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Dayi Ou; Cheuk Ming Mak

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Minimizing the transient vibroacoustic response of a window to sonic booms by using stiffeners (L)

Dayi Ou[a)]
School of Architecture, Huaqiao University, Xiamen, 361021, People's Republic of China

Cheuk Ming Mak[b)]
Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

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A stiffened-window strategy is proposed for reducing the window's transient responses to sonic booms. Additional movable and controllable stiffeners are used, which can improve the window's transient vibration and noise isolation performance without significantly reducing transparency. A simple prediction model is proposed as a design tool for implementing the stiffened-window structure, which allows for the computation of a plate with arbitrary elastic boundary conditions and arbitrarily located stiffeners. The predicted results agree well with experimental data. Also, the feasibility and validity of the stiffened-window strategy for improving the window's performance in response to sonic booms is demonstrated by parametric studies.
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I. INTRODUCTION

Human perception of sonic booms is a major impediment to overland supersonic flights.[1,2] In order to reduce the indoor annoyance caused by sonic booms, our earlier work[3] systematically examined the effects of elastic boundary supports of a window and proposed the use of boundary stiffness optimization to minimize the response of a residential window to sonic booms. However, there remain several impediments to the practical application of this "boundary condition optimization" technique, such as (1) although the optimized boundary condition may differ according to different sonic booms, the actual condition is not easy to change once the structure has been installed and, even more significant in practice, (2) at least at the moment, it is difficult to realize accurately a particular optimized boundary condition in a real building.

The aim of this study is to propose a more effective and easily-implemented strategy for reducing the transient response of a plate structure to sonic booms. It is known that adding stiffeners to a structure can influence its dynamic characteristics.[4–6] In the proposed strategy, additional movable stiffeners are used and attached to the structure to obtain a suitable structural stiffness and, finally, to reduce the transient responses to sonic booms.

II. STIFFENED-PLATE SYSTEM PREDICTION MODEL

Both the boundary conditions and stiffeners have significant effects and cannot be neglected in the analysis of real-life stiffened-plate structures. The prediction method must take into account both these effects. Consider a thin rectangular plate stiffened by a stiffener (or stiffeners) at an arbitrary position on the plate, as shown in Figs. 1(a) and 1(b). The plate has arbitrary elastic boundary supports along the edges, and is mounted on an infinite rigid baffle. The plate baffle system is immersed in an infinite light fluid medium (that is, air) and is subject to a time-varying excitation.

The time-domain finite element method and time-domain boundary element method described in Ref. 3 are used to calculate the transient vibration and sound radiation responses of the plate. As an extension to Ref. 3, the effects of the stiffeners are considered. The stiffeners can be represented as a combination of masses, translational (k_{ts}), and rotational (k_{rs}) springs.[6] The kinetic (T_{se}) and strain (Π_{se}) energy of the stiffener within the plate element [as shown in Fig. 1(c)] can be expressed as $T_{se} = \frac{1}{2}\{\dot{u}\}_e^T\{M_s\}_e\{\dot{u}\}_e$ and $\Pi_{se} = \frac{1}{2}\{u\}_e^T\{K_s\}_e\{u\}_e$. $\{M_s\}_e$ and $\{K_s\}_e$ are given as

$$\{M_s\}_e = \int (\sigma_s\{N\}^T\{N\})dl_{se}, \quad (1)$$

$$\{K_s\}_e = \int \begin{pmatrix} k_{ts}(\{N\}^T\{N\}) + k_{rs}\sin^2\alpha(\{N_x\}^T\{N_x\}) \\ -k_{rs}\sin 2\alpha(\{N_x\}^T\{N_y\}) + k_{rs}\cos^2\alpha(\{N_y\}^T\{N_y\}) \end{pmatrix} dl_{se}, \quad (2)$$

where l_{se} is the stiffener axis, k_{ts} is the translational spring constant, k_{rs} is the rotational spring constant, σ_s is the line density function describing the added-mass effect caused by the stiffener, $\{N\}$ is the shape function vector, N_x and N_y stand for $\partial N/\partial x$ and $\partial N/\partial y$, and α is the angle between the global axis and the local axis of the stiffener.

