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Measurement uncertainty and the components of variance in airborne sound insulation testing for heavy concrete floors

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Summary

This paper builds on earlier research which identified the components of variance associated with airborne sound insulation testing on lightweight Timber Floors. It uses a specific design of experiment (DOE) to draw out the component of variance due to the part, the operator and the instrumentation being used, and is commonly known as a Gauge Repeatability and Reproducibility (GRR) experiment. The Analysis of variance (ANOVA) is based on a balanced two-factor crossed random model with interaction, and targets the uncertainty due to the variability of the part, the operator and the instrumentation (Test kit) and also identifies if there is any interaction between the operators and the part being measured.

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] 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 [4] and Tsai [5] and the previous use of ANOVA in acoustic research is not without precedent, see Taibo and Glasserman de Dayan[6] and Davern and Dubout P [7, 8].

The main advantages of ANOVA are listed by Deldossi and Zappa [9] 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 [10, 11] and culminated in a monograph on the subject, including its special applications by Burdick et al [12]. 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 [10, 11, 13] and Burdick et al [12] 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) floor Robust Detail E-FC-4. See Figure 1:

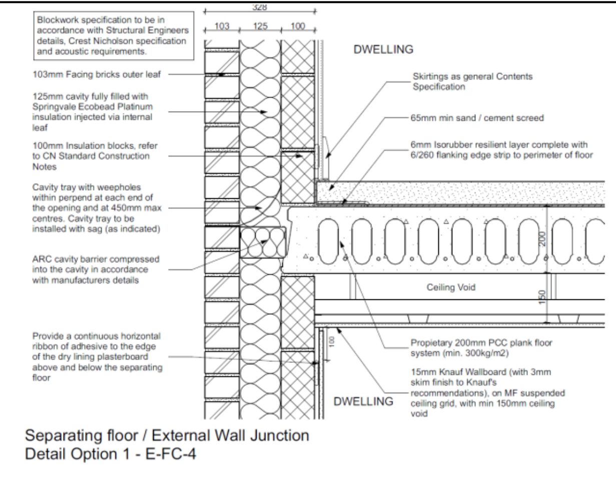

Figure 1: Separating floor section E-FC-4

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 [14] with the data analysed to BS EN ISO 717-1: 1997 [15]

The separating floor construction from the top down can be described as follows:

1. 65mm Sand/Cement screed;
2. 6mm Isorubber resilient layer;
3. 200mm PCC plank floor min 300Kg/m2;
4. MF Suspended ceiling 15mm Knauf Wall Board and 150mm ceiling void.

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) 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 (1):

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

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 = 5, o = 5 and r = 2

The definition of reproducibility in the GRR is covered in Burdick et al [12] 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..

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

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

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

3. Test Specimen Floors

The test site was a residential apartment block in Hitchin, Hertfordshire, UK and was located on a main road into the town centre adjacent to a traffic light controlled cross roads. The main background noise on site was therefore road traffic noise from external sources and as the time of the planned sound insulation testing was between 4pm and 10pm on a weekday it did include rush hour

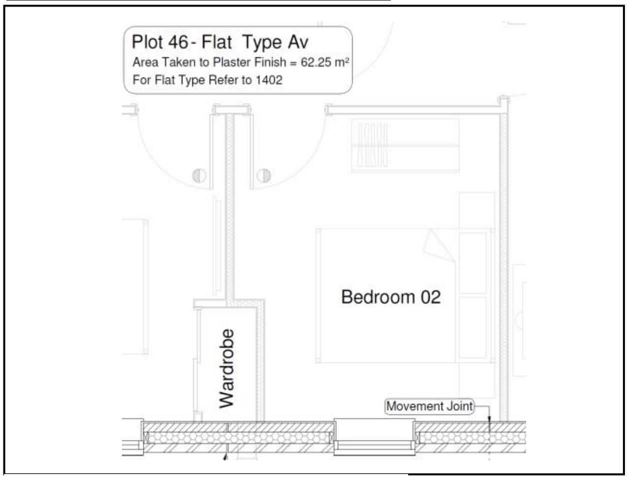

Figure 2: Test room

traffic. Background noise from construction activity on site and inside the building was intentionally minimised during testing because the majority of site operations stopped between 3pm - 4pm in the afternoon. The test rooms selected were the small bedroom (Bedroom 2) in the two bedroom flats. They were identical shape & size (approx 2.4m H x 3.05m W x 4.8m L) and 21.6m^3. The selection of identical shape and size room pairs was intentional in order to block 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 floor area under test being an identical size. All rooms in the test were small to replicate typical rooms in residential apartments. See Fig 2.

