Verification procedures for the impact force applied by the rubber ball used for impact sound insulation measurements

Susumu HIRAKAWA
*National Institute for Land and Infrastructure Management, Building Department, Equipment standard division, Japan
email:* *Hirakawa-s92ta@mlit.go.jp* *(**susu3u.h@gmail.com**)*

Carl HOPKINS
*Acoustics Research Unit, School of Architecture, University of Liverpool, UK
email:* *carl.hopkins@liverpool.ac.uk*

 Annex A of ISO 16283-2:2015 and Annex F of ISO 10140-5:2010+A1:2014 prescribe the rubber ball as a heavy-soft impact source for the measurement of the impact sound insulation of floors. They provide information on the expected impact force exposure level in octave bands and the impact force of the rubber ball as well as its material composition. However, no details are given on the verification procedures or equipment. In JIS A 1418-2:2018, there is a recommendation to use a force plate to measure the blocked force from at least 0.2 Hz to 1000Hz with a flat frequency response. The measurable range of force shall be at least 0 to 5000N, and the linearity within the range shall be ±2%, but it does not define the force plate itself. Annex A of ISO 16283-2:2015 states that the rubber ball only needs to be measured once after manufacture unless it is visibly cracked or damaged. Hence there is a need to give guidance on the measurement of the impact force for both manufacturers and test laboratories, preferably in an ISO Standard. This paper considers different types of force plates and considers factors influencing their accuracy, including potential issues with the resonance frequency of the plate and different piezoelectric sensors.

 Keywords: impact sound insulation, excitation, rubber ball, calibration, verification

# Introduction

The calibration or verification of a measurement instrument for use with measurement standards, regulations, guidelines, or research is essential. For this reason, ISO 16283-2:2015 and ISO 10140-5:2010 A1 2014 states requirements on the need for verification certificates from the competent laboratory which are summarised in Table 1 [1, 2]. The current standards do not impose the same requirement for the standard excitation sources for the impact sound insulation (tapping machine and rubber ball). They only state the physical requirement of the sources but not the verification method. Hence, there is uncertainty in the validity of the excitation applied by a standard impact source.

It is appropriate to verify the excitation source prior to the measurement to avoid errors. The ISO Standard implies that measurement of the force spectrum is needed when it is visibly cracked or damaged, but there is no information about what kind of measurement is required and what equipment should be used.

Table 1 Required verification/certificates for the measurement instruments in ISO 16283-2:2015 and ISO 10140-5:2010 A1 2014

|  |  |  |
| --- | --- | --- |
| **Instrument** | **Relevant standard** | **Verification/certificate** |
| Microphone, cables | IEC 61672-1 | YES |
| Filter | IEC 61260 | YES |
| Calibrator | IEC 60942 | YES |
| Reverberation time measurement equipment | ISO 3382-2 | YES |
| Tapping machine | NO | NO |
| Rubber ball | NO | NO |

The requirements outlined in JIS A 1418-2:2000 Annex 3 give recommendations on the force sensor, frequency analyser and oscilloscope for the calibration of the standard heavyweight source [3]: The force sensor used to measure the blocked force is a transducer which produces an electric signal corresponding to the force input. The transducer must withstand the force impact due to the standard impact source, and be capable of measuring forces from 0 to 5000 N. The housing for the transducer(s) needs to be sufficiently heavy to prevent unwanted motion from the impact. The sensing unit should be approximately 100mm in radius and installed horizontally with a measurable frequency range 0.2Hz to 1000Hz (flat spectrum). The frequency analyser must comply with the relevant standard of IEC 61260 Type 2 octave band filter or its equivalent. The indicator should comply with the specification of JIS C 1505 to calculate the impact exposure level (integration calculation) specified in the Annex [3]. Furthermore, to obtain the measurement of peak force and duration of the impact, reading should be started from the starting point until the first zero-crossing. The temperature should be 20°C during measurements. Note that in the commentary of JIS A 1418-2:2000 the calibration method is not yet established hence the measurement device and method are specified.

Force plates are sold by several manufacturers, often because they have applications in sports science for measuring the force applied by the human foot. However, as noted by Robinson and Hopkins [4], experimental quantification of the dynamic forces applied by footsteps is generally concerned with measurement of the Ground Reaction Force (GRF). Such devices may have a 0.01 Hz or 0.1 Hz high-pass filter, or without any high-pass filter at all. This means that the peak force can be very high due to an effective DC component, whereas the validation of the force from an impact source for acoustic measurements (normally with 20Hz as the lowest frequency of interest) does not need to consider this component.

