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

# Part to Part Variation in Sound Insulation – Separating Walls: Part 1

**Whitfield, William**
**Noise.co.uk Ltd**
**The Haybarn, Newnham Grounds, Bretford, Warks CV23 0JU England**

**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 separating wall construction) being measured and not any other contribution of measurement uncertainty from the measurement system or the person making the measurement. It demonstrates how the gauge repeatability and reproducibility (GRR) technique can be used to identify this variability in wall construction over the frequency range 100-3150Hz as well as the single figure values associated with field sound insulation testing in the UK.**

**Keywords:** Sound Insulation, ANOVA, Repeatability, Reproducibility, Part to part variation, Gauge Study, Measurement Uncertainty
**I-INCE Classification of Subject Number:** n/a

## 1. INTRODUCTION

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 airborne sound insulation in residential dwellings: in the Building Regulations in the UK 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.

Drawing on earlier research on identifying the components of variance in the field measurement of sound insulation by Whitfield and Gibbs [2, 3] and Whitfield and Fenlon [4] the experimental approach uses analysis of variance (ANOVA) and a specific design of experiment (DOE) called a Gauge Repeatability and Reproducibility (GRR) test method. The usefulness of these methods is mentioned by Mandel [5] and Tsai [6] and the previous use of ANOVA in acoustic research is not without precedent, see Taibo and Glasserman de Dayan [7] and Davern and Dubout P [8, 9].

The main advantages of ANOVA are listed by Deldossi and Zappa [10] 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 [11, 12] and culminated in a monograph on the subject, including its special applications by Burdick et al [13]. in which the ANOVA design, 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 [11, 12, 14] and Burdick et al [13] which forms the analytical framework, to separate out and quantify the components of variance in sound insulation measurement for one of the most commonly constructed concrete (heavyweight) wall types. In this experiment the cavity masonry wall is Robust Detail E-WM-17.

In line with the Building Regulation requirements in England and Wales and to be consistent with previous GRR experiments, the field testing of airborne sound insulation was carried out under a UKAS Accredited work procedure which follows BS EN ISO140-4: 1998 [15] with the data analysed to BS EN ISO 717-1: 1997 [16]

This GRR focuses on heavyweight separating walls, In this case the Robust Detail E-WM-17 wall is a cavity masonry wall with mineral fibre batt thermal infill. The separating wall construction can be described as follows:

1. 2 skins of 100mm 7N Stranlite block (dry density 1350-1400Kg/m3)
2. 100mm cavity with fibre batts in the cavity.
3. Finish gypsum based board min mass 8Kg/m2 mounted on dabs.

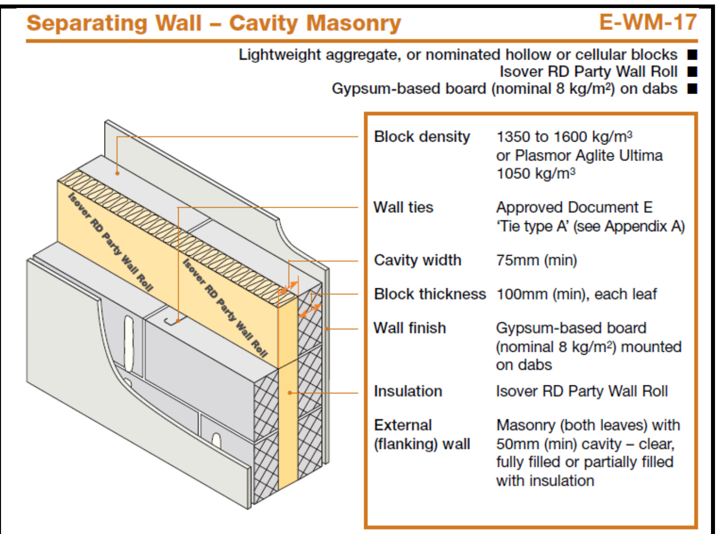


*Figure 1: Separating wall construction*

## 2. GRR

The GRR has a particular design of experiment (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) in this DOE, 4 UKAS accredited sound insulation test operators were used, each with their own test kit and tasked at measuring 3 wall specimens (parts) 2 times each.

