MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Numerical modelling of very low frequency sound transmission loss through walls from sonic boom

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ABSTRACT

Infrasound and audible sound at very low frequency may cause human annoyance by inducing building vibration, involving both rattling and whole body vibration sensing of humans. Here, we present results from a numerical modelling study of the very low frequency component of sonic boom and its effect on generating construction vibration conducted. The work is conducted within the H2020 RUMBLE project. The motivation is low frequency noise and sound induced vibration caused by aircrafts, in particular those from sonic boom. Results from field measurements conducted prior to RUMBLE is combined with sonic boom signals to give a first estimate of potential magnitude of boom induced vibrations. Then a Finite Element (FE) model developed in COMSOL Multiphysics is used to simulate the low frequency sound transmission loss for one lightweight structure and one concrete wall. Secondly, the floor construction is added for simulating the floor vibration. Furthermore, we discuss possible generalizations, such as changing room configuration, wall types, high rise buildings etc. An outline for a review of the acoustic properties for different construction types are also given. Altogether, we discuss how the interplay between the various elements discussed above can be combined to better quantify sonic boom induced building vibration.

Keywords: Sonic boom; vibration; transmission loss; numerical modelling
I-INCE Classification of Subject Number: 49

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1. INTRODUCTION

Outdoor sources such as wind turbines, aircrafts, heavy weapons and explosions induce significant sound pressure levels in the very low frequency range. Supersonic flights produce a particularly large low frequency sound pressure that might propagate far from the source compared to most conventional sound sources. A similar situation is expected for potential new aircrafts that are optimized for producing a so-called low boom, i.e., a boom with smaller peak frequency and smoother pressure-wave characteristics than a boom from present supersonic flights. If the low frequency component of the sound pressure is sufficiently strong, it may give rise to floor vibration and rattling inside buildings, which may in turn be negatively perceived by humans. The rattling due to the low frequency components of sonic booms have been subject to recent attention (Rathsam et al., 2015), as supersonic overland flight capabilities are presently being explored by NASA. In order to predict the vibration levels due to sonic booms and low booms, numerical models and measurements of sound-induced vibration are necessary and complementary components. As boom-induced vibrations share essential characteristics with vibration induced by other low frequency sound sources such as those generated by blasts or conventional aircrafts, models and data from such applications provide an important background.

The objective of this paper is to outline the multitude of aspects related to generation of low frequency induced building vibration from sonic booms, which is studied in the Horizon 2020 RUMBLE project (https://rumble-project.eu/i/). A substantial basis for understanding sound-induced vibration from subsonic flights was established for in a preceding research program (main findings are summarized in Norén-Cosgriff et al., 2016, and Løvholt et al., 2011, 2013, 2017). This research program consisted of laboratory measurements and development of numerical models for simulating low frequency sound transmission through buildings, as well as developing countermeasures for reducing the induced vibration. The focus was mainly on lightweight constructions. The effects of countermeasures were tested in full scale by measuring the low frequency sound transmission loss and floor vibration before and after the countermeasure was implemented (Norén-Cosgriff et al., 2016). The project also conducted a review and a compilation of previous field measurements of building-induced vibration in the field, to better understand the natural variability of how different buildings respond dynamically to low frequency sound. The main findings from the project are:

- Building vibration is caused by a two stage process: First, the outdoor sound is transmitted through walls, windows and roofs. Then, the indoor sound pressure generates floor vibration.
- Properties of joints and connections between elements in lightweight constructions and windows are important for correctly predicting transmission loss. The overall wall stiffness is important for characterising the transmission loss at low frequencies.
- Consequently, countermeasures towards sound-induced vibrations should focus on reducing the transmission loss at low frequencies by increasing, for instance, the wall stiffness.
- Building vibrations detectable by humans should be expected from conventional aircrafts if the low frequency energy in the relevant bandwidths exceed 75-80 dB.
- Individual buildings of similar types can produce significantly different vibrations depending on the quality of the building.
- The main factors influencing sound transmission loss is the quality and damping characteristics of windows and the stiffness and mass of walls and roofing.

