Acoutect Demonstrator for Multi-story buildings

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Recommendation for a Standard Rolling Noise Machine

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CHAPTER 1

Problem definition

In the world of building acoustics, a standard tapping machine has long existed for the purpose of replicating and regulating impact noise. This device, shown in Figure 1 below, was originally designed to mimic the sound of human footfall, and works by raising and dropping a series of hammers in order to generate impacts with the floor. While this is indeed one of the major sources of annoyance when it comes to indoor structure-borne noise, there still exist other sources (whose primary transfer path is through the floor) which could benefit from being considered when designing a building. One of these is rolling noise.

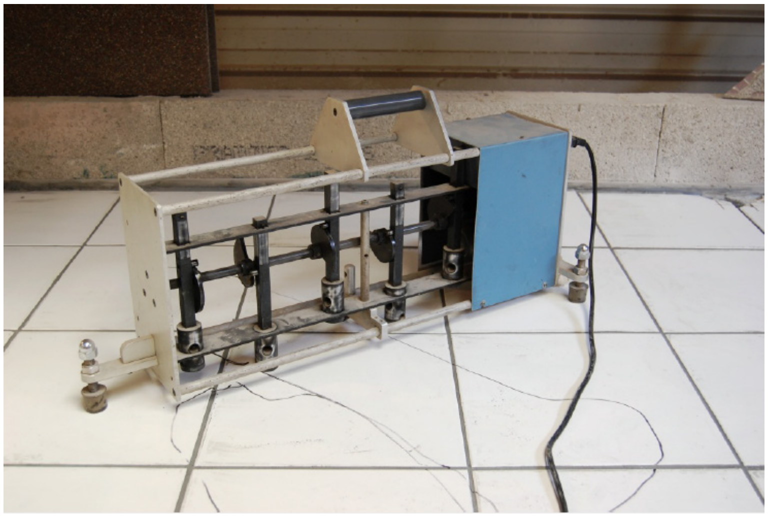


Figure 1: A typical tapping machine. The five hammers repeatedly drop in succession to generate impacts with the floor at a rate of 10 impacts per second.

Rolling noise is mainly characterized in regards to traffic noise such as railways and automobiles, but may also cause annoyance in multi-storey buildings. Among the potentially annoying activities for the residents living above commercial areas, those concerning delivery and supply activities are often mentioned. Indeed, the rolling of the supply trolleys or pallet trucks is transmitted, via the structure of the building, from the floor of the commercial spaces, or reserves, to apartments. Rolling noise can also be generated by items like children’s toys, suitcases, and rolling desk chairs in offices or apartments. It may seem that treating this problem requires a focus on the building construction, as is the case for impact noise. However, the sound originates from the vibrations generated by the small-scale roughness between the floor and wheels. As shown in Figure 2 , this causes structure-borne noise to propagate through the building as they roll across the floor.

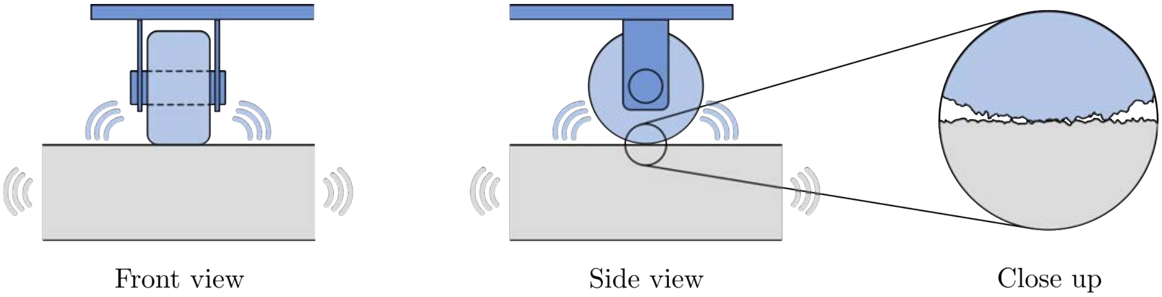


Figure 2: A typical rolling noise schematic. The small-scale roughness between the floor and wheel generates structural vibrations as the wheel rolls across the floor.

Solutions for acoustic treatments exist, but they are sometimes hard to implement and their effectiveness is difficult to evaluate. Hence, the absence of a standard method to characterize rolling noise makes it hard to treat it effectively.

