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Experimental study on the effects of N-wave sonic-boom signatures on window vibration

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For fulfillment of overland supersonic flight, it is important to understand the effects of sonic booms on buildings, since these effects, including vibration of walls and rattling noise from windows, are believed to be the main causes of annoyance in indoor spaces. In this study, the vibration of windows impacted by sonic booms is investigated through laboratory experiments by using a device developed at Japan Aerospace Exploration Agency (JAXA). Rattle is captured as high-frequency components of the acceleration of the windows. The effects of sonic booms having *N*-shape signatures with various values of peak overpressure, rise time, and duration are investigated. Results show general tendency of increase of rattle with increasing peak overpressure and with decreasing rise time, as expected. However, the results also indicate a possibility that these parameters, as well as duration, affect the time-frequency structure of the acceleration (and hence rattle) of windows in a somewhat complicated manner.

1 Introduction

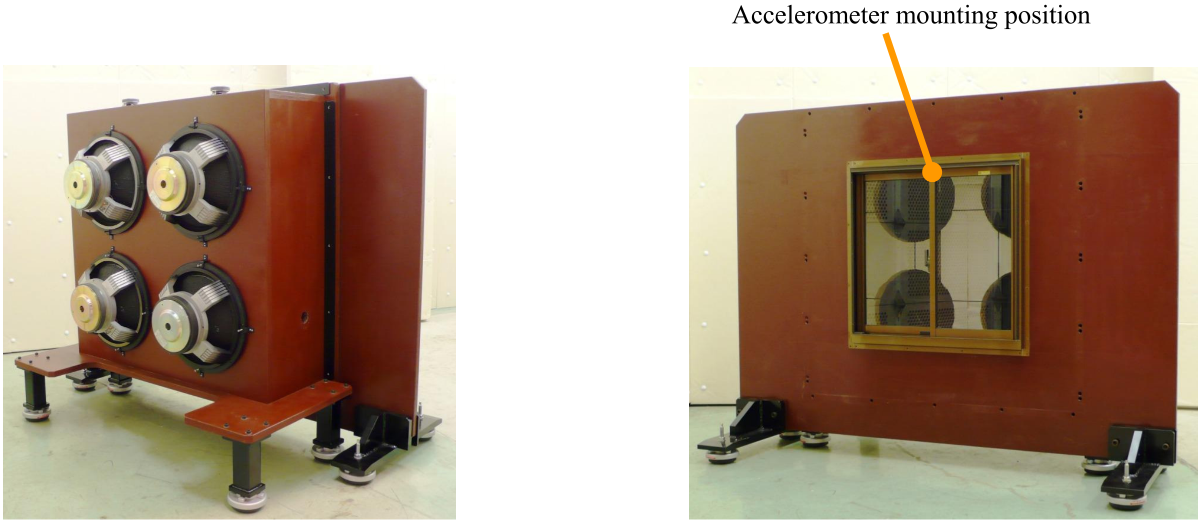
Due to intolerably loud sonic booms of conventional supersonic transport (SST), overland supersonic cruises, during which sonic booms are produced, are currently regulated in many countries and regions. However, with research on and development of tools for “low-boom” design of aircraft, it is now believed that sonic booms can be significantly reduced compared to those of conventional SST. In order to deregulate and fulfil overland supersonic flights for the next-generation SST, it is important to understand the acceptable levels and waveforms of sonic booms. For this purpose, subjective evaluation tests have been conducted by using sonic boom simulators [1-3].

It is reported that sonic booms are more influential indoors than outdoors due to, for example, vibration of walls and window rattles [3, 4]. For investigating the effects of sonic booms on buildings and the sonic booms heard indoors, a vibro-acoustic device has been developed [5] and experiments have been conducted mainly for a simple model of a building wall [6].

In this study, the vibration responses of a sash window to sonic booms are investigated through laboratory experiments. The effects of three parameters, i.e., maximum overpressure, rise time, and duration of an *N*-wave sonic boom, which is a typical waveform of a sonic boom produced by conventional SST, are investigated.

