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A New Terrain Sensing System (TSS) based on fatigue damage spectra

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ABSTRACT

This paper introduces a new ‘Terrain Sensing System’ (TSS) that is able to record the cumulative damage seen by a ground vehicle over its entire operational life. Used within a HUMS IT process, this information can be calibrated to represent directly the residual life of onboard equipment such as electronic control systems, instrumentation, radios, brackets, refrigeration plants and weapons systems, thus enabling field staff to rapidly prioritize vehicles for deployment, increase their operational effectiveness and improve through-life management of the fleet using ‘Condition Based Maintenance’ (CBM).

INTRODUCTION

A ground vehicle can be conveniently subdivided into three component categories.

1. Body mounted components (sprung mass)
2. Drive train components (engine and transmission)
3. Structural components (suspension, chassis and steering)

Each component category typically shares the same type of input loading and exhibits similar failure modes.

Body Mounted Components, such as radios, instrumentation, electronic control systems and brackets, fail as a result of vibration loads passing through the structure. These loads can arise from high frequency transmission induced vibration or, more frequently, ground induced shocks and resonance. Military vehicles also receive significant shock loading as a result of weapons discharge and adjacent detonations.

The loading on Drive Train Components is typically dominated by engine torque and speed, while factors of maintenance, neglect and operator abuse also play significant roles. Other ancillary engine components such as engine management systems, injectors and valves, also suffer from high frequency vibration and resonance in response to the many engine orders being emitted.

Failure of structural chassis, suspension and steering components is largely due to extreme shock loads as a result of terrain roughness and high lateral loading on the wheels or tracks.

Halfpenny [1] presents a detailed discussion on Health and Usage Monitoring (HUMS) of military land systems. In this paper we concentrate on the damage analysis of Body Mounted Components through terrain and transmission induced loading. Failure of these components can arise through extreme shock loads or the long term exposure to fatigue damaging vibrations which, although modest in amplitude, give rise to microscopic cracks that steadily propagate to failure. The traditional TSS measures acceleration levels on the unsprung suspension components of a ground vehicle and creates a cumulative count of the vibration intensity in a number of severity bands. Terrain severity is usually classified in qualitative terms such as off-road, rough-road, town-road, smooth-road, and vehicle idle. In this paper we introduce a new analysis that can record terrain severity in quantitative terms. By measuring acceleration on the sprung mass, this analysis uses the Shock Response Spectrum (SRS), devised by the American engineer Biot in 1934, along with an analogous Fatigue Damage Spectrum (FDS) developed by the French Ministry of Defense through the 1980s, to assess the cumulative damage seen by the vehicle and its onboard equipment. An algorithm is discussed that calculates these spectra in real time in response to terrain induced vibration. The spectra can be calibrated to the failure of independent components thereby offering a means of assessing the residual life of these components. A discussion is presented on how the calibration of various pieces of equipment is possible. The paper concludes with a case study illustrating how these techniques were used by the author during recent flight trials for an aerospace component.

REVIEW OF BACKGROUND THEORY

The basis of this theory originates from work done by the French Ministry of Defense in preparation of the military design standard, GAM EG-13 [2]. The approach is also proposed in the NATO document AECTP 200 [3]. In this section we introduce the two principal components of the TSS algorithm: the Shock Response Spectrum (SRS) and the Fatigue Damage Spectrum (FDS).

THE SHOCK RESPONSE SPECTRUM (SRS)

Consider a typical automotive component, for example, the front lamp on a vehicle. How would we assess the loading on the lamp unit as the vehicle traverses the terrain? It might be possible to measure the acceleration on the lamp itself but this is generally impractical because the lamp is just one example of many components fitted to the vehicle platform and it is not possible to measure each of them so we must rely on more generic data. The most likely source of data comes from acceleration measurements taken on the vehicle chassis. We must therefore find a way of using this data as a means to establish the loads seen by other components attached to the chassis.

Using measured chassis acceleration it is possible to determine the acceleration levels seen by the lamp unit. For this calculation we need to know the frequency response of the lamp and various bracket components. Next, we can filter the input acceleration by the frequency transfer function and, provided the system responds linearly, establish the acceleration levels witnessed by the lamp unit.

