A Study of Vehicle and Measurement NVH Variability

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Abstract

A range of nominally identical automotive vehicles have been tested for NVH variability by exciting the engine mount with an impact hammer and measuring the responses at different points on the vehicle. Normalised standard deviations were calculated from the mobility, which fell well within the boundaries of previous comparable measurements. The measurement variability was determined by taking repeat measurements on a single vehicle, which were found to be very repeatable, varying by up to 2.9%. A function that uses the coherence to determine the random error was applied to the data to determine the variability due to the measurement taking process. This was compared with repeat measurements taken on a single vehicle and was shown to agree well with one another. A design of experiments has also been created that determines the effect of each variable such as the temperature and angle of impact on the overall vehicle to vehicle variability.

1 Introduction

The levels of noise and vibration within the passenger cabin of automobiles are often used as perceived levels of quality by customers, particularly in the premium market, and therefore are of high importance. When recording noise, vibration and harshness (NVH) measurements for a number of vehicles, some variability is to be expected in the vibration frequency response functions. Variability occurs not only in older vehicles as a result of wear and tear, but because components in products just off the production line can also show variability as a result of manufacturing tolerances.

It is the aim of this investigation to both provide enough statistical data to describe the vibration variability found in the given vehicle of study. Several investigations have already been undertaken that quantifies vehicle to vehicle variability [1-6], showing that structure borne frequency response functions (FRF) of the nominally identical vehicles varied by as much as 15 dB in some cases. Causes for this variability are said to be down to the cabin panels and coupling methods between interfaces, however little is said on the variability as a result of the measurement taking process and external influences to ensure that different measurements are broadly comparable. Kompella and Bernhard's investigation [5], does take noise measurements on a reference vehicle; however they are shown to vary by more than 100% for much of the frequency range. Tests have previously shown that the structure borne FRF variability due to measurement techniques had a worst case value of ±2 dB, although on average the measurements varied by ±1 dB [6].

It is important therefore to have a reliable, repeatable experiment, and in this investigation a design of experiments has been undertaken, the results of which will be summarised at the end of the paper for reference. A description of the setup of the main study includes the testing of sixteen nominally identical

Range Rover Evoque vehicles to determine the vehicle to vehicle variability as well as the measurement error. Section two gives some background information into error analysis that is later applied to the study. An equation that links the test coherence to the normalised standard deviation (random error) is applied to the test data with the aim of developing a way of separating the measurement variability from the vehicle to vehicle variability. This will prove to be a powerful tool that when applied to future tests, will save much time that would have been spent recording extra reference data.

2 Error Analysis

Certain phenomena that allow us to predict the future behavior based on experimental results and physical knowledge is known as deterministic data. A great many other areas of engineering can be described as random, where each measurement with a certain time history cannot be repeated nor can it be predicted with accurate detail.

In this investigation, non-stationary data, where the average changes with each set of data by definition is studied. Classically non-stationary experiments can be repeated to obtain an ensemble of data in order to properly represent the behavior.

There are two main types of error [7], with the first being random errors, and the second being biased errors. Random scatterings of data are known as random errors, and averaging functions are needed in the analysis over a finite number of samples. The second type of error often has the same magnitude and occurs in the same direction throughout the data sets. This can be a result of the measurement equipment or applying windowing functions.

The random error is defined by the standard deviation and is determined by:

$$s(f) = \left(\frac{1}{n-1}\sum_{i=1}^{n}\left(\widehat{H}_{xy}\ (f)_i - \overline{\widehat{H}_{xy}}\,(f)\right)^2\right)^{\frac{1}{2}} \tag{1}$$

where s is the standard deviation, f is the frequency, n is the number of measurements, FRF_i is the data, which in this case is the noise/vibration transfer function or the i$^{\text{th}}$ vehicle, and $\overline{FRF}(f)$ is the mean of the FRF at a specific frequency obtained by:

$$\overline{\widehat{H}_{xy}}\,(f) = \frac{1}{n}\sum_{i=1}^{n}\widehat{H}_{xy\ i}\,(f) \tag{2}$$

It is also convenient to define the standard deviation in terms of a fraction of the measured data, which is also known as the normalised standard deviation, or the coefficient of variation.