2 Experimental device

An experimental device for investigating vibro-acoustic responses of building structures has been developed at Japan Aerospace Exploration Agency (JAXA) [5]. Figure 1 shows the overview pictures of the vibro-acoustic experimental device. By using four large, low-frequency loudspeakers and two small, high-frequency loudspeakers, sonic booms are simulated as pressure change of air inside the airtight enclosure of the device. The input signal to the sound-reproducing system is synthesized so as to cancel the effect of distortion of the system and the effect of reverberation inside the enclosure. As a result, the pressure change inside the device is fully controlled and intended sonic boom signatures are obtained. Compared to similar experimental equipment [7], the vibro-acoustic device at JAXA is superior in controlling the sonic boom waveforms. Figure 2 shows an example pressure time history measured inside the device, together with the target *N*-wave sonic boom signature. Although air leak makes it difficult to control the pressure waveform inside the device when a sash window is used as a test specimen, the measured signature of a simulated sonic boom shown in Fig. 2 is almost identical to the target waveform, demonstrating the validity of the sonic boom synthesis method even when used for window specimens.



(a) Back side.

(b) Front side.

Fig.1 Vibro-acoustic experimental device.

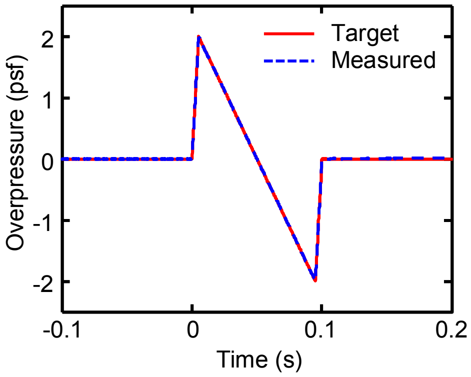


Fig.2 Example of well-controlled sonic boom signature.

3 Experiments

3.1 Test specimen

Different sizes and/or kinds of specimens can be mounted on the vibro-acoustic device, by using an appropriate frame to hold the specimen. In this study, a commercially available, relatively small window sash with 0.78 m wide and 0.77 m high and two single-pane glass windows were used as the test specimen. (See Fig. 1 (b).)

3.2 Sonic boom signatures

N-wave sonic boom pressure time histories with different parameter values were reproduced in the vibro-acoustic device, and the vibration responses of the window specimen were measured. The parameters of an *N*-wave studied in this study are peak overpressure $P_{\max}$, rise time τ, and duration T. These parameters are defined as shown in Fig. 3. The values of these parameters were set at $P_{\max} = 1$ and 2 psf, $\tau = 5$ and 10 ms, and $T = 100$ and 200 ms. The unit of the overpressure "psf" stands for pound force per square foot, and one psf approximately equals 48 pascals.

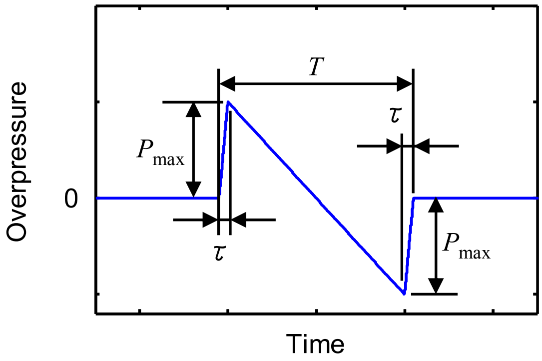


Fig.3 Parameters of *N*-wave sonic boom.

3.3 Measurements of vibration responses

Acceleration of the window was measured for each sonic boom signature. An accelerometer was mounted on the upper left corner of the window set on the right-hand side. (See Fig. 1 (b).) At this mounting location of the sensor, a window contact (or hit) the other window and the sash, and thus rattles can be clearly captured.

