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Building vibration induced by sonic boom - field test in Russia

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ABSTRACT

Infrasound and audible sound at very low frequency from sources such as military aircrafts, explosions and wind mills can induce building vibration involving both rattling and whole-body vibration strong enough to cause annoyance. Sonic boom is of special interest in this context due to its very low frequency content that coincides with the most important frequency range for both building vibration and human perception. This paper presents results from field tests with measurements of noise and building vibrations from sonic booms performed at the Tretyakovo airport in Russia. Transmission loss from outdoor to indoor noise, noise induced floor vibration and whole building vibration are determined. Furthermore, the measured acoustic vibration admittance is used to estimate vibration values in the same building from low boom flight passages using synthesized sound pressure time series. Boom induced floor vibration both from the measured flight passages in Russia and from synthesized low boom time series are estimated also for a lightweight wooden building, using previously measured acoustic vibration admittances. The results clearly show perceptible levels of vibrations from sonic boom along with a great influence of the building type which indicates that there can be a big difference between the European countries depending on the building tradition. Finally, it is shown that outdoor sound levels weighted with the C-curve correlates best with frequency weighted floor vibration values.

1. Introduction

Infrasound and audible sound at very low frequencies from sources such as military aircrafts, explosions and wind mills can induce building vibration, involving both rattling and whole-body vibration, of enough strength to cause annoyance. Sonic boom is of special interest in this context due to its very low frequency sound spectrum, which coincides with fundamental frequencies of the entire building and the fundamental frequency of the floor. This indicates that the sonic boom can be an effective source of building vibration.

Many studies of rattling and vibration from sonic boom are described in the literature. Some of these address annoyance, such as [1] and [2], which describe laboratory tests of the effect of rattling and vibration on the annoyance, respectively. Others focus on the vibroacoustic building response from sonic boom. In the 60 s, field measurements of noise and vibration from sonic boom were performed in two residential houses in England, [3]. The focus of this study was to assess possible building damages from sonic boom. Building vibration response to sonic boom were also measured in two buildings during flight tests in the vicinity of Edwards Air Force Base in the 60 s [4]. The results of these tests are compiled with other measurement data in [5] and relationships are proposed between outdoor noise level and vibration level in different building parts, e.g. walls, floors and windows. However, in both tests from the 60 s, only peak acceleration levels without frequency information were reported. The results are therefore of limited value when comparing with frequency dependent limit values and annoyance criteria. Of more recent date, NASA performed measurements of vibroacoustic response of two houses exposed to sonic booms in 2006 and 2007 [6]. A comprehensive measurement setup was used with many accelerometers on walls, windows and ceiling, and microphones outdoor and indoor. Although these measurements provided valuable information on low frequency sound transmission and rattling generation, they did not address floor vibrations. Since both test buildings were single-story houses, the measurements also did not address the entire building motion, which primarily will be experienced in multiple story buildings, [7]. In [8], results from field experiments using a small-scale test building exposed to simulated sonic booms are described. This test building was instrumented with accelerometers on the floor in addition to walls, windows and ceiling, and gave valuable knowledge about vibro-acoustic response at

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low frequencies. However, the small dimensions of the building and short floor spans make the results less suitable for assessing floor vibrations in normal buildings and whole building motion. Similarly, [9] describes a field test where vibroacoustic response of a wall with windows were measured when exposed to external pressure loading from simulated sonic booms, but floor vibrations and whole building motion were not addressed. Hence, there is a clear need to better understand and quantify mechanisms for vibration excitation of floors and whole building movements due to sonic boom and to understand their possible implications for humans.

In this paper, whole building movements and floor vibrations from field tests with supersonic military aircrafts in Russia are studied. Furthermore, floor vibrations from low boom flight passages are estimated using synthesised time series both for the test building in Russia and for another type of building, i.e. a Scandinavian type lightweight wooden building. Finally, the correlation between frequency weighted floor vibrations and different metrics describing outdoor noise is examined.

The study is performed within the EC H2020 RUMBLE project, which is dedicated to providing the scientific evidence requested by authorities to determine the acceptable level of overland sonic booms and the appropriate ways to comply with it. In the Rumble project Finite Element models have been developed to calculate whole building motion, outdoor to indoor sound transmission, and noise induced floor vibrations for different building types. The FE-models represent the range of building types in Europe, and both detached buildings and flats in multi-storey buildings have been studied [10]. In addition to providing information on typical vibration values from sonic boom, the results of the present study have been used to calibrate these models. This work will be presented in-depth in a related paper [11].

1.1. Limit values for noise and vibration from sonic boom

In most European countries limit values for noise are given as limits for equivalent noise, i.e. L_{den} or L_{eq}. However, for short duration events like sonic boom, equivalent requirements are not suitable since they will hardly ever be exceeded. According to WHO's guidelines from 1999 [12], sleep disturbance correlates best with maximum sound levels if the noise is not continuous. Negative effects have been observed at 45 dBA or less and noise events exceeding 45 dBA should therefore be limited if possible. The guidelines further claim that it should be possible to sleep with a bedroom window slightly open. It is also pointed out that for sources with low frequency content, disturbances may occur even though the sound pressure level during exposure is below 30 dBA. Special criteria for low frequency noise have been suggested. In [13] it is recommended to use the C-Weighted SEL as an indicator of potential for low frequency noise annoyance together with Tokita & Nakamura thresholds [14] when high levels of low frequency noise are present.

As far as we know, there are no regulatory limit values for building vibrations caused by sonic boom in Europe or elsewhere. General guidance values above which complaints due to building vibration could occur were given in ISO 2631-2:1989 [15]. In the second edition of the standard ISO 2631-2:2003 [16], these were removed but are reproduced in revised format in ISO 10137 [17]. ISO 10137 includes a base curve for RMS (Root Mean Square) acceleration together with multiplication factors for different type of buildings and applications. For residential buildings at night, the multiplication factor is 1.4. At daytime higher factors apply. According to ISO 10137, the probability of adverse comments is low for vibration values below the curve. The standard also contains an evaluation curve for wind-induced peak acceleration in buildings in horizontal directions. It is recommended that the peak acceleration with a one-year return period should not exceed this evaluation curve. The Norwegian Standard for land-based transport, NS 8176 [18] contains limit values in different classes. For class C, which corresponds to the minimum requirement for new buildings in Norway, the limit value for frequency weighted velocity RMS is v_w = 0.3 mm/s. This corresponds to a frequency weighted acceleration of a_w = 10.7 mm/s^2 (frequency weighted according to [16]). The limit value for class C in NS 8176 is in line with limit values in other countries [19]. A *meta*-analysis to determine exposure–response relationships for railway vibration described in [20] shows that about 22% of the residents are expected to be annoyed or highly annoyed by railway vibrations at a vibration level of v_w = 0.3 mm/s. However, it should be noted that both the limit values in NS 8176 and the exposure–response relationships in [20] apply to land-based transport, and that people may not respond equally to vibration from sonic boom.

1.2. Metrics

The literature does not provide clear recommendations of which metric is best suited to quantify sonic boom exposure. Different metrics seem to correlate best with annoyance depending on whether outdoor noise or indoor noise with or without rattling is used as a basis [1]. However, a review concerning a range of alternative metrics was presented in [21], and a limited set of suitable metrics that can be used to characterise sonic boom impact on humans was proposed. In a follow up study [22], this list of single events metrics was revised, and include A-SEL, B-SEL, D-SEL, E-SEL, Stevens Mark VII perceived level, and Indoor Sonic Boom Annoyance Predictor (ISBAP). These six metrics are presently used for community response studies for sonic boom. Based on some of these metrics, it was concluded that low sonic boom reduces these metric values and hence human annoyance compared to conventional boom. Furthermore, it was concluded that outdoor noise levels could be used as a proxy for indoor annoyance.

