# VERIFICATION FOR DIGITAL IMAGE CORRELATION FOR PYROSHOCK TESTING

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**KEYWORDS**

pyroshock, digital image correlation, satellite, environmental testing

**ABSTRACT**

This paper describes the verification of using digital image correlation (DIC) for the purposes of measuring a shock test. It compares the shock response spectrum (SRS) of both the data obtained using DIC and using traditional accelerometer methods. Other tests on the repeatability and the homogeneity of the system were also conducted. The results show that measurements made using DIC do correlate with the data made from accelerometers. The data gathered for the repeatability tests and homogeneity tests were also useful for deepening the understanding of the behaviour pyroshock simulator.

## 1. PYROSHOCK SIMULATOR

Pyroshock testing of spacecraft hardware is conducted at RAL Space using the SERMS Pyroshock Simulator described in [1], and shown in Fig 1. The pyroshock test simulates the shock experienced by a space-bound payload when it separates from the rocket, in space. The item under test (IUT) is attached to one side of a hanging resonant plate. Then a 2.25kg steel projectile is fired by an air cannon, colliding with the opposite side of the plate and producing a shock response spectrum (SRS) at the IUT interface. The resonant plate is constructed from steel with stiffeners on each long side. The IUT is attached to an interface plate, typically made from aluminium, to fit a 6x8 70mm grid of 10mm holes. Accelerometers are fitted to this interface plate to gather the acceleration data for the shock test.

An SRS is a theoretically calculated spectrum of the maximum acceleration experienced across a frequency range, based off the time history data measured by accelerometers. The SRS is calculated using the Smallwood method and a Q factor of 10. The calculation period used is 10ms and calculated between 10-10,000Hz. The target SRS typically has a logarithmic gradient up to ‘the knee’ at around 1000Hz, where the profile continues with zero gradient, up to 10kHz. Section 13.1.7 of the ECSS Mechanical shock design and verification handbook [2], specifies the tolerances of a shock test SRS as -3dB and +6dB of a given target SRS profile, to avoid under- or over-testing the IUT. ECSS standard also requires homogeneity with a variation of no more than 6dB between accelerometers around the IUT interface [2].

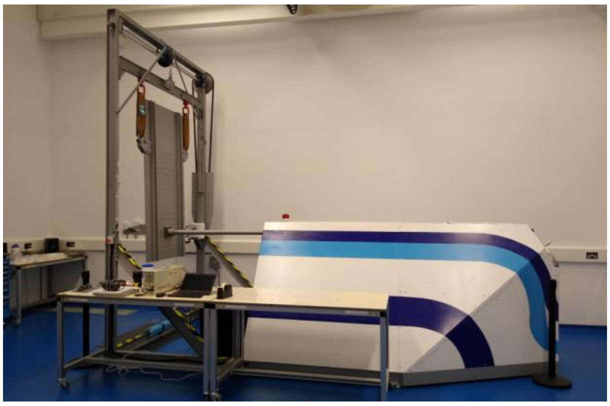

*Figure 1: The SERMS Pyroshock Simulator*

The target SRS profile is matched by adjusting the test parameters of the projectile’s propulsive pressure, resonant plate system mass, projectile mass, and the materials interposed at the projectile impact point. Different materials have distinct effects on the transmission of the shock to the IUT, and many target spectrums can be matched well for accelerometers positioned across the footprint of a test item. For the impact material, a 25mm mild steel anvil with a 5mm 1050 aluminium plate is always used. A combination of EPDM rubber, nylon and paper can be used to change different aspects of the SRS.

Alongside the test variables mentioned, the position of the whole or part of the IUT on the resonant plate, relative to the projectile impact point, may significantly affect the shock level experienced at a particular accelerometer. Investigating the homogeneity of the shock amplitude and frequencies across the resonant plate will enable the test operators to better meet the requirements set out in section 13.1.7 of the ECSS Mechanical shock design and verification handbook [2]. Providing the operators with a deeper understanding of energy dissipation across the plate, this knowledge will be especially useful for the verification of larger test items with a footprint that covers a substantial area of the resonant plate, aiding the avoidance of under- or over-testing particular parts of the IUT. It may also provide additional tuning options for complex tests with small IUTs, when refining an output SRS to match a target spectrum.

## 2. DIGITAL IMAGE CORRELATION

Digital Image Correlation (DIC) is an optically based measurement technique used to resolve full field 2D or 3D coordinates on a surface of a test item throughout a mechanical test. This correlation technique can define various quantities, such as displacements, strains, velocities, and curvatures. At its fundamental level, DIC estimates full-field coordinates and displacements from a series of digital images taken of a pattern on the surface of a test item during a mechanical test. An assumption made during DIC is that the pattern placed on the test item fully maps its distortion and movement.

The 2D coordinates of the surface can be measured using a single camera system. 3D coordinate measurements of the surface require a minimum of two cameras oriented at an angle to perform 3D photogrammetry in addition to image correlation; this is called stereo-DIC. Before any measurement can be made, a calibration of the camera's position in relation to the target test item is completed. This calibration is made using a known calibration target with set distances. To achieve an accurate global residuum, the focal lengths of the cameras must be similar (within 10%).

High-Speed, High Frame rate specialist cameras are used to achieve capture rates able to correlate shock characteristics. This project used Phantom VEO 1310L 1.23Mpx Cameras which can achieve frame rates of up to 10,000 FPS at max resolution.

## 3. STUDY SETUP

In this paper, three studies were conducted: the first assessed the repeatability of the pyroshock simulator; the second measured and mapped the homogeneity of the resonant plate at different frequencies of SRS; and the final compared SRS results obtained from accelerometers and with those obtained from DIC.