This research aimed to study, in terms of feasibility, the development of a standard rolling noise machine. Just as the standard tapping machine can be used a way of characterizing and comparing the performance of various floors with respect to impact noise, the development of a standard rolling device would enable the same evaluation and comparison to be made with respect to rolling noise.

Occurrence of the problem

As multi-storey buildings are widespread in urban areas, rolling noise has proven to be a source of annoyance for their occupants: whether in offices, commercial shops, or apartments. In work environments, the noise caused by the movement of users in their chairs may reduce employee's productivity by increasing their stress level. It can also affect the occupants' apartments adjacent to the offices.

The presence of commercial stores on the ground floors of multi-storey buildings is common in urban areas. The trolleys and pallet trucks which are commonly used to transport goods around the stores generate rolling noise which easily propagates to the floors above: disturbing the habitants therein. Furthermore, these deliveries are usually done early in the morning or late at night: when silence is most needed.

Looking for methods to characterize rolling noise effectively has become evident. Figure 3 below shows the sound spectra of a typical tapping machine and rolling noise on a classical concrete floor, as well as the attenuation of a classical floating floor. The sound signature of impact noise is quite different than that of rolling noise in both the time and frequency domains. Considering the prevalence of tapping machines, this mismatch means that focus is rarely given to the effects of rolling noise when designing acoustic treatment systems for floors, resulting in a gap in performance.

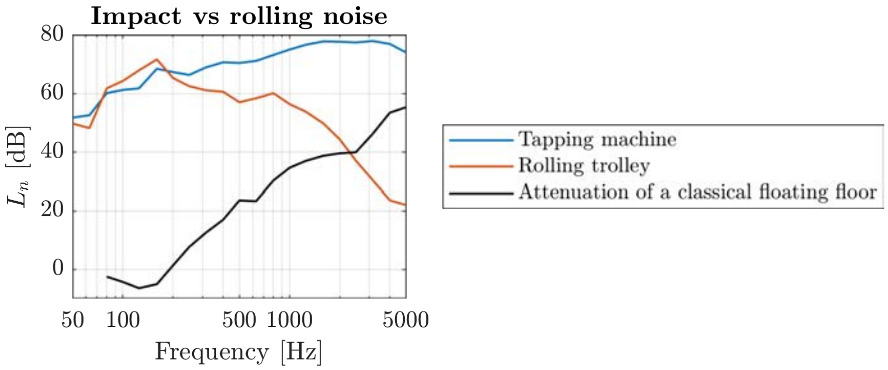


Figure 3: Comparison of the spectra of tapping noise and rolling noise on a classical concrete floor, as well as the attenuation of a classical floating floor (140 mm concrete slab + a decoupling layer + 400 mm screed).

State-of-art

The primary existing standard for characterizing indoor structure-borne noise is the tapping machine. There also exists a standard for a rubber ball, which is sometimes used when low frequency impacts are of greater interest. Since indoor rolling noise is a topic which has been scarcely studied until this point, there exists very little established methodologies for how to address it (hence the desire for a standard). Edwards et al have developed a model for predicting indoor rolling noise which used a two-wheeled cart, shown in Figure 4 below. This cart is pushed manually by an operator in order to replicate the noise of a trolley. While this appears to be a good start, there is still much room for improvement.

Figure 4: A rudimentary test cart used to generate indoor rolling noise.

Approach

The goal of this project was to design a prototype for a standard rolling noise machine. Just as the standard tapping machine can be used to characterize a building's performance with respect to impact noise, a standard rolling device enables the same evaluation to be made for rolling noise. This was accomplished in three phases: background research, rolling sources characterization, and prototype design.

As the long-existing standard for indoor impact noise, the history of the development of the tapping machine was used as guidance to inspire the development of the rolling machine. The rationale for the decisions that were made and design aspects that were prioritized were used as a roadmap for how to best develop the engineering requirements of the rolling machine. Following this, a range of indoor rolling items (e.g. trolleys, office chairs, suitcases, etc.) were tested to acquire a robust understanding of the range of sound signatures that may be encountered. Additional tests were conducted using special test trolleys which were developed to more accurately assess certain aspects of indoor rolling excitation. All of this served as insight for the final phase, which involved the design of the prototype itself.