[a)]Also at Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.
[b)]Author to whom correspondence should be addressed. Electronic mail: becmmak@polyu.edu.hk

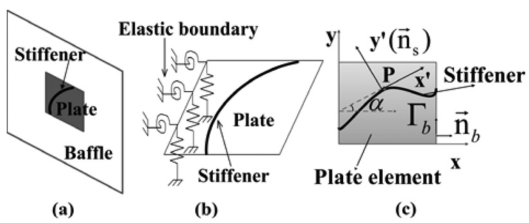

FIG. 1. Schematic illustration of a stiffened plate system. (a) A stiffened plate mounted on an infinite rigid baffle. (b) Elastic boundary supports along the edges (for simplicity, only the supports along the left edge are shown). (c) The stiffened plate element. A local (x', y') axis is set along the tangent to the stiffener at the integration point P making an angle α with the global (x, y) axis.

III. EXPERIMENTAL VALIDATION

A preliminary stiffened-plate system is designed. This system contains an aluminum (Al) plate, two identical steel beams, and two identical steel frames. As shown in Fig. 2(a), the Al plate is installed in the two steel frames, each of which is 34 cm square and 3 mm thick, with a 24 cm square opening cut out of the middle. The Al plate, which is 1.5 mm thick, is cut to 25.6 cm square so that it allows 8 mm of each edge to be fixed between the two steel frames. Screws at position #1 on the steel frames are used to fix the frames, while those at position #2 are used to fix the steel beams. The two steel beams, each of which is 23 mm in depth and 5 mm wide, can be placed on the Al plate on both sides (parallel to the bottom line of the plate) and work together to represent a single stiffener. The length of the stiffener is 24 cm. The height H of the stiffener can be adjusted by fixing the beams to the screws (#2) at different positions.

The measurements were conducted in two connected semi-anechoic chambers. Their common wall had a square port at its center, which was designed to hold the stiffened-plate system. Figure 2 illustrates the experimental setup. A Kistler 9726 A impact hammer was used to produce a transient impact force acting on the Al plate, and a B&K4935 microphone was located at the center line of the Al plate (20 cm away from it) to measure the radiated sound. The radiation pressures of the plate system with a stiffener at $H = 3.5$ cm (case I) and $H = 6.5$ cm (case II) were measured. The locations (Cartesian coordinate) of the impact point were (−7 cm, −2 cm) in case I and (−7 cm, −4 cm) in case II. The origin was set at the center of the plate, with X and Y parallel to its sides. All data were collected by PULSE (type B&K 3160-B-042) at a sampling rate of about 8.2 kHz (0.12 ms) for a recorded length of 1 s.

Before the experimental results can be used to compare with the predictions, the actual parameters of the stiffened-plate system need to be determined, which are given as follows. The boundary condition of the plate system is virtually identical before and after the stiffener is installed. Therefore, the actual boundary condition of the same plate system without the stiffener is first identified, and then treated as the approximate boundary condition of the stiffened-plate system. The boundary condition of this unstiffened-plate system is determined by the boundary condition identification method[7] and the results are $\bar{S}_t = 1162$ and $\bar{S}_\theta = \bar{S}_\phi = 7.69$. $\bar{S}_t$, $\bar{S}_\theta$, and $\bar{S}_\phi$ are the dimensionless forms[3] of S_t, S_θ, and S_ϕ, respectively. For the stiffener, the translational spring constant k_{ts} is supposed to be infinitely large, for the following reasons: (1) the steel beam is much stiffer than the Al plate, (2) the beam depth is far greater than the plate thickness, and (3) both the steel beams are hard pressed on the plate. The exact actual mass and rotational stiffness added to the plate system by the stiffener are not easy to assess. Fortunately they are found to have almost no effect on the system's vibration or sound radiation when k_{ts} is large. Lee and Kim[6] also note this phenomenon. Therefore, our prediction model represents the infinitely large value of k_{ts} as 1×10^{10} and σ_s and k_{rs} are set to zero for simplicity.

