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Components of Variation in Reverberation Time Measurement – Part 2: Field Testing Rooms of Heavyweight Construction

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ABSTRACT

This paper uses analysis of variance (ANOVA) and a specific design of experiment (DOE) and construction choice to isolate the component of variance associated with the part (or room) being measured along with individual contributions of measurement uncertainty from the measurement system and the person making the measurement.

It demonstrates how the gauge repeatability and reproducibility (GRR) technique can be used to identify the variability in reverberation time measurement over the frequency range 100-3150Hz and as individual component parts of the testing process associated with field sound insulation testing in the UK.

The experiment uses the measurement of reverberation time associated with the 'interrupted source method' from EN ISO 354: 2003.

Keywords: Measurement Uncertainty, Reverberation Time, ANOVA, GRR, Gauge, Repeatability, Reproducibility

1. INTRODUCTION

This paper is Part 2 of 2 papers looking at the measurement uncertainty associated with the measurement of reverberation time in the field and concentrates on residential rooms formed of heavyweight (concrete/masonry) floor construction.

The design of any scientific experiment must not only document and include details of the design of the experiment and the measurement procedure but must also attempt to attach a measurement error to the empirical results. Indeed some emphasise that an experiment is not complete until an analysis of the final result has been conducted ([1]). This is good practice as it allows the informed reader to understand, at a basic level, the likely variability in the measurement process and appreciate the precision which can be attached to the experimental procedure.

This paper looks at the uncertainty associated with the field measurement of reverberation time and focuses on this as a component of the pre-completion sound insulation testing requirements of the Building Regulations for England and Wales. Field tests are the ubiquitous method of demonstrating compliance with the sound insulation performance standards and the definitive method of demonstrating conformity with the minimum sound insulation values should compliance be contested. Annex B of Approved Document E [(2)] Part of the field test procedure requires the measurement of the reverberation time in the room in order to correct for the receiver room's effect on the sound insulation performance of the surface being measured. The sound insulation value calculated in each 1/3rd octave band is 'standardized' (DnT) to a 0.5 second reverberation time using the methods as detailed in the international standards [(3, 4)] for determining the airborne and impact performance of the surface.

This correction for reverberation time effect is detailed in equation (1):

$$\boldsymbol{D_{nT} = D + 10\lg\frac{T}{T_0}\, dB_i} \qquad (1)$$

Where:

D is the level difference,

T is the reverberation time measured in the receiving room;

T_0 is the reference reverberation time; for dwellings, T0 = 0,5 s

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In this paper we are interested in the measurement uncertainty in measuring '*T*'.

It is worthwhile noting the following from the standards: *'NOTE 1: The standardizing of the level difference to a reverberation time of 0,5 s takes into account that in dwellings with furniture the reverberation time has been found to be reasonably independent of the volume and of frequency and to be approximately equal to 0,5 s. With this standardizing, DnT is dependent on the direction of the sound transmission if the two rooms have different volumes.'* See Burgess & Utley et al and Diaz et al [(5, 6)].

This paper analyses the data from a special design of experiment (DoE) called a Gauge Repeatability and Reproducibility (GRR) experiment that was carried out on a residential block of flats of heavy-weight concrete/masonry construction where measurement of reverberation times were made in unfurnished bedrooms. In this GRR the room is the part being measured and its size and shape was 'blocked' in this instance by choosing rooms of identical dimensions to determine the rooms' effect on reverberation time from apparently identical parts. It was, however, noted that not all the rooms were completely clear of building materials and some had stacked plasterboard and paint tins evident on the floor which were not removed by the test engineers.

The measurement uncertainty is split into components of variance to identify the uncertainty contribution of the instrumentation, test engineer (operator) and the part (or in this case receiver room) being measured using advanced analysis of variance (ANOVA) which is described in more detail below.