One example of a commercial force plate is from RION Co. Ltd that sell a commercially available product (PF-10). The PF-10 is constructed from a circular metal plate with a diameter of 260mm and thickness of 15mm and a circular metal plate with a diameter of 220mm. Three force washers are installed in-between the two plates.

One example of a force plate used for research in the ARU (University of Liverpool) [4] has measured the variation in the measured force over the surface. This is relevant when the rubber ball drop is not exactly in the centre of the force plate. However, this information is rarely available for commercial products.

This paper considers various aspects relating to the construction of a force plate that need consideration if a force plate is to be used for verification purposes.

# Force plate construction and properties

Constructing a force plate requires consideration of the mass-spring resonance due to the piezoelectric sensor. A report published by PTB and Kistler indicates that the resonance frequency of the piezoelectric force measuring devices can be reduced to less than 1k Hz if large masses are coupled to the transducers, even though the piezoelectric force transducers may have high resonance frequencies in the kHz range [5]. To assess this effect, a force plate was initially constructed using an upper and lower plate constructed from a steel plate 35mm thick with a 350mm diameter (approximately 26.4kg). Figure 1 shows a schematic diagram of a force plate. Three force washers (Kistler 9041A) were installed between the plates and tightened by a torque wrench. The force-time spectrum was measured using the B&K PULSE Labshop system with a time resolution of 61.04µs and a frequency resolution of 1Hz. Post processing was carried out in Python (Ver 3.9.13) NumPy (Ver 1.21.5) *numpy.fft.fft* and *numpy.fft.fftshift*.

The time-force spectrum and frequency-force spectra are presented as shown in Figure 2. The responses from three force washers in the frequency domain (right) show a smooth spectrum up to 80 Hz, but above this frequency, the spectrum changes and shows a resonance effect at ≈330 Hz, around 1208 Hz and 1604 Hz. The resonance at 1208 Hz or 1603 Hz is possibly due to the resonance frequency of the steel circular plate which is estimated using the free edge circular plate equation using Eq.1 as 1453 Hz [6]. Hence, the resonance at 330 Hz is potentially due to the mass-spring effect of the force transducers [5]. The corresponding spring stiffness of the force transducers was calculated using Eq.2 to be 1.1294E8 MN/m.



Figure 1 Schematic diagram of a force plate with a heavy upper plate (left) and connection with the measurement system.



Figure 2 Output from three force transducers in-between two steel plates with excitation from a small force hammer impacting the centre of the force plate.

|  |  |  |
| --- | --- | --- |
|  | $$f\_{ij}=\frac{λ\_{ij}^{2}}{2πL\_{x}^{2}}\sqrt{\frac{EL\_{z}^{3}}{12ρ\_{surface}(1-ν^{2})}}$$ | **( 1 )** |

where *λij* is 5.253 (i=0, j=2 mode is assumed), $ρ\_{surface}=ρ\_{volume}L\_{z}$ and$ E=c\_{L}^{2}ρ\_{surface}(1-ν^{2})$.

|  |  |  |
| --- | --- | --- |
|  | $$k\_{total}=m\left(2πf\_{0}\right)^{2}$$ | **( 2 )** |

If the force plate lies on the floor, then a mass-spring mass (m-s-m) resonance may not be feasible because the lower plate can’t move independently of the floor. Hence, both the mass-spring and mass-spring mass resonance frequencies of the force plate due to the force transducer were calculated with the mass of the upper plate and the spring stiffness of three force washers to avoid the effect of resonances below 1000Hz. Figure 3 shows the mass-spring and mass-spring-mass frequency versus upper plate mass, the red and blue rectangle area is the safe range for the upper plate mass to avoid resonance. This shows the maximum mass of the upper circular plate should be less than 2.8 kg (for the mass-spring assumption) or 3.2 kg (for the mass-spring mass assumption). Figure 4 shows the weight versus thickness curve for the steel and aluminium with diameter of 280mm was assumed. t indicates the maximum thickness of 6.5 mm for the steel and 18 mm for the aluminium plate. With that information, an upper plate of 280 mm diameter, 18 mm thickness would have a mass of 2.99 kg and a resonance frequency of 1.13k Hz.



Figure 3. Resonance frequencies for different values of the upper plate mass.