4 Results and discussion

4.1 Overview

Figures 4-11 show measured acceleration for *N*-wave sonic booms with different parameter values. Panels (a) in these figures show the time history of the acceleration, and Panels (b) show the time-frequency structures (spectrograms) of the acceleration.

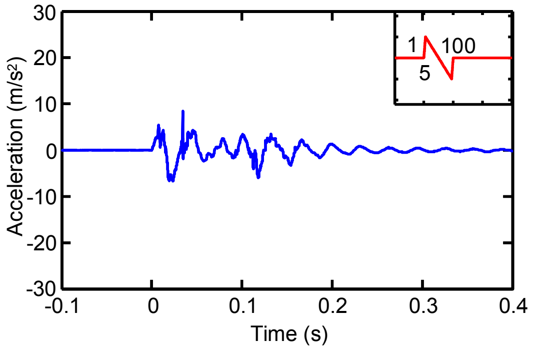
It is found in the plots of time histories (Panels (a)) in Figs. 4-11 that the overall waveform is dominated by a frequency component at between 25 and 35 Hz (30 to 40 ms of cycle). The frequency response analysis of the window using a swept sine signal revealed that this frequency component corresponds to the dominant resonant frequency of the window. Also observed is the high-frequency, shaky fluctuation near the local maxima and minima of the resonant oscillation, which is more obviously observed in the spectrograms (Panels (b)) as the vertical lines. Such fluctuation is not observed for a plate specimen [6], and these strong high-frequency components are not included in the simulated sonic booms that vibrate the window. Therefore, these high-frequency components are inferred to be the source of rattle.

Another finding is that the vibration behavior is different for the front and rear abrupt pressure rises in the *N*-waves sonic booms, although these two pressure rises have the same amount of pressure change and the same rise time. This is not the case for a plate specimen [6]. In all cases shown in Figs. 4-11, both the overall amplitude and the level of the shaky fluctuation (rattle) are larger after the first rise than the second one. Since the characteristics of the front and rear rises are the same, a possible reason for the different acceleration responses is the difference in change of the sonic boom pressure after the rises: The overpressure decreases after the first rise, while it keeps constant at zero after the second rise. Another possibility is the difference of the range of the overpressure. In the first rise, the overpressure increases from zero to the positive peak ($P_{\max}$), whereas in the second rise, the overpressure changes from the negative peak ($-P_{\max}$) to zero. In addition, the complicated, asymmetric structure of the sash window would probably be relevant [7, 8].

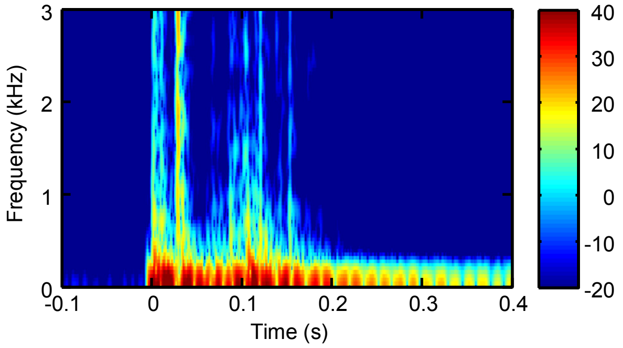
4.2 Effects of maximum overpressure

Panels (a) in Figs. 4-11 show general tendency of increase of the magnitudes of both the overall acceleration and rattle (high-frequency components) with increasing $P_{\max}$. However, unlike a wall (a plate specimen) [6], $P_{\max}$ does not seem linearly affects the magnitude of acceleration of the window. When $P_{\max}$ is doubled, the maximum magnitude of the acceleration (negative peak in most cases) increases more than twice. Furthermore, the waveforms are not kept.

Spectrograms (Panels (b) in Figs. 4-11) reveal that the change of $P_{\max}$ changes not only the magnitude, but also the time-frequency structures of the acceleration. When the values of $P_{\max}$ are varied, the time at which rattles occur changes. This is more clearly observed when $T = 200$ ms (Figs. 8-11).