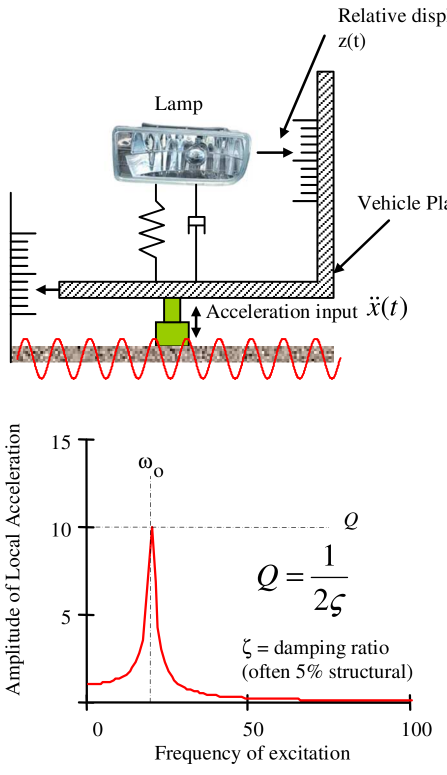


Figure 1: Single Degree of Freedom (SDOF) System

In reality the frequency response is usually quite complicated and impractical without detailed knowledge of all components and their failure modes. However, at the local failure location we usually observe that the transfer function is dominated by a single natural frequency as illustrated in Figure 1. This is known as a Single Degree of Freedom (SDOF) system. In 1932, the American engineer Biot [4] was researching the effect of earthquakes and used this assumption as a means of comparing their relative damage content. The SDOF response function is dominated by a single spike located at the natural frequency. At frequencies below the natural frequency, the component behaves quasi-statically, while at frequencies exceeding the natural frequency, the response is significantly attenuated. Around the natural frequency the component will respond dynamically and will become greatly amplified with its maximum response being limited only by the damping in the system. The ratio of the maximum dynamic response to the static response is known as the ‘Dynamic Amplification’ (Q) factor. For typical 5% structural damping, this has the value of Q = 10. Biot reasoned that as he did not know the actual natural frequency of his component beforehand, he could create a Spectrum of response by sweeping the natural frequency and plotting maximum response over a range of natural frequencies.

To compute Biot’s Shock Spectrum the input signal is filtered by a SDOF transfer function as illustrated in Figure 2, and the maximum of the response is calculated. The calculation is repeated a number of times over a range of natural frequencies and a plot made of the maximum response vs. the natural frequency. In 1934, Biot [5] published a paper on earthquake analysis and used the term ‘Shock Spectrum’ for the first time.

The Shock Response Spectrum (SRS), as it is now known, can be expressed in terms of acceleration or displacement response depending on the frequency response function used. For fatigue purposes, we are most interested in the displacement response. Fatigue cracks initiate and grow through the cyclic release of strain energy and, therefore, the displacement response provides a proportional relationship with the energy driving the failure. Acceleration might be the origin of the load but it is the resulting strain (displacement) that drives the structural failure. The SRS of displacement can therefore be used to quantify the damaging effect of the input acceleration for any SDOF system over a range of natural frequencies.

Biot proposed the SDOF assumption be made for all components under excitation regardless of the actual frequency response. Over the past years many have contested the conservatism of this assumption. Lalanne [6] documents a number of these studies which all conclude that the SDOF response, used in conjunction with a frequency sweep, is a suitably conservative assumption for all practical cases.

The arrival of digital computers has made it possible to calculate the SRS for long time signals very rapidly. Using the Z-transform, Irvine [7] derives the equations for a very efficient Infinite Impulse Response (IIR) filter. In this paper the author presents an algorithm to calculate the SRS in near-real time.