Such a prototype may serve as a tool for future acousticians wishing to characterize indoor rolling noise. By having a single device which can reliably produce the same excitation in multiple environments (e.g. different test labs or different sites in the field), further work in indoor rolling noise may be done in such a way that results from different measurement locations may be reliably compared. Furthermore, the performance of different flooring materials with regards to rolling noise may be evaluated with such a device, allowing for greater insight when designing buildings with multiple noise sources in mind.

Timeline & design process

Each phase of this project was completed in collaboration with various Acoutect partners. In 2018, the team visited the offices of NCC in Gothenburg, Sweden, to do background research on the history of the development of the tapping machine, in order to find inspiration for the correct process to follow when developing a rolling machine. In late 2019 and early, three weeks were spent measuring and characterizing a multitude of indoor rolling noise items at Level Acoustics & Vibration in Eindhoven, the Netherlands. Finally, the group worked together remotely throughout mid 2020 to develop the computer aided design (CAD) model for the rolling noise prototype, as well as a recommendation for how it should be used to produce reliable measurements. The team also received expert guidance during the entirety of the project from Matelys Research Lab: one of the leading laboratories in indoor rolling noise research.

To ensure the robustness and quality of the proposed device, the team adopted an iterative design methodology. In other words, a repeated cycle of the designing, assembling, testing, and redesigning the prototype. This approach allowed for rapid improvements of the prototype to ensure its design goals. Devices used to perform measurements must be reliable and self-aware of error. Therefore, the main design considerations were accuracy, repeatability and ease of use.

CHAPTER 2

Rolling household objects

Indoor rolling devices come in a wide range of shapes, sizes, and applications. Wheeled office chairs and rolling children's toys may differ greatly in how big they are and how they are used. However, one thing they have in common is they both have wheels, and they both generate rolling noise when moved. So, a question which may be raised is, how does the sound signature of these various rolling household objects differ from one to another? Are the differences in sound just as large as the differences in appearance and application? Or do they all more or less fit the same acoustic pattern?

Figure 1 below shows the sound spectra of various rolling household objects, which were all measured in the same laboratory environment. Photos of these objects are also shown in Figure 2. A very wide range in sound level exists between the different rolling devices, going from 30 dB for the suitcase all the way to over 60 dB for the large dolly. The spectra differ in frequency content as well (i.e. the general shape of the curve, ignoring differences in overall level), though to a lesser degree. They all follow the general trend of having the majority of the acoustic energy existing in the low frequency range, and tapering off rather quickly above 500 – 1 000 Hz.

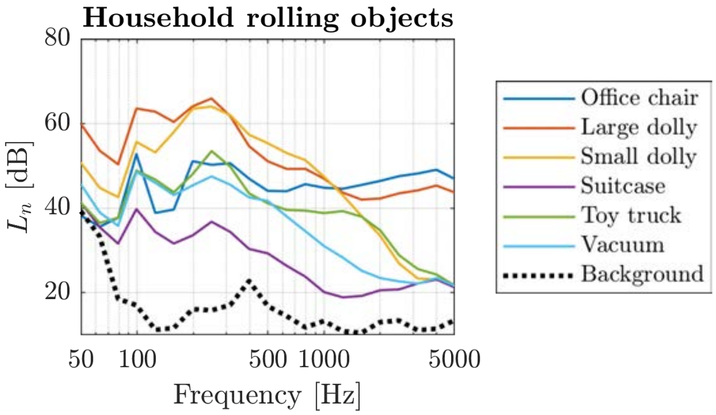


Figure 1: Normalized sound pressure level of common rolling household objects.

Figure 2: Rolling household objects measured (left to right): office chair, large dolly, small dolly, toy truck, vacuum, suitcase.

