Quantifying EMC Measurement Accuracy Using Feature Selective Validation

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Abstract – It is commonplace in the field of Computational Electromagnetics (CEM) for engineers to validate models against experimental results. In some cases, this is performed with little understanding about the accuracy of the experimental data used to validate the underlying calculations from which Electromagnetic models are formed. This paper therefore explores the accuracy and more importantly the areas of inaccuracy and variability that may be associated with experimental data. The Feature Selective Validation (FSV) method is used to assess each area of variability, and thus quantify the quality of test configurations and test samples. In examining experimental repeatability rather than comparison to electromagnetic analysis results, this paper concludes that, while substantial variation between experimental results can exist, the use of FSV provides considerable assistance in quantifying repeatability and therefore assigning confidence to measurements against which CEM results can be compared. While this paper is based on experience in the automotive sector, it is anticipated that these findings are more widely applicable.

Keywords: Computational Electromagnetics (CEM), Feature Selective Validation (FSV).

I. INTRODUCTION

Between the numbers of options open to a modeller to validate a numerical model, one of the most accepted is a direct comparison with experimental measurements. A natural tendency to explain differences between the modelled and measured results is to attribute the bulk of the error to the model. After all, there are known and accepted simplifications in any model through approximating physical structures, applying spatial, time and / or frequency discretization to the problem. However, this is not always or entirely correct. All experiments are subject to some inherent inaccuracy or loading and detailed knowledge of experimental repeatability can assist in determining levels of acceptable experimental error. Within the automotive sector, statistical coverage of component level testing is low, with most vehicle manufactures calling for two samples of the same component to be tested. At vehicle level only a single vehicle sample need be tested. Electromagnetic Compatibility (EMC) test facilities include uncertainty thresholds; however, it is difficult to interpret the actual quantitative/qualitative impact of these thresholds upon test results.

The nature of the variability between test results is important to be able to perform comparisons with a high level of confidence. This can be through:

- Validation of the results taken from different test samples,
- The results gained from marginally different test configurations,
- Repeated results from the same test sample.

This type of analysis allows the assessment of questions such as:

- Are the tests repeatable?
- Are different test samples of the same product similar?
- Do minor differences in test configurations (that fall within the parameters of the test specification) produce different results?

The quality of experimental data is influenced by the method of producing and recording the data, and the degree of perfection in the experimental procedure. In addition to these variables, the repeatability of test results for multiple samples of the same product will be affected by the build quality of the product and tolerance of the individual components used to manufacture the product.

Quantitative comparisons of experimental results are therefore required to remove as much subjectivity as possible from the assessment of results. This study presents results from a number of repeated experiments performed with two different test products using two slightly different test configurations and identifies their level of difference employing the Feature Selective Validation method [1-2]. From these investigations the origins of variability in the tests may be assessed and quantified.

The FSV method comprises two components; the Amplitude Difference Measure (ADM), and Feature Difference Measure (FDM). These measures are combined to form an overall assessment of the comparison in question or Global Difference Measure (GDM). It is these three measures that will be used in the subsequent study to assess the differences between the presented results. The ADM is obtained by, essentially, taking the normalised difference in the 'trend' ('envelope') information from two data sets to be compared, which is obtained by low-pass filtering the original data. The FDM is obtained from a composite of the differences in the derivatives of the low-pass filtered response and the high-pass filtered response to accentuate the 'high Q' feature differences between the data sets. One common way of using this information is to take the mean value of the ADM and FDM obtained across the domain of the original data as figures of merit. An overall figure of merit, the GDM, is obtained from

$$GDM = \sqrt{ADM^2 + FDM^2}\ . \qquad (1)$$

The FSV method benefits from its apparent ability to mirror human perception [3], while producing information that directly relates human variability and the confidence associated with it. The FSV method also builds on the common language of engineers and scientists alike, employing categories which relate to human interpretations of comparisons, namely: 'Excellent', 'Very Good', 'Good', 'Fair', 'Poor' and 'Very Poor'. The basic premise is that a value of zero for any of the difference measures represents perfect correlation. The interpretation for finite values is indicated in Table 1 below.

Table 1. Qualitative interpretation of FSV difference measures.

FSV Difference Measure "*x*"	**"Quality" of comparison**
$x<0.1$	Excellent
$0.1\le x<0.2$	Very good
$0.2\le x<0.4$	Good
$0.4\le x<0.8$	Fair
$0.8\le x<1.6$	Poor
$1.6\le x$	Very Poor

The qualitative interpretation of the difference measures has been developed from a statistical analysis [3] of the results of a series of selected visual assessments carried out by a group of experienced scientists and engineers. It is natural that different applications will have different expectations of what 'good' etc. actually is, but this is likely to be a shared understanding by the personnel involved.