4. Results

The total variability (variance) in the measurement process (sTotal2) is made up of the variance associated with the measurement system (sGRR2) and the variance associated with the part being measured (sp2). The test results for the concrete floor are detailed in Table I.

The third octave band standardised level differences (DnT) means for each floor and for all the floors are detailed in Fig 3:

The DnT test results show a typical spectrum performance shape for this type of heavyweight concrete floor.

The variability caused by the individual components of the measurement system (Gauge sGRR2) are detailed in Fig 4 and are broken down into instrumentation variance or repeatability (sr2) and reproducibility variance or (sR2). Both the repeatability (instrument) and the reproducibility (operator and operator by part) variances are dominated by a high degree of variability at low frequency, primarily due to non diffuse sound field in the relatively small source and receiver rooms and is expected. As the sound field becomes more diffuse at higher frequencies the variances fall, in this case below 1dB around 200Hz. The variance terms for r and R fall below 0.5dB after 400Hz. See Fig 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 [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 (so2) and the operator by part interaction (sp.o2). 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’.

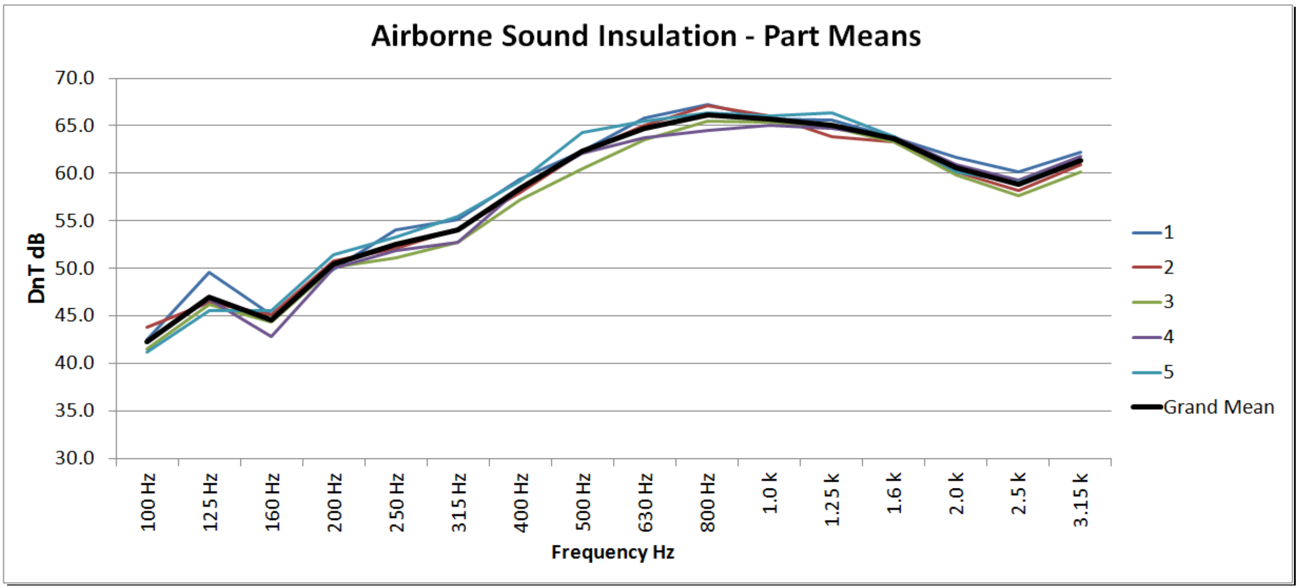

Figure 3: DnT means for each floor tested and grand mean of all floors

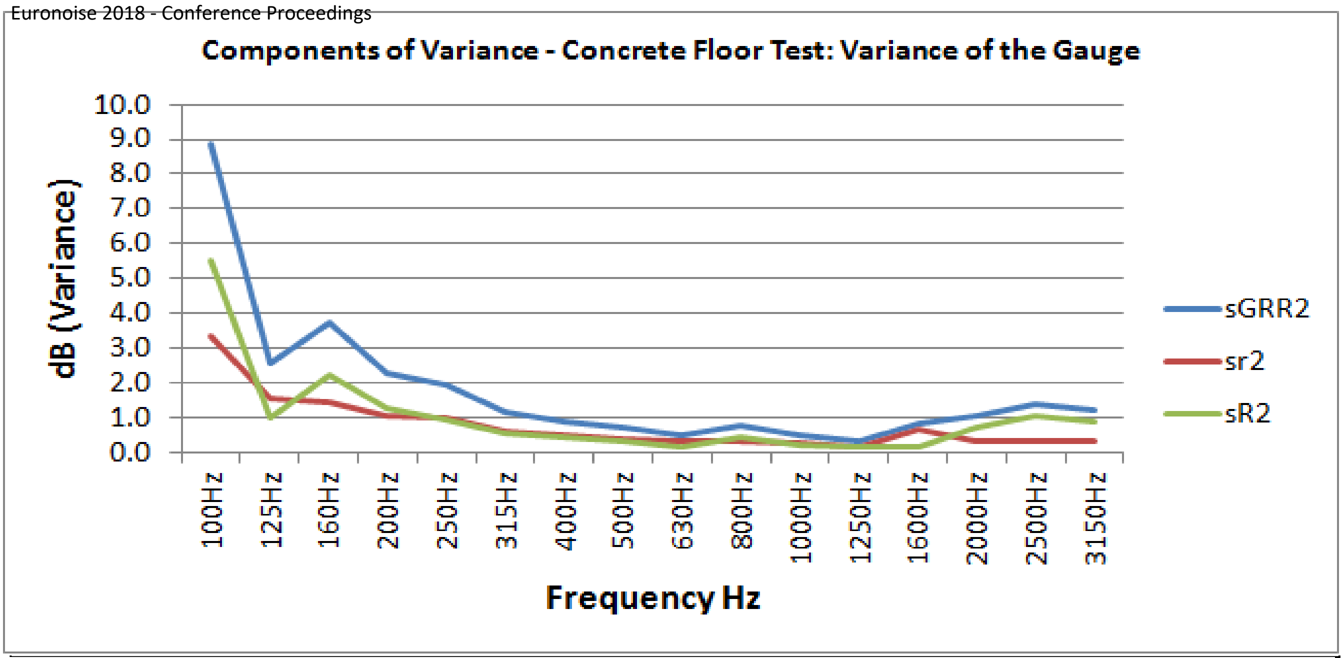

Figure 4: Variance components of the Gauge (Repeatability + Reproducibility)