Similar findings have been reported in broad studies investigating the effects of sonic booms on buildings carried out by NASA (see e.g. Remillieux 2012; Remillieux et al., 2013). However, both the studies by NASA and NGI have been focused on the effects on lightweight structures, whereas other types of structures have received much less attention. Moreover, the direct effect of floor vibrations generated by sonic booms and low boom signals on human perception and annoyance have not been studied. It is therefore apparent that better understanding, tools, and analysis of the interplay between buildings and sonic booms are necessary for providing a basis for future legislation, which is one of the objectives of the RUMBLE project. To this end, the present paper touches upon some different challenges for understanding better how vibration is generated by sonic booms. The work presented here is – to some extent – work in progress, and more detailed results are expected later.

This paper is organised as follows. In Section 2, we show an analysis of empirical vibration data from field measurements combined with sonic boom signals. This is not only important to characterise the building response to sound, but are also as input to studies of psychological effects of the vibration in other parts of the RUMBLE project. In Section 3 we discuss briefly the outline of a review of acoustic properties of different building types. This study serves as a background for setting up numerical simulation models for transmission loss and induced vibration in buildings, of which preliminary results are described in Section 4. This section focuses on numerical simulation of transmission loss into single rooms, but also discusses briefly an approach for modelling more complex structures such as multi-storey buildings. Finally, some very brief conclusions are presented in Section 5.

2. VIBRATION RESPONSE TO SONIC BOOM LOADING BASED ON FIELD MEASUREMENTS

2.1 Building vibration response to low frequency outdoor sound

Various measurements have been carried out in Norway to characterise the vibration response in building due to low frequency sound sources during the last two decades (Løvholt et al., 2009, Norén-Cosgriff et al., 2016). These measurements can be used to develop admittance functions that relate the vibration at a given frequency to a given sound pressure spectral amplitude. While the sound admittance is determined from other sound sources than sonic boom sources, the linearity of the problem allow us to use these measurements to study the effects of sonic booms in similar buildings.

As an initial approach to this problem, a set of commonly accepted sonic boom sound pressure spectra (Loubeau et al., 2015) combined with measured acoustic vibration building admittances derived from earlier extensive field tests in Norway (Løvholt et al., 2009, Norén-Cosgriff et al., 2016), are used to estimate boom-induced spectra for the mid-span floor vibration. These measured admittances mainly describe typical Norwegian wooden buildings. However, within the RUMBLE project they will be supplemented later with admittances for other buildings types typical for the European building tradition, obtained from FE simulations similar to those described in Section 4.

We define the acoustic vibration building admittance as the indoor floor velocity divided by the outdoor sound pressure as a functions of the frequency. Hence, a higher admittance value at a given frequency implies that a building is more prone to vibration at that frequency. Floors are often characterized by a pronounced first natural frequency where the admittance reaches a maximum. Figure 1 shows the measured acoustic vibration building admittance in vertical direction for six different test buildings in Norway.

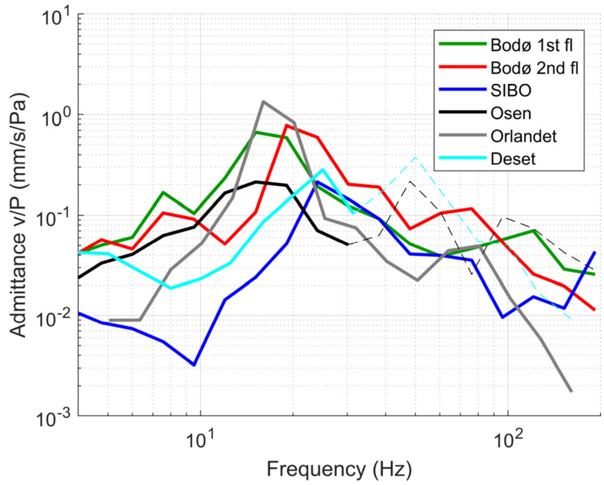


Figure 1: Measured acoustic vibration admittance for six different test buildings as a function of the 1/3 octave frequency. The figure shows admittance due to (vertical) vibration normal to the floor surface. Dashed lines indicated low signal-to-noise ratio.

As can be seen from Figure 1, there is a large variation in admittance between the various buildings. Both the 1st floor resonance frequency, and the amplification at resonance, varies 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), but the admittance may to some extent also be sensitive to the orientation of the acoustic load.