### 3.1. Repeatability Study

In order to get effective data, the DIC data acquisition method, and the accelerometer data acquisition method cannot be used simultaneously. Therefore, to increase confidence in the results, it was necessary to check the repeatability of the whole pyroshock rig system. To test this, one single axis accelerometer was placed on the plate as seen in Fig 2. Five tests were run using a 5mm 1050 aluminium plate and a 5mm EPDM rubber pad as the impact material. This was the same experimental setup reported in a previous paper [1] A projectile with a mass of 2.25kg was used and fired at a pressure of 2000mbar. This impact setup was used for all studies on homogeneity and DIC.

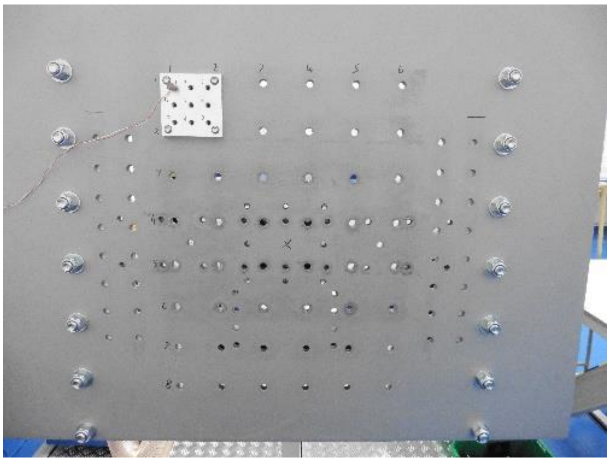

*Figure 2: Repeatability Study Setup*

### 3.2. Homogeneity Study

To better understand the results that the DIC data would give, a study was carried out to evaluate the homogeneity of the plate and investigate how the shock event disperses across the plate. To observe the SRS changes across the resonant plate, a 300g interface plate measuring 15mm x 90mm x 90mm with 9 accelerometer stud-mounting holes in a 3x3 grid pattern was affixed to the resonant plate in each position of the 6x8 grid of mounting holes. This gives a total number of 315 measurement points covering an area of 400mm x 540mm. This is shown in Fig 3, with the fixture plate at the first test position - coordinates 1,1 as measured from the upper left corner of the fixture plate. The fixture plate would next move to position 2,1, then 3,1 and so on. For each coordinate position of the fixture plate, a single axis shock accelerometer was mounted along the impact axis in each position 1-9.

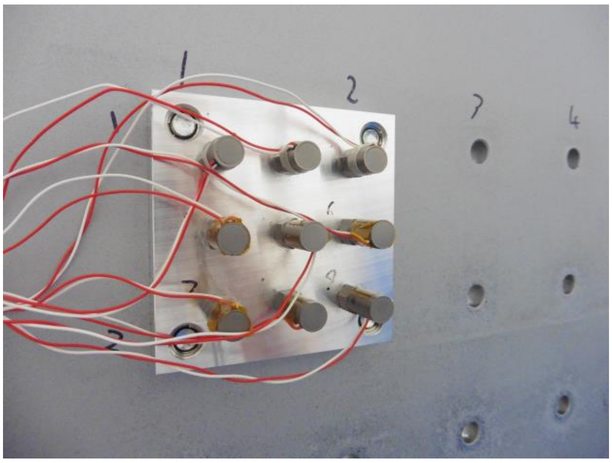

*Figure 3: Homogeneity Study Setup*

As the repeatability study showed good results, it was decided that only one shock pulse was needed for each position of the interface plate. This was necessary due to the number of tests needed to obtain the shock data for the entire resonant plate.

After the data was obtained, the SRS curve for each accelerometer in each position was calculated.

### 3.3. Digital Image Correlation Study

This section describes the project's physical and software DIC step-up. Fig 4 shows the overall physical setup for this study with the target position at 1,1. These setups were repeated for all of the different positions.

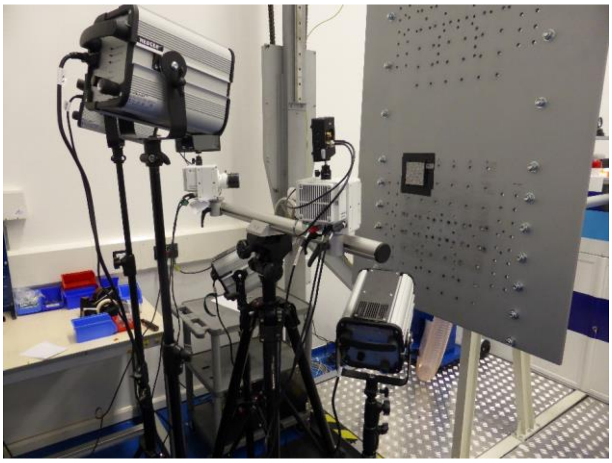

*Figure 4: DIC Camera Setup*

The physical setup for the project involved mounting and fixing the cameras in the correct positions with the associated equipment.

Two Phantom VEO 1310L cameras were mounted on a fixed tripod, with a mounting rail and rail adaptor to secure the cameras in fixed positions and directions. This fixed position was to keep alignment when calibrating.

25mm lenses were attached, and the aperture setting was set to a minimum of 2.6 to aid the focusing process. Digital displays were attached to each camera to aid in the positioning and focus of the cameras and lenses.

Due to the high frame rate needed and extremely low exposure time, four LED high power lights were used to illuminate the test item.

A speckle pattern was applied to achieve the best possible results for the correlation. A sticker with the speckle pattern minimises paint and contamination to the shock plate. The sticker was then stuck on the test block after it is attached to the plate. To minimise overexposure into the cameras, black tape was used, which surrounds the block to reduce reflections from the shock plate.

The cameras were connected to the control PC via a trigger box to synchronise the capture rate of the two cameras. The camera data was stored locally during capture and then transferred via ethernet cables to the PC after the test.

The software setup involved setting up all the different parameters in the software. The software setup was done in conjunction with the physical setup, as many parameters are defined by their physical characteristics. Before the setup, the frame rate was lowered, and the exposure rate was set to an appropriate setting.