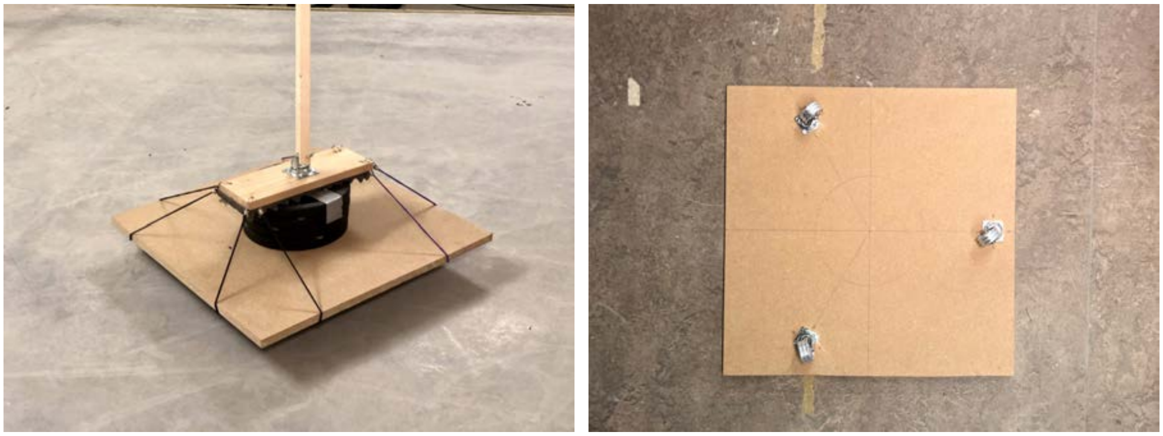
These measurements were conducted at Level Acoustics & Vibration in Eindhoven, the Netherlands. The sound generated by each device as it rolls across the floor was captured in a two-story transmission room: with the device being rolled in the top (emission) room, and the sound measured in the bottom (reception) room. The two rooms were separated by a 10 cm thick concrete floor, which was decoupled from the surrounding floor to eliminate sound transmitted to the reception room via flanking transfer paths. That is, the test floor was built in such a way that, when conducting measurements in the reception room, one can be sure that the only sound being measured is that which is transmitted directly through the structure of the floor in the vertical direction.

Influencing parameters

It is clear that a more thorough approach is necessary in order to determine how the different aspects of each device (it's mass, it's wheels, etc.) influence the kind of sound it will produce. Before work may begin on designing a standard rolling machine prototype, the factors which play a role in how this device will sound must first be understood. To this end, a second series of measurements were conducted in the same laboratory as the previous ones. This time however, a test trolley (shown in Figure 3) was used to generate the rolling noise, which was capable of having a number of its influencing parameters modified in a controlled manner. This functioned as a parametric study of sorts, in order to measure the effect of the following factors:

- The added mass on the device
- The distance between the wheels
- The material of the wheels
- The rolling trajectory of the device

The test trolley had three wheels, ensuring that no loss of contact would occur between the floor and one of the wheels (which can happen with 4+ points of contact), resulting in additional rattling noise.

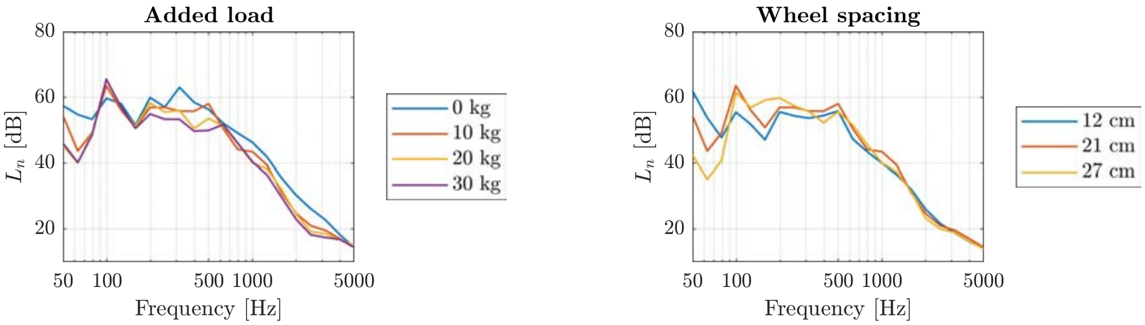


(a) Top view

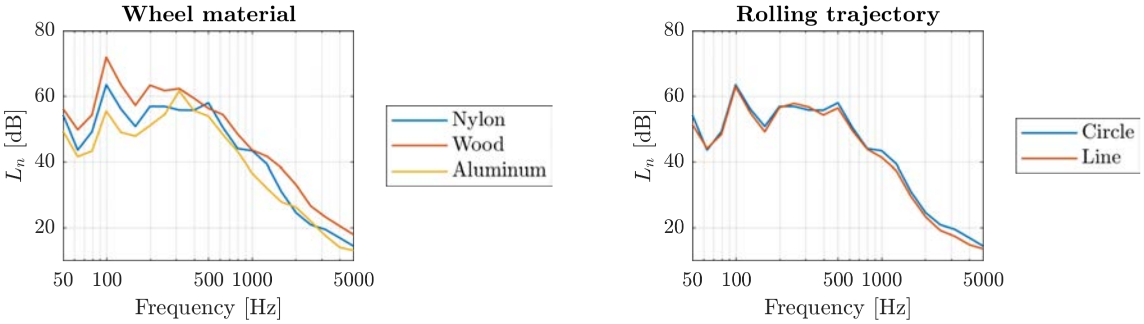
(b) Bottom view

Figure 2: Test trolley used in the parametric study.