Figure 3 presents the comparison of the predicted and measured radiated sound. In the prediction, the measured impact forces, as shown in Figs. 3(a) and 3(c), are used as the input, the damping factor is estimated at approximately 0.04 using a simple peak-picking method,[7,8] and the element number 64 is used. It can be seen that the predicted results are generally in good agreement with the experimental data.

IV. APPLICATIONS TO SONIC BOOMS

Straight-line stiffeners (parallel to the bottom line of window) in consideration of practical installation and operation are used in the following parametric studies and the stiffened-window design strategy developed in this subsection.

A. Stiffener effects on a window

The window is 0.9 m long, 0.9 m wide, and 1.5 mm thick. Young's modulus, density, Poisson's ratio, and damping factor are 65 GPa, 2500 kg/m^3, 0.25, and 0.04, respectively. The window is assumed to have uniform boundary supports along the four edges and to be impacted by a 2 psf (95.6 Pa) N-wave. The N-wave is assumed to be at normal incidence

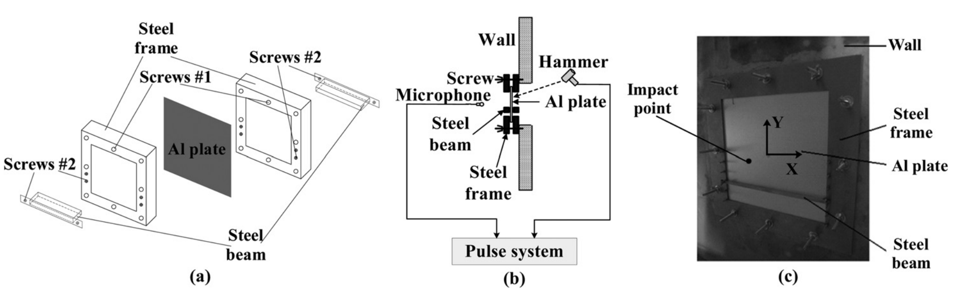

FIG. 2. Stiffened-plate system used in the experiments. (a) Assembly of the stiffened-plate system. (b) Experimental setup. (c) Picture of the system.

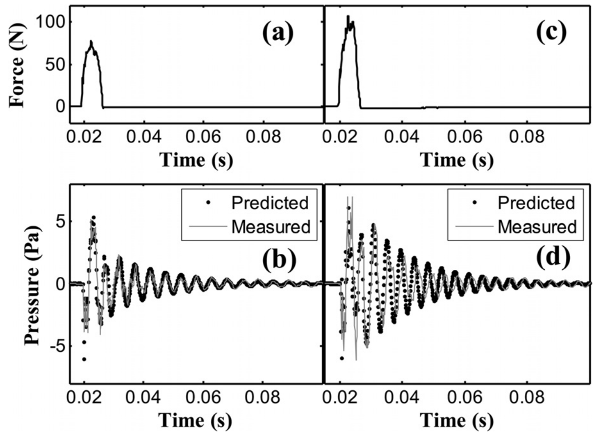

FIG. 3. Comparisons of predictions and experimental data. (a) Impact force time history in case I. (b) Pressure time history in case I. (c) Impact force time history in case II. (d) Pressure time history in case II.

for the purposes of simplification. The element numbers and time interval Δt used in the calculations are 16×16 and 0.4 ms, respectively. The calculated location of radiated sound is at the center line with 10 cm away from the window, while that of acceleration is at the maximum acceleration location over the window surface.