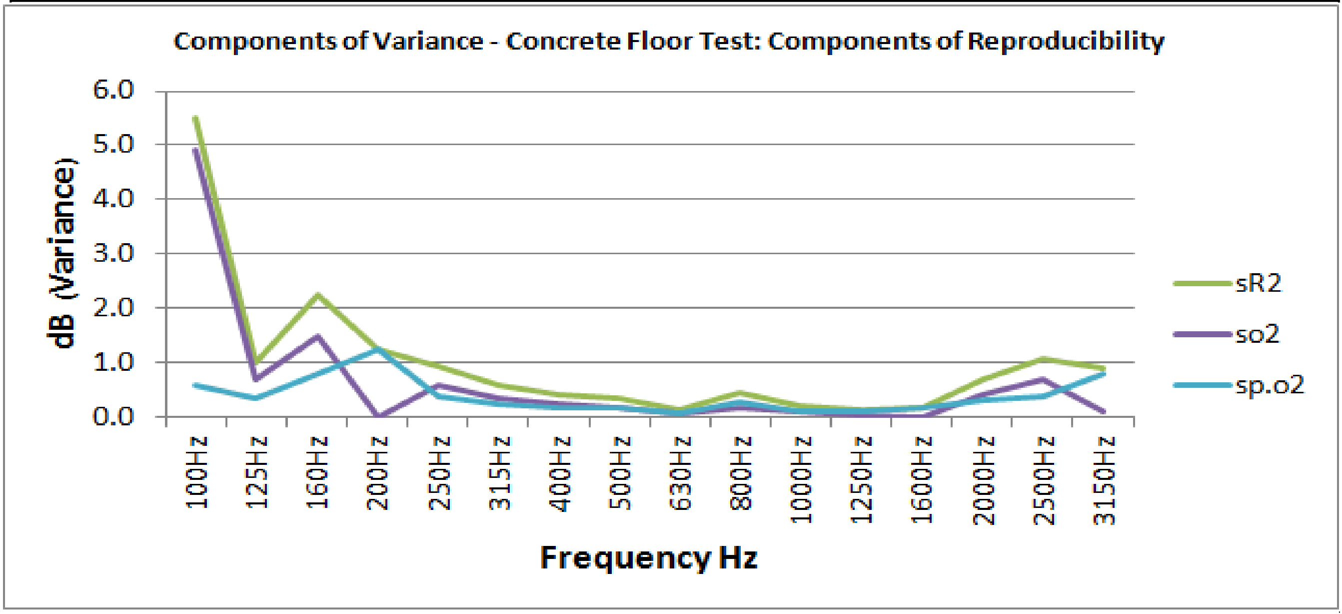

Figure 5: Variance components of Reproducibility (Operator + Operator by part interaction).

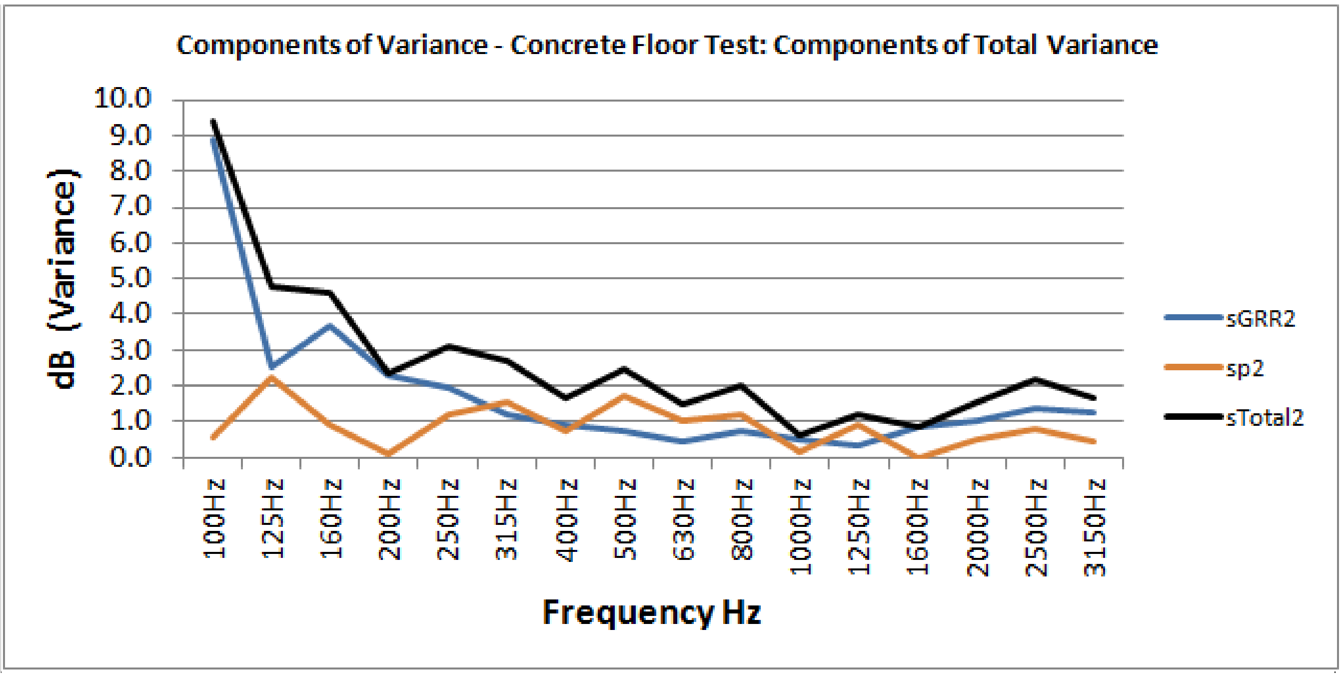

Figure 6: Total variance components (Gauge + Part to part)

The total variance can be split between the variance attributable to the gauge (sGRR2) and the part being measured, i.e. the heavyweight separating floor (sp2). See Fig 6.