In the present study, correlation is determined between frequency weighted floor vibrations and outdoor sound exposure level with the six metrics suggested by [22] and in addition unweighted SEL and C-SEL. Fig. 1 shows the A-, B-, C-, D- and E- frequency weighting curves. Stevens Mark VII perceived level and ISBAP cannot be described by simple frequency weighting curves and are therefore not shown in the figure. Fig. 1 shows that the

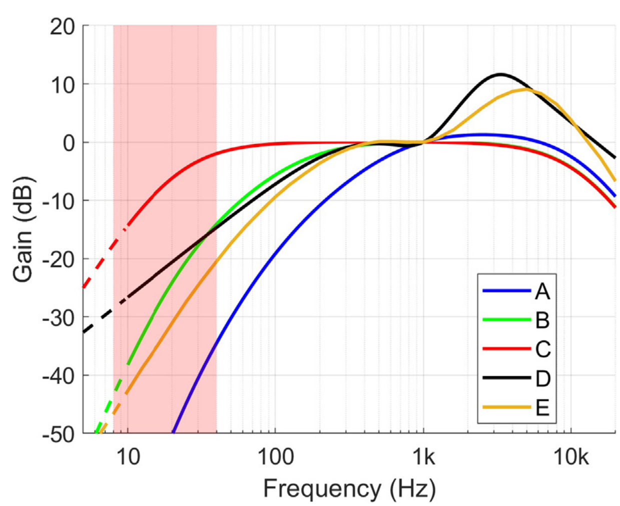

Fig. 1. The A-, B-, C-, D and E-noise weighting curves. The frequency range most important for floor vibrations is marked with red. The curves are extrapolated below 10 Hz. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

commonly used dBA level is a poor description for noise which is dominated by lower frequencies, since the A-weighting curve places most emphasis on higher frequencies and heavily suppresses components in the low frequency range. The C-weighting on the other hand, is the weighting filter that retains most energy in the low frequency range which generates vibration. The E-weighting was proposed by Stevens as a close (±2dB) approximation of the perceived level calculated according to Stevens' Mark VII procedure [23,24].

1.3. Onset of rattling

Studies show that the incidence of rattling increases the indoor noise levels and the degree of disturbance significantly [25,26]. In Hodgdon et al. [13] a study is described where a stone house with a rattle prone window was exposed to noise from a nearby air field. Acceleration levels were measured on the window and compared to outdoor maximum noise levels with different frequency weighting to identify a threshold value above which window rattling was likely to occur. The study showed that rattling occurred above a common threshold level of 97 dB for unweighted Sound Exposure Level and C-weighted maximum Sound Pressure Level. Since the energy from sonic boom is concentrated to a very short time, typically around 100–300 ms, the C-weighted maximum Sound Pressure Level with a short integration time, i.e. time weighting Fast (0.125 s), may be a better metric to address rattling from sonic boom than Sound Exposure Level and is therefore used in the present study to address rattling. Further, in Hodgdon et al. [13] a laboratory test of onset of rattling is described, where four different rattle prone windows were excited by swept sine noise and the onset of rattling at different frequencies were determined. In this study onset of rattling was registered already at a_{peak} = 1.4 m/s^2. In another laboratory study described in [27], more than 40 windows were tested for their response to low-frequency sound through swept sine noise excitation. The onset of rattling differed between the different windows and buildings. One example with onset of rattling at acceleration values below a_{peak} = 3 m/s^2 is shown.

2. Description of field measurements of noise and vibration from sonic boom in Russia

Field measurements of noise and vibration from sonic boom were performed at the Tretyakovo airport near Lukhovitsy, Moscow region, Russia. Two flight campaigns were conducted, one in July 2018 with three measured aircraft passages, using a Sukhoj Su-30 aircraft, and one in July 2019 and August 2019 with eight measured aircraft passages, using a Sukhoj Su-27 aircraft. The flight paths were recorded using GPS instrumentation onboard the airplanes. In addition, other parameters, such as Mach number and altitude were logged, see Table 1. The flight trajectories during the 2019 campaign are shown in Fig. 2 together with the location of the test building. All test flights were heading from north to south. Some information about the weather conditions during the tests are shown in Table 2.

During both campaigns sound measurements were performed outdoor at the façade and inside a test building at the Tretyakovo airport. During the flight campaign in 2019, simultaneous vibration measurements in the same test building were performed in addition to the sound measurements. This paper mainly focuses on the flight campaign in 2019 analysing the simultaneous sound and vibration measurements. However, some measurement results from the 2018 flight campaign are used to investigate the difference between sound insertion loss with open and closed windows.

2.1. Description of test building

The test building, which is the old flight control tower at the airport, is a 3-storey brick building constructed in 1954, see Fig. 3. The building has about 0.5 m thick brick walls and 0.20 m concrete floor slabs with parquet on top. Fig. 4 shows the measurement room in the second floor of the test building. The test room is oriented with the façade to the north-west. The measurement room is 5 m × 4.28 m × 3.15 m (l × w × h) with one outer wall with two 1.45 m × 1.82 m (w × h) casement windows. The windows, which are in poor condition, consists of wooden double-pane units with 175 mm distance between the two 4 mm glass panes in the units. The measurement room is furnished with desks, chairs and office supplies, but without curtains, carpets or other absorbent surfaces.

2.2. Instrumentation

Figure 5 shows the positions of the measurement sensors used in the two flight campaigns. During the 2019 flight campaign, the outdoor sound pressure was measured about 10 mm in front of the wall below the window (about 0.46 m below the windowsill) for flight passages 1–2 and in front of the window glass in 0.5 m distance for flight passages 3–8. In 2018, the outdoor sound pressure was measured in front of the window glass at short distance. The indoor microphones used further in this study, no 2 and no 3, were located about 1.4 m above floor during the 2018 campaign and 1.2 m above floor during the 2019 campaign. The instrument positions used for flight passages 1–2 in 2019 were according to the specification from the Rumble project, while the instrument positions used for flight passages 3–8 were determined by the Russian partner (mainly to study outdoor sound propagation). In this study we focus on results from flight passages 1–2, but all results are presented in tabular form.

Table 1
Flight data (determined when the distance to the test building was shortest).

Flight Campaign and aircraft	Date	Flight no	Mach number	Height above ground (m)	Min horizontal distance from flight path projection to building (m)
1st	22	1	1.79	11,547	245
Sukhoi 30	Aug.2018	2	1.72	11,303	485
		3	1.62	11,318	457
2nd	26 Jul.2019	1	1.62	11,375	2315
Sukhoi 27		2	1.81	11,293	584
	13	3	1.63	11,443	1428
	Aug.2019	4	1.65	11,459	2215
		5	1.63	11,457	245
		6	1.40	11,446	213
		7	1.63	11,452	1421
		8	1.87	11,786	183

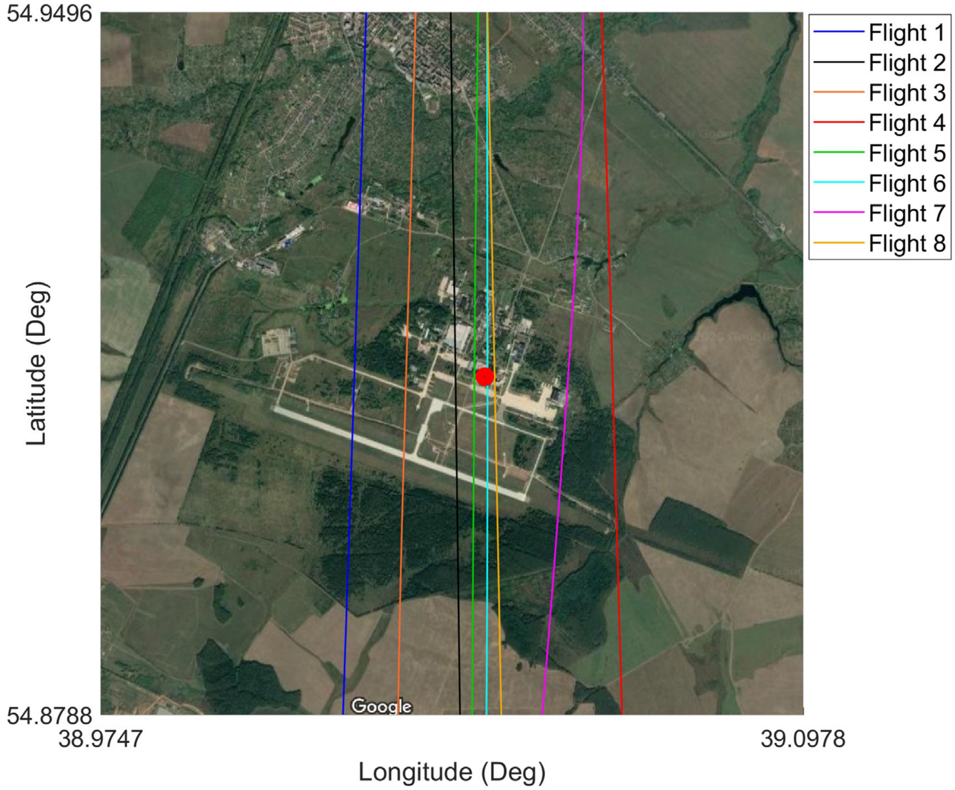

Fig. 2. Flight trajectories during the 2019 flight campaign. All flights were heading from north to south and the test room was oriented with the façade facing north-west (in parallel with the runway on the photo). The position of the test building at the Tretyakovo airport is shown with a red dot. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Weather data, collected at ground level in 2018 and at 10-meter height in 2019.