The position of the cameras along the mounting rails was made parallel to the plate, equidistant from the centre, and had a stereo angle of around 40°. Using the Dantec DIC software, fine positioning of the cameras is done, so each view looked similar.

The frame rate was set to 50,000 FPS, the highest achievable with the camera at the appropriate resolution. And the aperture setting was changed to 8 to increase the depth of field.

The lights were switched on and pointed at the target item. The exposure time was optimised to achieve the highest brightness and sharpness of the images without overexposing any area of the test item.

The camera's position was correlated by holding a calibrated test plate in the test area and positioning it at various angles and rotations. The DIC software then calculated the global positions of each camera by taking several images and calculating the overall focal lengths of each camera. These correlation parameters were saved and used when performing the DIC analysis.

The software was set to capture 2s of video time to allow for any error in triggering the capture.

During each test, cameras were triggered manually and cut down to the appropriate length post-capture to avoid large video files. The average final acquisition time is around 0.2s.

## 4. RESULTS

### 4.1. Repeatability Study Results

With the five runs completed, a mean SRS result can be seen in Fig 5. A 1/3 octave band analysis was used for all calculations on the repeatability of the system.

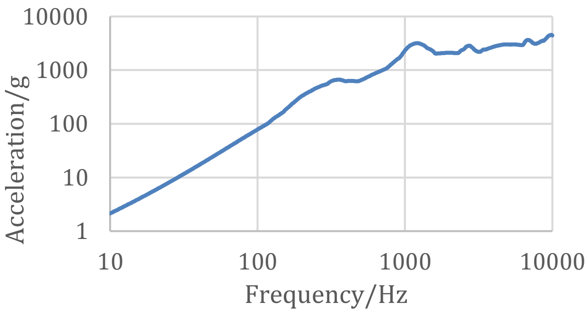


*Figure 5: Repeatability Study Average SRS*

Fig 6 shows the coefficient of variation (CV) across the 1/3 octave bands for a single accelerometer position. It shows all bands of 1600Hz and below have a coefficient less than 0.02 with a maximum coefficient of 0.0711 for the 6300Hz band.

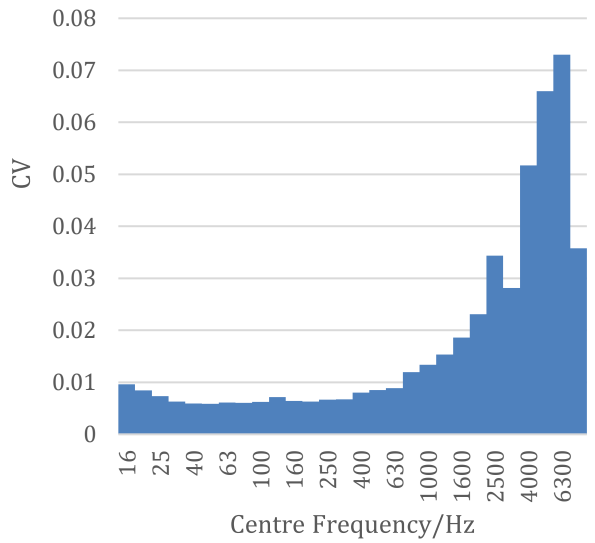


*Figure 6: 1/3 Octave Coefficient of Variance*

Fig 7 shows the total decibel range of the five different runs. This is important as the ECSS handbook (reference) states that the SRS results should be within a 2dB margin from each other for this type of pyroshock test. The graph shows that up to the 1600Hz band, the range of the tests was less than 0.2 dB with a maximum range of 0.68dB in the 6300Hz band.

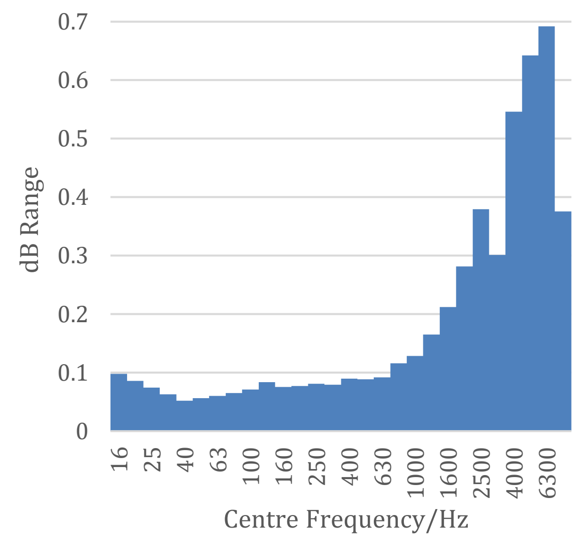


*Figure 7: 1/3 Octave dB Range*

### 4.2. Homogeneity Study Results

For the evaluation of the plate homogeneity, four variables were required to be represented: the position in X axis, position in Y axis, acceleration and frequency. In order to represent this, a series of 1/3 octave band heatmaps were used. The raw representation of the 63Hz band can be seen in Fig 8. To improve the representation a trilinear interpolation was used to repair the faulty data points. The repaired heatmap can be seen in Fig 9. Each square represents SRS data from one accelerometer. An overlay of the data over a photo of the resonant plate can be seen in Fig 10.