The model is detailed in equation (1):

$$Y_{ijk} = \mu + O_i + P_j + (OP)_{ij} + E_{k(ij)} \quad (1)$$

Where i = 1, 2,....., p : j = 1, 2, ......., o : k = 1, 2,…., r and;

p = number of parts,
o = number of operators and;
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 = 3, o = 4 and r = 2

The definition of reproducibility in the GRR is covered in Burdick et al [13] and incorporates the interaction term and is shown in equation (2): 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.

(2) $\sigma^2_{reproducibility} = \sigma^2_{O} + \sigma^2_{PO}$

(3) $\sigma^2_{gauge} = \sigma^2_{repeatability} + \sigma^2_{Reproducibility}$

(4) $\sigma^2_{total} = \sigma^2_{gauge} + \sigma^2_{part}$

## 3. Test Specimen Walls

The test site was a residential housing site featuring semi-detached and terraced homes in Bolsover, Derbyshire, UK and was located on the edge of town in a green field location. The main background noise on site was site noise from multiple site sources. The test rooms selected were ground floor living rooms in a standard semi detached house type. The room size was blocked in this experiment to allow more information about the variability of the wall performance to be gathered. The rooms selected were all identical shape & size (approx 2.4m H x 3.5m W x 4.5m L = 38m$^3$). The selection of identical shape and size room pairs was intentional in order to block, as far as possible the variability in sound insulation test performance due to the room shape and size and fix the flanking detail to the outside wall with the separating wall area under test as 8.4m$^2$. See Fig 2. As the rooms were identical in size operators chose the test direction i.e. the source and receiver rooms, themselves.

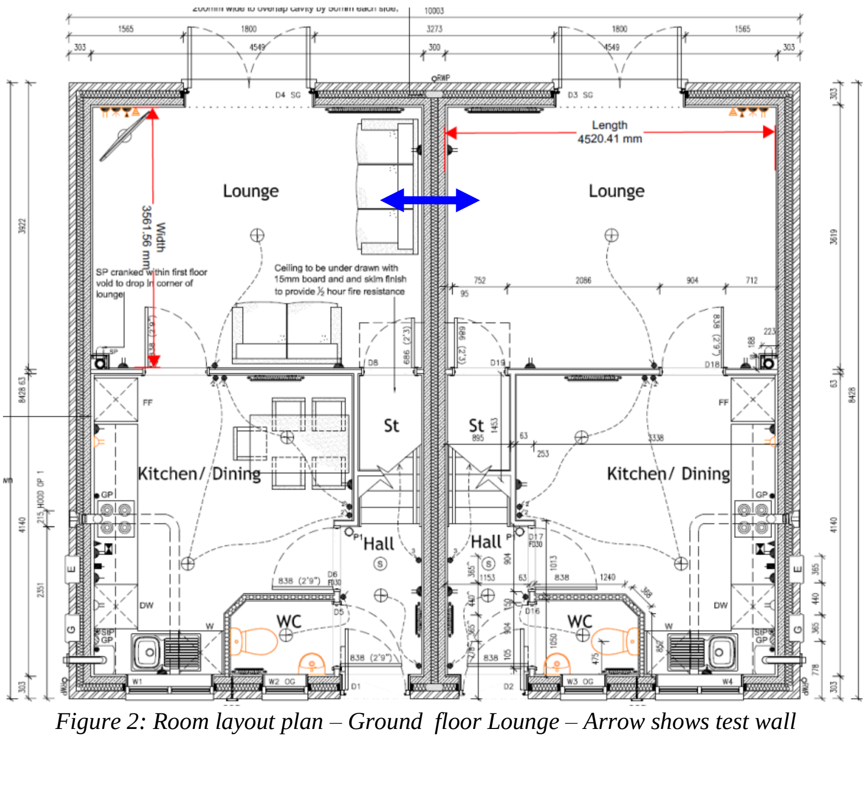


*Figure 2: Room layout plan – Ground floor Lounge – Arrow shows test wall*

## 4. Test Site

The site had on going construction activity and was very active with both internal and external construction work in progress and most plots being tested had site occupants e.g. plumbers, carpet fitters and decorators involved as the plots being tested were under time pressure for completion as all were sold and awaiting occupation. It was a typical noisy site and the test operators had to negotiate with site operatives in each pair of plots to carry out the survey. Although each operator attempted to minimise extraneous background noise there was always some audible noise occurring during the GRR experiment from some part of the constructions site and therefore this would inevitably be expected to affect the test results to some degree. It was also pertinent to note that the rooms were not empty during the test as stored materials, fixtures and fittings and waste products featured in at least one room in all room pairs tested.