Date	Temperature (°C)	Humidity (%)	Wind speed (m/s)	Wind dir (° from north)
22 Aug.2018	18	45	-1)	-1)
26 Jul.2019	26–27	46–48	5–7	0–27
13 Aug.2019	24–25	41–48	3–7	151–222

1) No information is available.

Indoor and outdoor sound pressures were measured with GRAS 40BE ¼"microphones with frequency range 4 Hz – 80 kHz and 4 mV/Pa sensitivity. Floor vibrations were measured with a PCB393B04 accelerometer with frequency range 0.06 Hz–450 Hz and 1000 mV/g sensitivity, while wall and window vibrations were measured with PCB333B32 accelerometers with frequency range 0.5 Hz–3000 Hz and 100 mV/g sensitivity. All channels were logged synchronously. During the 2019 flight campaign the sampling frequency was 32 kHz and the collected time series were 2.05 s long, while during the 2018 flight campaign the sampling frequency was 96 kHz and the length of the timeseries was 0.68 s.

3. Data analysis

The signal processing and analysis are performed in MatLab. All collected time series are zero padded in the start and end to obtain a total length of 2.5 s before analysis. Peak sound pressure levels, Maximum pressure levels and Sound exposure levels from all flight passages are determined. Sound Exposure Level (SEL) is defined as that constant sound level which has the same amount of energy in one second as the original noise event and is calculated from the measured sound pressure over the duration of the event, using the following formula [28]:

$$SEL = 10\log\left(\frac{1}{T_0}\int_{-\infty}^{\infty}\frac{p(t)^2}{p_0^2}dt\right) \tag{1}$$

where T_0 is reference duration of 1 s, p(t) is sound pressure and p_0 is reference sound pressure of 20 μPa.

Furthermore, sound induced vibrations in floor (vertical direction) and in wall (horizontal direction) are determined as peak values and as frequency weighted maximum RMS values according to ISO 2631-2. The results are compared to the limit values in NS 8176 and to guideline curves in ISO 10137.

3.1. Transmission loss and acoustic vibration admittance

The measured indoor sound pressure levels and vibration values are affected both by the properties of the building and by the characteristics of the sound source. Transmission loss from outdoor to indoor and the acoustic vibration admittance, on the other hand, are independent of the sound source as they are normalized with the outdoor sound pressure. These metrics are therefore

Fig. 3. left: Measurement building with measurement room in second floor, right: detail of heavy façade (facing north-west) with outdoor microphone position used during flight 1–2 in the 2019 flight campaign.

Fig. 4. Left: measurement room with microphone position no2 and no3 during flights 3–8 in 2019, middle: wooden double-pane unit windows, right: window with outdoor microphone in 2018.

better suited to describe the characteristics of the building with respect to its dynamic response.

In this study, the transmission loss, TL, and the acoustic vibration admittance, β, are defined as functions of the frequency f according to Eq. (2) and Eq. (3) respectively. Eq. (2) is a simplification, as the acoustic properties of the room are not taken into account. This can be justified by the fact that room acoustic properties are difficult to determine in the frequency area below 50 Hz, which is of special interest for sonic boom.

$$TL(f) = -10\log\left(\frac{p_{In}^2(f)}{p_{Out}^2(f)}\right) \tag{2}$$

$$\beta(f) = \frac{u(f)}{p_{Out}(f)} \tag{3}$$

where p_{In} is the indoor pressure, p_{Out} is the outdoor pressure and *u(f)* is the vibration velocity in the floor or at the wall.

The determination of transmission loss and admittance from measurements using Eq. (2) and Eq. (3) is prone to disturbance from unrelated noise and vibration sources in the building. A more robust way to determine transmission loss and the acoustic vibration admittance are from measured frequency response functions (FRF) according to Eq. (4) [29]. In Eq. (4), the influence of random noise is reduced by averaging. However, the influence of unrelated stationary sources of indoor noise and vibration will not be removed, and retaining these in the signal may lead to an overestimation of the admittance and/or underestimation of the transmission loss. The coherence determined according to Eq. (5) provides a measure of the extent to which indoor noise and vibration are caused by outdoor noise. The coherence is between zero and one. A coherence equal to one implies that the indoor noise and/or vibration originates fully from the measured outdoor noise and a coherence close to zero that the indoor noise and/or vibrations are caused by other unrelated sources.

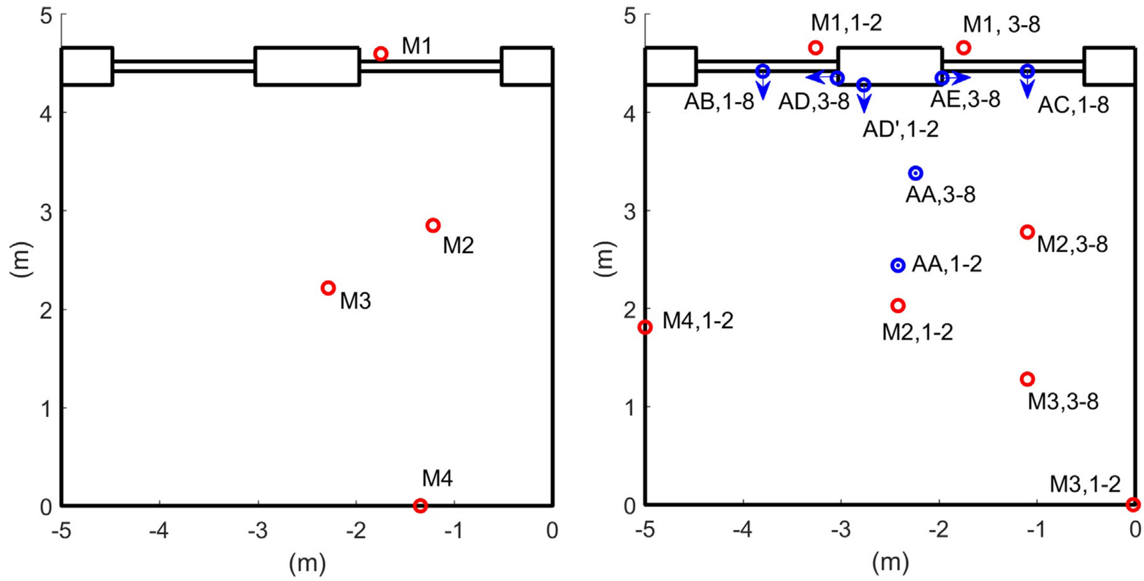

Fig. 5. Instrumentation, red circles microphones, blue circles accelerometers (direction shown with arrows). Left: 2018 flight campaign, right: 2019 flight campaign July (flights 1–2), Aug (flights 3–8). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$\widehat{H}(f) = \frac{\widehat{S}_{yx}(f)}{\widehat{S}_{xx}(f)} \tag{4}$$

$$\widehat{\gamma}^2_{xy}(f) = \frac{\left|\widehat{S}_{yx}(f)\right|^2}{\widehat{S}_{xx}(f)\widehat{S}_{yy}(f)} \tag{5}$$

where $\widehat{H}(f)$ is the average frequency response function from outdoor noise to indoor noise or vibration, $\widehat{\gamma}^2_{xy}(f)$ is the coherence between outdoor noise and indoor noise or vibration, $\widehat{S}_{yx}(f)$ is average of the cross spectral density between outdoor noise and indoor noise or vibration from several flight passages, $\widehat{S}_{xx}(f)$ is the average of auto spectral density of the outdoor noise from several flight passages and $\widehat{S}_{yy}(f)$ is the average of auto spectral density of the indoor noise or vibration from several flight passages.

In the present study, the acoustic vibration admittance is used to evaluate how the test building in Russia would respond to a low boom excitation, as well as to estimate the dynamic response of a typical lightweight wooden building to sonic boom and low boom excitation.

4. Results from the field measurements

In this section measured sound and vibrations during the field tests in Russia in 2018 and 2019 are presented and compared to the limit values and the annoyance criteria described in section 1.1. Furthermore, transmission loss and acoustic building admittance are determined according to section 3.1 and discussed. The transmission loss and acoustic building admittance are further used in section 5.2 to estimate noise and vibration from low boom excitation and to compare the dynamic properties of the Tretyakovo test building with other type of buildings.

4.1. Sound pressure

Figure 6 shows measured sound pressure time series and frequency spectra for flight passage no 2 during the 2019 flight campaign. The signal to noise ratio for this flight passage was 24 dB for the outdoor microphone and 18 dB for the indoor microphone. Fig. 6 demonstrates that the main sound energy from the sonic boom is in the frequency range below 40 Hz with the peak in the spectra between 4 Hz and 7 Hz. Note that the microphones used have a nominal measurement range from 4 Hz and above. The results below 4 Hz are therefore subject to progressively greater uncertainty for decreasing frequencies and should not be emphasized.