$$\hat{s}(f) = \frac{s(f)}{\overline{\widehat{H}_{xy}}\,(f)} \tag{3}$$

This will produce a non-dimensional number; for example $\hat{s}(f) = 0.1$, then the data would have a scatter of 10% of the point that is has been averaged about. If a value of 0.1 is found for the normalised standard deviation, it can be often described by a Gaussian function and a 68% confidence region is therefore given by:

$$\widehat{H}_{xy}\ [1-\hat{s}] \leq \overline{\widehat{H}_{xy}} \leq \widehat{H}_{xy}\ [1+\hat{s}] \tag{4}$$

and a 95% confidence region is given by:

$$\hat{H}_{xy}\,[1-2\hat{s}] \leq \overline{\hat{H}_{xy}} \leq \hat{H}_{xy}[1+2\hat{s}]. \tag{5}$$

A function developed by Bendat [8] in 1978 provides a method of calculating the normalised standard deviation without the use of the frequency response functions directly. Instead, the only inputs into the equation are the coherence, γ and the number of data sets, n_d see equation 6:

$$\varepsilon\left[\left|\hat{H}_{xy}\right|\right] = \frac{var\left(\left|\hat{H}_{xy}\right|\right)}{\left|\hat{H}_{xy}\right|} \approx \frac{(1-\gamma^2)^{1/2}}{|\gamma|\sqrt{2n_d}} \tag{6}$$

where $\hat{H}_{xy}$ is the frequency response function and $\varepsilon\left[\left|\hat{H}_{xy}\right|\right]$ is the normalised standard deviation, or the expected random error. A full derivation can be found in Bendat's 1978 paper [8].

A design of experiments was undertaken before the main testing with the use of an impact hammer to create the force input and an accelerometer to measure the mobility; the results of which will now be summarized. The best case results produced normalised standard deviation values in the range of 0.02-0.03, and 0.07-0.08 in the worst cases. Some of the tested variables that are certain not to change significantly between measurements include the equipment: the hammer tip and the wires, and the impact positioning. Variables such as the temperature and the accelerometer positioning are not so easily controlled in a planned test.

- Measurement variability will increase as the number of boundaries between the excitation point and the measurement point increases.
- Change in accelerometer position up to ±1cm will cause a change in variability of up to 1% when looking at point mobility.
- A decrease in temperature of 10°C can decrease the variability of the results by up to 1%, as the majority of materials will become stiffer at a lower temperature.
- A nylon tip when using an impact hammer will produce a lower variability over a smaller frequency range than when using a metal tip.
- Ideally the positioning of the impact needs to be as far from the engine and suspension, and as close to the bodywork as possible. The area on which the impact hammer will strike should also ideally have a hard surface to allow maximum energy transmission.
- For small variations in the angle of incidence (90° ±20°) at which the impact hammer strikes the excitation point, negligible changes to the overall measurement variability can be expected for cases where the coherence is good.
- A larger number of points measured over a given frequency range will provide a more accurate result, although this may result in a higher variability.
- Decreasing the time interval between each measurement point in the force- time profile will decrease the measurement variability, as it allows for a smoother, more detailed force impact profile.

2.1 Measurement Procedure

The set up for all testing includes the use of a data acquisition kit with the software RT Pro Photon, an accelerometer and an impact hammer to excite the structure. Several tests were taken at points of high stiffness in order to optimise the amount of energy that passes between the impact hammer to the vehicle, and repeat measurements were taken to determine the measurement variability. All of the vehicles being tested were 5 door, right hand drive Range Rover Evoque models, all featuring the same engine variant and body structure (incorporating panoramic roofing).

Multi Vehicle Testing

Three points on the vehicle exterior were chosen as measurement response points, points two and three of which can be seen in Fig. 1. These include the lower and upper A-pillar with the first measurement response site being a near point to the chosen hammer impact site.

Figure 1: The three measurement response points can be seen, as these are the points at which the accelerometer will be placed. A more detailed imaged of the positioning of the accelerometer at site 1 can be seen in Fig. 2a, which is obscured by the bonnet in Fig. 1.