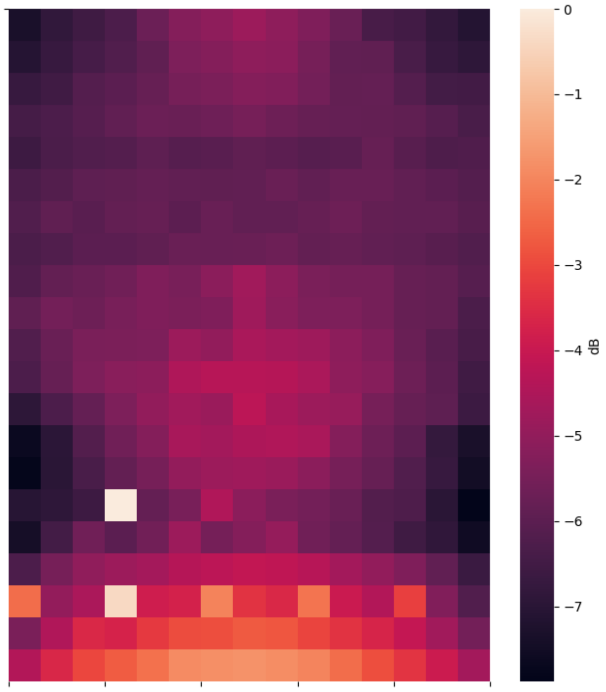


*Figure 8: Raw Representation of 63Hz Band SRS*

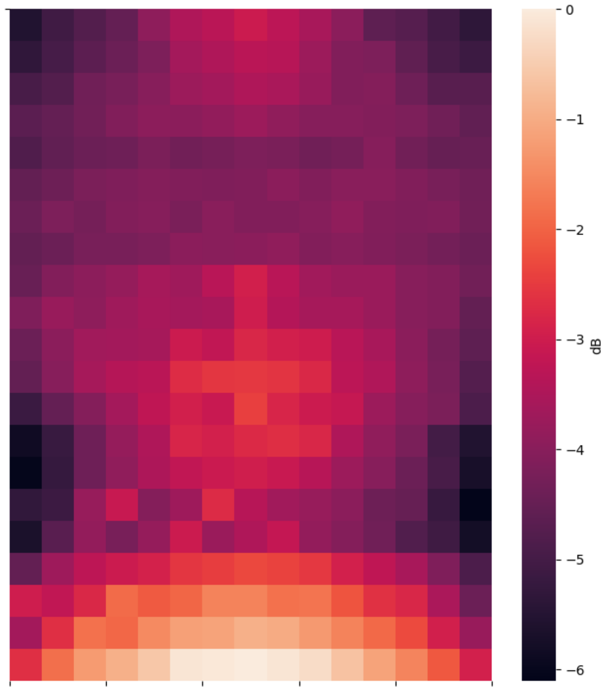


*Figure 9: Repaired Representation of 63Hz Band SRS*

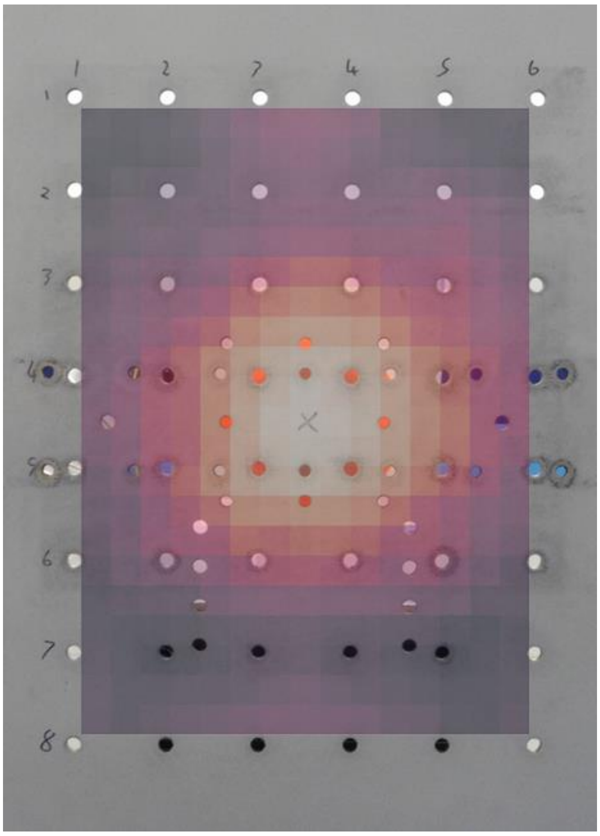

*Figure 10: Heatmap Overlayed onto Resonant Plate*

### 4.3. Digital Image Correlation Study Results

The DIC analysis was calculated in the DANTEC software system ASTRA, which calculates parameters like displacement by comparing one video frame to all the others. A region of interest was put over the reference frame to eliminate the surrounding border and other sections that may not correlate well. For this project, the first frame of every video is the reference frame. Facet size and spacing were chosen, where the larger the size and spacing, the more accurate the result; however, this will reduce the number of points. A facet size of 25 pixels with grid spacings of 20 pixels was deemed suitable for this project to achieve accurate results for the nine positions of each accelerometer.

The system calculates coordinate points for each facet in correlation with the parameters collected during setup. Nine displacements were picked from the relation position along the plate. These displacements are then differentiated twice to obtain all nine accelerations. An SRS calculation was then performed to get the results.

## 5. DISCUSSION

All of the studies done has provided very useful and insightful data on both the operation of the pyroshock simulator and the effectiveness of DIC in obtaining SRS results.

### 5.1. Repeatability Study

Two different methods to quantify the repeatability were used: coefficient of variance and the decibel range. The 1/3 octave histograms of these results show similar results.

#### *5.1.1. Coefficient of Variation*

The data in Fig 6 shows that the CV is steady at a low level up to the 2000Hz band where it starts to rise. This means that the simulator has very good repeatability at the lower frequency ranges. The maximum CV of 0.0711 at the 6300Hz band is still an acceptable result.

#### *5.1.2. Decibel Range*

The data in Fig 7 shows a similar result to the CV with a low result up to the 200Hz band and a maximum result in the 6300Hz band. The fact that the maximum spread is 0.68dB is very useful to know as the ECSS handbook (reference) states that the spread should be less than 2dB between tests.