Table 3 shows measured indoor and outdoor peak sound pressure levels and sound exposure levels from all flight passages. In addition, the outdoor C-weighted and the indoor A-weighted maximum sound pressure levels, $L_{C,max,F}$ and $L_{A,max,F}$, are tabulated for comparison with window rattling criteria (see section 4.4) and WHO's guidelines (see section 1.1) respectively.

All measured indoor sound levels are well above WHO's recommended $L_{A,max,F}$ = 45 dBA limit, which indicate that sleep disturbances are likely, especially since the noise clearly has a lot of low frequency content. In Fig. 7 calculated unweighted indoor SEL from flight passage no 2 (open window) and no 3 (closed window) in 2018 are compared to Tokita & Nakamura's criteria for perception of low frequency noise. This comparison indicates that the measured indoor noise is in the annoying range and for the situation with open window in the range where vibrations are likely to occur.

4.2. Sound induced vibrations

Sound-induced vibration generation in buildings has two main transmission paths: 1) Outdoor sound transmits through the façade and sets up an indoor sound pressure, which in turn sets up vibrations in the floors and other indoor surfaces. This transmission path depends on the transmission loss of the wall and window. 2) Outdoor sound acts directly on the outside of the building and induces a horizontal motion of the whole building at very low frequencies corresponding to the first natural frequencies of the building. This transmission path depends on the global properties of the building. Fig. 8 shows measured acceleration time series and frequency spectra of vibration velocity (integrated from acceleration) on the wall and on the floor in the Tretyakovo test building from flight passage no 2 during the 2019 flight campaign. The signal to noise ratio for this flight passage was 15 dB for the floor accelerometer and 18 dB for the wall accelerometer. The wall

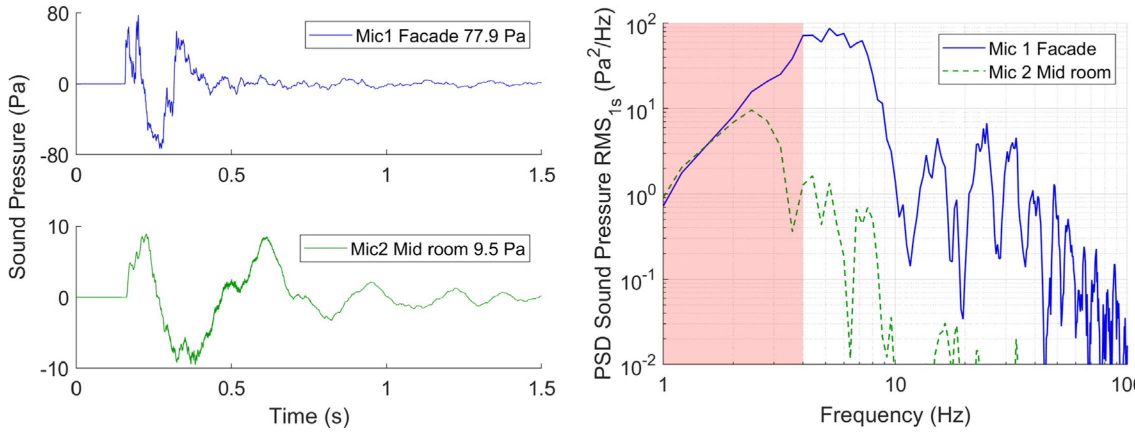

Fig. 6. Outdoor and indoor sound pressure from flight 2–2019, left: time series, right: Power Spectral Density (PSD) of Sound Pressure RMS 1 s. The frequency range below the microphones nominal measurement range is marked with red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Measured outdoor and indoor Sound Levels (dB). Maximum of microphone no 2 and no 3 in Fig. 5. Peak (L_{Peak}), SEL (L_E), A-weighted SEL (L_{AE}), A-weighted Maximum Level ($L_{Amax,F}$) and C-weighted Maximum Level ($L_{C,max,F}$).

Flight campaign and aircraft	Date	Flight no	Outdoor			Indoor			
			L_{Peak}	L_E	$L_{Cmax,F}$	L_{Peak}	L_E	L_{AE}	$L_{Amax,F}$
1st	22 Aug.18	1[1)]	136	120	120	127	116	82	89
Sukhoi 30		2[1)]	137	121	121	130	118	83	91
		3	133	121	116	118	108	71	76
2nd	26 Jul.19	1	131	119	115	114	106	65	69
Sukhoi 27		2	132	120	117	114	106	71	75
	13 Aug.19	3	130	117	113	112	105	65	70
		4	131	119	117	112	104	70	75
		5	134	120	119	114	105	74	77
		6	130	119	114	115	106	66	71
		7[2)]	–	–	–	–	–	–	–
		8	136	120	119	115	107	75	79

1) One window was open during this flight passage.
2) The noise registration system failed during this flight passage.

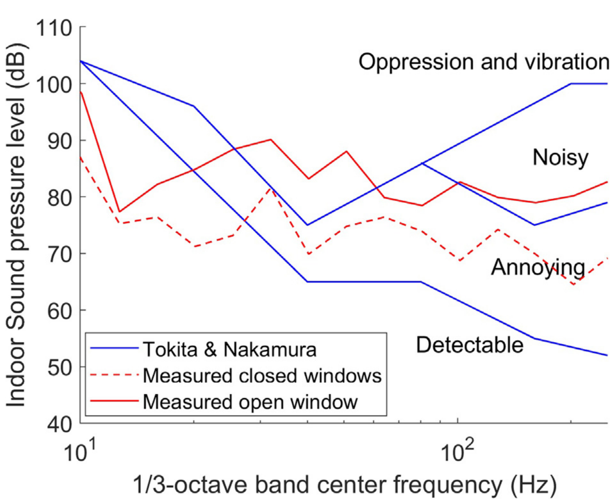

Fig. 7. Comparison of calculated indoor SEL from flight passage no 2 (open window) and no 3 (closed windows) in 2018 with annoyance criteria from Tokita & Nakamura.

vibration measurements show strong horizontal components at about 3 Hz and 5 Hz which could correspond to fundamental frequencies for the movement of the whole building. According to [30] the typical range for the fundamental natural frequencies for detached one- and two-story dwellings is 5 Hz – 10 Hz. For higher buildings the fundamental natural frequency will be lower and can for reinforced concrete frame buildings be estimated using Eq. (6) [31]. For a 10 m high three-story building, this gives a first natural frequency of about 3 Hz.

$$f_n = \frac{1}{\left(0.075 \cdot H^{0.75}\right)} \tag{6}$$

where H is the building height.

The floor measurements show peaks at about 3 Hz, 8 Hz, 14 Hz and 22 Hz. Most of these peaks coincide with peaks in the horizontal direction and it is not immediately clear from the results shown in this figure which peak corresponds to the fundamental frequency of the floor. However, as described in section 4.3, the admittance provides a better answer to that question.

Table 4 shows measured sound induced vibrations in floor (vertical direction) and in wall (horizontal direction) as peak levels and frequency weighted maximum RMS values according to ISO 2631–2. Note that the measurement positions on floor and wall were moved in between the two measurement days during the flight campaign in 2019. The horizontal measurement direction on wall was also changed from transversal to longitudinal between the two measurement days (see Fig. 5).

The results show that all frequency weighted RMS values, a_w, are below the limit value for class C in NS 8176, which corresponds to a_w = 10.7 mm/s^2. Fig. 9 shows measured maximum unweighted

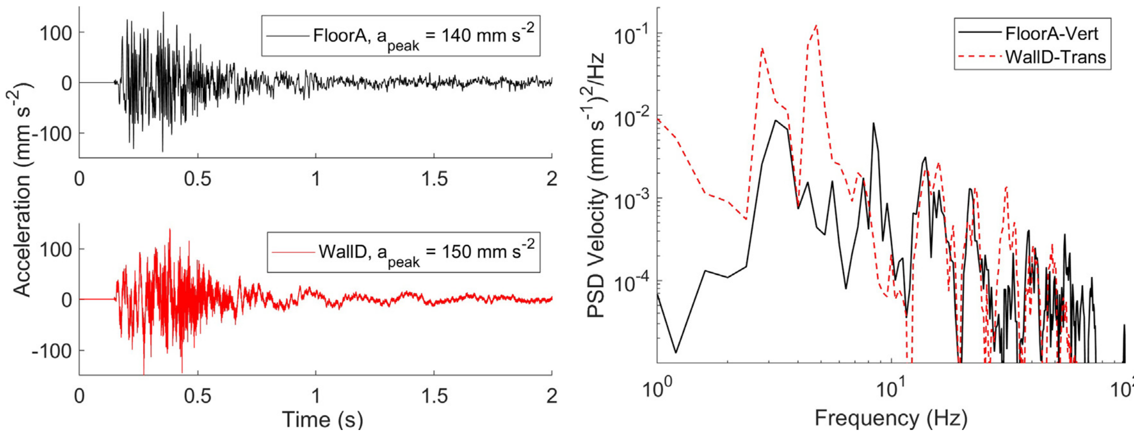

Fig. 8. Vibrations measured on floor in vertical direction and on wall in horizontal direction perpendicular to the wall from flight no 2 in 2019, left: time series of acceleration on floor (top) and wall (bottom). Right: Power Spectral Density (PSD) of velocity RMS 1 s.