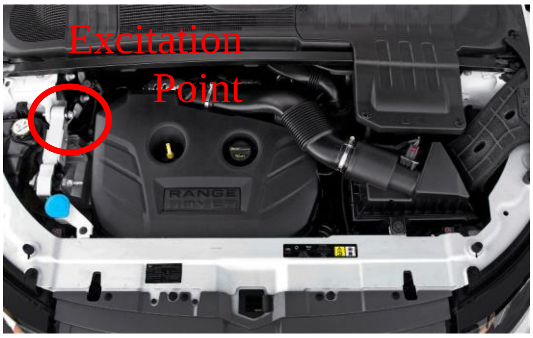

Figure 2 (a): The bonnet interior of a Range Rover Evoque, with the site at which the vehicle is excited with the impact hammer.

Figure 2 (b): Close ups of the measurement response position above upper A-pillar.

Bad hits were rejected in the same way as in the preliminary testing section, and notes of the vehicle serial numbers as well as any changes that might affect the results were noted including the temperature.

3 Results and Discussion

Measurement Variability

Repeat measurements were taken from the engine mount to the suspension strut 35 times and then from the engine mount to the lower A-pillar a total of 19 times on the same vehicle. A sample of the mobility determined from the response functions can be seen in figure 3, and the normalised standard deviations, calculated from equations 1-3, for the respective tests can be seen in figure 4. Coherence data and records of the force impact, the frequency spectrum and the force output were also been recorded for analysis. The

FRFs were recorded from 0-1000Hz without the use of any windowing functions due to the large time sampling distribution of approximate 1s with intervals of 0.15μs. The use of a metal tipped impact hammer meant that the force profile occurs within a 0.1ms time span, so it was necessary to have small enough intervals to obtain a smooth impact profile.

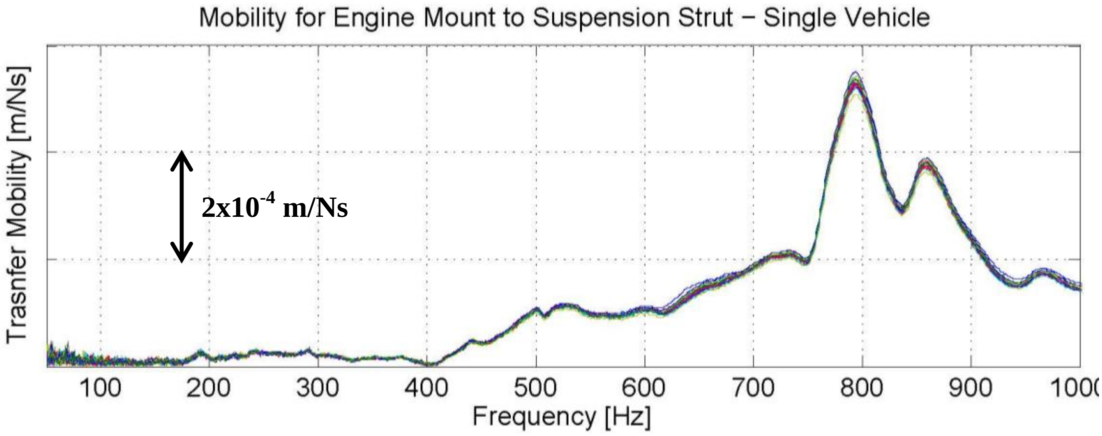

Figure 3: The transfer mobility of the engine mount to the suspension strut can be seen above for a single car where the measurements have been repeated 35 times on the same vehicle.