2.2 Estimated sonic boom induced building vibration

The measured admittances and the sonic boom time series cannot be combined directly, since an approach using measurement data without modification introduces major errors at frequencies where the coherence is low. In particular, such a crude approach would severely distort the inversely transformed time domain data when convolving the data with source information, hence producing a spurious vibration signal. To overcome this issue, the building admittances were represented through an idealized filter function. As a simple approach, the floor response on the outside sound pressure can be described by use of a single degree of freedom system (SDOF), with a transfer function as described by:

$$H_\omega = \frac{C}{((i\omega)^2 + 2Di\omega\omega_n + \omega_n^2)} \tag{1}$$

where the parameters C, f_n and D are determined by curve fitting the SDOF system to the measured admittances around the first resonance frequency in each direction. Figure 2 shows the measured admittances and fitted transfer functions for one of the test buildings for which results are presented in Figure 1.

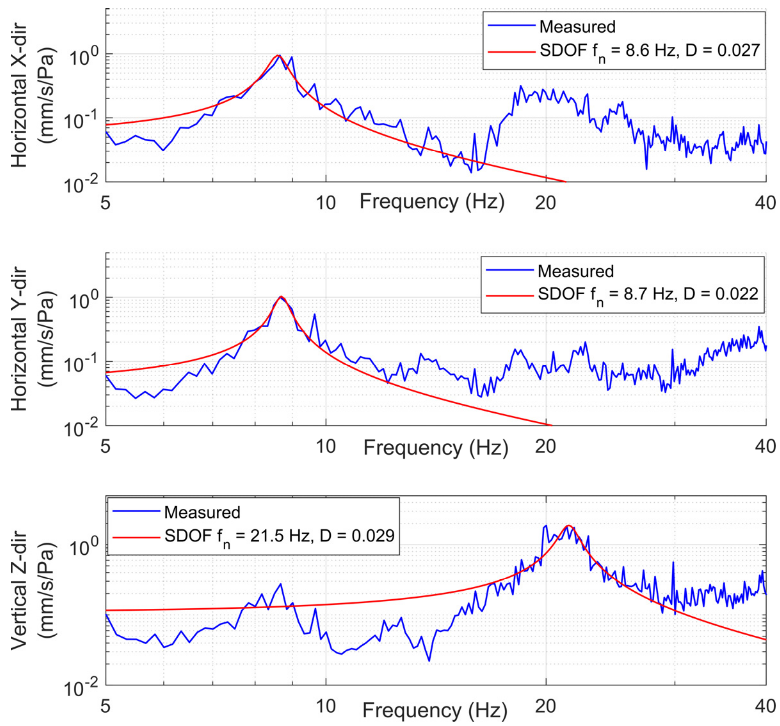


Figure 2: Test building Bodø 2nd floor. Magnitude of the acoustic vibration building admittances. Measured (blue) and curve fitted (red) SDOF transfer function as described by Equation 1.

The idealized vibration building admittances filter functions are combined with the commonly accepted outdoor sonic boom time series (Loubeau et al., 2015) to obtain floor vibrations time series in the following way: First, the sonic boom time domain signals are transformed into the frequency domain via the Fast Fourier Transform (FFT). Secondly floor vibration spectra are calculated by taking the product of the sonic boom frequency spectra with the simplified admittance transfer function given in Equation 1. Subsequently, the calculated floor vibration spectra are transferred back to the time domain via the inverse FFT, and time series of floor vibration in all three directions are obtained.

Comparing different boom signals, we found that steeper sonic boom pulses generates more broadband noise, and longer sonic boom pulses generate more low frequency noise. Figure 3 shows an example of a sonic boom time series together with calculated floor vibrations. The top panel shows the floor vibration time series together with the sonic boom time series. The lower panel shows the 1/3 octave spectra of the maximum RMS 1s floor vibration and sound pressure. Frequency weighted RMS 1s velocities according to NS8176, are given in the legend, to facilitate comparison between different sonic booms and buildings.