The results of these tests, showing the influence of each of the measured factors, are shown in Figure 4. Perhaps counterintuitively, increasing the mass on the trolley does not increase the sound level. Quite the opposite happens, as a matter of fact. The heavier the trolley, the more modes are dampened, and the less vibration occurs. So, does this mean our standard rolling machine should be as light as possible? Not quite. The trolley must be heavy enough to ensure the wheels always remain in contact with the floor (even for a two or three wheeled trolley, loss of contact may occur if the trolley is light enough and the relative roughness between the floor and the wheel is large enough). Once this criterion is met, there is no need to increase the mass any further.



(a) Influence of the added mass **(b) Influence of the relative spacing of the wheels**



(c) Influence of the wheel material **(d) Influence of the rolling trajectory of the trolley**

Changing the distance between the wheels (that is, the wheel spacing) does have a noticeable effect in the low frequency range. Similar to changing the mass, changing the wheel spacing will change which structural modes on the trolley are excited. The relationship between wheel spacing and sound level will thus depend partially on the structural geometry of the trolley.

The largest influencer, of those tested, is the wheel material. This result was expected, as it is known that a softer wheel will “absorb” more of the excitation energy into the material itself, thus damping the vibration. A harder wheel material will conversely result in a higher sound level. Though this must also take into account the roughness of the wheel surface, not just the material. Even between two wheels of the same material (e.g. PVC), if the surface of one wheel is rougher than the other, it will result in a higher sound level. Both the material and the surface roughness must be taken into account when designing the standard rolling machine.

Finally, the trajectory of the trolley (i.e. whether it was moved in a continuous circle, or back and forth repeatedly in a line) was found to have little influence on the sound level. As long as the average speed over the entire duration of the rolling event is the same, more or less the same amount of acoustic energy is being generated in either case.

Implications for a standard rolling machine design

The tests conducted lead to the conclusion that, in designing a standard rolling machine, the goal is to replicate the “worst case scenario” of a real rolling device. The standard rolling machine needs to generate a sound level which can be reliably measured on even a highly resilient floor. To this end, the goal of the prototype design will be to fabricate a device that has a low mass (though not so low as to allow rattling), hard wheels, and a structural design which allows for adequate modal excitation. As the trajectory does not play a large role, either linear or circular may be chosen. As an alternative to smooth wheels, wheels with flat spots could also be used to ensure a loud enough sound level is accurately recorded on highly resilient floors.

Moving forward, the next step is to refine the test trolley used in the parametric study to a prototype design which incorporates the above findings. This will be presented in chapter 3.

CHAPTER 3

Final prototype design

The plan which was chosen by the team for the final prototype was a two-wheel, manually pushed design. When it comes to standardized devices, simplicity is paramount. It was identified through testing that the rolling trajectory and presence of a human operator (i.e. their footsteps, provided they walk softly) does not contribute in a significant way to changing the recorded rolling noise level. A two-wheel, manually pushed design removes any sophisticated components which would be required if the device were to be automated.

Figure 1 shows the computer aided design (CAD) model which was developed as a result of this project. It consists of a T-shaped steel frame welded to a hemisphere shaped plate. The wheels, which contain press-fitted roller bearings, are affixed to the frame via threaded axle bolts. A post extends from the plate, which allows typical gym weights to be added on top for added mass. A hemisphere shaped foam pad is placed between the plate and the weights (as well as small felt pads between each subsequent weight) to ensure no rattling occurs during rolling. As the frame is made from a hollow steel tube, it is filled with sand and capped at the end to eliminate ringing.

(a) Front view

(b) Side view

(c) Isometric view

(d) Bottom view

Figure 1: Standard rolling device prototype CAD model.

A wooden extension pole may be connected to the handle end of the frame and affixed via a standard bolt and wingnut. This allows the operator to use the length of the pole to push the trolley a greater distance without moving their body. As such, a distance of 3 m may be covered by the rolling trolley with only one or two steps forward and backward by the operator.