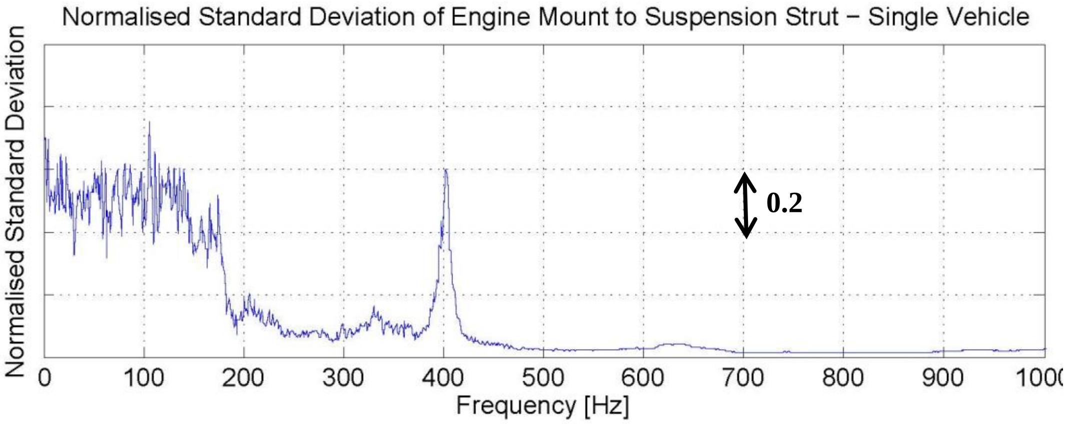

Figure 4: The normalised standard deviation of the mobility for the engine mount to the suspension strut is given above. All analysis is only taken for frequency bands in which the coherence is good (approximately 1). In this case the analysis is taken from 450 to 900Hz.

The data is found to vary by up to 2.5% and 2.9% for the engine mount to suspension strut and engine mount to lower A-pillar respectively. The analysis was taken over a frequency band of 450-900Hz where the coherence had an approximate value of 1. Lower coherence values can mean that the data is unreliable for various reasons and in this case it is likely that the close presence of the engine and the suspension meant that energy at lower frequencies was absorbed. In order to access the lower frequency characteristics with confidence in the results, the engine would have to be removed before the testing was done. A sample of the coherence results can be seen in figure 5 for the engine mount to suspension strut positioning.

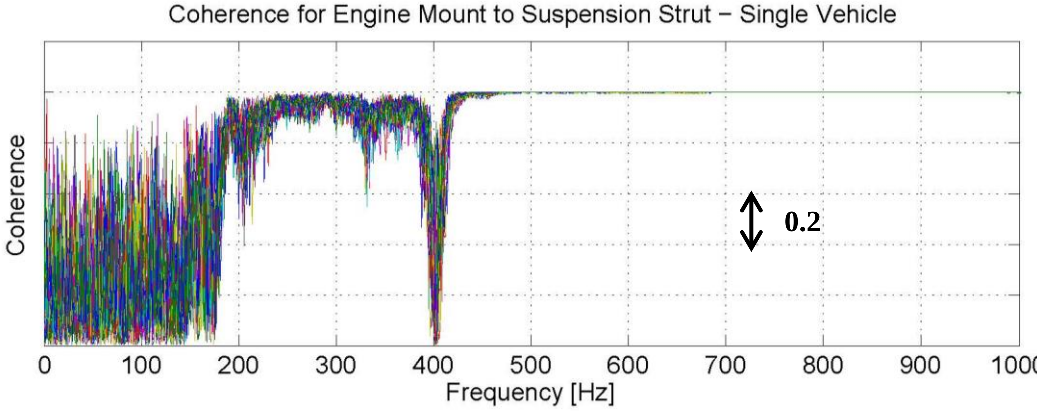

Figure 5: The coherence for the engine mount to the suspension strut. Each of the 35 colours represents the results of five repeat measurements.

Vehicle to Vehicle Variability

Testing on 16 nominally identical Range Rover Evoque models was carried out following a similar method to the previous set of testing. All cars were 5 door right hand drives, with panoramic roofing, and all had the same engine. The mobility graphs which have been calculated from the frequency response functions with the use of equation 1 for each respective position are given in figures 6-8. Each individual line plotted on the mobility graphs is an average over five individual hits.