Table 4
Measured acceleration on floor in vertical direction and on wall in horizontal direction (mm/s^2). Peak (a_{peak}), RMS (a_{rms}) and frequency weighted RMS (a_w). Note that the measurement position on floor and the measurement positions and directions on wall were moved in between the two measurement dates in 2019 (Fig. 5).

Flight campaign and aircraft	Date	Flight no	Floor			Wall		
			a_{peak}	a_{rms}	a_w	a_{peak}	a_{rms}	a_w
2nd	26 Jul.2019	1	150	26	4.9	110	17	6.5
Sukhoi 27		2	140	22	4.8	150	22	8.7
	13 Aug.2019	3	190	6.3	1.7	82	8.3	4.1
		4	270	8.5	1.8	150	11	4.1
		5	300	14	2.1	240	12	3.0
		6	220	8.5	2.2	94	7.8	4.5
		7	930	8.9	1.7	140	8.3	3.4
		8	420	12	2.3	270	12	4.6

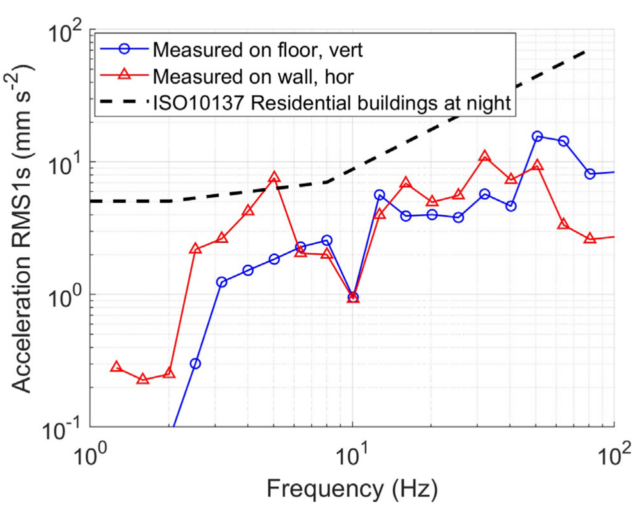

Fig. 9. Comparison of measured RMS vibration acceleration with magnitudes of vibration below which the probability of adverse comments is low according to ISO 10,137 (valid for residential buildings at night time).

RMS values, a_{rms}, in vertical and horizontal direction in 1/3-octave bands together with the curve from ISO 10137, under which there is low probability for adverse comments. The comparison shows that the measured wall vibration values coincides with the curve, while the floor vibration values are clearly below the curve. This indicates that in this building, horizontal vibrations from the sonic boom may be associated with a higher probability of adverse comment than vertical vibrations.

The peak values, a_{peak}, in Table 4 are largely controlled by higher frequencies. In contrast, the criteria for wind induced vibrations in ISO 10,137 assumes low frequency, < 5 Hz, motion of the buildings. To compare with the criteria in ISO 10137, all time series are low pass filtered to remove frequency components above 5 Hz. The highest low pass filtered peak acceleration for all flight passages is $a_{peak<5Hz}$ = 14 mm/s^2. Assuming the first natural frequency to be about 3 Hz, this is well below the criteria for wind induced vibrations with one-year return period in ISO 10137, which is 60 mm/s^2 at 3 Hz. However, it should be noted that the criteria in ISO 10,137 presuppose infrequent occurrence, i.e. a one-year return period, while sound induced vibrations from sonic boom may occur significantly more often than once a year in areas with well-trafficked air routes. It is possible that the criteria for wind induced vibrations in ISO 10,137 would have been stricter if a shorter return period had been considered (e.g. one day or a few hours).

4.3. Transmission loss and admittance

Figure 10 shows measured transmission loss and coherence with open and closed windows from the 2018 flight campaign in the frequency range from 1 Hz to 100 Hz determined according to Eq. (4) and Eq. (5). The frequency range below 30 Hz is of particular interest for the generation of floor vibrations. For the measurements with open window, the coherence is close to 1.0 in this frequency range, which indicates that the indoor sound pressure is solely caused by sonic boom excitation. For the closed window situation, only one flight was measured during the flight campaign in 2018 and the coherence can therefore not be calculated. In the frequency range below about 12.5 Hz, the figure shows a large and increasing difference in the measured transmission loss with

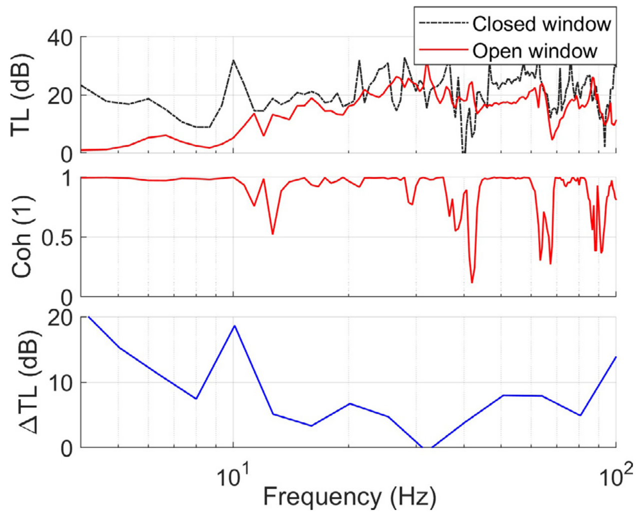

Fig. 10. Transmission loss (TL) with closed and open window determined from the 2018 flight campaign, top: transmission loss, middle: coherence, bottom: difference in transmission loss with closed and open windows (in 1/3 octave bands).

decreasing frequency between closed and open windows. A possible reason for this could be that low frequency sound is not reduced for the lowest frequencies in the presences of an opening. However, the measurement results do not show that the indoor sound pressure exceeded the outdoor sound pressure as would be expected due to Helmholtz resonance [32]. Hence, the Helmholtz resonance effect does not seem to be prominent in present measurements.

Figure 11 shows the acoustic vibration admittance and coherence for the floor and wall calculated from flight passages no 1 and 2 in the 2019 flight campaign. The measured acoustic vibration admittance in the horizontal direction has two main peaks at about 3 Hz and 5 Hz, which are interpreted as fundamental frequencies of the entire building. The coherence is close to 1.0 at these peaks, which indicates that they are caused by the sonic boom excitation. In the vertical direction, the main peak in admittance appears at 14 Hz, which is interpreted as the fundamental frequency of the floor. The coherence around this peak is also fairly high, which indicates that this peak is caused by the sonic boom excitation. According to [33], typically values for the fundamental frequency of floors are 8 – 20 Hz.

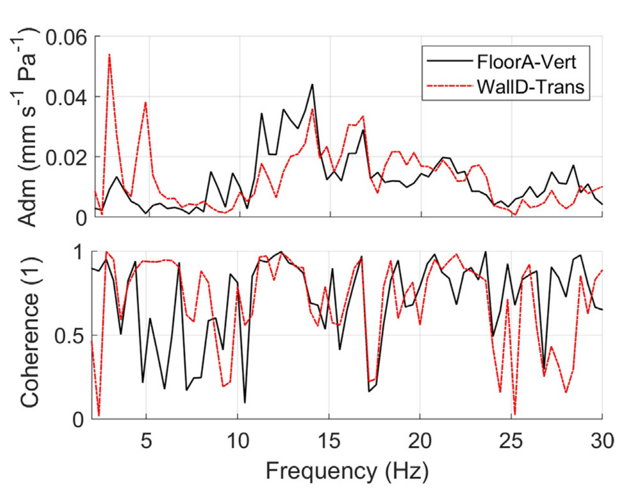

Fig. 11. Acoustic vibration admittance for floor and wall from flight no 1 and no 2 in the 2019 flight campaign, top: admittance, bottom: coherence.