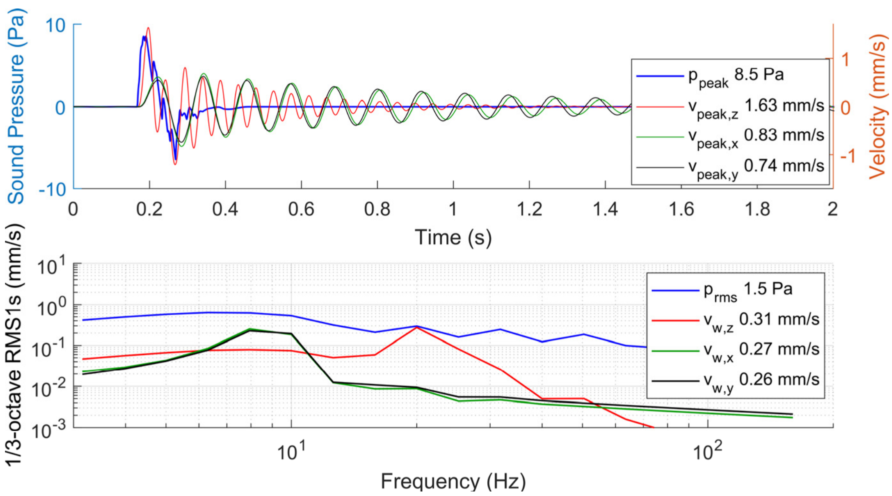


Figure 3: Test building Bodø 2st floor. Sound pressure and calculated floor mid-span velocity in time and frequency domain for a sonic boom time series.

3. REVIEW OF TYPICAL STRUCTURES SUBJECT TO SONIC BOOM

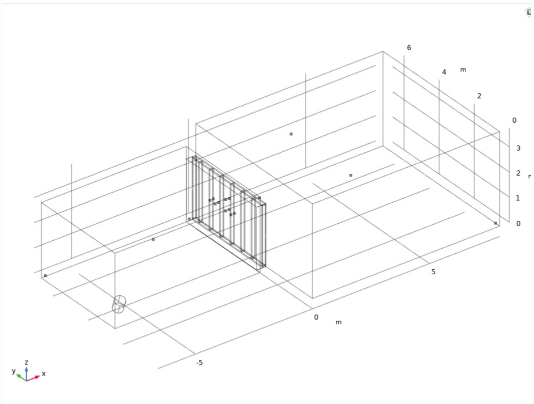
Different building types will respond differently to the low frequency noise caused by sonic boom and low boom. Since the building tradition varies greatly between countries, a review of typical building constructions in Europe with emphasis on the vibro-acoustic response have been initiated as part of the RUMBLE project. This classification encompasses buildings with fundamentally different dynamic properties. Importantly, the review will therefore include buildings with drastically different dynamic properties than the 1-2 storey wooden buildings analysed in Section 2, e.g., masonry buildings, concrete buildings, multi-storey buildings etc. Both the properties of the outer construction that control the transmission of sound into the building, and the properties of the floors that control the vibration response, will be described. Building types which are representative of the building traditions in different part of Europe, and are believed to respond differently on sonic boom, will then be selected for further study and FE-modelling. The basis for the selection will be the reports from the Cost Action TUO901 and C16. These reports provide information about typical constructions in different part of Europe, as well as information about the age of the housing stock and the distribution between apartments and detached houses in the European countries.

4. SIMULATION OF TRANSMISSION LOSS AND FLOOR VIBRATION FOR DIFFERENT TYPES OF STRUCTURES

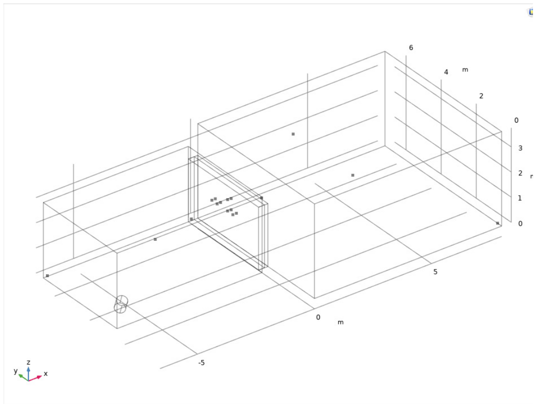
4.1 Transmission loss through different types of walls

We here demonstrate the effect of wall types on the low frequency transmission loss by simulating two types of walls using the FE package COMSOL Multiphysics. The methodology for setting up the numerical simulations in COMSOL are described in Løvholt et al., (2017), which for brevity, is not repeated here. The two structures merely demonstrate possible results, and will be expanded later in the RUMBLE project to include several types of structures based on the literature review described in Section 3.