II. TEST PROCEDURES

It was decided that within the field of Automotive EMC measurement, acceptable repeatability may be set at a GDM value not greater than 0.4 (i.e. 'Good'). This value was distilled from cumulative group experience and was agreed throughout the project team. The choice of this value in other test and measurements fields is dependent on the inherent sensitivity of the measurements and the level of precision that can be associated with the configuration of the test equipment. In an attempt to assess the influence of a products complexity on the repeatability of measurements, a complex electrical unit (DC to DC Converter) and a simple electrical unit (windscreen washer pump motor) were chosen as the devices under test for the subsequent study. For the purpose of providing a 'golden measurement' to compare models against, a GDM of 'Very Good' or even 'Excellent' may be required.

Three DC to DC converters with identical part numbers were obtained from a worldwide electronic component manufacturer. These are referred to as samples A, B, and C throughout this study. It should be noted that while the three DC to DC converters shared the same part numbers, inquiries into the manufacturing background of samples A, B, and C led to the discovery that sample C had been manufactured significantly later than either samples A and B and that the manufacturing plant producing these parts had moved geographically within that time interval. The three windscreen washer pump motors used in this study were from the same manufacturing batch and are referred to in this study as samples D, E, and F.

A comprehensive test regime was constructed to allow assessments to be made on the variability:

a) of repeated tests performed using identical test configurations and samples;
b) when the test configuration is altered slightly but within the scope of the test specification;
c) between three samples of the same product.

To assess these three areas of variability, an emissions measurement was performed, and upon completion of the initial test sweep a second test sweep was carried out with no interference to the test configuration. The sample was then incremented and the process repeated. This gave rise to repeated test results (a and b) for each sample (A to F). The test configuration was then altered slightly and the complete suite of tests was repeated as detailed in the test matrix of Table 2.

Table 2. Test matrix.

	DC to DC Converter					
	Sample A		Sample B		Sample C	
Configuration 1	01a	01b	02a	02b	03a	03b
Configuration 2	04a	04b	05a	05b	06a	06b
	Windscreen Washer Pump Motor					
	Sample D		Sample E		Sample F	
Configuration 1	07a	07b	08a	08b	09a	09b
Configuration 2	10a	10b	11a	11b	12a	12c

The standard test method [4] requires a 1.5 m section of test harness to be exposed to the measurement receive antenna. This 1.5 m section is clearly illustrated in Fig. 1 as the foremost straight section running 100 mm behind, but parallel with, the front edge of the ground plane. The Directive also calls for the product under test to be located 200 mm behind the front edge of the ground plane.

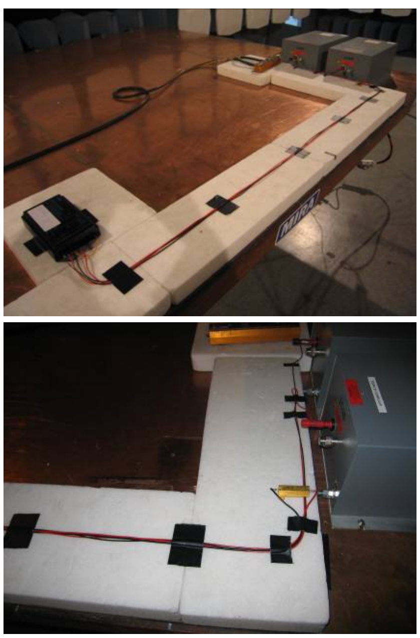

Fig. 1. Generic 2004/104/EC (Annex VII) test configuration.

Test configurations 1 and 2 were both set up within the defined test method of [4]. Small variations were introduced between them to provide a test of the sensitivity of the configurations to small changes. Configuration 1 used identical power and ground cable lengths, and the surplus of power cable due to the location of the test Line Impedance Stabilisation Networks (LISNs) was coiled slightly, see Fig. 1. Configuration 2 used the same length ground cable as configuration 1 but the overall length of the power cable was reduced by approximately 300 mm to avoid having to coil surplus cable when connecting to the test LISN.

III. TEST RESULTS

Results from the tests detailed in Table 2 are illustrated in Fig. 2 to 7.

In order of severity, it is observed from a visual evaluation that; there are significant differences between test configurations 1 and 2; the emissions profile of test sample C is significantly lower in magnitude compared to those of samples A and B; and all repeated test results are very similar for each sample tested when the same test configuration is used.