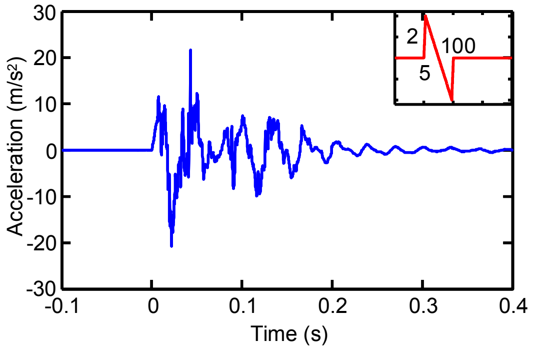


(a) Time history.

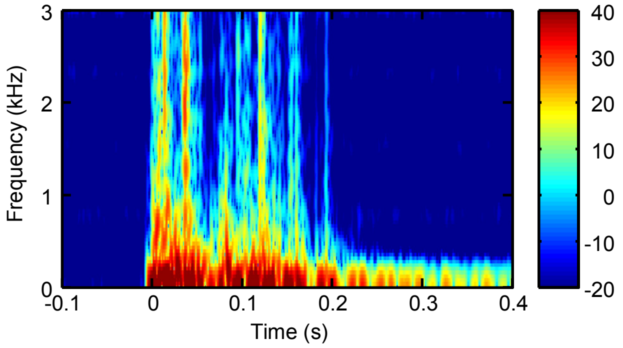


(b) Spectrogram.

Fig.4 Acceleration response of window to an *N*-wave sonic boom with $P_{\max} = 1$ psf, $\tau = 5$ ms, $T = 100$ ms.

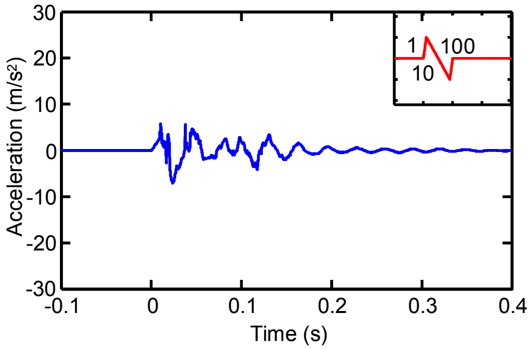


(a) Time history.

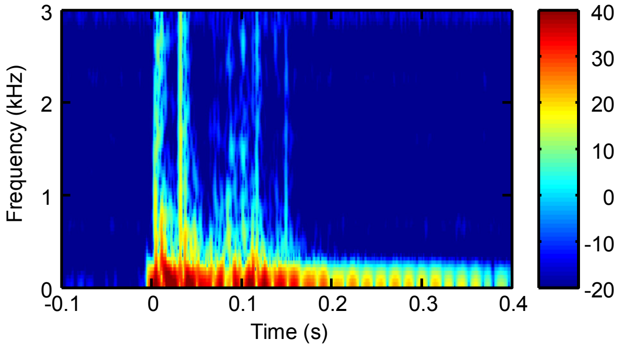


(b) Spectrogram.

Fig.5 Acceleration response of window to an *N*-wave sonic boom with $P_{\max} = 2$ psf, $\tau = 5$ ms, $T = 100$ ms.

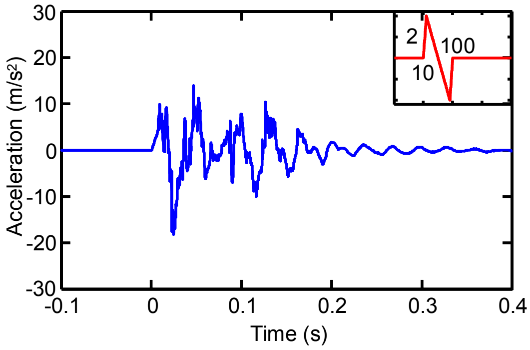


(a) Time history.