It is possible to discern groups of resonant peaks. All three of Figs. 6-8 show a large variability in both the phase and the amplitude of each test. Clusters of resonant peaks appear to be shifting by frequencies of up to 100Hz in some cases. The variability is shown a little more clearly in Fig. 9 which give the normalised standard deviation of the most variable position (engine mount to the upper A-pillar). These were calculated using equations 1-3 and for sections where the coherence is good, an average has been taken. It can be seen even without the coherence graphs that the measurements below 400Hz are poor as only noise can be seen for this frequency band. When averaged all frequencies from 450-900Hz, the data was found to vary by 25.3%, 33.5% and 37.3% for the suspension strut, the lower A-pillar and the upper A-pillar respectively. It is possible that this increase in variability with the increase in distance between the impact hammer and the accelerometer is due to the vehicle’s inherent variability, but it is much more likely that not enough energy is able to reach the measurement response point. By observing the coherence recorded at the upper A-pillar and comparing with the coherence found in figure 5 (at the suspension strut), it is apparent that the range of poor coherence increases from 0-400Hz up to 0-500Hz. When the coherence is good, reliable measurements can still be taken, however testing in the future with an electromagnetic shaker with an incorporated force transducer may resolve these problems.

Figure 10 shows the results from five different vehicles, each of which has several repeat measurements. By having the repeat measurements, it is possible to conclude that the variability is not a result of the measurement procedure. This is also backed up by the design of experiments investigation in section 2.

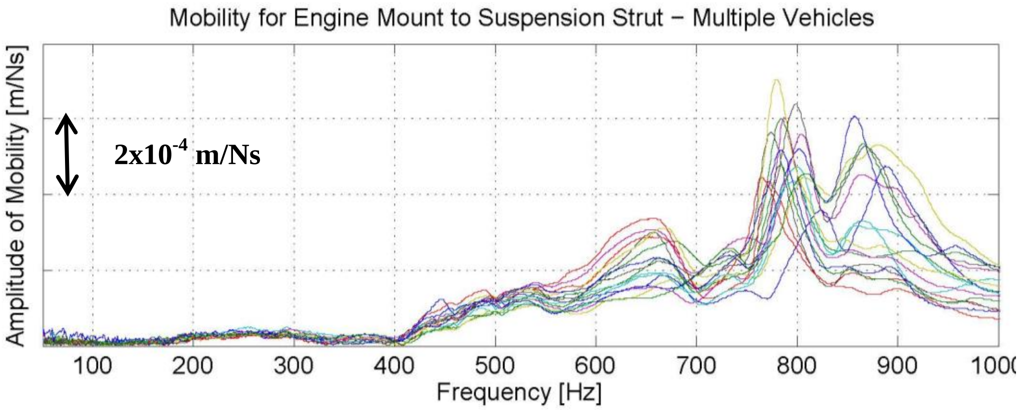

Figure 6: A comparison of mobility graphs for the 16 nominally identical Range Rover Evoque vehicles tested with an impact hammer from the engine mount and measured with an accelerometer above the suspension strut.

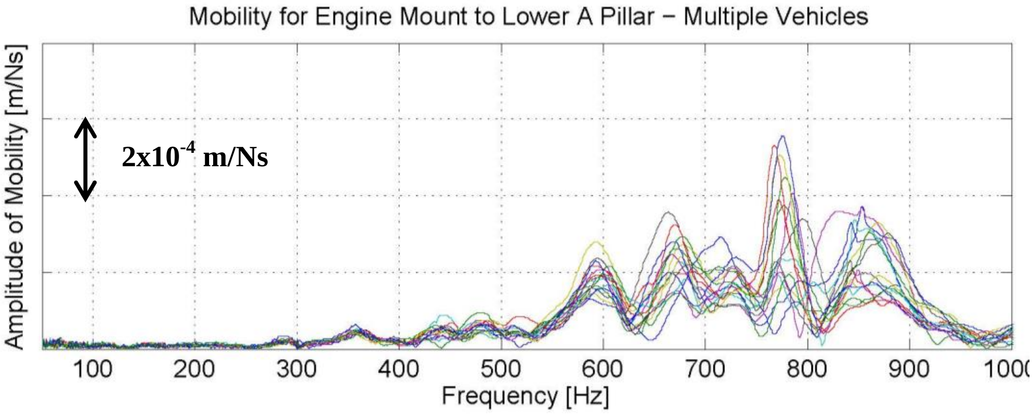

Figure 7: Comparison of the mobility graphs for the 16 nominally identical Range Rover Evoque vehicles tested with an impact hammer from the engine mount and measured with an accelerometer at the lower A-pillar.

