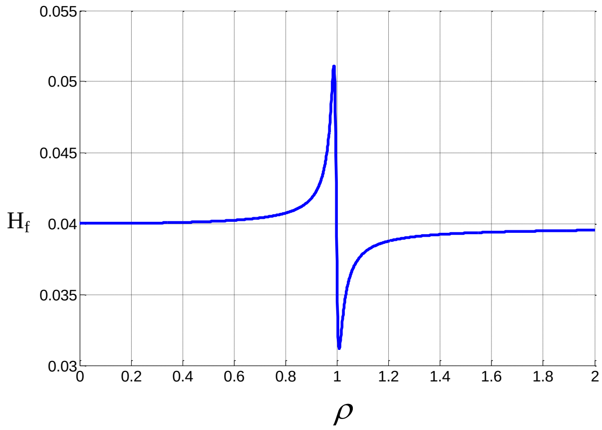
Tall building with conventional façade could be represented as a SDOF although it could not be a precise model, but it could show the main performance of the structure. To illustrate the performance of the system, dynamic amplification factors are plotted with ρ values ranging from 0 to 2. The mass ratio between DSF and primary structure is assumed to be 1% and also DSF frequency 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 having a frequency ratio about 50 represents the 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:

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

In order to get the maximum dynamic amplification factor for single degree of freedom (SDOF) could be obtained from Eq.17. It can be concluded that The curve in figure 2a is meant to provide a system with stiff connector which is representative of conventional façade. By comparing the result of Eq.17 and the pick In Figure 2b, dynamic amplification factor is less than 1 which means that there is no dynamic amplification for the DSF in this case.

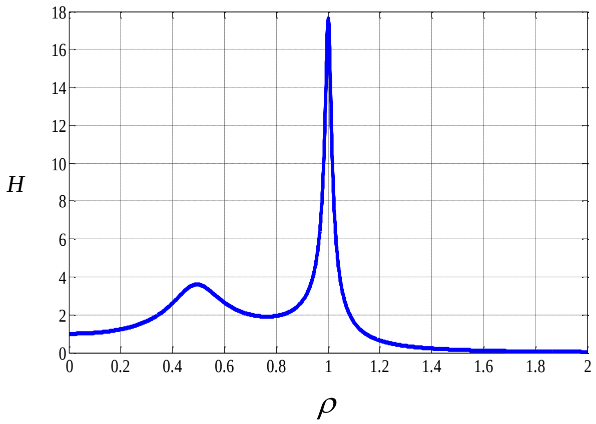


(a)H Plot

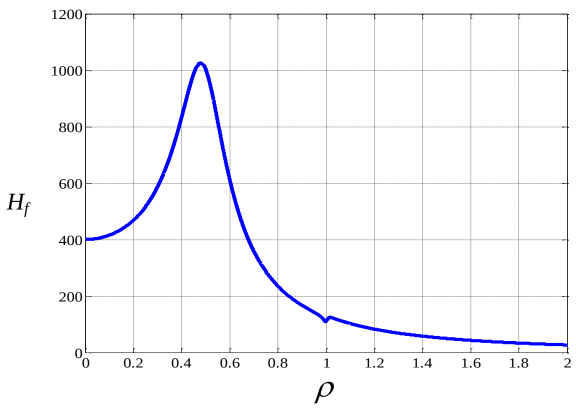


(b) H_f plot

Figure 2. Dynamic amplification factors for the primary structure (H) and DSF outer skin (H_f) with f (DSF outer skin frequency/primary structure frequency) =50.