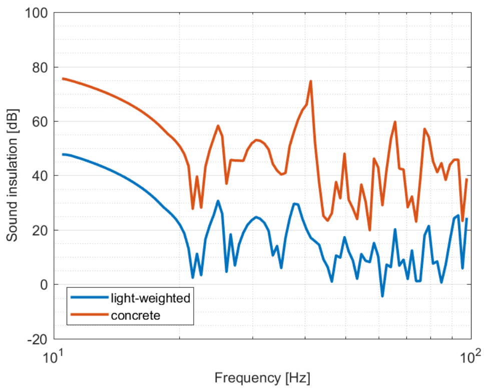
The following structures are modelled: (a) a lightweight wall of 148mm thickness, consisting of vertical studs (60cm spacing) separated by two plasterboards of 9 mm and 13 mm thickness, respectively; and (b) a wall of similar geometry but made of concrete blocks of 148mm thickness. The latter is naturally much stiffer than the former, thus giving much higher transmission loss. Presented in Figures 4a-b are the geometries of the two FE models, which include a source room (left box), a receiver room (right box) and the in-between finite-thickness wall. All the boundaries in the models, except those facing the wall, are given zero-flux (fully reflecting) boundary conditions. Figure 4c compares the transmission losses resulting from the two different simulations. It is clear that the concrete wall provides a much larger low frequency transmission loss than the lightweight wall. To this end, the two structures might possibly be end members with respect to the magnitude of the transmission losses, as the simple wooden structure provides a small large transmission loss, whereas the concrete wall is very efficient blocking the low frequency sound transmission. As windows are expected to be important, the transmission loss properties of the separating walls are expected to change substantially in later analysis where windows will be included.



(a)



(b)



(c)

Figure 4: (a) FE model of the lightweight wall (similar to the standard wall without window in Løvholt et al, 2017); (b) FE model of the concrete wall, a concrete-block wall of the same thickness of 148mm); (c) comparison of transmission losses calculated for the two different walls.

4.2 Floor vibration admittance

Next, we calculate the admittance within a room whose FE model consists of a wall and a floor, shown in Figure 5a. The wall is the same type as that shown in Figure 4a, but is longer and has a double-glass window attached at the north end. The floor is made of wood studs with 30 cm spacing and 223mm height. The admittance is calculated by dividing the vertical velocity (measured at the middle of the floor) by the pressures calculated at the top corners near the wall, and is depicted in Figure 5b. Figure 5c displays the mode shape of the FE model together with pressure distribution plotted in colour scale on the model boundaries at ca 15.9Hz. The amount of displacement is exaggerated simply to make the model shape visible in the figure.