2. SITE SURVEY – ROOM AND CONSTRUCTION DETAILS

2.1 Site

The airborne sound insulation tests were carried out on a residential scheme which was nearing completion. The floor elements were between matched room pairs and five individual operators were used, each with their own test systems. An aim of this approach was to minimise systematic deviations in the measurement and thus the variability in measurement test data. Each "test system" was employed to test 5 notionally identical room pairs, or 'parts', to determine the performance of the separating floor. In all, the 5 room pairs were tested by each tester (reproducibility) on two separate occasions (repeatability) over the space of one day. This resulted in 10 test results for each system.

The measurement procedure was designed to represent the noise.co.uk Ltd UKAS Accredited method statement using a static sampling approach during a normal operational day. The test method for measurement of reverberation time used the 'interrupted source' method from the standard [(7)]. Each test operator complied with the following procedure: Position the Loudspeaker in the receive room taking care to ensure that the speaker is more than 0.5m from any of the room boundaries, ensure that the microphone positions used to measure the reverberation time are set up to be greater than 2m from the source, 1.5m from each other and 1m from any room boundary where practicable, take a reverberation time (RT) measurement, Repeat the RT measurement step for a further minimum 5 runs, making 6 readings in total. Measurements should be made using at least one speaker position, with two readings at three selected microphone positions.

The tests were carried out in a small bedroom (Bed 2) that measured approximately 3.1m long x 2.975m wide x 2.375m high with an approximate room volume of 21.3m^3. Five identical room pairs were selected across the development. See Figure 1 below.

The rooms were of bare concrete floor, plasterboard wall and ceilings and were unfurnished. The floor element being measured on the test was a concrete construction and was Robust Detail E-FC-4, which from the top down consisted of: 65mm sand/cement screed; 6mm Isorubber resilient layer complete with 6/260 flanking edge strip to perimeter of floor layer; Proprietary 200mm PCC plank floor system (min. 300kg/m^2); plasterboard ceiling consisting 15mm Knauf Wallboard (with 3mm skim finish to Knauf's recommendations), on MF suspended ceiling grid, with min 150mm ceiling void.

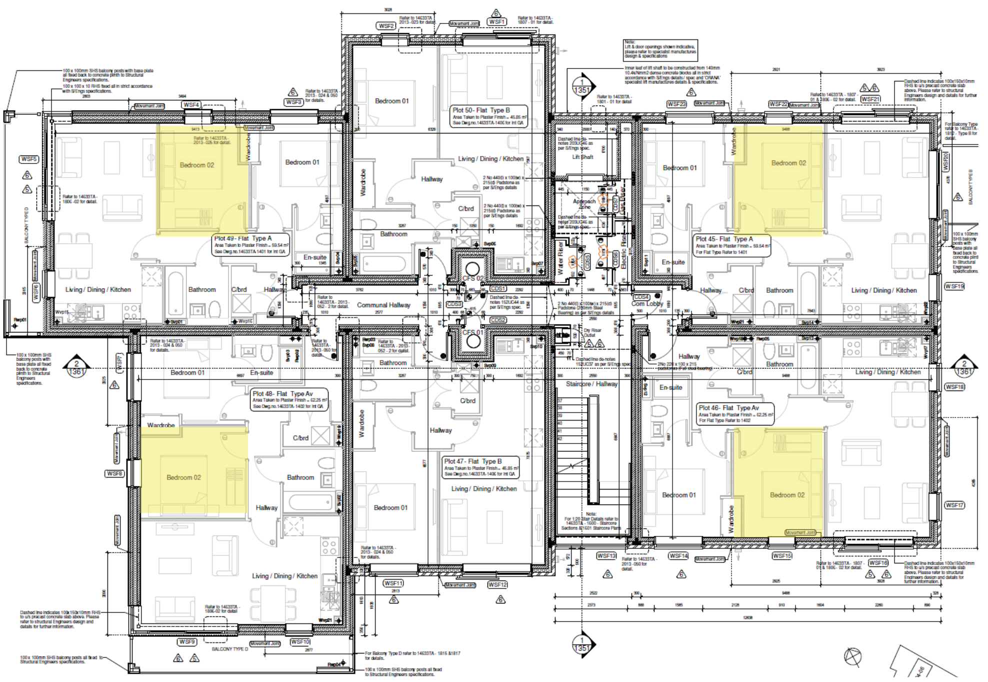

Figure 1: 4 out of the 5 Matched room pairs, Bed 2 shown on site layout plan.