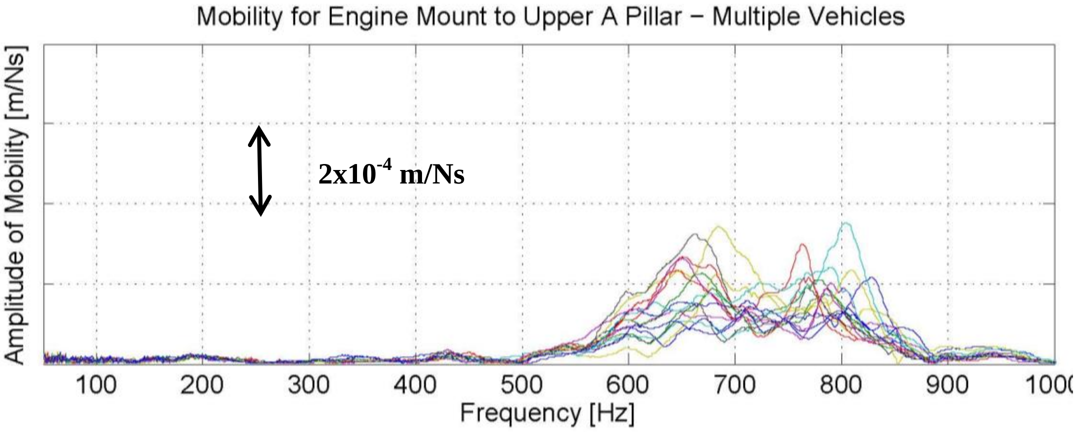

Figure 8: Comparison of the mobility graphs for the 16 nominally identical Range Rover Evoque vehicles tested with an impact hammer from the engine mount and measured with an accelerometer at the upper A-pillar.

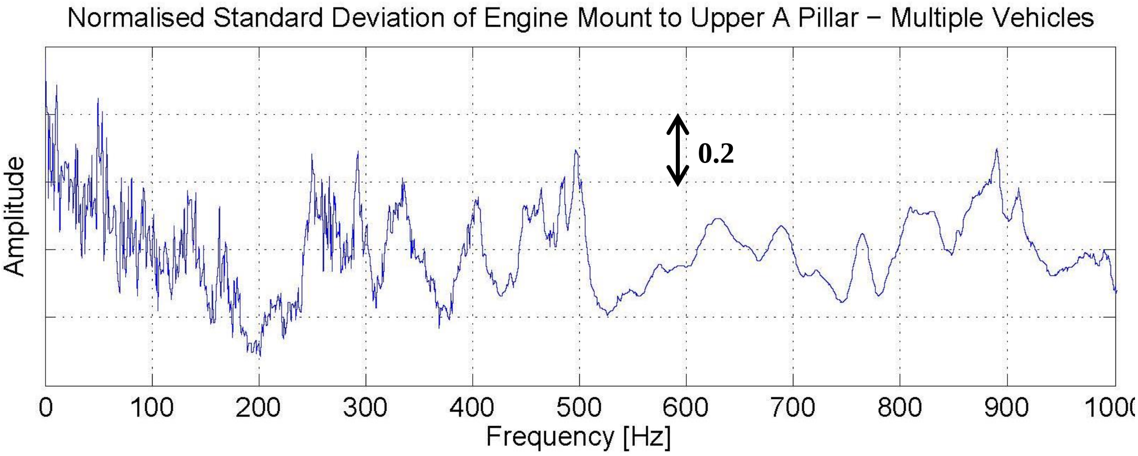

Figure 9: Normalised standard deviation for each frequency, calculated from equations 1-3 of the engine mount to the upper A-pillar.