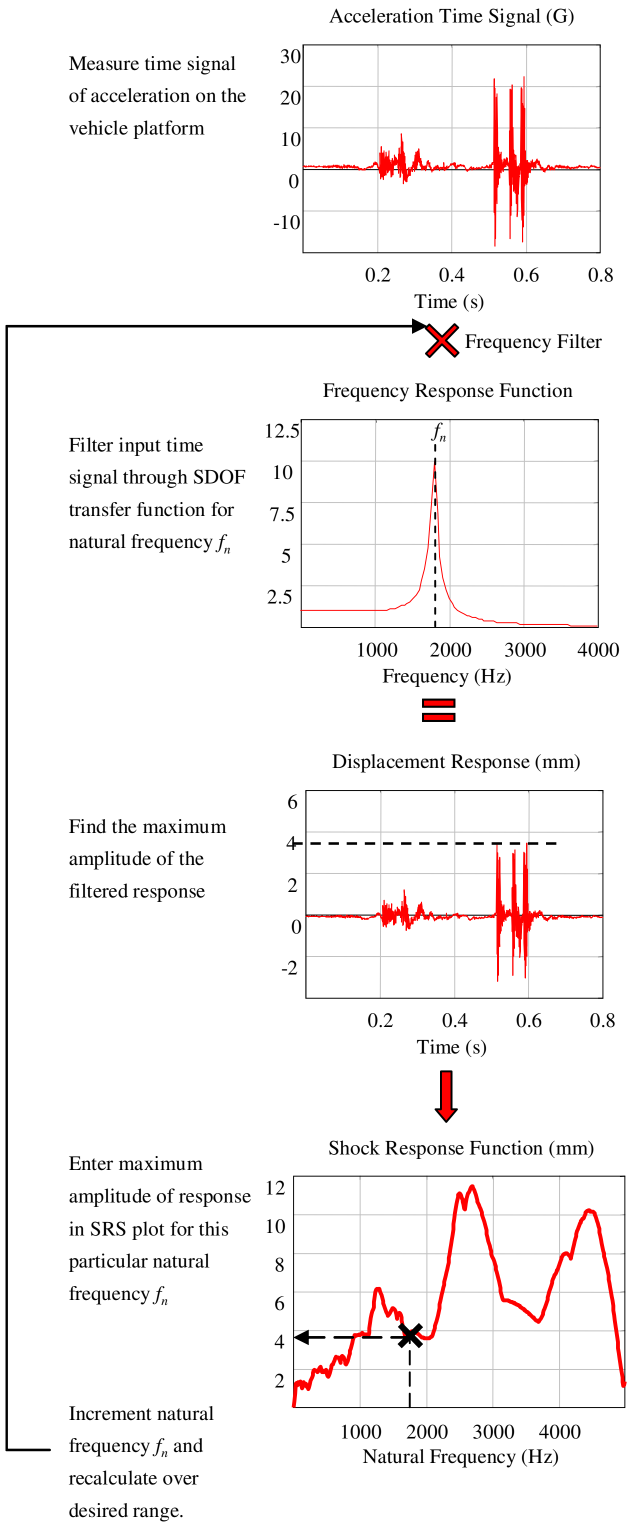


Figure 2: Calculating the Shock Response Spectrum (SRS)

THE FATIGUE DAMAGE SPECTRUM (FDS)

Lalanne [8], working on the hypothesis of the Shock Response Spectrum (SRS), proposed an equivalent Fatigue Damage Spectrum (FDS). This provides a relationship between fatigue damage and natural frequency. Although Lalanne only provides formulae for deriving this spectrum in the frequency domain, the author has derived an analogous approach in the time domain which makes it suitable for transient shock based input such as that produced by the terrain. The FDS is calculated in the same way as the SRS but rather than simply finding the maximum displacement response, the filtered displacement response is now rainflow cycle counted and the fatigue damage obtained using a Wöhler calculation. An explanation of fatigue theory and rainflow analysis is beyond the scope of this paper. For more details consult Halfpenny [9] and Downing et al. [10] respectively.

TERRAIN SENSING SYSTEM (TSS)