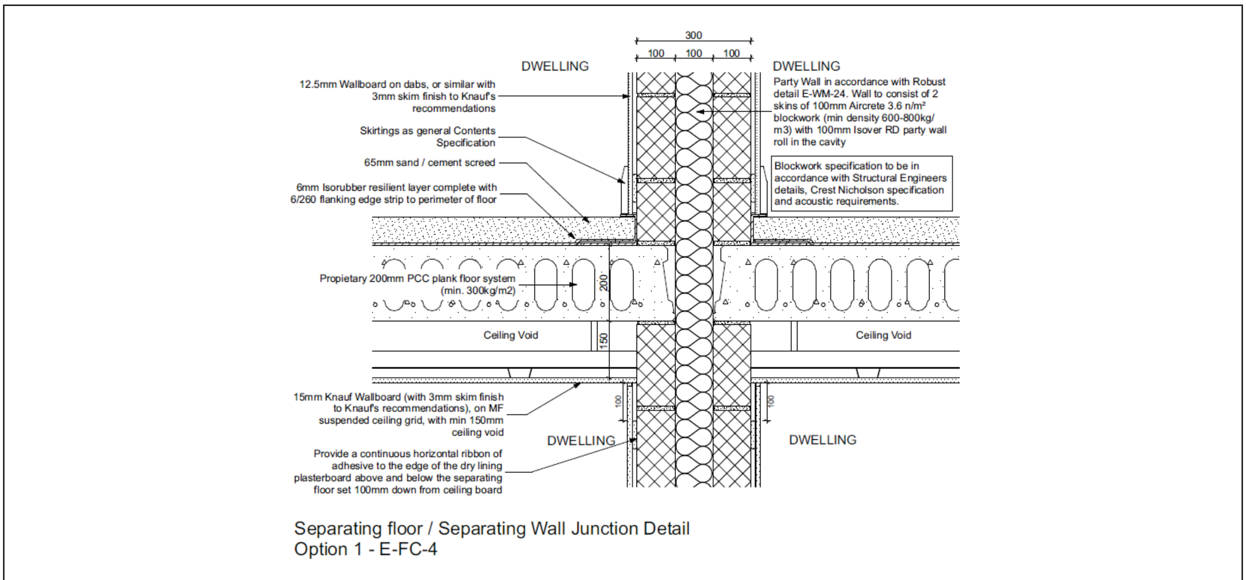

Figure 2: Light weight floor section whose sound insulation was being measured during the test.

Drawing on earlier research on identifying the components of variance in the field measurement of sound insulation by Whitfield and Gibbs, [(8-10)] the experimental approach uses (ANOVA) and a (GRR) test method. The usefulness of these methods is mentioned by Mandel [(11)] and Tsai [(12)] and the previous use of ANOVA in acoustic research is not without precedent, see Taibo and Glasserman de Dayan [(13)] and it has also been used for measurement of reverberation time, all be it in the context of measuring the absorption of an element in a laboratory environment,see Davern and Dubout P [(14, 15)].

The main advantages of ANOVA are listed by Deldossi and Zappa [(16)] and include the ability to determine the contribution of the operator and part and operator by part interaction. A key contribution to the development of GRR was written by Montgomery and Runger [(17, 18)] and culminated in a monograph on the subject, including its special applications by Burdick et al [(19)], in which the ANOVA design, for the purpose of this research, is described as a Balanced Two Factor Crossed random model with interaction. It informs this research on achieving an accurate and reliable estimate of the variability in the measurement process due to the part, the operator and the instrument. It is this model and additional information provided by Montgomery [(17, 18, 20)] and Burdick et al [(19)] which forms the analytical framework to separate out and quantify the components of variance in reverberation time measurement.