(a)H Plot

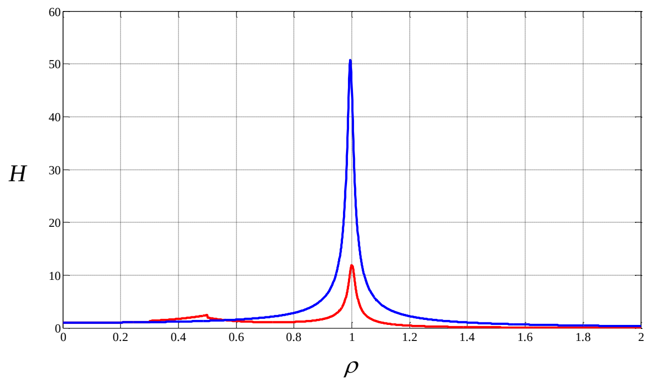


(b) H_f plot

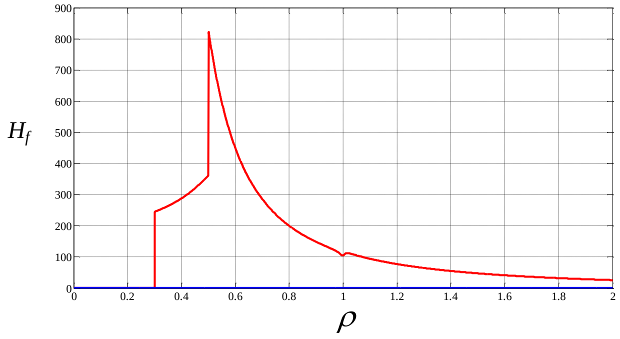
Figure 3. Dynamic amplification factors for the primary structure (H) and DSF outer skin (H_f) with f (DSF outer skin frequency/primary structure frequency) =0.5.

Reducing the stiffness of connectors to the point where the DSF frequency has half the value of the primary structure frequency leads to a noticeable reduction in the dynamic response of primary structure and as Figure 3a shows around, the maximum H occurs when the forcing frequency is almost the same as the DSF connector frequency. With f=0.5, Figure 3b shows that the DSF dynamic amplification factor increases by about 1000 times with 20% damping. Compared to the conventional case without the proposed DSF system, the dynamic response of the primary structure is reduced by more than 35pc. Above equations are obtained based on a linear system and constant values for stiffness and damping ratio. However, using a low frequency façade system could reduce the response of a structure, but it will also 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 and maintaining a similar reduction in response of structure.

The following case represents the results of using different stiffness in connectors. The blue lines represent the behaviour of the structure with conventional brackets and the red line should represent the each case study. As shown in previous result having low stiffness connectors is critical to reduce the structural response by 50pc. Maximum response of the structure occurs when the ratio of force frequency to primary structure frequency (H) is equal to one. However, with variable f, this response decrease by more than 50pc. Figure 4b shows that the new arrangement of stiffness could be able to control the DSF dynamic amplification factor. Compared to the conventional case without the proposed DSF system, the dynamic response of the primary structure is reduced by more than 50pc.



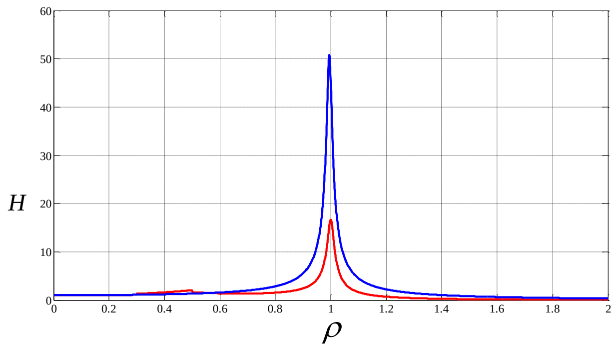
(a)H Plot



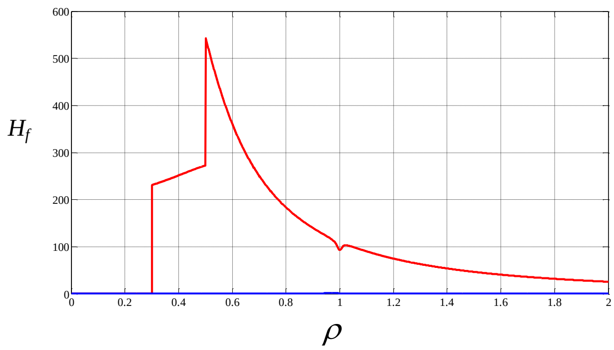
(b) H_f plot

Figure 4. Dynamic amplification factors for the primary structure (H) and DSF outer skin (H_f) with f (DSF outer skin frequency/primary structure frequency) =0.4 with 20pc damping

By contrast, in figure 4 and 5; increasing the damping ratio, play an important role in controlling the DSF outer skin frequency ratio, but also increasing the damping ratio has the reverse effect on primary structural response as well. As shown in figure 5b the maximum outer skin frequency are reduced noticeably which make it more realistic to build.