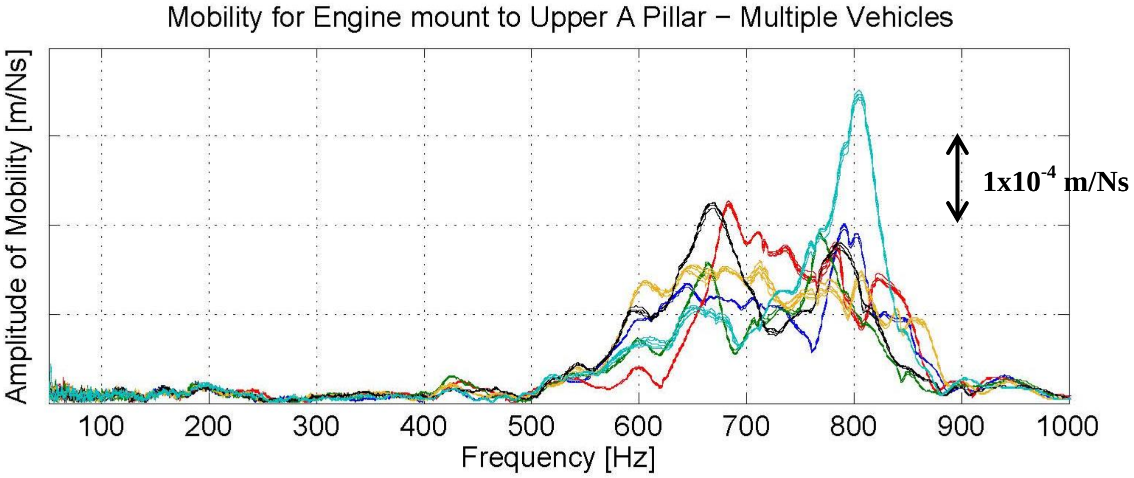

Figure 10: A sample of five vehicles is shown along with several repeat measurements for each vehicle in order to illustrate the two different types of variability.

Measurement Variability Prediction

Being able to separate different types of variability with the use of a single formula would provide an invaluable tool that would save time and money. By applying the model described by Bendat [8] to the measured vehicle data, the influence on the overall variability from the measurement process will be known without having to actually do a separate test. Theory describing the formulas is given in section 2, and a derivation is given by Bendat [8].
Equation 6 is applied both to the data measured on a single vehicle, and compared with the normalised standard deviations. The equation is then applied to the vehicle-to-vehicle variability test data, and the results will be compared to the normalised standard deviation data taken from the measurements.

Figure 11 shows the normalised standard deviation of a set of thirty repeat measurements. The directly measured data in the green plot can be compared to the predicted results in blue, which were calculated with the use of equation 6 and the coherence data. A similar match can be seen which shows that equation 6 is a good method for predicting the measurement variability, however there is still some deviation between the two plots. The predicted data is slightly lower in amplitude for the majority of cases above 150 Hz. This could be because of a bias error that has not been accounted for. One objective in the continuation of this work would be to observe the effects of a biased error on the predicted error.

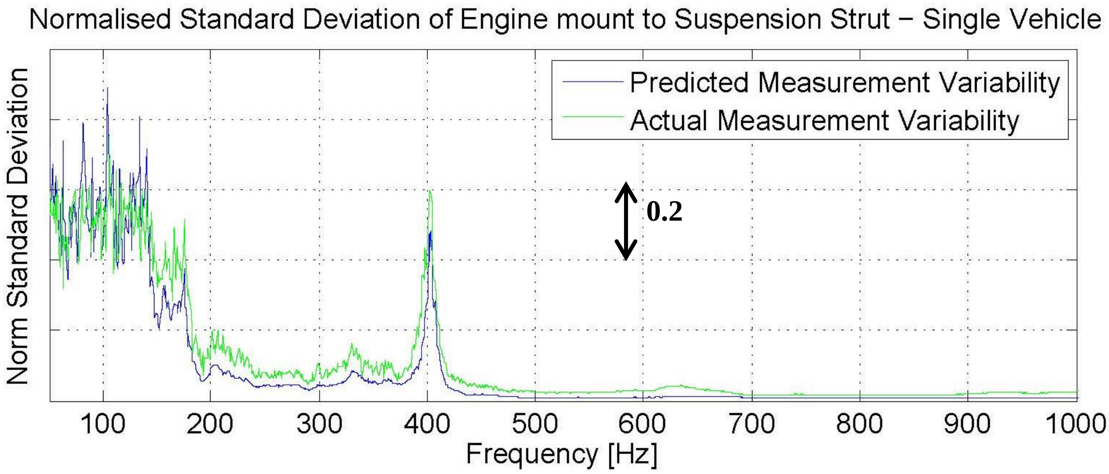

Figure 11: The graph shows the both the predicted and the measured normalised standard deviation for the engine to suspension strut data in the case of a single vehicle.