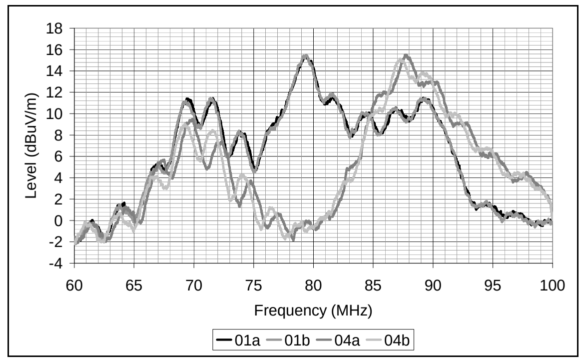

Fig. 2. Results sample A.

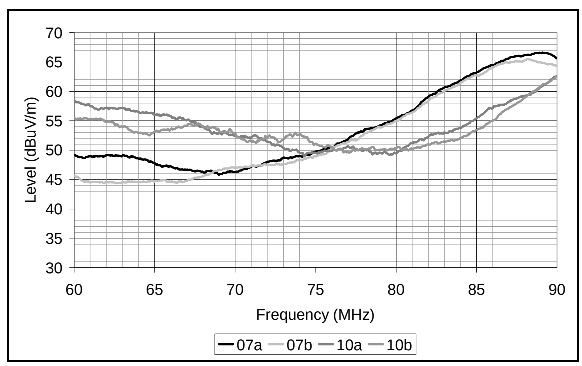

Fig. 3. Results sample D.

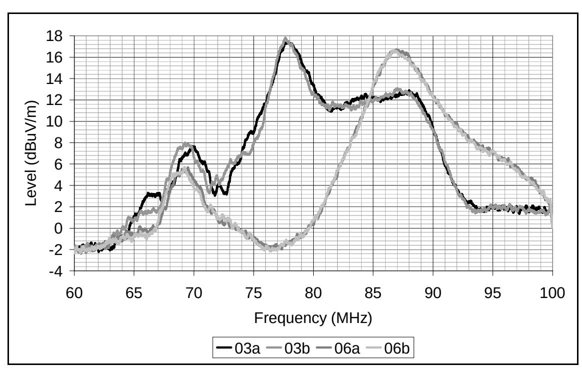

Fig. 4. Results sample B.

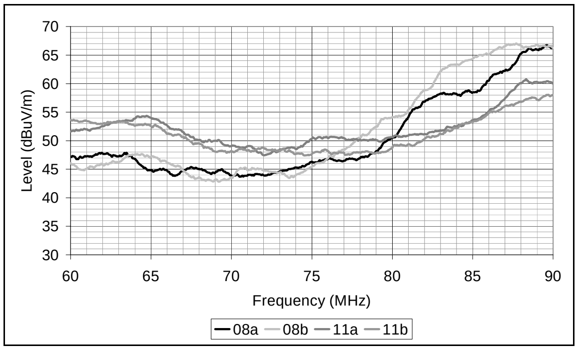

Fig. 5. Results sample E.

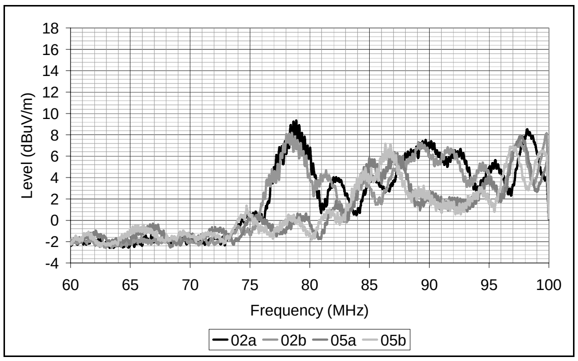

Fig. 6. Results sample C.

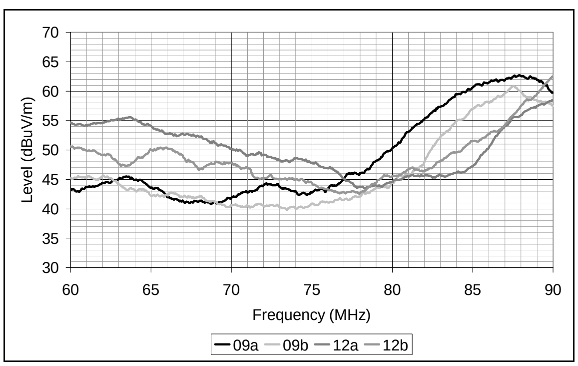

Fig. 7. Results sample F.