In this case the individual components of variance that make up the total variance vary according to frequency. The individual components of variance that are dominant i.e. contribute most in relation to the overall variance (sTotal2) measured can be identified, or in some cases we would conclude that there may be no significant dominance by any single component or that the total variance is very low e.g. summarised and this is done in Table II.

Visual inspection of Figure 6 shows that the measurement system sGRR2 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 315Hz band where its variance is dominant in the mid frequencies 315 – 800Hz 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 floor 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 floor and not due to any additional 'room effects'.

The part to part variance for this particular heavyweight floor construction can be documented and saved for future reference purposes.

5. Conclusions

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 floor.

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 – 200Hz, and at higher frequency (at 1600Hz and above) range with the part to part variance being more influential in the mid frequencies.

More data from GRR experiments is desirable to investigate further how the operators are interacting with the part being measured in field test environments and the frequency dependent nature of the uncertainty contributions for other wall and floor constructions and this is now being adopted by other acoustic practitioners, see Dong and LoVerde [18].

6. Acknowledgements

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Table I. GRR Complete components of variance table – Heavyweight floors (rounded to 1decimal place)

Measurement	Total GRR	Repeatability	Reproducibility	Operator	Part*Operator	Part	Total
dB Concrete	σ_{GRR}^2	σ_r^2	σ_R^2	σ_o^2	$\sigma_{p.o}^2$	σ_p^2	σ_{Total}^2
100Hz	8.9	3.4	5.5	4.9	0.6	0.6	9.4
125Hz	2.5	1.5	1.0	0.7	0.3	2.2	4.8
160Hz	3.7	1.5	2.2	1.5	0.8	0.9	4.6
200Hz	2.3	1.0	1.2	0.0	1.2	0.1	2.4
250Hz	1.9	1.0	0.9	0.6	0.4	1.2	3.1
315Hz	1.2	0.6	0.6	0.3	0.2	1.5	2.7
400Hz	0.9	0.5	0.4	0.2	0.2	0.8	1.6
500Hz	0.7	0.4	0.3	0.1	0.2	1.7	2.4
630Hz	0.5	0.3	0.1	0.1	0.1	1.0	1.5
800Hz	0.8	0.3	0.5	0.2	0.3	1.2	2.0
1000Hz	0.5	0.3	0.2	0.1	0.1	0.1	0.6
1250Hz	0.3	0.2	0.1	0.0	0.1	0.9	1.2
1600Hz	0.8	0.6	0.2	0.0	0.2	0.0	0.8
2000Hz	1.0	0.3	0.7	0.4	0.3	0.5	1.5
2500Hz	1.4	0.3	1.1	0.7	0.4	0.8	2.2
3150Hz	1.2	0.3	0.9	0.1	0.8	0.5	1.7

Table II.– Heavyweight floors - Summary of dominant components of variance by frequency.

Measurand/ Frequency	Major influences on measurement uncertainty from individual components of variance
Concrete	Comment Summary
DnTw	There is no significant component of variance that affects the single figure value both Gauge and Part contribute equally at <0.5dB
DnTw+Ctr	In this case the Gauge affects the single figure value and in that it is the Reproducibility component associated with the ‘Operator’ that is dominant.
100Hz	The gauge is dominant in the total variance at 100Hz with the major component being the ‘Operator’ and a significant contribution from the ‘instrument’.
125Hz	The gauge is the major component of variance closely followed by the part
160Hz	There is variance from the operator and some interaction by part contributing to the largest R component
200Hz	Repeatability and interaction are the dominant contributors
250Hz	Operator and instrument are the dominant contributors
315Hz	The part is the major contributor at this frequency
400Hz	The part is the major contributor at this frequency
500Hz	The part is the major contributor at this frequency
630Hz	The part is the major contributor at this frequency
800Hz	The part and instrument are the major contributors at this frequency
1000Hz	Nothing significant
1250Hz	The part is the major contributor at this frequency
1600Hz	The instrument is the dominant component
2000Hz	The instrument and the operator are the dominant contributors
2500Hz	The instrument and the operator are the dominant contributors
3150Hz	The instrument and the operator by part interaction are the dominant contributors

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