4.4. Window rattling

The measured C-weighted outdoor sound pressure levels in Table 3 are between 113 and 121 dBC, which are well above the 97 dB rattling threshold value proposed by Hodgdon et al. [13]. Rattling can also clearly be heard on the recordings from the measurements. The measured acceleration on the window glasses in the Tretyakovo test building varied between a_{peak} = 10–180 m/s^2 for the different flight passages. The high vibrations are mainly dominated by high frequencies. According to [27], rattling is more effectively set up by low frequency excitation, but the excitation mechanism is non-linear which leads to rattling appearing as high frequency vibrations. A comparison between the original time series of acceleration measured on the window in pos C during flight passage no 2 in 2019 and the low pass filtered time series, using a cutoff frequency of 200 Hz, shows an onset of high frequency vibrations which indicates rattling already early on in the time series at peak vibration values around 2 m/s^2, Fig. 12 left. This is in accordance with the findings in [13] and [27].

Furthermore, the frequency spectrum of the window acceleration shows a distinct peak at 16 Hz corresponding to the first bending mode of the glass pane of the windows, Fig. 12 top right panel. This frequency is in the important frequency range for floor vibrations. The transmission loss between outdoor and indoor noise, shows a dip around the same frequency, Fig. 12 bottom right panel. A comparison with the frequency spectra for the wall acceleration (pos D), shows much lower acceleration values on the wall, indicating that the transmission loss around this frequency is completely controlled by the windows, and not by the walls. This is in accordance with earlier findings for lightweight wooden buildings in Løvholt et al. [34] and [35] and is probably even more pronounced for the Tretyakovo test building with its thick and very stiff brick walls.

5. Estimated indoor noise levels and vibration values for different sonic boom signals

In this section, indoor noise and floor vibrations from low boom flight passages are estimated in the Tretyakovo test building using synthesised time series. Furthermore, floor vibrations both from conventional boom and from low boom are estimated for another type of building, i.e. a typical Scandinavian type lightweight wooden building. The synthesised time series originate from the second AIAA workshop [36] and a recent simulation of low boom design, C25D, [37]. Fig. 13 shows the different signatures as time series and frequency spectra in 1/3-octave bands. Signature 0–3 and C25D are low boom simulations, 4–5 are N-waves and 6–7 are conventional supersonic aircraft signatures. These time series describe a wide range of possible scenarios for low booms, with different amplitudes and spectra.

5.1. Tretyakovo test building

The low boom realizations (0–3 and C25D) are used to estimate floor vibration and indoor sound pressure induced from low boom in the Tretyakovo test building. The transformation from outdoor sound pressure to floor vibration and indoor sound pressure is performed in the frequency domain by applying measured and simulated admittance and transmission losses on the frequency spectra of the low boom in 1/3-octave bands. Table 5 shows the estimated indoor noise level and vibration in the Tretyakovo test building from the low boom realizations.

The calculation shows that although the indoor sound pressure level from the low boom realizations are much lower than measured in the Russia test building from regular sonic booms, two

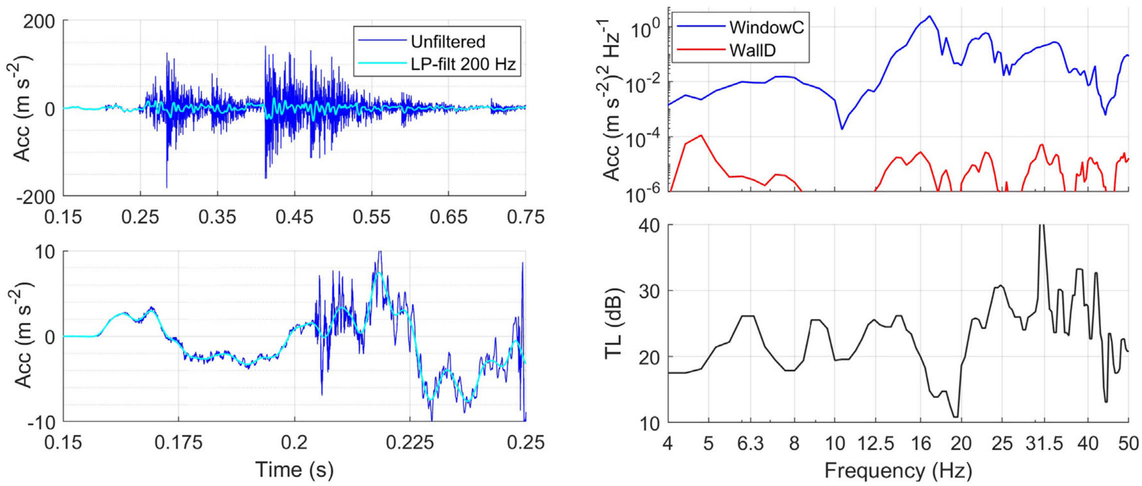

Fig. 12. Flight no2 in 2019. Left: unfiltered and low pass filtered (<200 Hz) time series of window acceleration (pos C). Right top: Power Spectral Density (PSD) of window (pos C) and wall (pos D) acceleration RMS 1 s, bottom: transmission loss between outdoor and indoor sound pressure.

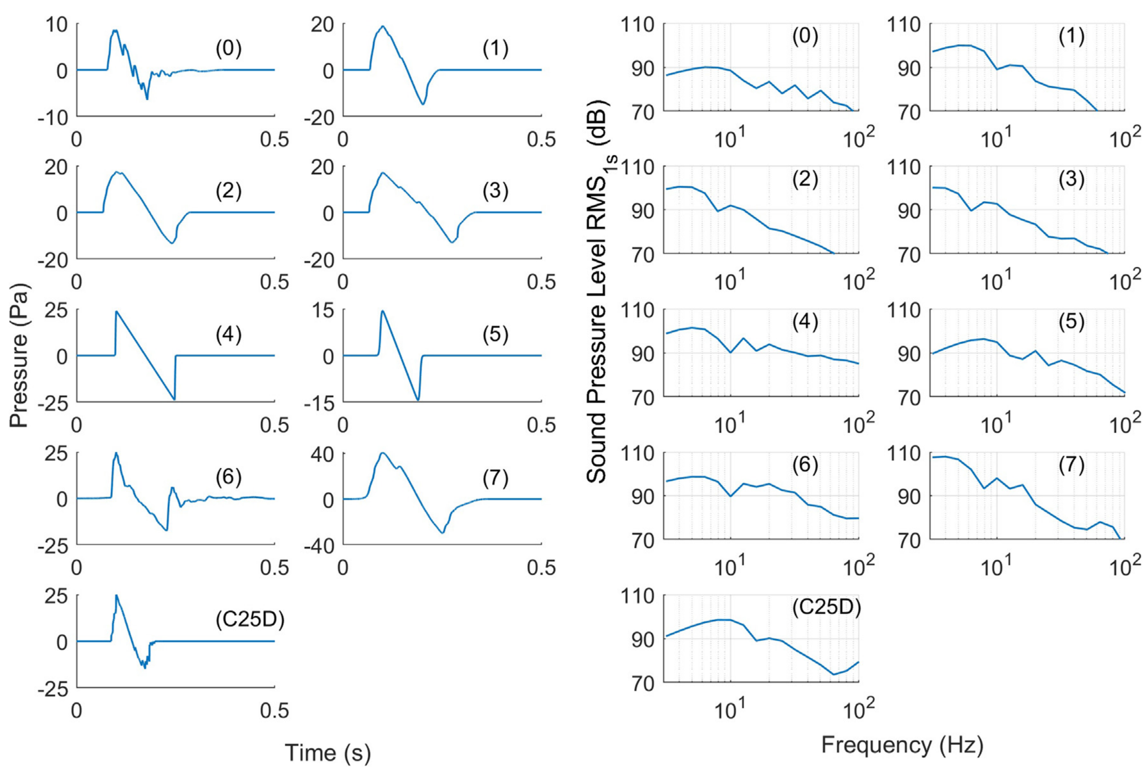

Fig. 13. Synthesised boom time series, left: time series of Sound Pressure, right: Sound Pressure Level RMS 1 s in 1/3 octave bands.

Table 5
Estimated indoor sound levels (dB) and acceleration (mm/s^2) in the Tretyakovo test building from the low boom realizations. SEL (L_E), A-weighted SEL (L_{AE}), A-weighted Maximum Level ($L_{Amax,F}$) and frequency weighted acceleration RMS1s (a_w).

Low boom time series	Open window			Closed window				
	L_E	L_{AE}	$L_{Amax,F}$	L_E	L_{AE}	$L_{Amax,F}$	a_w floor	a_w wall
0	94	37	46	84	32	41	0.6	0.7
1	103	33	42	90	30	38	1.1	1.9
2	104	33	41	88	29	37	1.0	2.0
3	103	34	41	87	29	37	1.0	1.8
C25D	101	41	50	90	37	46	1.7	1.6

of the realizations still exceed WHO's recommended limit of $L_{Amax,F}$ = 45 dBA with open window and one of these also exceeds the recommendation with closed windows. The calculated floor and whole buildings vibration values are lower than the limit value for class C in NS8176, corresponding to a_w = 10.7 mm/s^2, for all studied low boom realizations.