1. Case 1 (simply supported, a single stiffener, and 200 ms N-wave)

In this case, the window is supposed to be simply supported and stiffened by a single stiffener, which itself is supposed to be rigid with spring constants set to be the same as those used in Sec. III. Our experiments prove that this kind of stiffener can be conveniently implemented. Unless we state otherwise, the same stiffener spring constants are used in the following numerical calculations.

The sense of "oppressive chest vibration" and tactile feelings are two important elements of the human perception of sonic booms.[3,9,10] The variables, EX_{op} and EX_t, defined in Ref. 3, are used here to evaluate the window's performance. EX_{op} and EX_t are calculated from the spectra of the radiated sound and acceleration of the window, respectively, and represent the excesses of the "oppressive and vibration" threshold[9] and Hubbard tactile threshold.[11]

Figures 4(a) and 4(b) shows the results of the calculation (black bars). For a better comparison, the results are converted into decibels using the general definition $Q(\text{in dB}) = 10\log_{10}(Q/Q_{\text{ref}})$. Also, the results for the same window without stiffeners are included. It can be seen that even a single stiffener (including its location) can have notable effects on the window's performance. In this case, the window with a stiffener located at the height of 31.5 cm, that is 35% of the window width (or 45 cm/50%) yields the minimum EX_{op} (or EX_t), about 15 dB (or 8 dB) smaller than that of the unstiffened window.

2. Case 2 (clamped, a single stiffener, and 200 ms N-wave)

In this case, the window is supposed to be clamped and stiffened by a single stiffener. The other parameters are the same as those used in case 1. Figures 4(a) and 4(b) shows the results of this calculation (gray bars). It can be seen that the window with a stiffener located at the height of 36 cm, that is, 40% of the window width (or 40.5 cm/45%) displays the minimum EX_{op} (or EX_t), about 7 dB (or 6 dB) smaller than that of the unstiffened window.

3. Case 3 (simply supported, a single stiffener, and 100 ms N-wave)

In this case, the window is supposed to be simply supported and impacted by a 100 ms N-wave. The other parameters are the same as those used in case 2. Figures 4(a) and 4(b) show the results of the calculation (white bars). It can be seen that the window with a stiffener located at the height of 31.5 cm, that is, 35% of the window width (or 40.5 cm/50%) displays the minimum EX_{op} (or EX_t), about 16 dB (or 9 dB) smaller than that of the unstiffened window.

4. Case 4 (General boundary condition, two stiffeners, and 100 ms N-wave)

This case uses a more general boundary condition $\bar{S}_t = 1162$, $\bar{S}_\theta = \bar{S}_\phi = 7.69$, which is the same as the actual boundary condition of the plate system used in our experiments (see Sec. III). One or two stiffeners are used. The other parameters are the same as those used in case 3. The effects of the stiffeners are examined and shown in Tables I and II (stiffener at height $H = 0$ denotes no stiffener present).

The results presented in Tables I and II again demonstrate the notable effects of stiffeners on window performance. In this case, compared with the results for the unstiffened window, a maximum reduction of 12 dB in EX_{op} (or 4 dB in EX_t) can be obtained by setting a single stiffener at a height of 27 cm (or 45 cm), while a maximum reduction of 15 dB in

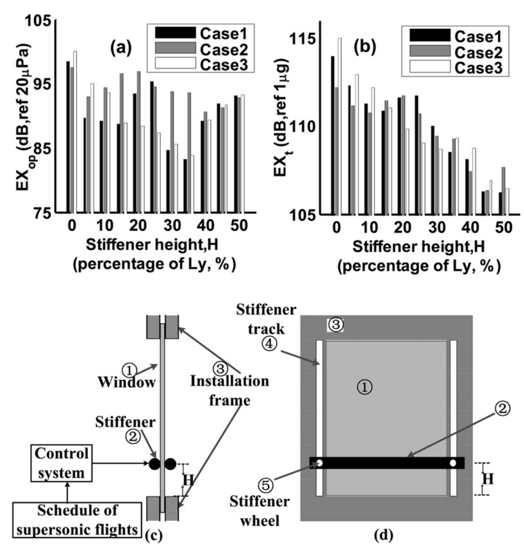

FIG. 4. Results of the parametric studies and the stiffened-window strategy. (a) Excess of "oppressive and vibration" threshold ($H = 0$ represents the unstiffened window). (b) Excess of tactile threshold. (c) Schematic illustration of the stiffened-window strategy (for simplicity, only a single stiffener is shown). (d) Elevation view of the stiffened-window design.