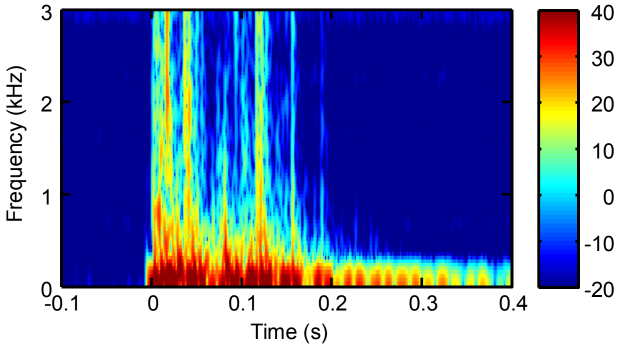


(b) Spectrogram.

Fig.6 Acceleration response of window to an *N*-wave sonic boom with $P_{\max} = 1$ psf, $\tau = 10$ ms, $T = 100$ ms.

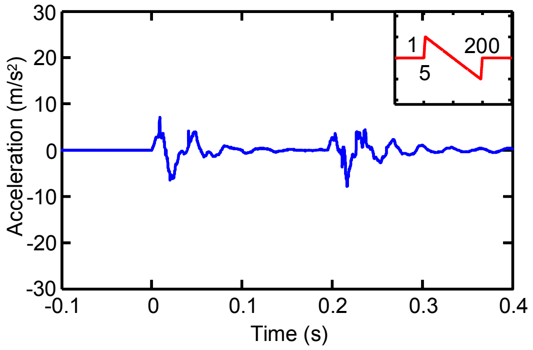


(a) Time history.

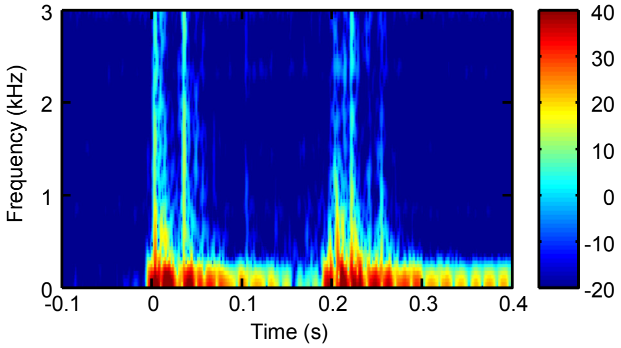


(b) Spectrogram.

Fig.7 Acceleration response of window to an *N*-wave sonic boom with $P_{\max} = 2$ psf, $\tau = 10$ ms, $T = 100$ ms.

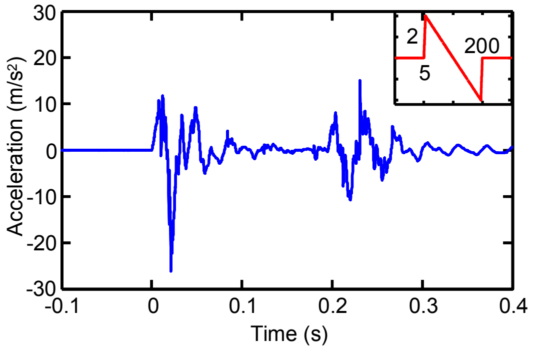


(a) Time history.

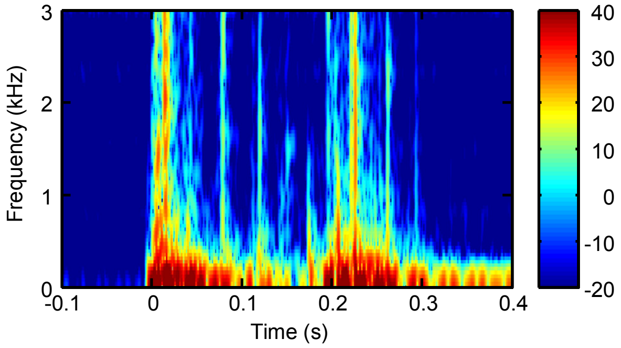


(b) Spectrogram.