## 5. Results

The total variability (variance) in the measurement process ($s_{Total}{}^2$) is made up of the variance associated with the measurement system ($s_{GRR}{}^2$) and the variance associated with the part being measured ($s_p{}^2$). The test results for the concrete floor are detailed in Table 1 with analysis regarding the dominant component of variance in Table 2.

The third octave band standardised level differences ($D_{nT}$) means for each wall and the mean for all the walls are detailed in Fig 3, it is noted that the walls, although supposedly identical in size and construction vary in measured performance.

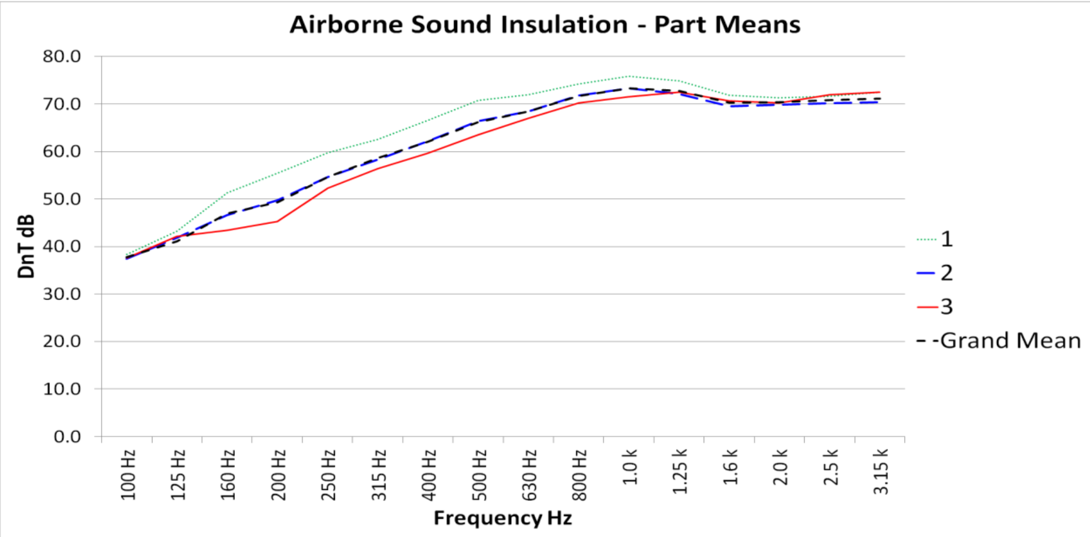


*Figure 3: DnT means for each floor tested and grand mean of all walls*

The $D_{nT}$ test results show a typical spectrum performance shape for this type of heavyweight concrete wall.

The variability caused by the individual components of the measurement system (Gauge $s_{GRR}^2 s_{GRR}{}^2$) are detailed in Fig 4 and are broken down into instrumentation variance or repeatability ($s_r^2$) and reproducibility variance or ($s_R^2$). The repeatability variances are below 3dB between 100-800Hz and then rise with frequency to 8.5dB at 3.15KHz. For reproducibility (operator and operator by part interaction) the variances are affected by the interaction term at lower frequency, then are below 1dB or tend to zero between 200Hz – 2000Hz before rising to 6.3dB at 3.15KHz. See Fig 5. Apart from the frequency range 100-160Hz the repeatability term is dominant in the uncertainty associated with the Gauge ($s_{GRR}^2$).