3. GRR

3.1 DOE

The GRR has a particular DoE which relies on a number of gauge "operators" to measure a number of test specimens (parts) a repeated number of times. In this DoE due to the onerous test procedure required to capture one result (test) 5 UKAS accredited sound insulation test operators were used, each with their own test kit and tasked at measuring 5 floor specimens (parts) 2 times each. The model is detailed in equation (2):

$$Y_{ijk} = \mu + O_i + P_j + [\![(OP)]\!]_{ij} + E_{(k(ij))} \tag{2}$$

where: $i = 1, 2,....., p$: $j = 1, 2, ..., o$: $k = 1, 2,…., r$ and;
p = number of parts;
o = number of operators;
r = number of repetitions; and,

O_i, P_j, $[\![(OP)]\!]_{ij}$, and $R_{(k(ij))}$ are random variables representing the effects of the operator, parts, operator by part interaction and the replications on the measurement and μ is an overall mean. Clearly, in the experiment described here p = 5, o = 5 and r = 2

The definition of reproducibility in the GRR is covered in Burdick et al [(19)] and incorporates the interaction term and is shown in equation (3): The combined Gauge variance components are shown in equation (3) and the total variance shown in equation (4) which describes the total measurement uncertainty associated with the field testing of this particular part.

$$\sigma^2_{reproducibility} = \sigma^2_O + \sigma^2_{PO} \tag{3}$$

$$\sigma^2_{gauge} = \sigma^2_{repeatability} + \sigma^2_{Reproducibility} \tag{4}$$

$$\sigma^2_{total} = \sigma^2_{gauge} + \sigma^2_{part} \tag{5}$$

It should be noted that in a GRR the reproducibility term does not contain the repeatability term by definition. This is different to the method of assessment in BS5725 [(21)] where repeatability is embedded in the reproducibility term resulting in reproducibility always being greater than repeatability. In GRR, the reproducibility can be separated out into two components of variance, defined as the operator variance (σ^2_O) and the operator by part interaction (σ^2_{PO}). This is an important feature of ANOVA because it detects any interaction the operator has with the part being measured. In some cases the interaction term can be significant, and dominant as demonstrated by Whitfield and Gibbs [(22)] and it would remain hidden if using the BS5725 method of calculating repeatability 'r' and reproducibility 'R'. Typical RT results for a typical single operator repeating measurements are detailed in **Figure 3** and across all operators sampling a single room in **Figure 4**:

The difference in the RT measured by operator 'SP' in Room 1 are not easily explained as measured levels from their sound level meter were consistent over both repeat measurements made. It is possible to now use the repeated measured values with the reproduced values of other operators to reduce the total uncertainty of measurement into its component parts.

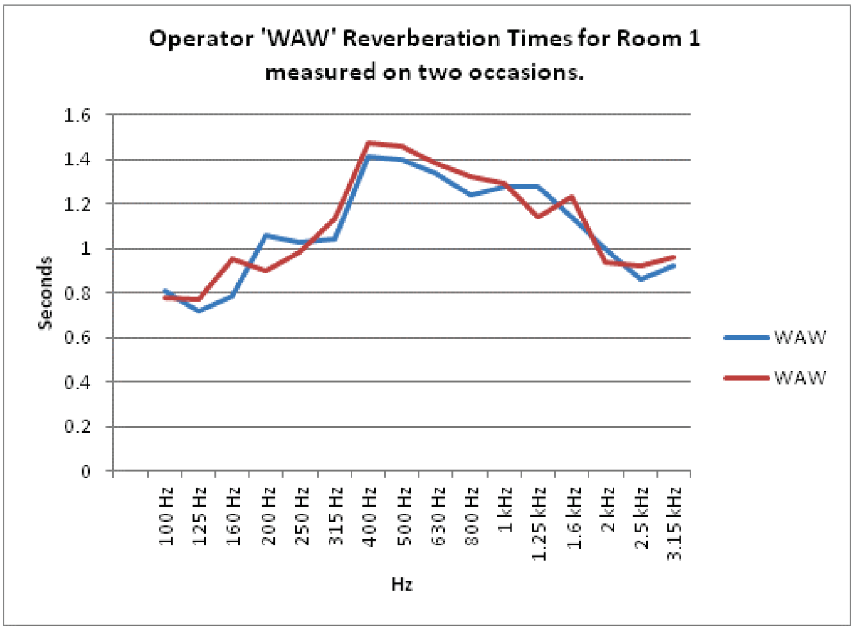

Figure 3 : Typical operator RT for Room 1 (Secs)