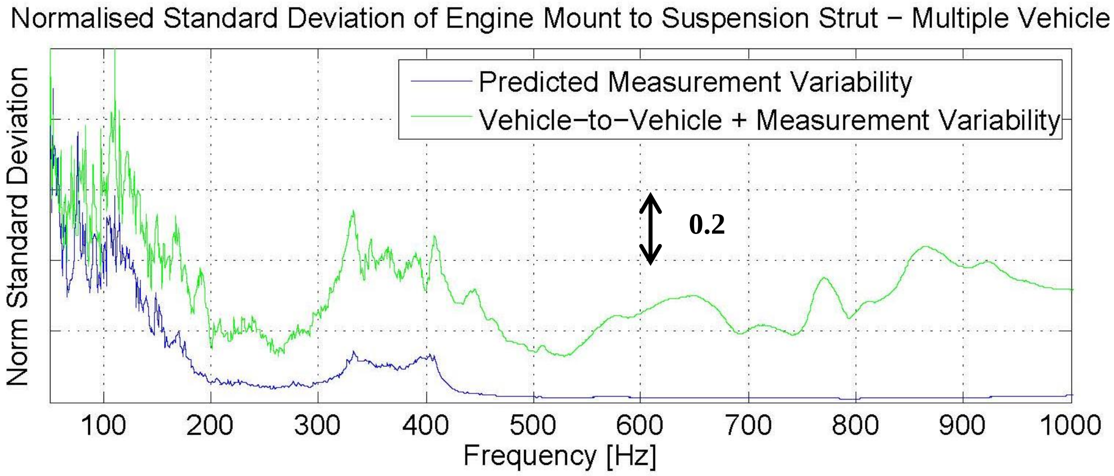

Figure 12: The graph shows the both the predicted and the measured normalised standard deviation for the engine to suspension strut data for all 16 vehicles.

The formula is also applied to the vehicle to vehicle measured variability data. This can be seen in Figure 12, where the blue plot is the combined vehicle to vehicle and measurement variability recorded from the sixteen nominally identical vehicles, and the blue plot shows the measurement variability after it has been separated from the overall variability data. The combined variability data shows that even when the formula is applied to the 16 vehicle measurements, the average measurement variability will still be a value in good agreement with the directly taken averaged measurement variability as seen in Figure 11.

4 Conclusions

Vibration tests have been run on an ensemble of 16 Range Rover Evoque vehicles to determine both the vehicle to vehicle and the measurement variability. The measurement variability was obtained first, where a single vehicle was tested 35 times with an impact hammer and accelerometer. The normalised standard deviation was calculated, and the measurement results were found to vary by up to 2.9% which falls within the standard range recommended by the literature [8].

The vehicle to vehicle variability was obtained by testing 16 nominally identical vehicles with the use of an impact hammer and accelerometer. Three measurement response positions were tested comprising the suspension strut, the lower A-pillar and the upper A-pillar. An engine bracket mount was used as the excitation point. The normalised standard deviation produced values of 25.3%, 33.5% and 37.3% for the respective positions. Coherence data was taken which was used to determine whether the measurement was acceptable or not. It was noticed that with increasing distance between the accelerometer and the impact hammer, the coherence would become increasingly worse. It is possible that this is due to the increasing number of potential variable components between the excitation and response point as well as a result of the lack of energy from the impact hammer reaching the accelerometer.

The coherence data was further used for the testing of an uncertainty prediction function. This function was developed by Bendat and by applying it, the measurement and the vehicle-to vehicle-variability can potentially be separated. The equation was applied to a sample of the measurement variability data which showed a very close match. There was an offset, which can be explained as the bias error which has not yet been accounted for. When the formula was applied to the vehicle-to-vehicle variability data, values very similar to the measurement variability data were also produced. Continued work to create an accurate predictable measurement error will be done on this topic to get an even closer match by taking into account the bias error.

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