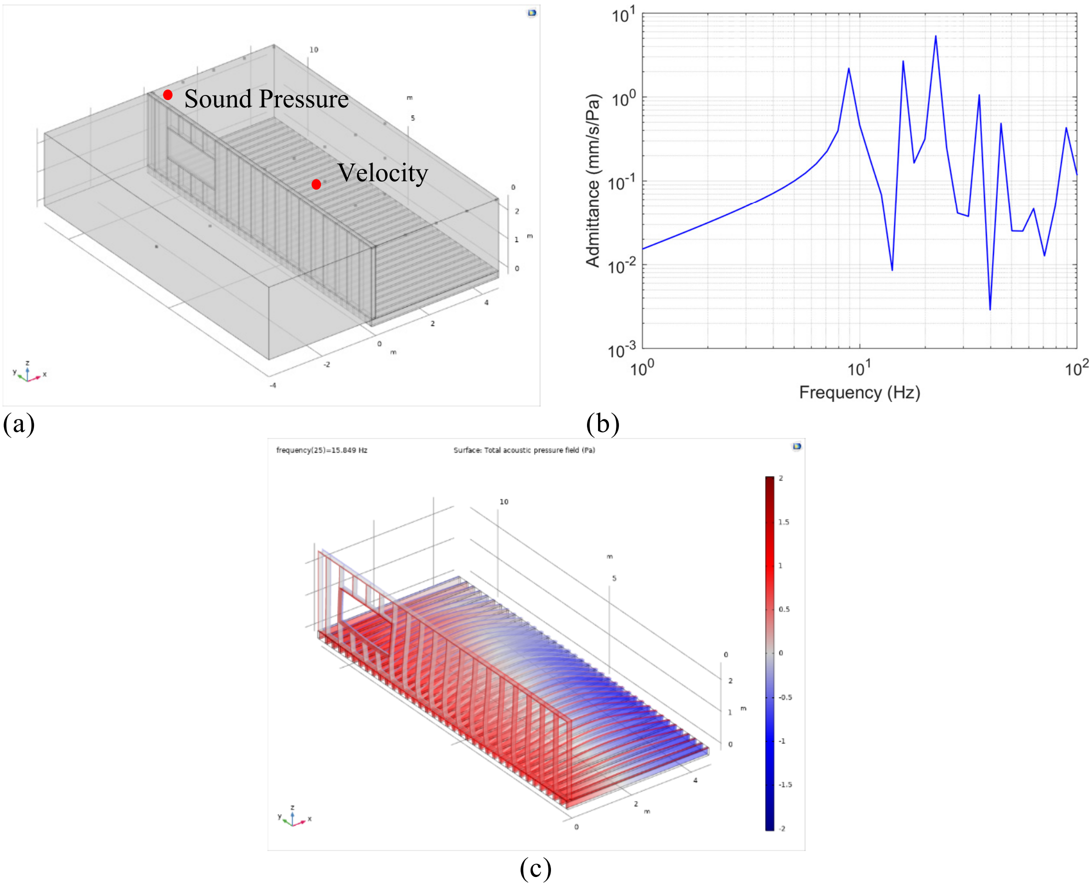


Figure 5: (a) geometry of an FE model with a lightweight wall with a window and a floor; (b) comparison of two admittances calculated as the vertical velocity at the floor middle divided by two pressures calculated at the top corner; (c) an example of mode shape of the FE model together with pressure distribution plotted on the model boundaries.

4.3 Modelling sound-induced vibrations in multi-storey buildings – some considerations

Simulating sound-induced vibrations in large, multi-storey buildings using the detailed 3D FE model described above is impractical due to the prohibitive computational demand such an analysis would entice. To overcome this issue, the numerical model must be substantially simplified. We therefore assume that the acoustic-structure interaction problem can be decomposed into two parts: (1) the room-specific acoustic response, characterized by the transmission loss and vibration admittances described in Sections 4.1 and 4.2; and (2) the global dynamic response, characterized by the overall vibration modes of the building. The first of these involves mainly vertical vibrations induced by indoor sound pressures, whereas the latter, particularly in the case of multiple storeys, involves largely horizontal vibration in the shape of the vibration modes of the building, induced by the outdoor sound pressures.

For capturing the global, boom-induced response of these buildings (i.e. the second of the above problems), the approach proposed by Andersen et al. (2012a and b) will be implemented, which involves the following assumptions:

- The acoustic air inside the rooms is not modelled, only the external pressure loading applied to the outside of the building.

- The building is decomposed into modules defined by its horizontal and vertical divisions (i.e., wall panels and floors), which are connected together by a regularized artificial "skeleton" of low stiffness.
- Each of these individual modules are represented in the global model by a substructure that retain only a few degrees-of-freedom relative to the detailed FE model of each module.

This way, the number of degrees-of-freedom in the global model, and hence the computational time, is drastically reduced, while the overall accuracy in computing the sound-induced building vibrations are largely maintained. Initial results demonstrate that this approach is able to provide results of sufficient accuracy to estimate sound-induced vibrations; more work on this topic is currently ongoing. We further note that due to linearity, it is expected that the acoustic problem for a single room may be superimposed with the global analysis to estimate the total vibration inside a room.

5. CONCLUDING REMARKS

In this paper, we have reviewed different aspects related to building vibration caused by sonic booms, and have outlines some steps that are needed for predicting such vibrations. The main component of this modelling strategy is developed within the COMSOL Multiphysics FE tool, with supporting basis from previous laboratory and field measurements. In the paper, we have showed that sonic booms may induce significant vibrations in buildings due to the low frequency nature of the boom that tends to coincide with the natural frequency of many building types. Some initial modelling results are presented, mainly aimed to illustrate the different steps that are needed to model sonic boom-induced vibrations under different conditions and for different building types. In the future, we expect that by using the outlined methods, the effects of sonic boom vibration on different building types will be illuminated and populated with a wide range of examples.

6. ACKNOWLEDGEMENTS

The RUMBLE project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 769896.

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