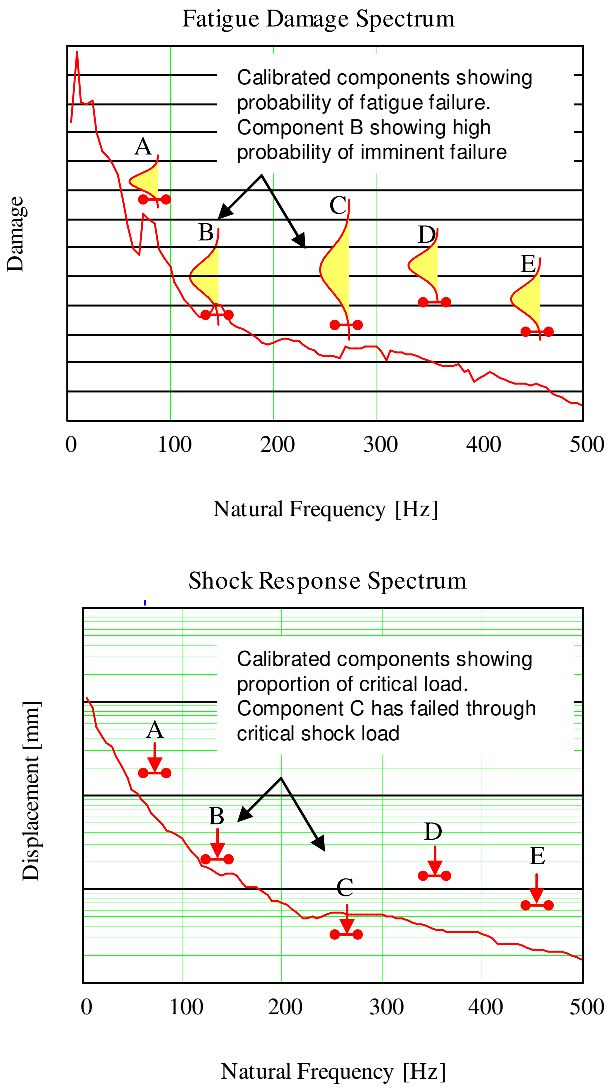


Figure 3: Examples of FDS and SRS

The new Terrain Sensing System (TSS) calculates the Shock Response Spectrum (SRS) and Fatigue Damage Spectrum (FDS) in near-real time. The SRS is used to warn of failure from extremes of load such as impact, collision or loads resulting from an explosion or weapons discharge. These extremes can result in a catastrophic failure as the component stress exceeds its design strength. The FDS, on the other hand, is used to accumulate the damage caused by long term exposure to fatigue damaging vibrations which, although modest in amplitude, give rise to microscopic cracks that steadily propagate to failure. Typical examples of both spectra are presented in Figure 3.

The FDS is seen to rise throughout the life of the vehicle. The failure threshold of various components (represented as A-E) can be assigned to the plot. In reality, failure is highly statistical, so rather than providing a go/no-go indication, this is best presented as a probability of failure. The field commander can then make an informed decision on whether to deploy a vehicle based on risk of failure and the objective value. He is also able to rank vehicles in order of their likelihood of success and arrange for replacement equipment or exchange equipment between vehicles.

The TSS is transparent to the vehicle crew. It calculates and maintains the SRS and FDS but does not necessarily keep a record of the inventory of installed components or their failure thresholds. The TSS is designed to work within the context of a HUMS IT structure and this task is usually performed by the onboard inventory control system or HUMS server. The HUMS server uses the FDS and SRS to calculate the cumulative damage on each piece of onboard equipment. This ‘damage ratio’ is maintained within the inventory so equipment can be freely exchanged between vehicles and the damage ratio transferred with the item, therefore the damage record is not lost. For more information then please refer to Halfpenny [1].

TSS ACCELEROMETER SENSORS

If we assume that the vehicle acts as a solid body, we can measure the accelerations of the body and assume these act on all the installed components. In practice, this assumption is not strictly true because local dynamic modes of the body panels and structure will affect the loads seen by the individual components. However, these are accounted for implicitly in the calibration of the FDS provided the components are not repositioned in the vehicle.

Any rigid body possesses 6 degrees of freedom about 3 axes in 3 dimensional space as per Figure 4. These consist of three lateral displacements: surge, sway and heave, and rotations about these axes: roll, pitch and yaw. The axes converge at the centre of gravity of the vehicle.

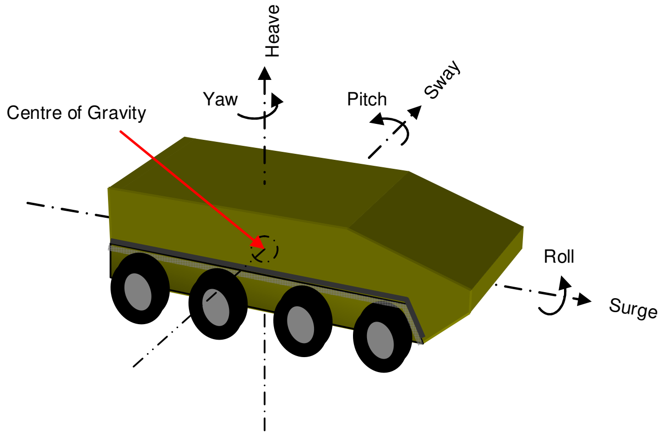


Figure 4: Rigid body motions of a solid body in 3 dimensional space

In theory we can measure the accelerations in all 6 degrees of freedom using 6 accelerometers located as per Figure 5 along with a coordinate transformation to bring these relative to the centre of gravity.