5.2. Lightweight wooden building

In the past, extensive measurement of low frequency noise and sound induced vibrations have been performed in buildings in Norway with blasts, fighter aircrafts and loud speakers as sound sources [35] and [38]. Fig. 14 shows the measured acoustic vibration admittance on floor in vertical direction for six different test buildings together with the results from the Tretyakovo test building in the present study. Note that in the Norwegian measurements presented in Fig. 14, low frequency microphones with a measurement range down to 0.1 Hz and floor accelerometers with 10 V/g sensitivity were used. This may affect the comparison with the results from Tretyakovo in the very low frequency range. However, in the frequency range important for floor vibrations, i.e. from about 8 Hz to 40 Hz, the limitations of instrumentation used at Tretyakovo are not considered to affect the measurement results significantly.

As can be seen from Fig. 14 there is a large variation between the admittance for the various buildings. Both the 1st resonance frequency, and the amplification at the 1st resonance frequency vary between the buildings. This reflects the fact that the buildings have different dimensions (e.g. floor span) and construction (e.g. type of joists and building materials). The rather stiff and heavy Tretyakovo test building represents the lower end of measured admittances with considerably lower values compared to the light wooden buildings that form the Norwegian experience basis.

To investigate which vibration values that can be obtained on the floor in another type of building representing the other end of the stiffness scale, measured acoustic vibration admittance for one of the Norwegian test buildings, Bodø 1st floor in Fig. 14, is convolved with measured outdoor sonic boom time series from the Russian flight test and with the low boom realizations in Fig. 13. The transformation from outdoor sound pressure to floor vibration is performed in the frequency domain by applying the admittance on the frequency spectrum of the sonic boom sound pressure signal, then the calculated floor vibration spectrum is transferred back to the time domain to obtain a time series of floor vibration. However, the measured admittance cannot be applied directly to the sonic boom sound pressure time series because of low coherence between the outdoor pressure and floor vibration in large parts of the frequency range of interest in the measured admittances. Such an approach would distort the time domain data in the convolution process, producing spurious vibration signals. Therefore, the building admittances are presented through an idealized filter function described by Eq. (7).

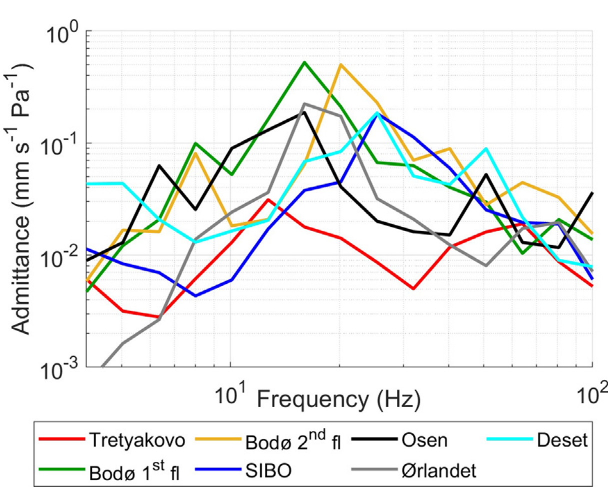

Fig. 14. Acoustic vibration admittance (vertical floor vibration/outdoor sound pressure) in the Tretyakovo test building determined from flight no 1 and no 2 in the 2019 flight campaign plotted together with admittances determined from previous measurements in Norway.

$$H_\omega = \frac{C_1 + C_2 i\omega}{\left((i\omega)^2 + 2Di\omega\omega_n + \omega_n^2\right)} \tag{7}$$

where the parameters C_1, C_2, f_n and D are determined by curve fitting the filter to the measured admittances around the first resonance frequency.

Figure 15 upper panel shows the curve fitted vibration building admittance describing the Bodø wooden building, while Fig. 15 lower panels show estimated floor vibrations in the Bodø building from sonic boom time series measured during flight passage no 2 in 2019 and from the low boom realization C25D. Note that the used procedure includes uncertainties and that the calculated floor vibrations should be considered as estimates of possible floor vibrations in a lightweight building.

The resulting frequency weighted velocity value is v_w = 1.7 mm/s (a_w = 61 mm/s^2) for the regular boom from the Russian flight test, which is much higher than the vibrations expected to cause complaints, and about six times higher than the limit value for class C in NS 8176. The frequency weighted velocity value for the low boom realization C25D is v_w = 0.4 mm/s (a_w = 15 mm/s^2), which is slightly above the limit value for class C in NS 8176. The results indicate that sonic boom and low boom may induce perceivable building vibrations.

5.3. Correlation between noise metrics and floor vibration

To investigate which noise metric is best suited to capture risk for sound-induced building vibrations, the correlation between frequency weighted floor vibration and outdoor sound pressure described by different metrics are determined, through linear regression. Degree of correlation is expressed by the Pearson's linear correlation coefficient. The correlation coefficient can have a value between + 1 and −1, where + 1 indicates total positive linear correlation, zero means no linear correlation, and − 1 indicates total negative linear correlation. Statistical significance is measured through the p-value, which is the probability that the result would have been found if the correlation was zero. The correlation coefficient is considered statistically significant if the p-value is lower than a certain number (0.01 is often used).

The correlations are investigated for four different datasets: 1) measured floor vibrations in the Tretyakovo test building, 2) calculated floor vibrations in the Bodø building using the measured outdoor sound pressure levels from the 2019 flight campaign as input, 3) calculated floor vibrations in the Tretyakovo test building using the 9 different boom realizations in Fig. 13 as input and 4) calculated floor vibrations in the Bodø building using the same 9 boom realizations as input. For the measured floor vibrations in the Tretyakovo test building, the dataset is limited to flight passages 3–6 and 8, since the sensor positions were different for flight passage 1 and 2 and outdoor noise levels are missing for flight passage no 7. All data sets are normalized with the highest sound pressure (in Pa) and floor vibration value (in mm/s^2) in each data set, before the datasets are merged and linear regression is applied. This is done to get equal weight on the different data sets as the large variation in data will otherwise favor the much higher responses