Both of these analyses show that the repeatability of the simulator is very good at the lower frequencies. The repeatability worsens slightly at the higher frequencies so the results of the homogeneity and DIC should take this into account. It is likely that this spread is due to the fact the at these frequencies the displacement of the vibrations to achieve the accelerations are in the order of microns. A relatively small change in the displacement at these frequencies can have a large effect on the acceleration.

### 5.2. Homogeneity Study

For the purposes of this discussion, the repaired 1/3 octave heatmaps will be used.

The results from this study provided some very useful insight into the behaviour of the resonant plate. It was predicted that the resultant SRS acceleration would be highest at the point of impact with the acceleration reducing in a radial pattern. This is the case for some frequency ranges however there is some other noteworthy behaviour in different frequency bands.

For the very low frequency bands there is a high spot at the impact point but there is also a region of high response around the bottom of the plate. This region has the highest response between frequency ranges 31.5Hz and 200Hz. This disappears at higher frequencies. Alongside this, it is also worth noting that the 100Hz band has the best homogeneity result with the lowest area at -4dB of the highest acceleration. This can be seen in Fig 11.

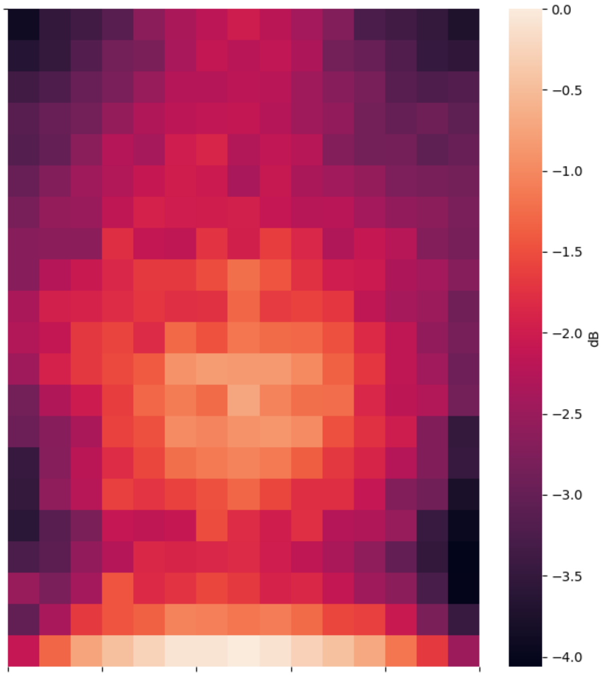


*Figure 11: Heatmap of SRS Results for 100Hz Band*

The homogeneity starts to reduce notably in the frequency bands above 1250Hz with the 2500Hz band having the worst homogeneity. This can be seen in Fig 12. The shape of the energy dispersion is similar to what was predicted. The highest acceleration is at the impact point with the energy reducing radially around the centre.

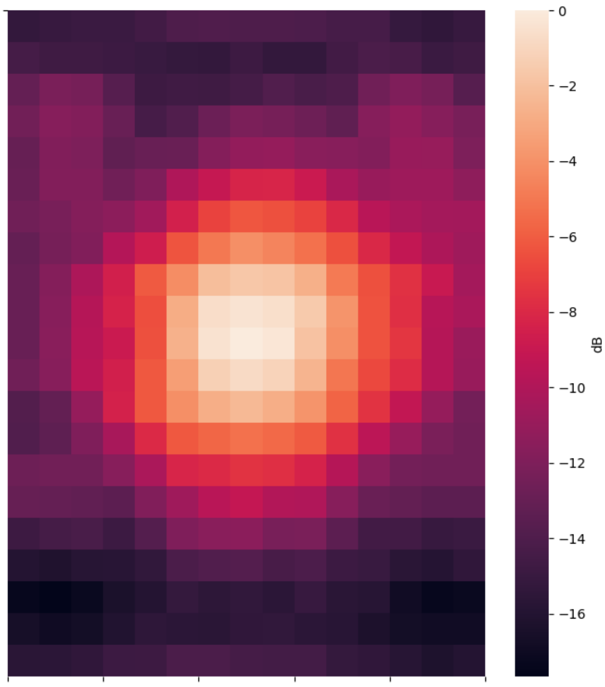


*Figure 12: Heatmap of SRS Results for 2500Hz Band*

At frequencies above this, higher response lines appear, originating from the impact point. The most obvious lines are in the 5000Hz band with four approximately 90 degrees out from each other, as seen in Fig 13, and 8000Hz band where 8 lines, 45 degrees from each other can be seen in Fig 14.