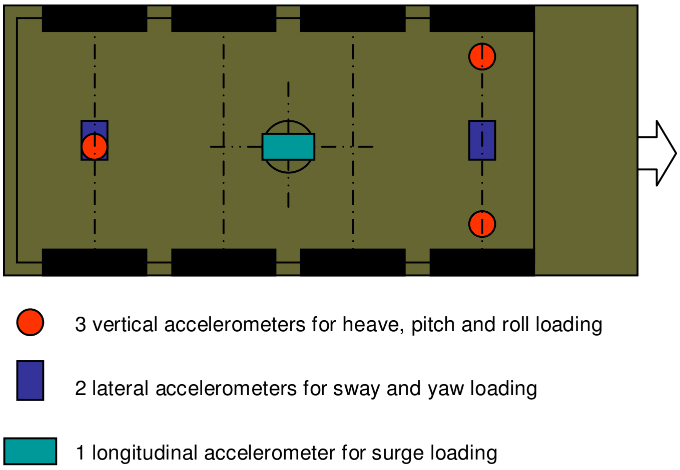
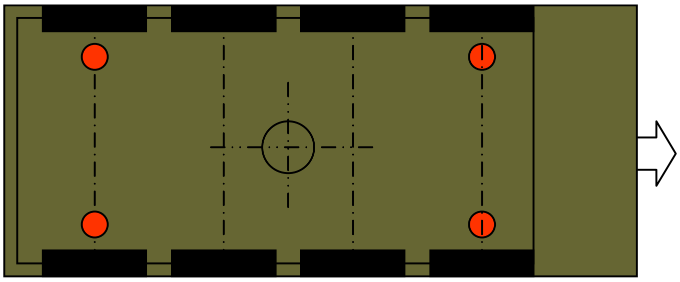


Figure 5: Ideal configuration for accelerometers to determine the rigid body motions of a ground vehicle

Coordinate transformations like those described above are only valid on the measured time signals and are not possible once these have been transformed in terms of FDS and SRS. This is because the spectra lack phase information. For terrain induced loads we often find the dominant acceleration on any component on the body of a vehicle is proportional to the vertical acceleration measured on the vehicle. Satisfactory measurements can therefore be obtained using vertical accelerometers mounted at the centre of each quadrant as illustrated in Figure 6. While these are sufficient for assessing the damage from terrain induced acceleration, additional accelerometers may be required to adequately account for other loads incurred from weapons discharge, etc.



● 4 vertical accelerometers for heave, pitch and roll loading

Figure 6: Preferred configuration of accelerometers

TSS ALGORITHM

A flow chart of the TSS algorithm is given in the Appendix. This is divided into two parts:

1. Digitizing the measured acceleration data
2. Calculating the SRS and FDS

Digitization

Ground vibration typically occurs over a low frequency range between 0 – 20Hz, while shock and impact loads give a broader range of response. Tracked vehicles and those with deep tread tires will also yield higher frequency response. To ensure a reasonable frequency range, the first prototype TSS units are set to acquire acceleration data at a continuous 5kHz sample rate. An antialiasing filter is provided at 1kHz to prevent aliasing while still maintaining adequate amplitude resolution.

Data is accumulated in a memory buffer before being passed to the SRS/FDS calculation process. The digitization process runs concurrently with the calculation process to ensure no loading events are missed.

SRS/FDS Calculation

The process loops through the natural frequency range of interest as illustrated in Figure 2. The highest frequency is limited by the sample rate and antialiasing filter used in the digitizing process. For each frequency of interest, the buffered acceleration data is filtered using a IIR filter. The maximum response is used to update the SRS while the rainflow cycle count is processed and the cumulative damage calculated. This is then used to update the FDS.

The arbitrary nature over which the acceleration data is buffered means some fatigue cycles are not closed in a single buffer. A residual rainflow stack is therefore held for each filter frequency to ensure unclosed cycles can be closed in subsequent buffers.

The algorithm is very sensitive to signal drift and DC offsets. A high pass filter is provided to prevent anomalous results. The algorithm is also sensitive to impulsive ringing caused by electrical spikes, and care is taken to eliminate these from the system.