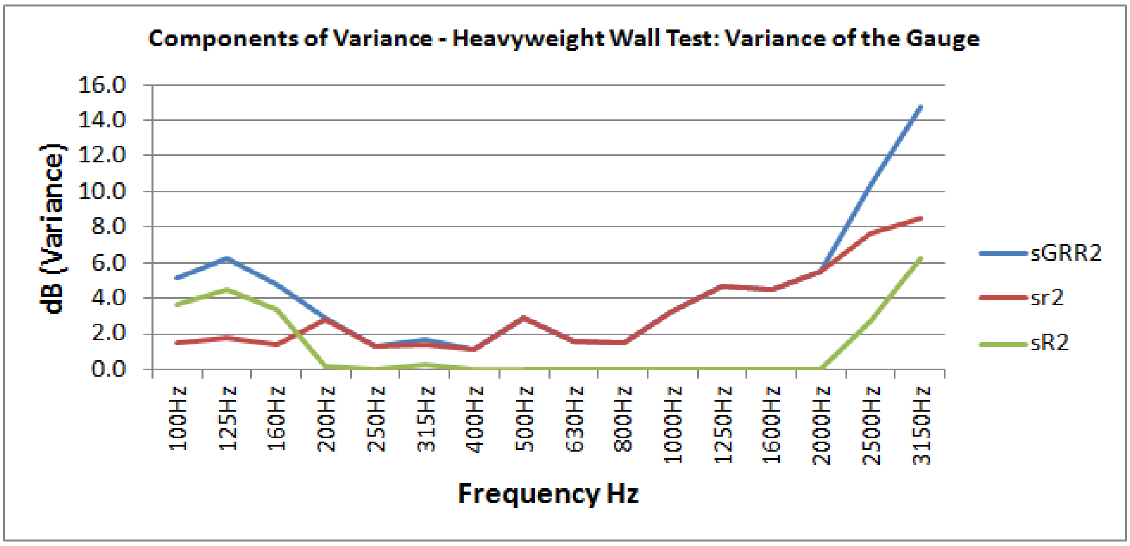


*Figure 4: Variance components of the Gauge (Repeatability + Reproducibility)*

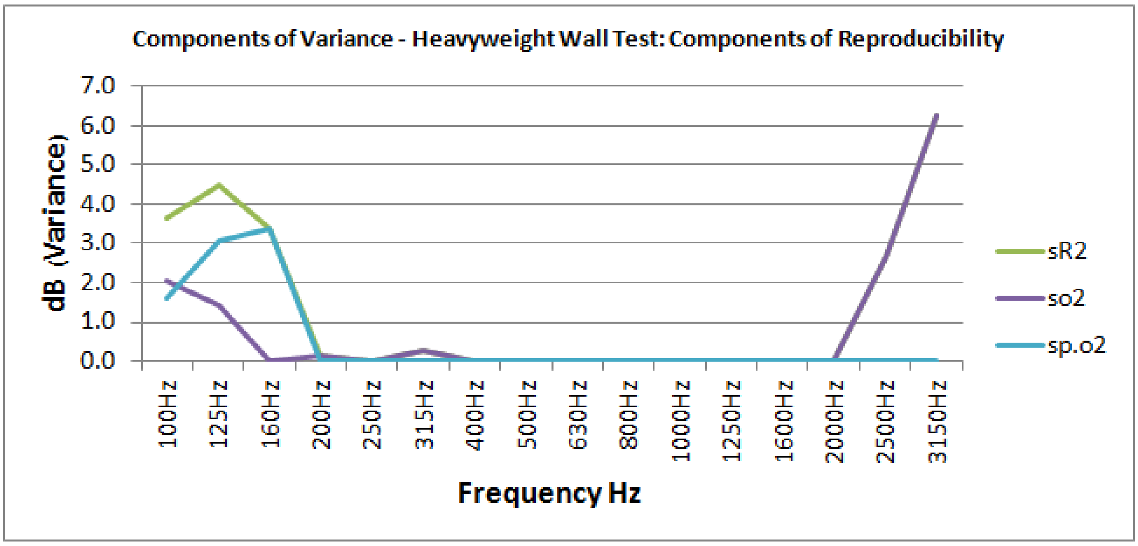


*Figure 5: Variance components of Reproducibility (Operator + Operator by part interaction).*