Two types of ellipsoidal wheels have been designed: one smooth, and one with a series on non-periodic flat spots placed around its circumference. The latter may be used in situations where a highly resilient floor (e.g. a thick concrete slab) requires a higher excitation. The ellipsoidal shape of the wheel ensures that an elliptical contact is always formed between the wheel and the floor, and that this area of contact remains constant over the lifespan of the wheel. A cylindrical wheel, by contrast, has the chance of only contacting the floor on the inner or outer edge if the wheel is not perfectly level with the floor. An example of these two contact scenarios is shown in Figure 2.

(a) Cylindrical wheel, straight axle.

(b) Cylindrical wheel, bent axle.

(c) Ellipsoidal wheel, straight axle.

(d) Ellipsoidal wheel, bent axle.

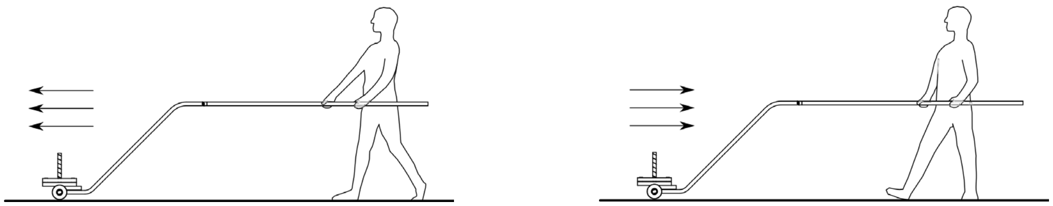
Figure 2: Contact of cylindrical and ellipsoidal wheels.

Measurement procedure

After determining the source and receiving room, the sound measurement equipment shall be calibrated according to IEC 60942. As with impact noise, evaluating rolling noise requires background noise level, sound pressure level (SPL) and reverberation measurements. For background noise and SPL measurements, microphones can be handled using the existing methods for impact noise from the international standard ISO 10140-3: fixed microphones at multiple sampling points, hand-held moving microphone or a mechanical rotating microphone stand. Measurement microphones shall be performed at least 0.5 m away from any walls.

Operating this rolling noise device requires “rolling paths”: 3-meter-long rectilinear floor paths which are clear from any obstacles. When evaluating a floor, the device shall be operated over at least two rolling paths which do not split the room symmetrically. The paths shall be as orthogonal to one other as possible.

Once the rolling paths haven been determined, the start and end points of the path shall be marked. An operator will then roll the device, back and forth, between the start and end of the path in period of 3 seconds as shown in Figure 3. The average speed of the rolling device shall be 1 m/s. This was determined experimentally as the preferred push speed of a moderately heavy trolley (10-50 kg), being slightly below the human preferred walking speed of 1.4 m/s. The use of a metronome (listened to by operator via an earpiece to avoid contaminating the measurements) or other silent visual cue (such as a strobe light) shall be used to ensure the correct speed is achieved.



(a) Forward rolling

(b) Reverse rolling

Figure 3: Illustration of the device with extension pole rolling back and forth along the rolling path.

Measurement recordings shall commence once the rolling device operator achieves a steady rolling rhythm. The sound of moving rolling device shall be recorded for at least 30 seconds. After measurements are performed over all rolling paths, the recordings shall be time-averaged and then used to calculate the energy-average rolling noise sound pressure level in the reception room. The procedure specified in the international standard ISO 10140-3 for calculating the normalized sound pressure level shall be used for expressing the results.

Perspectives

This work is linked to the recently accepted proposal to the European Committee for Standardization (CEN / TC 126 / WG 7) for a New Work Item: *Measurement of rolling sound insulation*. The complete CAD model, including engineering drawings and assembly files, may be found at https://www.acoutect.eu. Using a device such as the one proposed here, indoor rolling tests may be conducted by different organizations with confidence that their measured results may be comparable to one another. Indoor rolling noise is a subsection of building acoustics which is at its infancy. As the field grows and more research beings to take place, the use of a standardized measurement method will help ensure that a splintering of efforts does not occur. The measurements conducted with this device may help identify the acoustic materials which are better or worse at reducing indoor rolling noise.

Acoutect Demonstrator for Lightweight constructions

Recommendation for a Standard Rolling Noise Machine

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