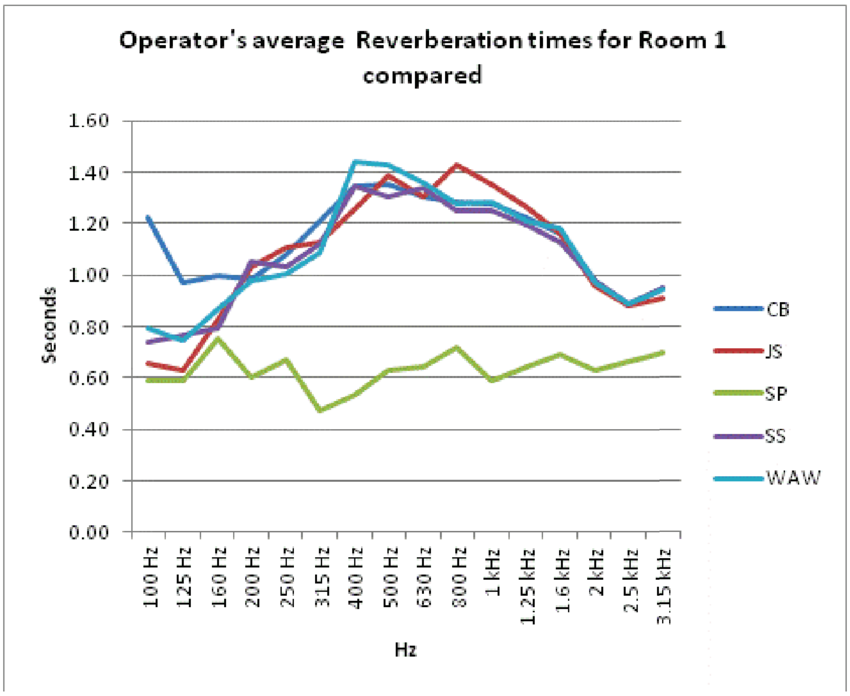

Figure 4: Average operator RTs for Room 1 (Secs)

The results of the ANOVA analysis are graphically illustrated in Figure 5 for individual components of variance. The total variance of the RT measurement process ranges between 0.019 and 0.33 seconds and shows a steadily rising level peaking at 500Hz and falling steadily to 2500Hz. This characteristic is replicated in the components associated with the engineer (operator), operator by part interaction term and the part to part variation across the same frequency range and these variances are broken down in Figure 5 to show the components associated with Reproducibility '*R*' the operator by part interaction and part to part (Room) components of variance. It is noted that the ANOVA of the data determined there was significant interaction between the operator and the part being measured so the variance associated by 'reproducibility' includes this term. It is likely that as the floors of some of the rooms had stacked building materials the random measurement process was constrained, leading to interaction of the operator and the part; for example: it was difficult to place the loudspeaker in certain areas of the room due to stacked plasterboard.