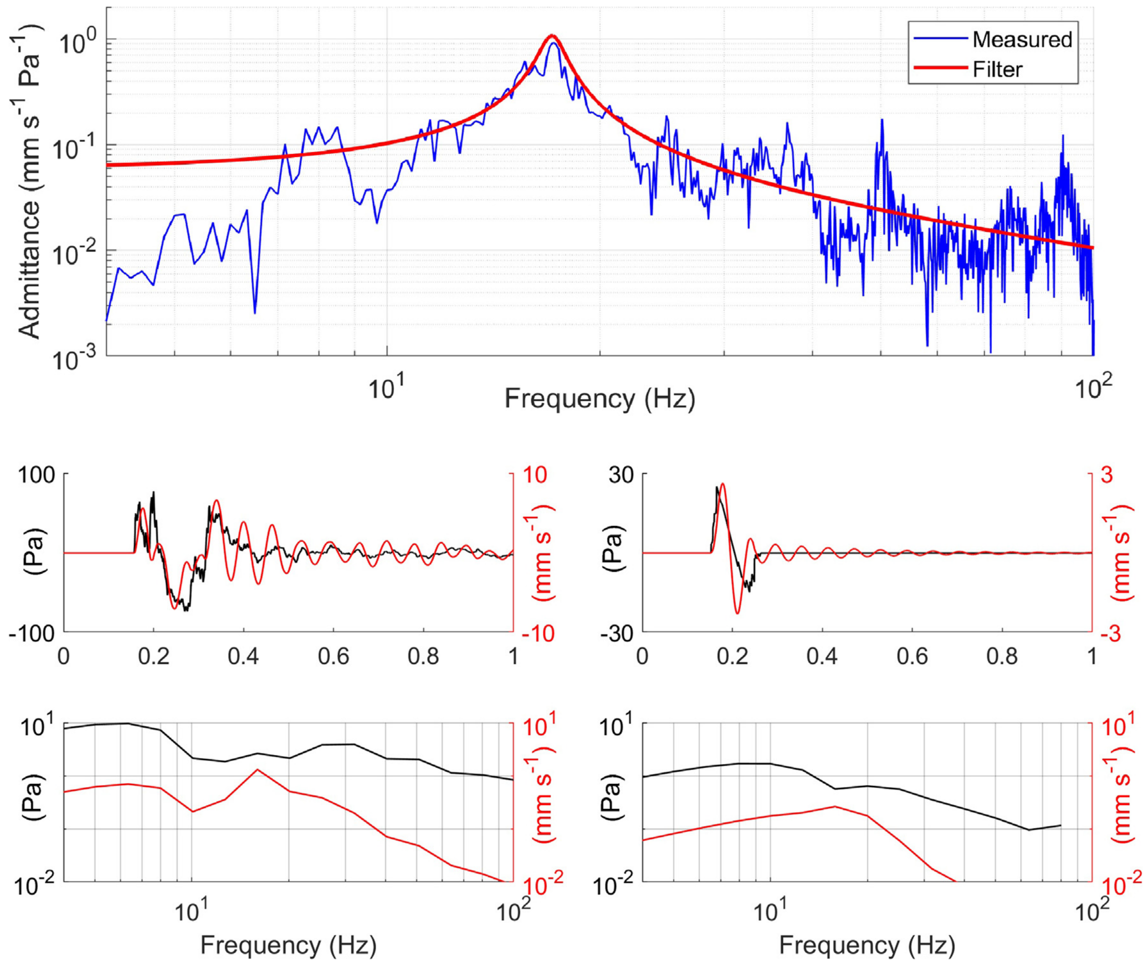

Fig. 15. Top: Bodø 1st floor. Floor admittances in vertical direction. Measured (blue) and curve fitted (red). Bottom: Calculated floor vibration in the Bodø building assuming exposure to the sonic boom time series from Left: flight no 2 in the 2019 flight campaign in Russia. Right: The low boom realization C25D. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

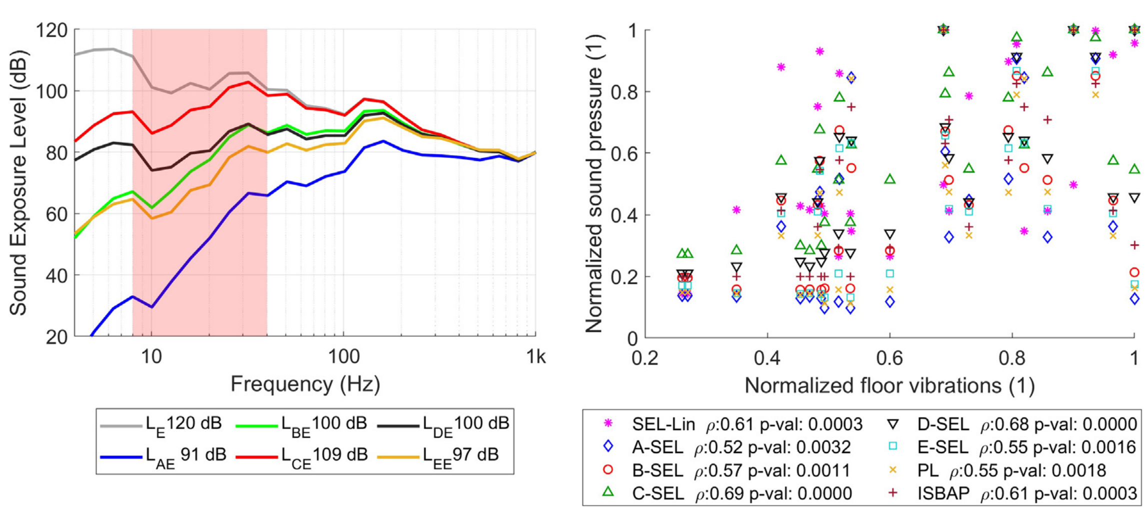

Fig. 16. Left: Outdoor SEL in 1/3-octave bands for flight passage no 2 in 2019 with different frequency weighting. The important frequency range for floor vibrations is marked with red. Right: normalized floor vibration plotted against normalized outdoor sound pressure described by different metrics. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Outdoor noise levels and indoor floor vibration from flight passages during the 2019 flight campaign and the low boom realizations in Fig. 13.

Data source	Outdoor noise metric (dB)								Floor vib a_w (mm/s^2)	
	L_E	L_{AE}	L_{BE}	L_{CE}	L_{DE}	L_{EE}	PL	ISBAP	Tretyakovo	Bodø
Flight 1–19	119	89	99	108	98	96	105	113	–	42
Flight 2–19	120	91	100	109	100	97	106	114	–	60
Flight 3–19	117	88	96	106	96	93	102	109	1.7	42
Flight 4–19	119	89	100	109	99	97	105	113	1.8	45
Flight 5–19	120	94	102	111	102	100	109	116	2.1	71
Flight 6–19	119	86	97	106	96	93	102	110	2.2	37
Flight 8–19	120	95	104	111	103	101	111	118	2.3	87
Sim TS 0	98	62	75	86	75	71	75	85	0.6	7.5
Sim TS 1	107	59	73	89	77	68	73	85	1.1	14
Sim TS 2	107	61	73	87	76	69	75	85	1.0	13
Sim TS 3	107	61	73	86	76	69	75	85	1.0	10
Sim TS 4	109	79	89	97	88	86	92	99	1.9	19
Sim TS 5	103	60	78	91	79	72	76	89	1.1	17
Sim TS 6	107	69	83	96	84	78	85	96	1.8	19
Sim TS 7	115	61	75	92	82	71	76	89	2.1	28
Sim C25D	106	77	84	93	85	82	90	97	1.7	15

from the Bodø test building due to the 2019 flight test over the other datasets.

Figure 16, left, illustrates the effect of the different frequency weightings curves, namely the A- B- C- D- and E- curves, applied on the Sound Exposure Level (L_E) measured for the flight passage no 2 in 2019. Fig. 16, right, shows calculated correlation coefficients and p-values between the different metrics and the floor vibrations. Table 6 tabulates the floor vibration and outdoor sound level described by the different metrics. The comparison shows that C-weighted SEL has the best correlation with frequency weighted floor vibration, while A-weighted SEL has lowest correlation. The results are as expected since all weighting filters reduces influence of the low frequencies noise which is most important for building vibrations, and the C-weighting filter cuts least and the A-weighting filter most in the low frequency range. These results are in accordance with the findings in Hodgdon et al. [13]. It should be noted that the discovered correlation between the different metrics and the frequency weighted floor vibrations is different than for noise. In Töpken and Van de Par [39] it was found, using the same simulated boom realizations as in the present study, that the A-weighted SEL had the best correlation with short-term annoyance and loudness, while [1] reports that when the sound includes rattling the outdoor C-weighted SEL has higher correlation with annoyance than A-weighted SEL.

6. Conclusions

Measurements of outdoor and indoor noise and noise induced building vibrations from sonic boom are performed in a test building at the Tretyakovo airport in Russia, using Sukhoj Su-27 and Su-30 aircrafts. The results show that the indoor noise levels are well above the recommendations from WHO and that the outdoor noise levels are clearly above proposed rattling threshold values. Rattling can also be heard clearly in the recordings from the measurements. Measured floor and wall vibration values are below the limit value for class C in NS 8176, which corresponds to a_w = 10.7 mm/s^2. However, measured wall vibrations in lateral direction coincides with the curve for residential buildings at night time in ISO 10137, while the vertical floor vibrations are clearly below the curve. This indicates that in this building, horizontal vibrations from the sonic boom may be associated with a higher probability of adverse comment than vertical vibrations.

The test building is a rather stiff construction and the measured vibrations may therefore not be representative for normal dwellings. To investigate which floor vibration values that can be obtained in another type of building representing the other end of the stiffness scale, measured admittance from a light wooden building is convolved with measured outdoor sonic boom time series from the Russian flight test. The resulting floor vibrations are about six times above the limit value for class C in NS 8176 and far above vibration values that are expected to cause complaints.

Synthetic low boom realizations from the second AIAA workshop, as well as the C25D low boom realization, are used to estimate floor vibrations from low boom in both the rather stiff Tretyakovo test building and in the lightweight wooden building. The vibration values from the low boom realizations are well below the limit value for class C in NS 8176 in the Tretyakovo test building and slightly above the limit value for class C in NS 8176 in the lightweight wooden building. The results show that also low boom may cause perceptible levels of floor vibrations and that the building type has a great influence. This indicates that there can be a big difference between the European countries depending on the building tradition.

A correlation study shows that outdoor Sound Exposure Levels with C-weighting correlates best with frequency weighted floor vibration values and that Sound Exposure Levels with A-weighting has the lowest correlation.

In the Rumble project Finite Element models have been developed to calculate whole building motion, outdoor to indoor sound transmission, and generation of floor vibrations for different buildings types. The FE-models represent the range of building types in Europe and both detached buildings and flats in multi-storey buildings have been studied. In addition to providing information on typical vibration values from sonic boom, the measurement results have been used to calibrate these models.

CRediT authorship contribution statement

Karin Norén-Cosgriff: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Ivan Belyaev:** Funding acquisition, Investigation, Project administration, Resources, Writing - review & editing. **Finn Løvholt:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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