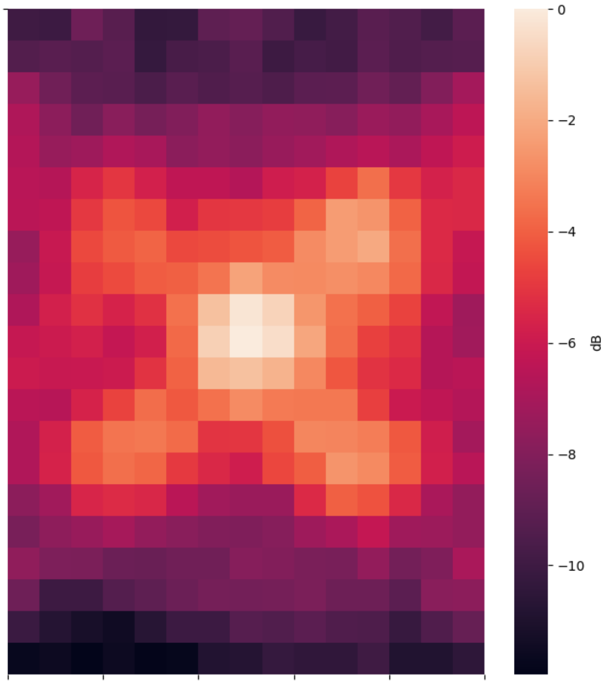


*Figure 13: Heatmap of SRS Results for 5000Hz Band*

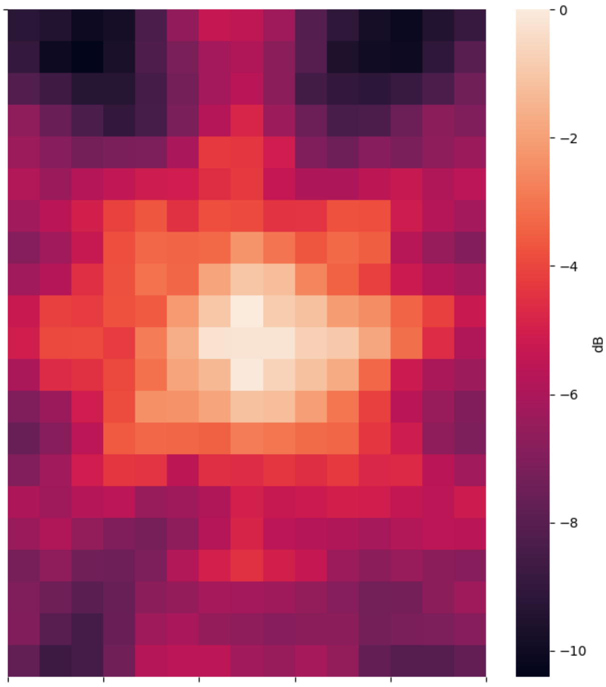


*Figure 14: Heatmap of SRS Results for 8000Hz Band*

The final point to note from the heatmaps is that for the 315Hz, 400Hz and 500Hz the energy dissipates radially from the highest point as with the highest frequencies; however, the highest point is not at the impact point. The highest response also appears to move down the plate as the frequency increases. This can be seen in Figs 15-17.