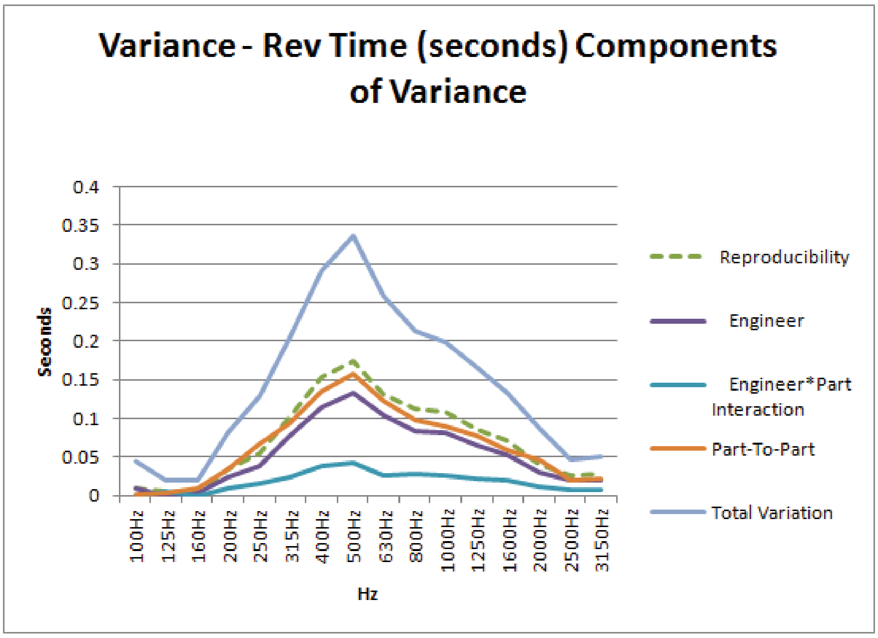

Figure 5: Total Variance with (r) (instrument), (R) (Operator), interaction and part (Room) variances

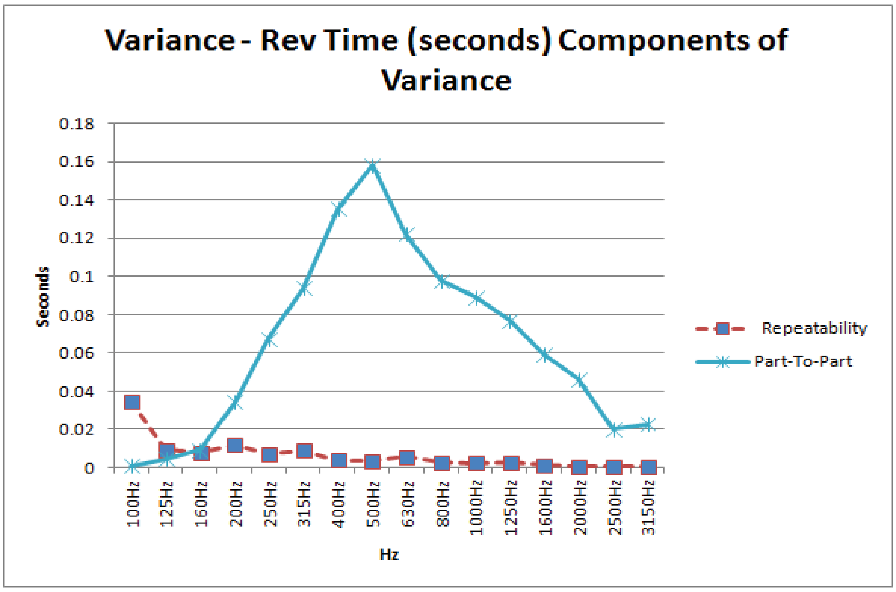

Figure 6: Variances associated with the instrument (r) and the Part (Room)

The ability to detect interaction is an important feature of ANOVA because it detects any interaction the operator has with the part being measured. In some cases the interaction term can be significant in a measurement routine, at certain frequencies can also be dominant as demonstrated by Whitfield and Gibbs [(23)] and it would remain hidden if using the BS5725 method of calculating repeatability '*r*' and reproducibility '*R*'or assuming an approach using GUM [(24)].

What's notable from the GRR data shown in Figure 6 is that the variance associated with the instrument (*r*) is generally higher at the lower frequencies falling after peaking at 0.034 seconds at 100Hz to below 0.012 seconds above 200Hz which generally indicates high levels of repeatability in the measurement process. The higher variance at lower frequencies is likely partly due to the limitations of the sound level meter,RT response at lower frequencies and the less diffuse sound field in the relatively small rooms.

This is in contrast to the variance attributable to the part being measured which shows the variance levels are lower than the variance associated with the instrument between 100-125Hz and significantly higher at 160Hz and above. The part to part variation in this case was likely due to abandoned building materials in some of the receiver rooms which could not easily be moved by the on site test teams. Even so the room dimensions are as far as practical equivalent and the variance due to the part in this case dominates over the variance associated with the instrument and the operator.