The TSS unit has persistent storage for the SRS, FDS and residual rainflow stacks, so this information is not lost when the unit is powered down. The unit is usually run when the vehicle is in motion or in transit. The SRS and FDS outputs are available at any time for use by the HUMS IT system. The FDS accumulates throughout the life of the vehicle, whereas the SRS can be reset by the HUMS administrator.

TSS CALIBRATION TO COMPONENT FAILURE

The SRS records the greatest input shock load to a component while the FDS records a ‘potential damage’ value. Both these outputs can be calibrated to the failure of a range of components. Failure calibration is achievable using one or more of the following options:

1. CAE design analysis of the component
2. Proving ground test or laboratory based simulation
3. In-service failure records
4. Established safe life targets

Modern CAE tools are used early in the design of a vehicle to assess its durability and reduce development time and costs. These models can be used to calibrate the failure points on the SRS and FDS plots for a whole range of failure modes. The CAE analysis will quickly establish the likely failure points in the component and calculate the dominant frequency response. The SRS is then calibrated from the static strength of the component and the FDS from the fatigue endurance. The TSS utilizes the same mathematical models as those used in the CAE tools so the calibration values are easily transferable.

Before a new platform is released for service, it is usually tested under proving ground conditions and under laboratory-based simulation. The test vehicles usually carry advanced data acquisition equipment that monitors the input load and stress response on many important systems. This data can also be used to calibrate the SRS and FDS based analysis.

Despite our best design endeavors, in-service failure of some components can still arise. Failure records can be used to establish a safe range of SRS and FDS values. A failed component would be inspected to find the initial point of failure and the dominant frequency response determined by CAE or modal analysis. The failure calibration is then established by observing the SRS and FDS readings from the vehicles at the time of component failure.

It is not usually possible to calibrate fatigue failure to a definite value. The very nature of fatigue gives rise to high statistical variability between apparently identical components. For this reason the FDS is usually calibrated for a probability of failure, however, the SRS can usually be calibrated to an exact value because the statistical variability is only slight.

CASE STUDY

A large aerospace Tier-1 supplier was contracted to provide underslung stores for use on a fast jet aircraft. An existing and proven stores pod was used as the basis for this new design, however, the pod had previously only been used on large sub-sonic tanker aircraft, and concern was voiced over its suitability for flight trials. The flight envelope of the fast jet significantly exceeded the original design spectrum of the pod and the supplier had to assess whether the pod, originally designed for 1000 hours on a tanker, would safely endure the required 20 hours of flight trials on the fast jet.

An assessment of the main structure and mounting system showed this to be adequate for the proposed loading, however, it would be impossible to perform a full CAE analysis of every internal ancillary component before the flight trials. An engineering approach was devised which would combine frequent structural inspections of the pod with a mathematical analysis of the accumulated damage using a Fatigue Damage Spectrum (FDS) approach. The accumulated damage was calculated from the acceleration measured at the fixing points and compared with the certified capacity of the pod to ensure that it did not encroach too far towards the certified level. A Shock Response Spectrum (SRS) analysis was performed to ensure that no single high acceleration event would induce loads in excess of the design envelope.

nCode International was contracted to provide the necessary signal processing, fatigue analysis and HUMS software. An engineering analysis was performed before the flight trials to estimate the likely overload potential of the new environment. A comparison was made between the FDS given for the fast jet flight envelope over a 20 hour flight trial with that of the certified sign-off test. The comparison is illustrated in Figure 7 having been transformed into an equivalent PSD flight spectrum for more intuitive interpretation.

The analysis revealed an anticipated overload in the peak acceleration of 70% with a consequential reduction in fatigue life from 1000 hours to 125 hours. The supplier proposed a change in material for all key structural items to improve the fatigue performance. The resulting improvements were substantial and offered several orders of magnitude greater fatigue resistance. Improvement, however, was restricted only to those components using the new material and careful observation was given to areas of stress concentration along with other internal components to ensure there were no signs of distress throughout the trials. The trials were scheduled carefully to allow engineers time to inspect the pod after each sortie, and sorties were arranged in terms of increasing severity. The cumulative FDS was calculated using the measured acceleration data at each inspection interval and the damage compared with that of the certified sign-off test.