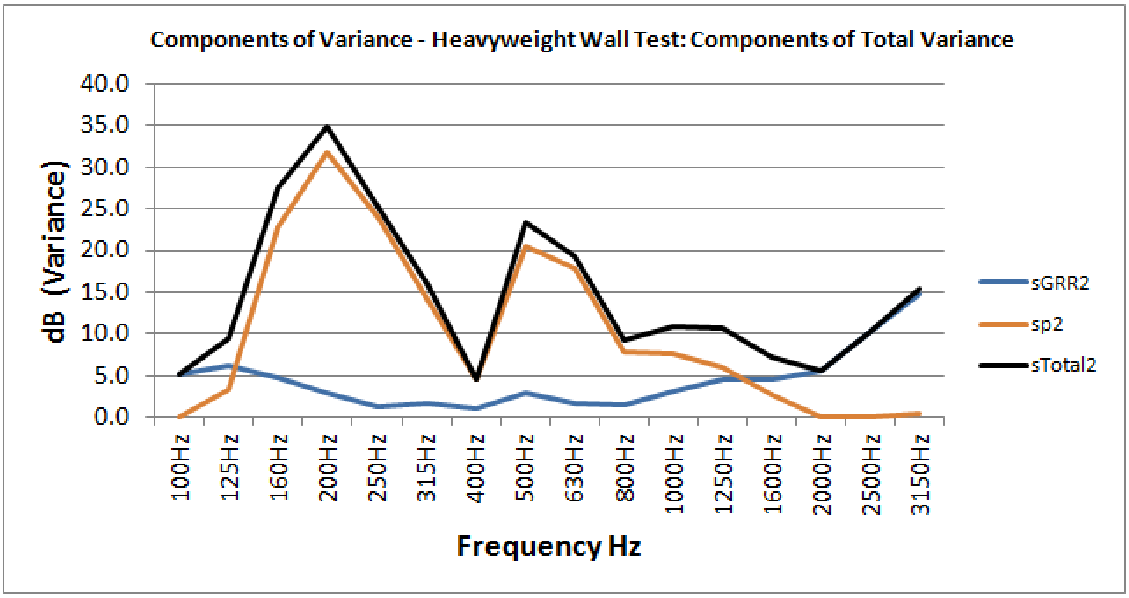


*Figure 6: Total variance components (Gauge + Part to part)*

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 [16] 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 ($s_O^2$) and the operator by part interaction ($s_{OR}^2$). 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 [17] and it would remain hidden if using the BS5725 method of calculating repeatability '$r$' and reproducibility '$R$'. In this GRR the interaction term is the dominant component of reproducibility in the low frequency bands 125Hz and 160Hz, with the operator term taking over above 1600Hz see Fig 5.

The total variance ($s_{Total}^2$) can be split between the variance attributable to the gauge ($s_{GRR}^2$) and the part being measured, i.e. the heavyweight separating wall ($s_p^2$). See Fig 6. In this experiment the part to part variance is significant and dominates the measurement uncertainty of the test results in all but the 100, 125Hz and 1600-3150Hz frequencies. This is likely to be due to the state of the wall construction when tested.

Visual inspection of Figure 6 shows that the measurement system $s_{GRR}^2$ is the dominant contributor to total variance at the 100Hz low frequency band, at 125Hz the part to part variance is similar but slightly lower than the gauge variance and doesn't become the dominant component until 160Hz band where its variance is dominant in the frequencies 160 – 1250Hz range. At 1600Hz and above the gauge becomes dominant again.

The identification of the part to part variance is useful because it describes the variability of the performance of the separating wall being measured. In this particular case, careful selection of identical room size and configuration means that the part to part variance is due to the construction of the wall and not due to any additional 'room effects'.

The part to part variance for this particular heavyweight wall construction can be documented and saved for future reference purposes. However, it is noted that only in one case was the wall finished apart from decoration (Test Wall 1), in the other two cases the wall was plasterboarded but had no skirting boards fitted or doors to the under stair cupboard, this may have contributed to the overall variability of the result relating to the part and confounds the attempt to identify the construction variability to some degree.

## 6. CONCLUSIONS

The Calculation of measurement uncertainty in field testing of sound insulation has historically been carried out using BS EN 5725 set of standards. Using the same experimental effort valuable additional information can be obtained from the data collected.

Analysis of variance and in particular GRR methods commonly used in the engineering industry can be applied to the field testing of sound insulation to determine the usual uncertainty components associated with repeatability and reproducibility but also, if care is taken over the DOE uncertainty attributable to the construction of the part being measured, in this case a heavyweight separating wall.

The blocking of the room effect allows further information to be obtained from the GRR experiment in that the dominant contribution to the total variance appears to be frequency dependent with the variance associated with the Gauge component dominating at lower frequencies 100 – 125Hz, and at higher frequency (at 1600Hz and above) with the part to part variance being more influential in the other frequencies.