The dominant contributor to the total uncertainty associated with the measurement of reverberation time in this experiment is, therefore, dependent on frequency and is due in the main to the part being measured closely, followed by the operator's contribution, with the instrument offering only a small contribution at 125Hz and above.

4. CONCLUSION

4.1 ANOVA GRR

The calculation of measurement uncertainty in the measurement of reverberation time in the field testing of sound insulation can be carried out using a specialist DoE based on ANOVA. This allows the components of variance to be broken down into the uncertainty associated with the instrument , that associated with the operator , and that associated by the part being measured.

In order to identify how the part, in this case the room in which the reverberation time is measured, contributes to the overall uncertainty of measurement this factor can be 'blocked' by choosing identical rooms of the same shape size and finish varying only by the workmanship used to create them. It is noted that the GRR type experiment uses the same experimental effort as that required by traditional means of identifying '*r*' and '*R*' e.g. BS5725, but allows the researcher to splice out significantly more detail from the same data about the contributors to the overall uncertainty including any interaction between the operators making the measurement and the part being measured. The blocking of the room effect in this experiment was affected by the on site condition of the rooms as some had stored building materials in them which was not ideal. It did, however, show that in field test situations there are additional contributory factors that add to the uncertainty of measurement and initiate interactions, however unwanted, into the randomized measurement process. The GRR ANOVA methods highlight these effects and add detail to the understanding of uncertainty that is beyond the scope of the BS5725 or GUM methods for assessing measurement uncertainty in the survey process.

Variance Secs	σ_{GRR}^2	σ_r^2	σ_R^2	σ_o^2	$\sigma_{p.o}^2$	σ_p^2	σ_{Total}^2	Major influences on uncertainty
100Hz	0.044	0.035	0.009	0.009	0.000	0.001	0.044	The instrument is the main contributor to total variance
125Hz	0.015	0.009	0.006	0.000	0.006	0.004	0.020	The instrument is the main contributor to total variance
160Hz	0.011	0.008	0.004	0.004	0.000	0.009	0.021	The part is the main contributor to total variance
200Hz	0.047	0.012	0.035	0.025	0.010	0.034	0.081	The part is the main contributor to total variance
250Hz	0.062	0.007	0.055	0.039	0.016	0.067	0.130	The part is the main contributor to total variance
315Hz	0.111	0.009	0.102	0.078	0.024	0.094	0.205	The part is the main contributor to total variance
400Hz	0.156	0.004	0.153	0.115	0.038	0.135	0.292	The part is the main contributor to total variance
500Hz	0.178	0.004	0.174	0.132	0.042	0.158	0.336	The part is the main contributor to total variance
630Hz	0.135	0.005	0.130	0.105	0.025	0.122	0.257	The part is the main contributor to total variance
800Hz	0.115	0.003	0.112	0.083	0.028	0.098	0.212	The part is the main contributor to total variance
1000Hz	0.110	0.002	0.108	0.082	0.026	0.089	0.199	The part is the main contributor to total variance
1250Hz	0.088	0.003	0.086	0.064	0.021	0.077	0.165	The part is the main contributor to total variance
1600Hz	0.073	0.001	0.072	0.052	0.020	0.059	0.132	The part is the main contributor to total variance
2000Hz	0.042	0.001	0.041	0.030	0.011	0.046	0.088	The part is the main contributor to total variance
2500Hz	0.027	0.001	0.026	0.019	0.007	0.020	0.047	The part is the main contributor to total variance
3150Hz	0.029	0.000	0.028	0.020	0.008	0.023	0.051	The part is the main contributor to total variance

Table 1 : Components of variance table for RT measurement across the frequency range 100-3150Hz

The contributions from the instrument, operator and part together with the operator by part interaction is summarised in Table 1 for ease of reference.

More data from GRR experiments is desirable to investigate further the uncertainties associated with the measurement of RT in field test situations and include other room types, constructions and room sizes. There is also the possibility to extend the frequency range of interest to include both higher and lower frequency bands e.g. 50 Hz – 5KHz providing the instrumentation used, room size and its absorption areas allows these to be reliably measured.

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