(a)H Plot

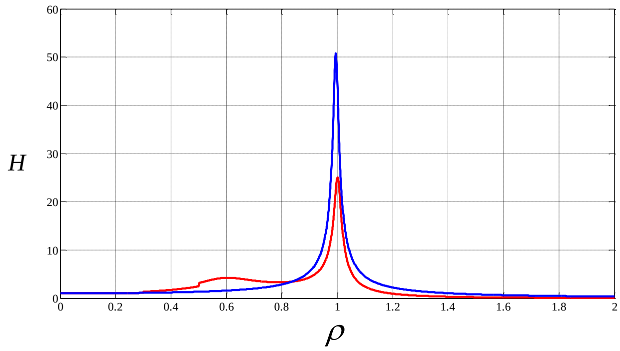


(b) H_f plot

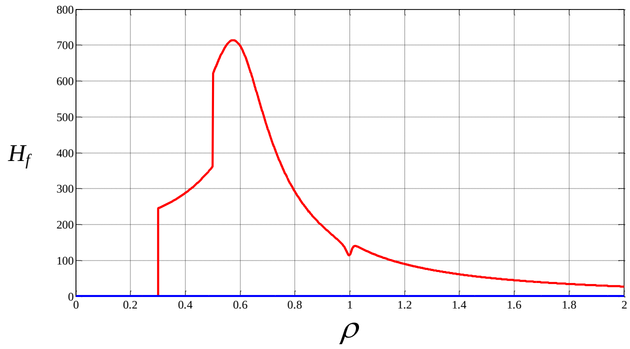
Figure 5. Dynamic amplification factors for the primary structure (H) and DSF outer skin (H_f) with f (DSF outer skin frequency/primary structure frequency) =0.4 with 40% damping

As stated earlier, decreasing the maximum ratio of outer skin frequency to primary structure, frequency is the aim to make it potential for buildings. Significant frequency movement is occurring when the forcing frequency to primary structure, frequency ratio is from 0.4 to 0.6. As can be seen from figure 4b the ratio of DSF outer skin frequency is reduced where the DSF frequency has half the value of the primary structure frequency, however, H_f=800 is still potentially undetermined.

With minimum $f=0.6$, Figure 6b shows that the DSF dynamic amplification factor increases by about 700 times with 20pc damping. Compared to the conventional case without the proposed DSF system, the dynamic response of the primary structure is reduced by more than 37pc (Figure 6a).



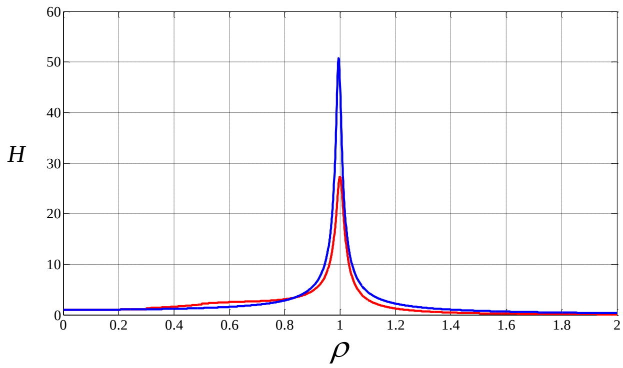
(a)H Plot



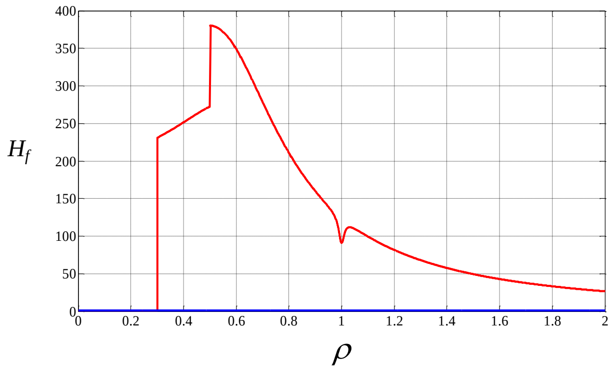
(b) H_f plot

Figure 6. Dynamic amplification factors for the primary structure (*H*) and DSF outer skin (H_f) with *f* (DSF outer skin frequency/primary structure frequency) =0.6 with 20% damping

According to early stated, damping has tremendous effect on the Dynamic amplification factors for DSF outer skin. Regardless of primary structure, increasing the damping ratio could be able to control the façade panel response. As figure 7 shows by increasing the damping ratio by 20pc more or less the response of the primary structure has same efficiency and also the dynamic response of panels is limited to 400.