Fig.8 Acceleration response of window to an *N*-wave sonic boom with $P_{\max}$ = 1 psf, τ = 5 ms, T = 200 ms.

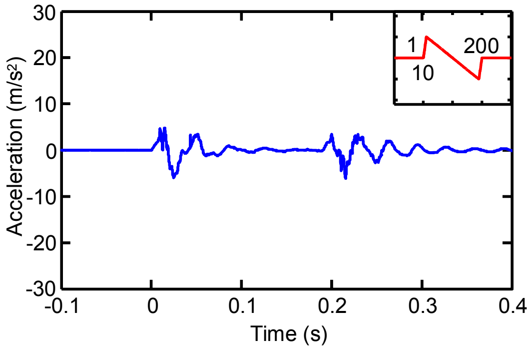


(a) Time history.

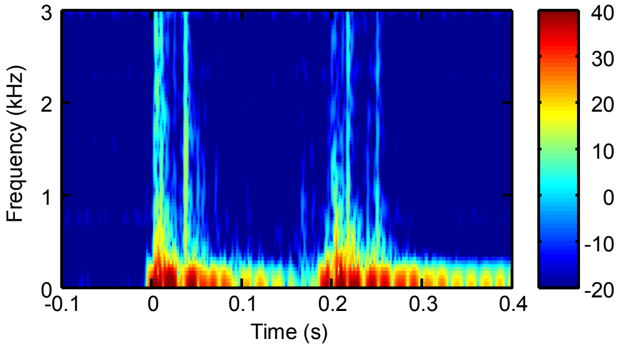


(b) Spectrogram.

Fig.9 Acceleration response of window to an *N*-wave sonic boom with $P_{\max}$ = 2 psf, τ = 5 ms, T = 200 ms.

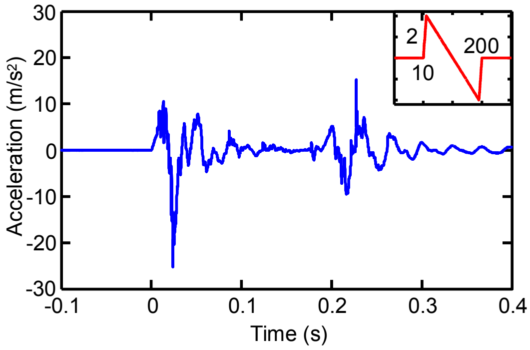


(a) Time history.

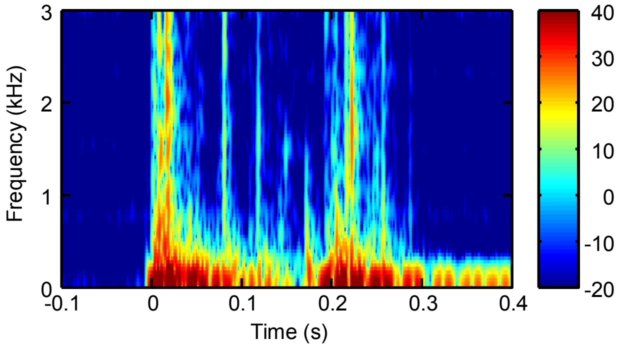


(b) Spectrogram.

Fig.10 Acceleration response of window to an *N*-wave sonic boom with $P_{\max}$ = 1 psf, τ = 10 ms, T = 200 ms.



(a) Time history.



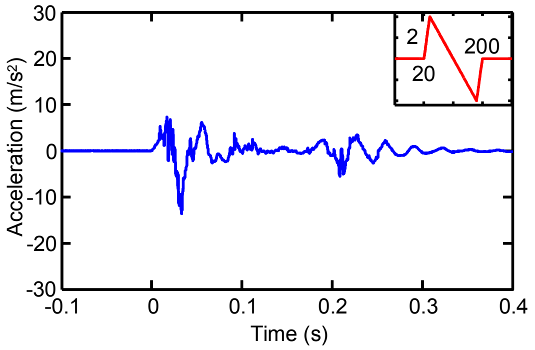
(b) Spectrogram.