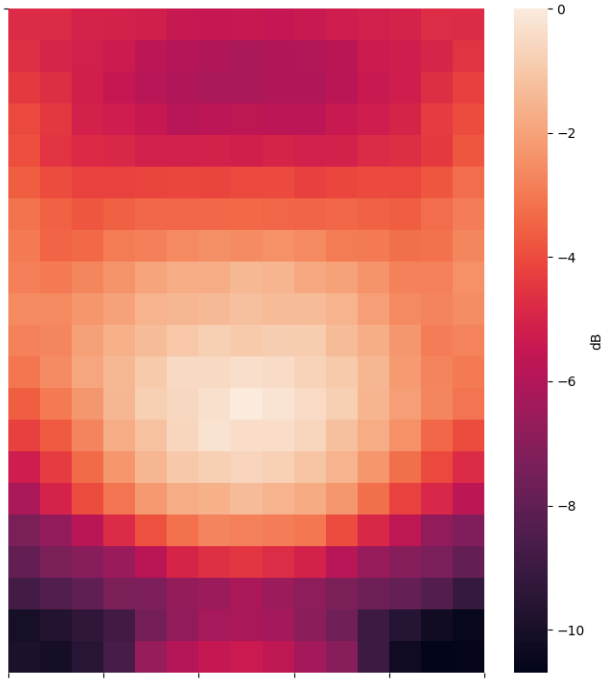


*Figure 15: Heatmap of SRS Results for 315Hz Band*

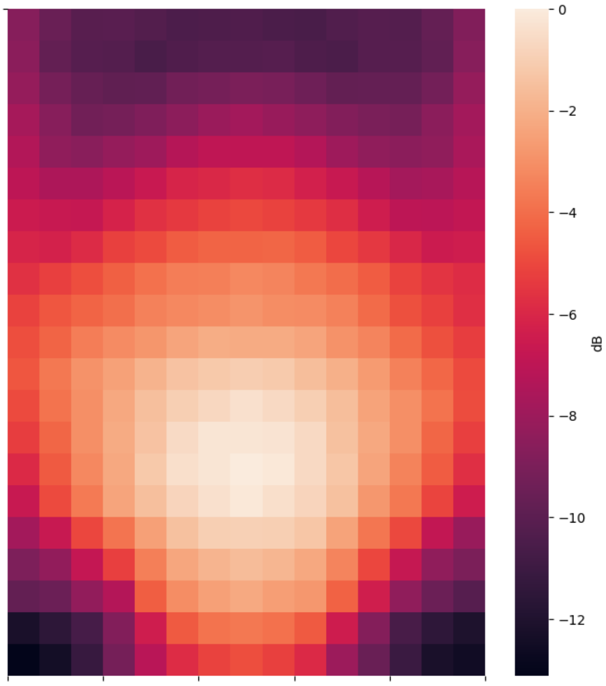


*Figure 16: Heatmap of SRS Results for 400Hz Band*

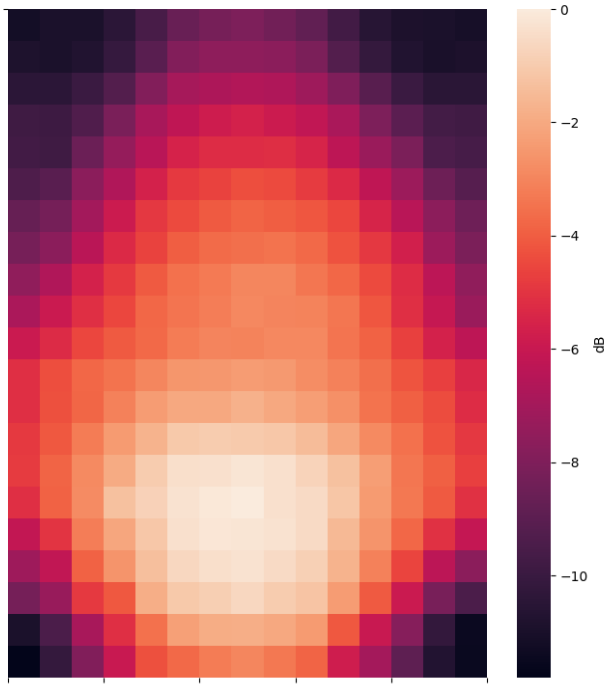


*Figure 17: Heatmap of SRS Results for 500Hz Band*

It is likely that these responses are due to the resonant behaviour of the plate. It is proposed that the heatmaps are illustrating the interaction between the impact point deflection and the mode shapes of the plate. For frequencies where the impact point is close to an antinode the acceleration is concentrated at that point. Whereas for frequencies where the impact point is closer to a node then a more dispersed pattern of amplitudes variation is seen. Similarly, the frequencies where the highest point is not at the impact point are likely frequencies where the plate has particularly large modes. The energy is put into the plate and the response is driven by the plate resonance rather than the impact. This is likely a similar reason for the high response at the bottom of the plate for the very low frequency bands.

### 5.3. Digital Image Correlation Study

Overall, the data shows that the data obtained from DIC is close to the result from the accelerometers.

Figs 18-21 show the average SRS results from both the accelerometer data and the DIC data at various positions.

A 1/3 octave analysis was done on the DIC SRS curves. This was compared to accelerometer