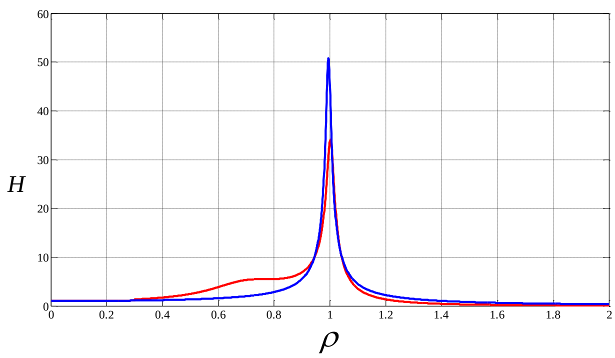
(a)H Plot



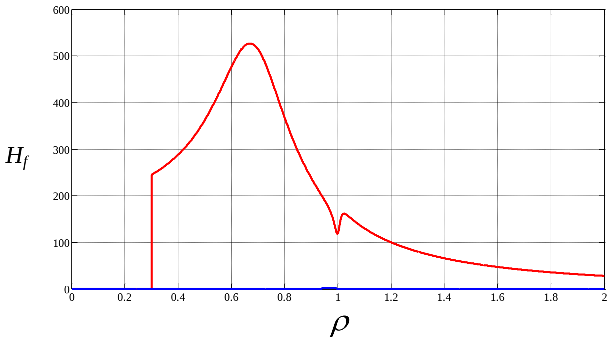
(b) H_f plot

Figure 7. Dynamic amplification factors for the primary structure (*H*) and DSF outer skin (H_f) with *f* (DSF outer skin frequency/primary structure frequency) =0.6 with 40% damping

The case with f=0.7, shown in figure 8, simulates the scenario which has a less beneficial effect compared to other above cases, but still it reduce around 30pc of the response of the structure. In this case the pick of *H* value is close to 30 which is higher than before, but the dynamic response of the panels shows the value could be close to 500 which is the smallest value compared to other response with 20pc damping in connectors.



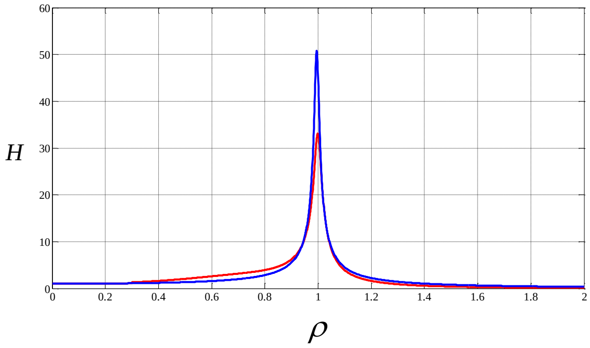
(a)H Plot



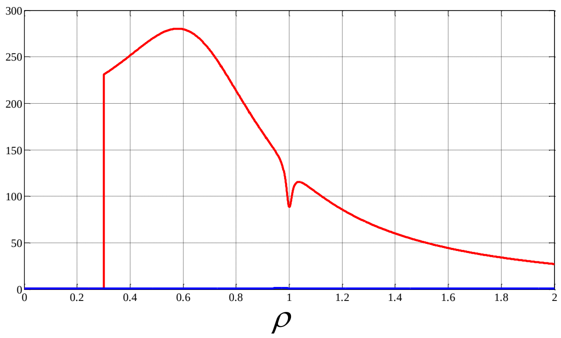
(b) H_f plot

Figure 8. Dynamic amplification factors for the primary structure (*H*) and DSF outer skin (H_f) with *f* (DSF outer skin frequency/primary structure frequency) =0.7 with 20% damping

To adjust the scale accordingly to accommodate the changes ratios between dynamic amplification factors for the primary structure (*H*) and DSF outer skin (H_f) i.e. reducing the dynamic amplification factor of primary structure is obtained by increasing the frequency ratio of DSF outer skin. Nevertheless, the curves in figure 9 are meant to provide a clear view of this adjustment. As shown in figure 9b, H_f is in the lowest value comparing to previous results and also 35pc reduction is achievable with this arrangement.



(a)*H* Plot



(b) H_f plot

Figure 9. Dynamic amplification factors for the primary structure (*H*) and DSF outer skin (H_f) with *f* (DSF outer skin frequency/primary structure frequency) =0.7 with 40% damping

It is worth taking into consideration that there is an adjustment which leads to 35pc reduction in structural response and also has potential to be developed and built.

5 CONCLUSIONS

Double skin façades in tall buildings is one of the most advanced forms of façade systems available today. This study investigated another potential functional of double skin façades in tall buildings as lateral motion control devices. The results of this study show that using façade as a control system is feasible. Using the outer skin to filter input energy has significant effects on the response of the primary structure. Previous research shows that this system has potential to dissipate the energy, but requires a very large façade movement which is not practical. This study represents a unique solution to make movable façade practical. By controlling the connector stiffness and introducing variable stiffness, one could reduce the primary structure response and also limit the movement of the outer skin of the façade to a practical value.

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