As this particular site was extremely active and the actual wall construction not entirely completed between 2 house pairs the resulting measurement uncertainty components of variance are likely to be affected by these confounding factors to the extent that one would conclude the part being measured was not of similar construction? It would be preferable if this wall construction were assessed again when in a more completed state with rooms cleared of debris and possibly with less interference from site activity. In any event the site conditions may have resulted in non-ideal test conditions *but* the wall results still showed compliance with the minimum airborne sound insulation performance standards required by the Building Regulations Approved Document E [17] revised 2015.

With respect to the measurement uncertainty associated with the gauge the components of variance identified the instrument as particularly dominant above 160Hz band. This is counter to expectations although again, the controlled design of the GRR experiment is arranged specifically to separate out these components and as mentioned previously the reproducibility term does not contain the repeatability term in this experimental design.

## 7. ACKNOWLEDGEMENTS

The author is grateful to Rob Hannan and Bryan Jepson for selection of the test site in Bolsover and allowing access for the test and to the noise.co.uk Ltd UKAS test team for carrying out the sound insulation testing.

*Table 1: GRR Complete components of variance table – Heavyweight Walls (rounded to 1decimal place)*

| Measurement | Total GRR | Repeatability | Reproducibility | Operator | Part*Operator | Part | Total |
|---|---|---|---|---|---|---|---|
| dB Cavity Wall | $\sigma_{GRR}^2$ | $\sigma_r^2$ | $\sigma_R^2$ | $\sigma_o^2$ | $\sigma_{p.o}^2$ | $\sigma_p^2$ | $\sigma_{Total}^2$ |
| DnTw | 0.8 | 0.6 | 0.1 | 0.1 | 0.0 | 10.5 | 11.3 |
| DnTw+Ctr | 2.2 | 0.7 | 1.5 | 0.3 | 1.1 | 3.9 | 6.1 |
| 100Hz | 5.1 | 1.5 | 3.6 | 2.0 | 1.6 | 0.0 | 5.1 |
| 125Hz | 6.3 | 1.8 | 4.5 | 1.4 | 3.1 | 3.3 | 9.6 |
| 160Hz | 4.8 | 1.4 | 3.4 | 0.0 | 3.4 | 22.8 | 27.6 |
| 200Hz | 2.9 | 2.8 | 0.1 | 0.1 | 0.0 | 31.8 | 34.8 |
| 250Hz | 1.3 | 1.3 | 0.0 | 0.0 | 0.0 | 24.0 | 25.2 |
| 315Hz | 1.7 | 1.4 | 0.3 | 0.3 | 0.0 | 14.3 | 16.0 |
| 400Hz | 1.1 | 1.1 | 0.0 | 0.0 | 0.0 | 4.5 | 4.7 |
| 500Hz | 2.9 | 2.9 | 0.0 | 0.0 | 0.0 | 20.6 | 23.5 |
| 630Hz | 1.6 | 1.6 | 0.0 | 0.0 | 0.0 | 17.8 | 19.4 |
| 800Hz | 1.4 | 1.4 | 0.0 | 0.0 | 0.0 | 7.7 | 9.2 |
| 1000Hz | 3.2 | 3.2 | 0.0 | 0.0 | 0.0 | 7.7 | 10.9 |
| 1250Hz | 4.7 | 4.7 | 0.0 | 0.0 | 0.0 | 6.1 | 10.7 |
| 1600Hz | 4.5 | 4.5 | 0.0 | 0.0 | 0.0 | 2.7 | 7.2 |
| 2000Hz | 5.5 | 5.5 | 0.0 | 0.0 | 0.0 | 0.0 | 5.5 |
| 2500Hz | 10.3 | 7.7 | 2.7 | 2.7 | 0.0 | 0.0 | 10.3 |
| 3150Hz | 14.8 | 8.5 | 6.3 | 6.3 | 0.0 | 0.5 | 15.3 |