Fig.11 Acceleration response of window to an *N*-wave sonic boom with $P_{\max}$ = 2 psf, τ = 10 ms, T = 200 ms.

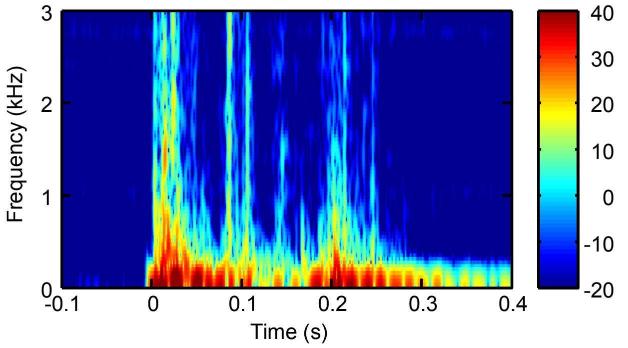
4.3 Effects of rise time

When increasing τ from 5 ms to 10 ms while keeping $P_{\max}$ and T the same, only slight reduction of the magnitudes of acceleration and rattle is observed in Figs. 4-11. A possible reason for such small effects is the choice of the values of τ. Change of τ yields change of the spectral level of a sonic boom in the high-frequency region. When increasing τ from 5 ms to 10 ms, the spectral level decreases at frequencies higher than 32 Hz ($1/\pi\tau$ Hz for $\tau = 10$ ms) [9]. In this case, the level of spectrum does not change significantly at the resonant frequency of the specimen window, which lies between 25 and 35 Hz. In order to confirm the relationship between rise time and resonant frequencies, a vibro-acoustic experiment was conducted for an *N*-wave sonic boom having $\tau = 20$ ms, for which the level of spectrum decreases at the frequencies higher than 16 Hz. The result is shown in Fig. 12. The overall magnitude of acceleration and the level of rattle are significantly reduced compared to the cases with shorter rise time (Figs. 9 and 11), as expected.

For larger windows with lower resonant frequencies, the effects of rise time is anticipated to be limited, as rise time of a typical *N*-wave sonic boom is shorter than 10 ms, for which the spectral level below 32 Hz does not change.



(a) Time history.



(b) Spectrogram.

Fig.12 Acceleration response of window to an *N*-wave sonic boom with $P_{\max} = 2$ psf, $\tau = 20$ ms, $T = 200$ ms.

4.4 Effects of duration

For the same values of τ and $P_{\max}$, change of T changes the time length of pressure fall in the middle of an *N*-wave (between the front and rear abrupt pressure rises), which eventually changes the rate of change of the pressure fall. In Figs. 4-11, the major discrepancy is found in this region. Overall, rattles are stronger for shorter duration. This result coincides with Ref. [8]. When $P_{\max} = 2$ psf, the time interval between rattles changes for different values of T: The interval is shorter for $T = 100$ ms than for $T = 200$ ms. Such effect is not observed for $P_{\max} = 1$ psf. These complicated effects are unlikely explained by just exploring the spectra of the sonic booms, as the change of T yields change of spectrum at very low frequencies; lower than 6 Hz in the cases studied in this paper.

5 Conclusions

Vibration responses of a sash window to *N*-wave sonic booms are investigated through laboratory experiments. Rattles are captured as high-frequency components of acceleration of a window. Unlike walls, vibro-acoustic responses of windows are different after the first and second abrupt rises of an *N*-wave. Overall magnitude of the acceleration and rattle tend to increase with increasing maximum overpressure and with decreasing rise time or duration. However, the parameters seem to affect the vibration of window in a complicated, nonlinear manner, and they might be dependent on each other. For further investigation on the complicated vibration responses of windows, more experiments with different parameter values and sonic boom waveforms for different sizes and kinds of windows would be necessary.

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