TABLE I. Predicted EX_{op} results for case 4 (unit: dB).

H_2/Ly (%) \ H_1/Ly (%)	0	10	20	30	40	50	60	70	80	90
0	99	90	89	87	91	95	91	87	89	90
10	90	90	89	94	92	89	93	89	96	90
20	89	89	89	95	92	88	89	90	89	96
30	87	94	95	87	89	90	84	91	90	89
40	91	92	92	89	91	93	92	84	89	93
50	95	89	88	90	93	95	93	90	88	89

TABLE II. Predicted EX_t results for case 4 (unit: dB).

H_2/Ly (%) \ H_1/Ly (%)	0	10	20	30	40	50	60	70	80	90
0	113	111	109	110	109	109	109	110	109	111
10	111	111	110	110	110	106	105	107	111	110
20	109	110	109	111	110	108	105	106	108	111
30	110	110	111	110	110	109	105	104	106	107
40	109	110	110	110	109	109	105	105	105	105
50	109	106	108	109	109	109	109	109	108	106

EX_{op} (or 9 dB in EX_t) is produced by fixing two stiffeners at the heights of 27 and 54 cm (or 27 and 63 cm), respectively.

B. Discussion of the results of the case studies

All the results show that the stiffeners have a significant effect on the window's responses. Adding a stiffener (or stiffeners) at the right position can improve the window's performance. The results also show that the factors, such as the boundary condition, stiffener (location and number) and N-wave type (duration time), affect the window's responses and hence should be taken into account in the practical design of a stiffened window.

C. Design strategy for the stiffened window

Since a residential window usually has other functions, such as allowing daylight to enter the room and ensuring the occupants can see outside the building, a practical and applicable strategy must take these issues into account and retain the window's transparency as much as possible.

In this subsection, a flexible and convenient design strategy for use in practical applications is proposed. Figures 4(c) and 4(d) show this strategy in schematic form. The stiffened window system includes a window, installation frames, stiffeners (such as steel beams), stiffener tracks, and stiffener wheels. Both beams are hard pressed on both sides to serve as a single rigid stiffener and the stiffener (or stiffeners) can move on the tracks. The beams are of a circular cross-sectional design to give them more mobility. A simple control unit is used to control the position (or positions) of the stiffener (or stiffeners). In order to retain the window's original visual appearance, the regular position of the stiffener is set at the edge, then adjusted to its optimization position during periods of sonic boom. The optimization stiffener position corresponding to a particular sonic boom can be determined in advance by using the proposed prediction model. Also, it is likely that commercial supersonic aircrafts will have relatively strict flight schedules, enabling the timings of sonic booms to be estimated.

The key feature of this strategy is that the position of the stiffener (or stiffeners) is variable and controllable. It can be conveniently adjusted to its optimization positions to reduce the window response according to different sonic booms, or be "suspended" at the edge during intervals when no supersonic aircrafts are passing in order to reinstate the window's original visual appearance (that is, full transparency).

V. CONCLUSION

This study reports the design of a preliminary stiffened-plate system to investigate the effects of the stiffener on the plate's transient responses and a prediction model developed to systemically investigate these responses. The predicted results agree well with experimental results.

Based on this prediction model, a simple and practical stiffened-window strategy is proposed for reducing the window's transient responses to sonic booms. It makes use of extra movable and controllable stiffeners, which can significantly improve the window's transient vibration and noise isolation performance without greatly affecting its transparency.

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