**Figure 4.** Weight-thickness chart of the upper steel and aluminium circular plate (280mm diameter).

Following on from these findings, another force plate is considered which has had modifications to the upper plate. It is constructed from a lower plate of 35 mm thick circular steel with a 350 mm diameter (26.4 kg) and an upper plate of 15.2 mm thick circular aluminium with a 110 mm radius (1.5 kg). This upper plate has a modal resonance estimated using the free edge circular plate equation (Eq.1) as 1546 Hz. Three force transducers (Kistler 9041A) are bolted between the two plates. Experimental validation of the force plate was carried out by comparing the transient force from a force hammer impacting the centre of the force plate, and the summed output from the force plate. The measurement results were post-processed using Python. The fifth-order Butterworth low pass filter with 1000 Hz cut-off frequency was created with SciPy (ver1.9.1) *scipy.signal.butter* function to make a *sos* coefficient for the filter and applied with *scipy.signal.sosfilt* to the input signal.

Figure 6 shows the comparison between the input force from a force hammer and the output force from the force plate. A force hammer (B&K Type 8202) was used to input approximately 1000 N force at the centre of the force plate. The peak value obtained from the force hammer was approximately 964 N and the sum of the three force washers was approximately 917 N which is within 5 % of the force hammer. Figure 7 shows the frequency response from 8 Hz to 1000 Hz. Between 8Hz and 500Hz there was a difference of ≈1 dB, from 8 Hz to around 500 Hz, then the difference becomes ≈1.3dB around 500 Hz, then the difference again reduced to below 1dB. Figure 8 shows the output response without a low-pass filter.



Figure 5. Force plate with light upper plate.



Figure 6. Comparison of the measured force in the time domain.

 

Figure 7. Comparison of the measured force in frequency domain. Absolute value(left) and difference (right) for a force hammer hit on the force plate.



Figure 8. Comparison of the measured forces from the force hammer and the force plate in the frequency domain without low-pass filter.

The blocked force of the rubber ball was measured by dropping a rubber ball 1m from the upper surface of the force plate. Comparing the force spectrum from the JIS A 1418-2:2000 with measurements shown in Figure 9 indicates that the duration was 19.2 ms and it is within the limit in the standard of 20 ms±2 ms. The measured peak force was 1542 N, and the rubber ball is approximately 1500 N [2, 3].

Figure 9 right shows the impact force exposure level; it is calculated from the octave band filtered slices of the force spectrum to determine the single event level at each octave band value for the given duration of the force measurement (1s) and converted to dB scale by reference to 1N. The graph shows that the measured force spectrum is within the lower and upper limit of the standard value from the 31.5 to the 500 Hz octave band but at 500 Hz it is just 0.1 dB above the lower limit (although this was only a single measurement with one rubber ball). Figure 10 shows the narrow band FFT spectrum where the force rapidly decays above 31.5 Hz.

Post-processing was carried out in Python using SciPy *scipy.signal.butter* function to make a third-order numerator/denominator (b and a term) filter coefficients and apply it with *scipy.signal.lfilter* for the octave-band filtering for the input signal [8]. To calculate the single event level of the octave-band filtered time domain signal the *numpy*.*std* function was used.



Figure 9. Measured time domain response (left). Single event level of the rubber ball drop from 1m height measured on the force plate with JIS higher and lower confidence limit (right).



Figure 10. Rubber ball drop from 1m height: Measured frequency domain response in narrow bands.

# Conclusions

This paper reviewed bespoke force plates used in research to verify the force from a rubber ball. An awareness is needed of the resonance frequency of the plate with different piezoelectric sensors. To avoid the risk, one needs to use a suitable mass for the upper plate to avoid a structural resonance frequency of the plate itself as well as avoiding a mass-spring resonance frequency due to the stiffness of the piezoelectric sensor. This paper only considered one type of piezoelectric sensor hence further research could investigate other piezoelectric sensors.

REFERENCES

1. ISO 10140-5:2010+A1:2015. Acoustics – Laboratory measurement of sound insulation of building elements – Part 3: Measurement of impact sound insulation, (2014).
2. ISO 16283-2:2015 Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 2: Impact sound insulation, (2014).
3. Japanese Standards Association, JIS A 1418-2:2000 Acoustics - Measurement of floor impact sound insulation of buildings - Part 2: Method using standard, (2000).
4. Robinson, M. and Hopkins, C., 2015. Prediction of maximum fast time-weighted sound pressure levels due to transient excitation from the rubber ball and human footsteps. Building and Environment, 94, pp.810-820
5. Kumme, R., Mack, O., Bill, B., Gossweiler, C., and Haab, H. R.. "Dynamic properties and investigations of piezoelectric force measuring devices," pp. 161-171. (2002)
6. Brevins. R.D. "Free edged Circular Plate Fundamental Frequency." (1979)
7. Brandt A. Brandt, Noise and vibration analysis: signal analysis and experimental procedures. doi:10.1002/9780470978160. (2011)