IV. VALIDATION RESULTS

The test results were cross-validated in sets to give rise to the following assessments:

Comparisons of repeated tests performed using identical test configurations

SET A1. Configuration 1 Samples A through C.
SET A2. Configuration 1 Samples D through F.
SET A3. Configuration 2 Samples A through C.
SET A4. Configuration 2 Samples D through F.

Comparisons of tests performed using 2 different configurations

SET B1. Configuration 1 vs. Configuration 2 - Samples A through C.
SET B2. Configuration 1 vs. Configuration 2 - Samples D through F.

Comparisons between three samples of the same product

SET C1. Test Samples A through C – cross-validation.
SET C2. Test Samples D through F – cross-validation.

The quantitative and qualitative FSV validation results (GDM, ADM and FDM) for each validation sub-set detailed above are given in Table 3, 4, and 5. The final three columns indicate the average quantitative and qualitative FSV results for each validation sub-set. It is these average results that are used in the subsequent discussions.

In Table 3, the average GDM results of sub-sets A1 and A2 indicate that test configuration 1 has a ‘Very Good’ level of repeatability. The results of sub-sets A3 and A4 indicate that test configuration 2 only has a ‘Good’ level of repeatability and therefore incurs considerably more variability in repeated test results even though no changes were made to the test configuration between each repeated test.

Results presented in Table 4 from sub-sets B1 and B2 illustrate only a ‘Fair’ level of similarity between test configurations for the same test sample. This indicates that if the test samples were unknown to an engineer making visual evaluations of the results presented in this study, it would be difficult to conclude that it was the same product tested in configurations 1 and 2.

Cross-validation of the results for the DC to DC converter samples (A, B and C) presented in Table 5 indicates a ‘Fair’ level of similarity which illustrates that the samples were significantly different. The cross-validation of samples A and B indicate that the sample variability of the DC to DC converter product is ‘Good’ when the samples are taken from the same batch.

Conversely, the validation results for sub-set C2 indicates that there is a ‘Very Good’ level of similarity between the three windscreen washer pump samples (D, E and F).

V. DISCUSSION AND CONCLUSIONS

Recognising that a preferred approach to the validation of computational electromagnetics is to compare the results of the models against an experimentally obtained reference, this paper has been concerned with investigating an approach to determining the repeatability of measurements, with a view to using this quantification to establish a level of confidence in any comparison with numerical models. It assessed three areas of experimental variability, namely:

- Test repeatability,

- Test configuration,
- Test sample variability.

Using the predefined tolerance for accurate results set earlier in this paper at a GDM value no greater than 0.4 or ‘Good’; the results indicate that repeated test using the same test configuration (without modification) and for the same product are adequate as expected. It is also confirmed that test samples from the same batch tested using the same test configuration offer results with a high level of confidence.

It has also been illustrated that only a small modification (within the scope of the overall test specification) to a test configuration can have a significant impact upon the confidence that can be associated with the test results.

This paper illustrates that variability between test samples, particularly those from different batches, and differences in test configurations, have the potential to modify experimental test results to such a degree that it would be difficult to conclude that the same product was tested.

Table 3. FSV validation results – test repeatability.

		Quantitative			Qualitative			Average (Quantitative/Qualitative)		
SET	**Comparison**	**GDM**	**ADM**	**FDM**	**GDM**	**ADM**	**FDM**	**GDM**	**ADM**	**FDM**
A1	01a Vs 01b	0.05	0.00	0.05	EXCELLENT	EXCELLENT	EXCELLENT	0.15	0.01	0.15
	02a Vs 02b	0.21	0.02	0.20	GOOD	EXCELLENT	GOOD			
	03a Vs 03b	0.20	0.01	0.20	GOOD	EXCELLENT	GOOD	V GOOD	EXCELLENT	V GOOD
A2	07a Vs 07b	0.09	0.04	0.06	EXCELLENT	EXCELLENT	EXCELLENT	0.15	0.07	0.10
	08a Vs 08b	0.19	0.09	0.11	V GOOD	EXCELLENT	V GOOD			
	09a Vs 09b	0.18	0.08	0.12	V GOOD	EXCELLENT	V GOOD	V GOOD	EXCELLENT	V GOOD
A3	04a Vs 04b	0.24	0.02	0.23	GOOD	EXCELLENT	GOOD	0.24	0.04	0.22
	05a Vs 05b	0.36	0.10	0.32	GOOD	V GOOD	GOOD			
	06a Vs 06b	0.11	0.00	0.11	V GOOD	EXCELLENT	V GOOD	GOOD	EXCELLENT	GOOD
A4	10a Vs 10b	0.26	0.16	0.18	GOOD	V GOOD	V GOOD	0.27	0.17	0.17
	11a Vs 11b	0.22	0.11	0.13	GOOD	V GOOD	V GOOD			
	12a Vs 12b	0.34	0.24	0.20	GOOD	GOOD	GOOD	GOOD	V GOOD	V GOOD

Table 4. FSV validation results – test configuration variability.