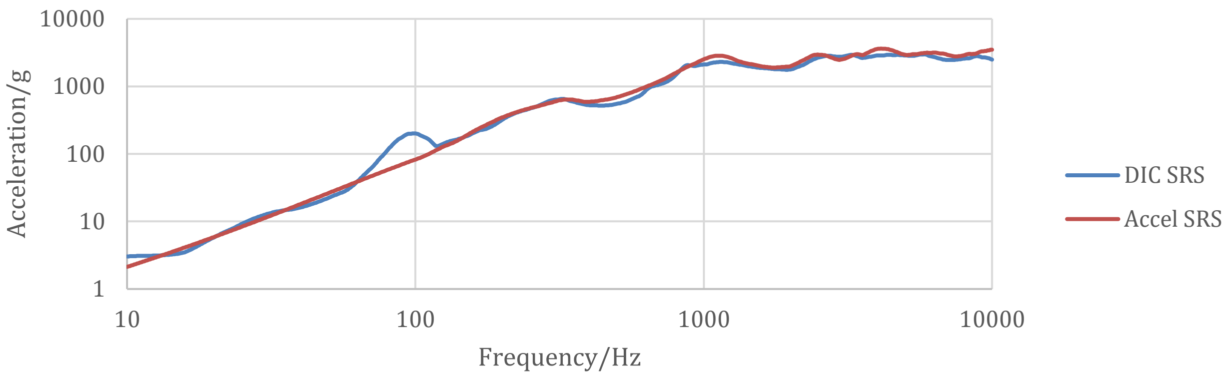


*Figure 18: SRS Results in Position 1,1*

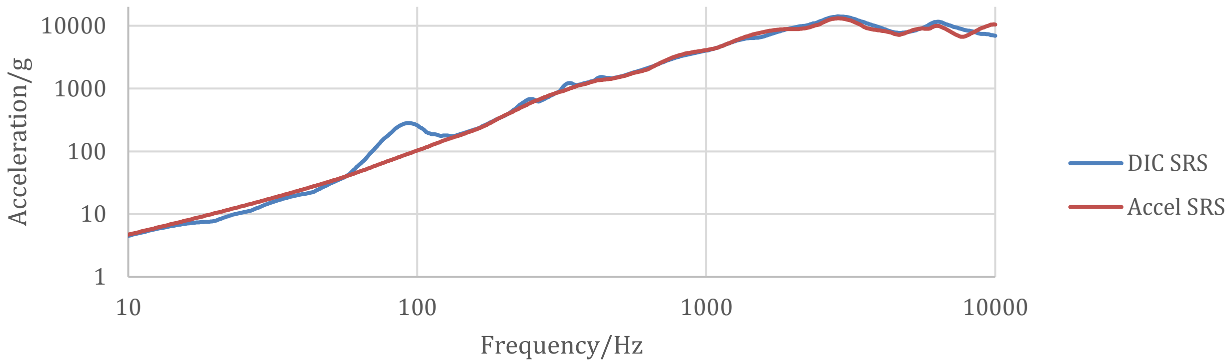


*Figure 19: SRS Results in Position 3,4*

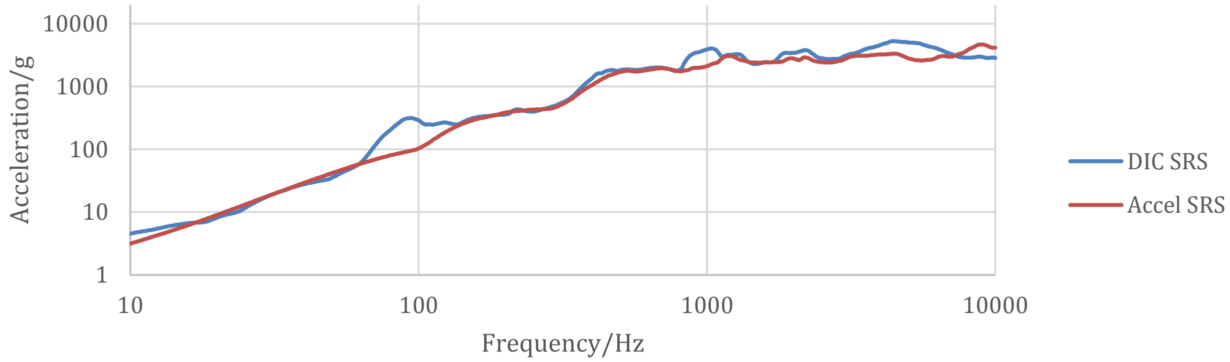


*Figure 20: SRS Results in Position 3,7*

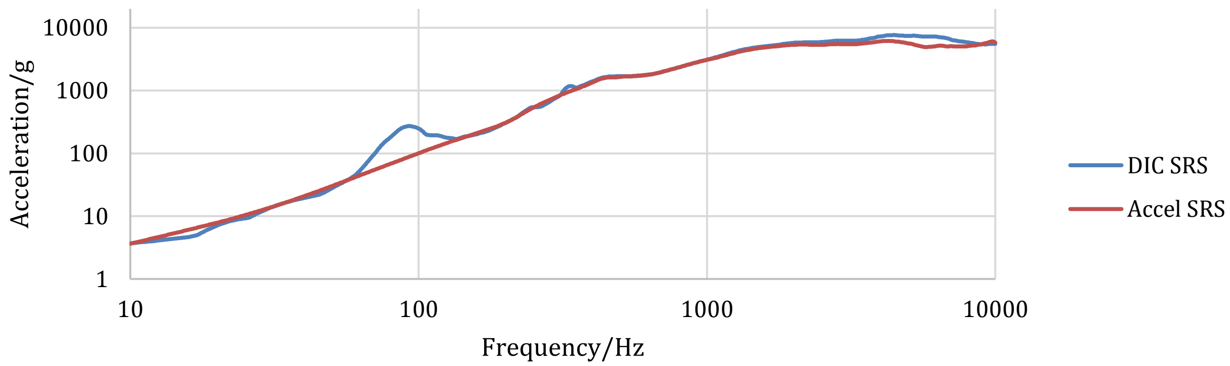


*Figure 21: SRS Results in Position 4,5*

results to give a decibel difference value between the two results. These results can be seen in Figs 22-25.

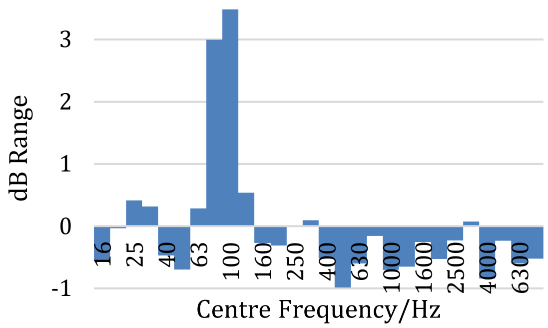


*Figure 22: dB Range for Position 1,1*

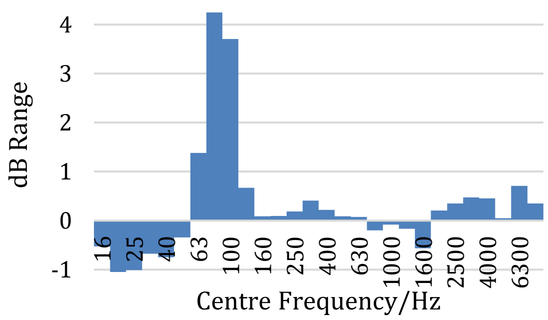


*Figure 23: dB Range for Position 3,4*

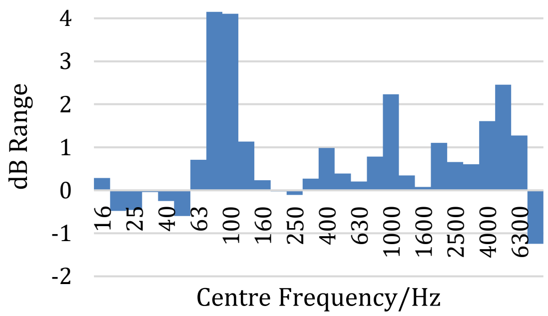


*Figure 24: dB Range for Position 3,7*

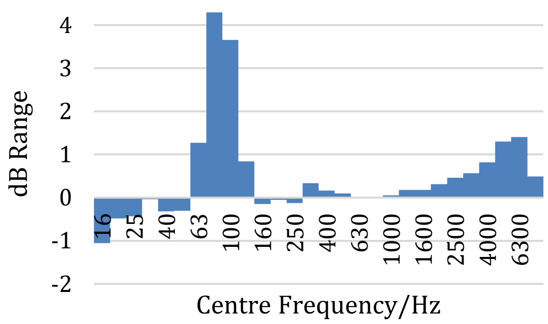


*Figure 25: dB Range for Position 4,5*

As seen in the SRS curves, a commonality across all of the locations is the ‘bump’ in the DIC graph at 100Hz which does not exist in the accelerometer graph. This causes a very large increase in the dB difference in the 80Hz and 100Hz frequency bands. It is likely that this is due to a low pass filter being used on the SRS calculation for the accelerometer data and not on the DIC data.

Outside of the 80Hz and 100Hz bands, the difference between the results is small. In positions 1,1, 3,4 and 4,5 most of the results are less than 1dB from each other. This is higher than the dB spread measured in the repeatability trials so this error would be due to the DIC measurement.

For position 3,7, the results do not follow the same trend as the others. The difference between the DIC data and the accelerometer data is larger than in the other positions. It is not clear why this is the case, but it could be due to the shock pulse behaving differently due to an edge effect with the plate.

There are however some limitations of using DIC. The facet size used requires a trade-off between the accuracy of the result and the resolution of the measurement area. A smaller facet size can increase the number of measurement points across the item however the accuracy of the measurement will be poorer. There is also the limitation of the frame rate of the cameras used. In order to measure higher frequency vibrations, the frame rate will also need to increase. To do this, the video resolution will need to be lowered which will reduce the accuracy. For this study, the frame rate, which for DIC is equivalent to sample rate, for the DIC study was half of what the accelerometers used.

## 6. CONCLUSION

It seems that the use of DIC can be used for the purpose of measuring an SRS during a shock event. Further investigation would be necessary to refine and improve the results produced.

## 7. REFERENCES

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