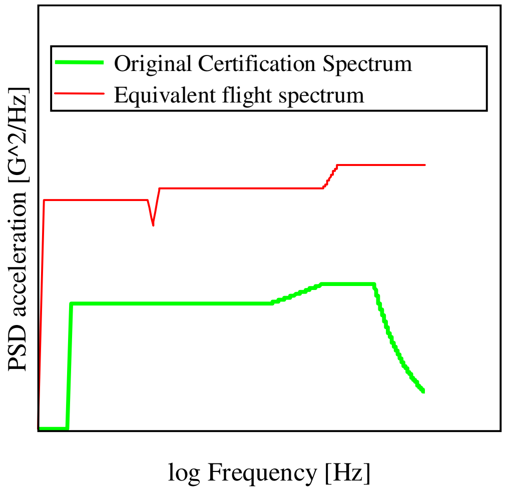


Figure 7: Comparison between flight spectrum and certified spectrum

At no time did the trials exceed the design FDS or SRS of the pod, and in all cases the maneuvers were found to be significantly less damaging than the original flight spectrum had predicted. Operational constraints were imposed on flying the aircraft with the pod installed and this, in conjunction with the inboard mounting of the pod on the aircraft, contributed to significantly lower service loads. Using the measured acceleration data at various locations on the pod, the supplier was able to derive an equivalent flight spectrum for comparison with the certified sign-off test. The comparison is given in Figure 8 and shows the flight response to be lower than the existing certified test in all but one case. Even then, the flight spectrum only encroaches on the certified test at one measurement point and only in the high frequency region and is not considered to be a problem.

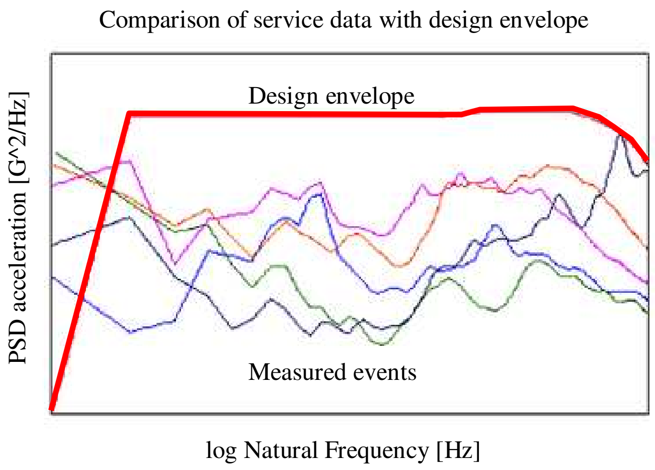


Figure 8: Comparison between service measurements and design envelope

CONCLUSION

This paper introduces a new ‘Terrain Sensing System’ (TSS) that is able to record the cumulative damage seen by a ground vehicle over its entire operational life. Used within a HUMS IT process, this information can be calibrated to represent directly the residual life of onboard equipment such as electronic control systems, instrumentation, radios, brackets, refrigeration plants, and weapons systems, enabling field staff to rapidly prioritize vehicles for deployment, increase their operational effectiveness and improve through-life management of the fleet using ‘Condition Based Maintenance’ (CBM).

The paper has introduced the Shock Response Spectrum (SRS) and Fatigue Damage Spectrum (FDS) as a means of calculating the maximum critical loads and the accumulating fatigue damage on a vehicle platform respectively. It has discussed the TSS unit and presented information on the sensor configuration and damage accumulation algorithm. It has discussed how damage values are calibrated to individual failure modes of onboard equipment and presented a case study showing how similar analyses were performed to assess the damage potential of flight trials during the development of a new aerospace component.