		Quantitative			Qualitative			Average (Quantitative/Qualitative)		
SET	**Comparison**	**GDM**	**ADM**	**FDM**	**GDM**	**ADM**	**FDM**	**GDM**	**ADM**	**FDM**
B1	01a Vs 04a	0.46	0.31	0.26	FAIR	GOOD	GOOD	0.45	0.29	0.29
	02a Vs 05a	0.42	0.23	0.27	FAIR	GOOD	GOOD			
	03a Vs 06a	0.48	0.32	0.33	FAIR	GOOD	GOOD	FAIR	GOOD	GOOD
B2	07a Vs 10a	0.51	0.43	0.17	FAIR	FAIR	V GOOD	0.49	0.40	0.17
	08a Vs 11a	0.39	0.31	0.15	GOOD	GOOD	V GOOD			
	09a Vs 12a	0.56	0.46	0.20	FAIR	FAIR	GOOD	FAIR	FAIR	V GOOD

Table 5. FSV validation results – sample variability.

		Quantitative			Qualitative			Average (Quantitative/Qualitative)		
SET	**Comparison**	**GDM**	**ADM**	**FDM**	**GDM**	**ADM**	**FDM**	**GDM**	**ADM**	**FDM**
C1	01a Vs 02a	0.33	0.13	0.28	GOOD	V GOOD	GOOD	0.45	0.27	0.29
	01a Vs 03a	0.52	0.29	0.29	FAIR	GOOD	GOOD			
	02a Vs 03a	0.51	0.39	0.31	FAIR	GOOD	GOOD	FAIR	GOOD	GOOD
C2	07a Vs 08a	0.13	0.05	0.10	V GOOD	EXCELLENT	V GOOD	0.12	0.05	0.10
	08a Vs 09a	0.10	0.04	0.07	V GOOD	EXCELLENT	EXCELLENT			
	08a Vs 09a	0.14	0.07	0.12	V GOOD	EXCELLENT	V GOOD	V GOOD	EXCELLENT	V GOOD

The results also conclude that the windscreen washer pump samples (D, E and F) exhibit a higher level of similarity in comparison to the DC to DC converter samples (A, B and C). Over and above the reason presented earlier for this result (batch difference) it is also noted that the DC to DC converter is a significantly more complex system in comparison to the windscreen washer pump. As a result more variability is expected between results from samples of more complex products over those of lesser complexity. However, the level of sample variability should still be within the tolerance ('Good') set previously in this paper.

It is concluded that when validating CEM models against experimental results, a great deal of care should be taken. Batch differences between test samples may infer a number of areas of variability including; the tolerance of components used to manufacture the product and their origins; the manufacturing plant used for production and the build level/quality of the product. These are just a few areas of concern. Therefore, information about the variability of a product or structure should be assessed thoroughly and test configurations must be planned and accurately followed.

The use of the approach discussed in this paper will also allow a sensitivity analysis to be undertaken on the configurations used for validation. This will enable to modeller to substantiate any claims that certain differences between the results are acceptable while others are not.

Further work will look at building on this groundwork to formulate a more readily applicable methodology for quantifying confidence in the reference measurements being used to validate numerical models. Additional work is anticipated on the application of the FSV method to the area of EMC problem solving as a tool for quantifying EMC countermeasures.

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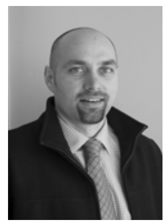
Alan Denton studied Electrical and Electronic Engineering at the University of Nottingham, completing a PhD in Electromagnetic Compatibility in 2001. Since 2001 he has worked at MIRA Limited as an EMC Technical Specialist where he works closely with component suppliers and vehicle manufacturers resolving EMC issues and designing compliant components, systems and vehicles. His current research interests are the design of bespoke RF filters for specialist applications, data validation techniques for EMC testing, the RF susceptibility characteristics of vehicle airbag systems and advanced EMC test method development. He is a member of the Institution of Engineering and Technology and a Chartered Engineer.



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