*Table 2: Heavyweight Walls - Summary of dominant components of variance by frequency*

| **Measurand/ Frequency** | Major influences |
|---|---|
| dB Cavity Wall | Comments |
| DnTw | The part is the main contributor to total variance |
| DnTw+Ctr | The part is the main contributor to total variance |
| 100Hz | The gauge is responsible for the variance at 100Hz with the major component down to the operator then the instrument |
| 125Hz | The gauge is responsible for the variance at 125Hz with the major component down to the operator by part interaction |
| 160Hz | The part is the main contributor to total variance |
| 200Hz | The part is the main contributor to total variance |
| 250Hz | The part is the main contributor to total variance |
| 315Hz | The part is the main contributor to total variance |
| 400Hz | The part is the main contributor to total variance |
| 500Hz | The part is the main contributor to total variance |
| 630Hz | The part is the main contributor to total variance |
| 800Hz | The part is the main contributor to total variance |
| 1000Hz | The part is the main contributor to total variance |
| 1250Hz | The part is the main contributor to total variance |
| 1600Hz | The gauge is responsible for the variance with the major component down to the instrument |
| 2000Hz | The gauge is responsible for the variance with the major component down to the instrument |
| 2500Hz | The gauge is responsible for the variance with the major component down to the instrument |
| 3150Hz | The gauge is responsible for the variance with the major component down to the instrument |

## 8. REFERENCES


1. Hughes, I.G.H., Thomas, P.A., *Measurements and their Uncertainties - A Practical Guide to Modern Error Analysis*. 2010: Oxford University Press.
2. Whitfield W.A, G.B.M., *MEASUREMENT UNCERTAINTY IN AIRBORNE SOUND INSULATION: UNCERTAINTY COMPONENTS IN FIELD MEASUREMENT.*, in *ICSV 22*. 2015: Florence.
3. Whitfield W.A and B.M. Gibbs. *VARIATION IN FIELD MEASUREMENT OF AIRBORNE SOUND INSULATION OF LIGHTWEIGHT TIMBER FLOORS*. in *Noise in the Built Environment,*. 2010. Ghent.
4. Whitfield W.A , F., *Measurement uncertainty and the components of variance in airborne sound insulation testing for 'Heavy' concrete floors*, in *Euronoise 2018 Crete*. 2018.
5. Mandel, J., *Repeatability and Reproducibility*. Journal of Quality Technology, 1972. **4**(2).
6. Tsai, P., *Variable Gauge Repeatability and Reproducibility Study Using The Analysis of Variance Method.* Quality Engineering, 1988. **1**(1): p. 107-115.
7. Taibo, L. and H. Glasserman De Dayan, *ANALYSIS OF VARIABILITY IN LABORATORY AIRBORNE SOUND INSULATION DETERMINATIONS.* Journal of Sound and Vibration, 1983. **91**((3)): p. 319-329.
8. Davern W, A.D., P, *First report on Australasian comparison measurements of sound absorption coefficients*. 1980, Commonwealth Scientific and Industrial Research Organization - Division of Building Research.
9. Davern W.A., D.P., *Second report on Australaisian comparison measurements of sound absorption coefficients*. 1985, Commonwealth Scientific & Industrial Research Organisation - Division of Building Research.
10. Deldossi, L., Zappa, D., *ISO 5725 and GUM: comparison and comments.* Accreditation and Quality Assurance, 2009. **14**: p. 159-166.
11. Montgomery, D.C., Runger,G.C, *Gauge Capability and Designed Experiments. Part 1: Basic Methods.* Quality Engineering, 1993. **6**(1): p. 115-135.
12. Montgomery, D.C., Runger,G.C, *Gauge Capability Analysis and Designed Experiments. Part II: Experimental Design Models and Variance Component Estimation.* Quality Engineering, 1993. **6**(2): p. 289-305.
13. Burdick, R.K., Borror,C.M, Montgomery,D.C., *Design & Analysis of Gauge R&R Studies.* 2005: SIAM.
14. Montgomery, D.C., *Design & Analysis of Experiments*. 5th ed. 2001: John Wiley.
15. *BS EN ISO 140-4. Acoustics-measurement of sound insulation in buildings and of building elements. Part 4. Field measurements of airborne sound insulation between rooms*, in *BS EN ISO 140-4.* . 1998.
16. *BS EN ISO 717-1: Acoustics-rating the sound insulation in buildings and of building elements. Part 1. Airborne sound insulation*, in *BS EN ISO 717-1*. 1996.
17. HMSO, *Approved Document E: Resistance to the passage of sound*. 2003, HMSO.