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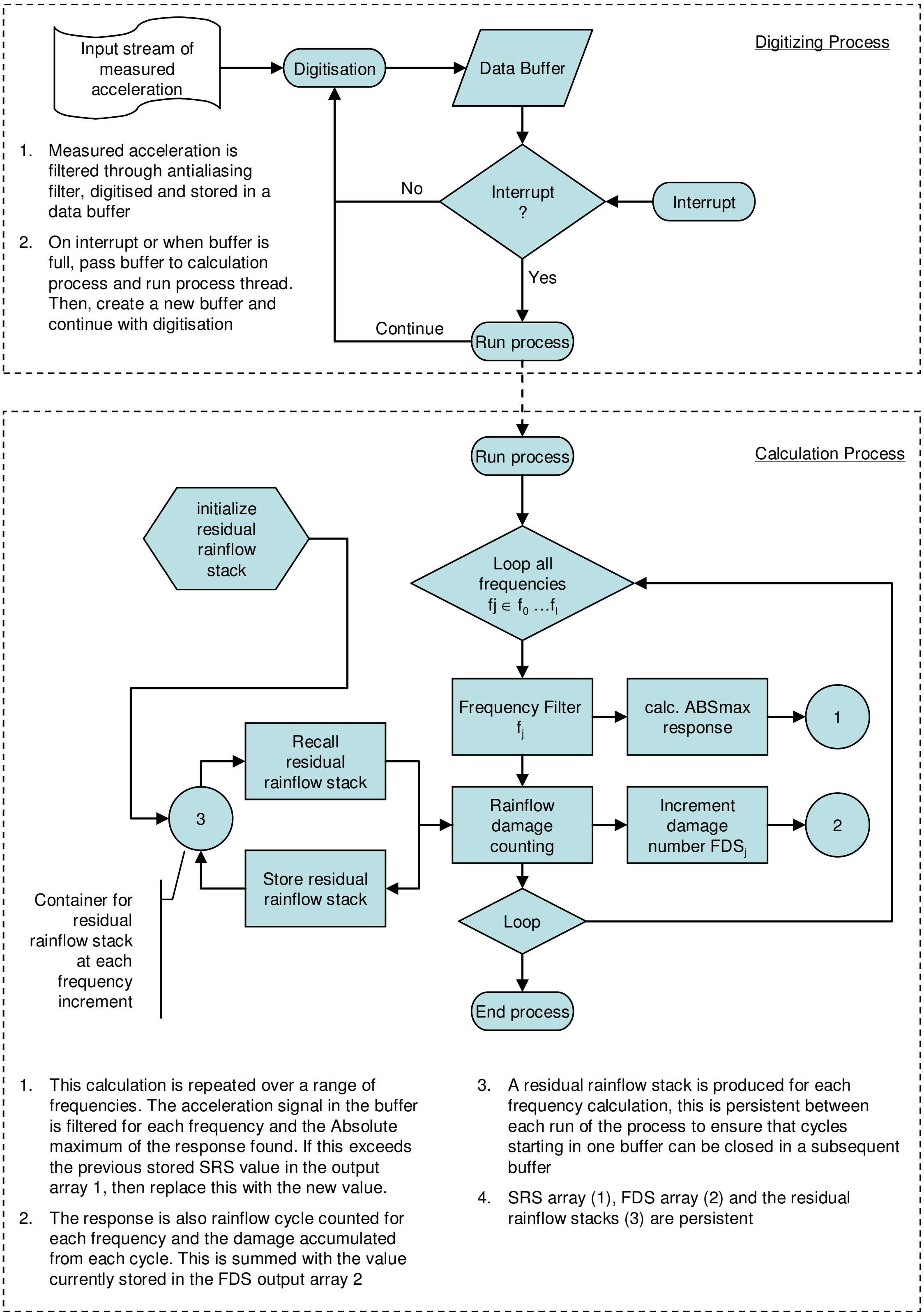
DEFINITIONS, ACRONYMS, ABBREVIATIONS

TSS: Terrain Sensing System
FDS: Fatigue Damage Spectrum
SRS: Shock Response Spectrum
HUMS: Health and Usage Monitoring System
CBM: Condition Based Maintenance
RCM: Reliability Centered Maintenance
SDOF: Single Degree of Freedom system
CAE: Computer Aided Engineering
RCM: Reliability Centered Maintenance

APPENDIX: TERRAIN SENSING SYSTEM (TSS) ALGORITHM FLOW CHART



1. Measured acceleration is filtered through antialiasing filter, digitised and stored in a data buffer
2. On interrupt or when buffer is full, pass buffer to calculation process and run process thread. Then, create a new buffer and continue with digitisation

1. This calculation is repeated over a range of frequencies. The acceleration signal in the buffer is filtered for each frequency and the Absolute maximum of the response found. If this exceeds the previous stored SRS value in the output array 1, then replace this with the new value.
2. The response is also rainflow cycle counted for each frequency and the damage accumulated from each cycle. This is summed with the value currently stored in the FDS output array 2
3. A residual rainflow stack is produced for each frequency calculation, this is persistent between each run of the process to ensure that cycles starting in one buffer can be closed in a subsequent buffer
4. SRS array (1), FDS array (2) and the residual rainflow stacks (3) are persistent