CBM FOR VIBRATING EQUIPMENT ON ROTORCRAFT

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ABSTRACT

This paper describes a device and an algorithm which is capable of real-time analysis of the Vibration Damage Dosage (VDD) of components mounted on a helicopter platform. The device can be used as part of a Condition Based Maintenance (CBM) system to determine the fatigue life consumed of any component mounted on the aircraft. It is useful for CBM analysis and aircraft relifing. It can also be used to assess the severity of different missions and provide data for creating tailored vibration certification tests in accordance with MIL-STD-810F, Annex A [1].

The paper presents a review of the technology along with a case study of how the algorithms have been used to define qualification tests for the Super Lynx 300 helicopter by AgustaWestland in the UK.

INTRODUCTION

The vibration levels on a helicopter are among the worst of any aircraft. Long-term exposure of equipment to vibration gives rise to microscopic cracks that eventually propagate to failure; a failure mode referred to as 'Fatigue'. Equipment is tested and qualified against standards such as the MIL-STD-810F part 514 [1]. Equipment is subjected to a vibration test and is expected to survive a specified duration without signs of failure. However, premature failures still occur in flight because standard vibration tests seldom consider the particular characteristics of each type of helicopter or changes in the configuration or usage spectra throughout the life of the aircraft.

In this paper we introduce a new approach for real-time calculation of Vibration Damage Dosage (VDD) which is directly comparable with the vibration qualification tests performed on the equipment. From this analysis we can determine the residual life of any equipment on-board the helicopter. We can also 'drill-down' through the data to compare the severity of each flight event and see immediately how changes in usage will impact on the endurance of the aircraft. This analysis is particularly useful during times of conflict when we need to make rapid decisions about the condition of an aircraft following non-standard maneuvers.

Used as part of an integrated CBM system VDD information will reduce the number of in-service failures and increase aircraft safety whilst reducing the logistics chain and minimizing maintenance costs. The data can also be used to create tailored vibration tests in accordance with MIL-STD-810F Annex A, which can be used to increase the reliability of future procurements. It can also be used as quantitative evidence during equipment re-lifing studies to extend the operational life of equipment.

The new system works by continually monitoring the vibration levels at a few key positions on the helicopter. These positions should be indicative of the regions defined in MIL-STD-810F; (i.e. main fuselage, instrument panels, on/near drive system elements, and external stores); although the resolution of the measurement locations will vary depending on cost-benefit relationships. The system calculates the cumulative shock and Vibration Damage Dosage values in real-time and these are compared with the original qualification tests performed on the equipment. Used as part of an integrated CBM system, the cumulative vibration damage dosage can be attributed to individual pieces of equipment on the helicopter and tracked throughout its life. The paper presents case studies describing how these techniques have been used with in-flight measurements to define new qualification tests for equipment mounted on operational military helicopters by AgustaWestland in the UK.

REVIEW OF BACKGROUND THEORY

The basis of this theory originates from the work of American engineer Biot in 1934. Extensive development on this basic approach was conducted by the French Ministry of Defense in preparation of the military design standard GAM EG-13 [2] in the 1980's. It is also covered by the US MIL-STD-810F [1] and RTCA D0-160E [3] and is proposed in the NATO document AECTP 200 [4]. In this section we introduce the two principal components of the vibration damage dosage algorithm: the Shock Response Spectrum (SRS) and the Fatigue Damage Spectrum (FDS). It is the real-

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time calculation of these spectra that allows us to use this within a CBM system.

The VDD sensor calculates the Shock Response Spectrum (SRS) and Fatigue Damage Spectrum (FDS) in real-time. The SRS is used to warn of failure resulting from extreme shock events such as severe landings, impact, weapons discharge or nearby explosions. These extreme events can give rise to catastrophic failure as component stresses exceed the 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 over time and lead to eventual fatigue failure.

THE SHOCK RESPONSE SPECTRUM (SRS)

Consider a typical component, for example, a radar unit mounted to the fuselage of a helicopter. How would we assess the severity of vibration on the radar unit during flight and how does this compare with the original certification of the unit? The most common approach would be to compare the RMS (Root Mean Square) levels; however, this does not consider the frequency content of the vibration signal which is particularly important and is also unsuitable for measuring the effect of short duration transient shocks. The Shock Response Spectrum (SRS) offers a much better approach. The SRS is presented as a plot of the worst shock amplitude vs. frequency and a typical plot is given in Figure 3.

The SRS was developed by the American engineer Biot in 1932 [5]. To compute Biot's Shock Spectrum the measured acceleration signal is first of all filtered by a Single Degree of Freedom (SDOF) transfer function centered on a specified natural frequency as illustrated in Figure 1. The maximum value of the filtered response is then calculated and this represents a single point in the SRS plot. This calculation is repeated over a whole range of natural frequencies to create the entire SRS. In 1934, Biot [6] published a paper on earthquake analysis and used the term 'Shock Spectrum' for the first time.

Biot used the SDOF response function as a frequency filter because of its ability to select a specific frequency in a manner consistent with the physical response of a structural system. It is also mathematically stable and is ideally suited to rapid time-domain convolution.

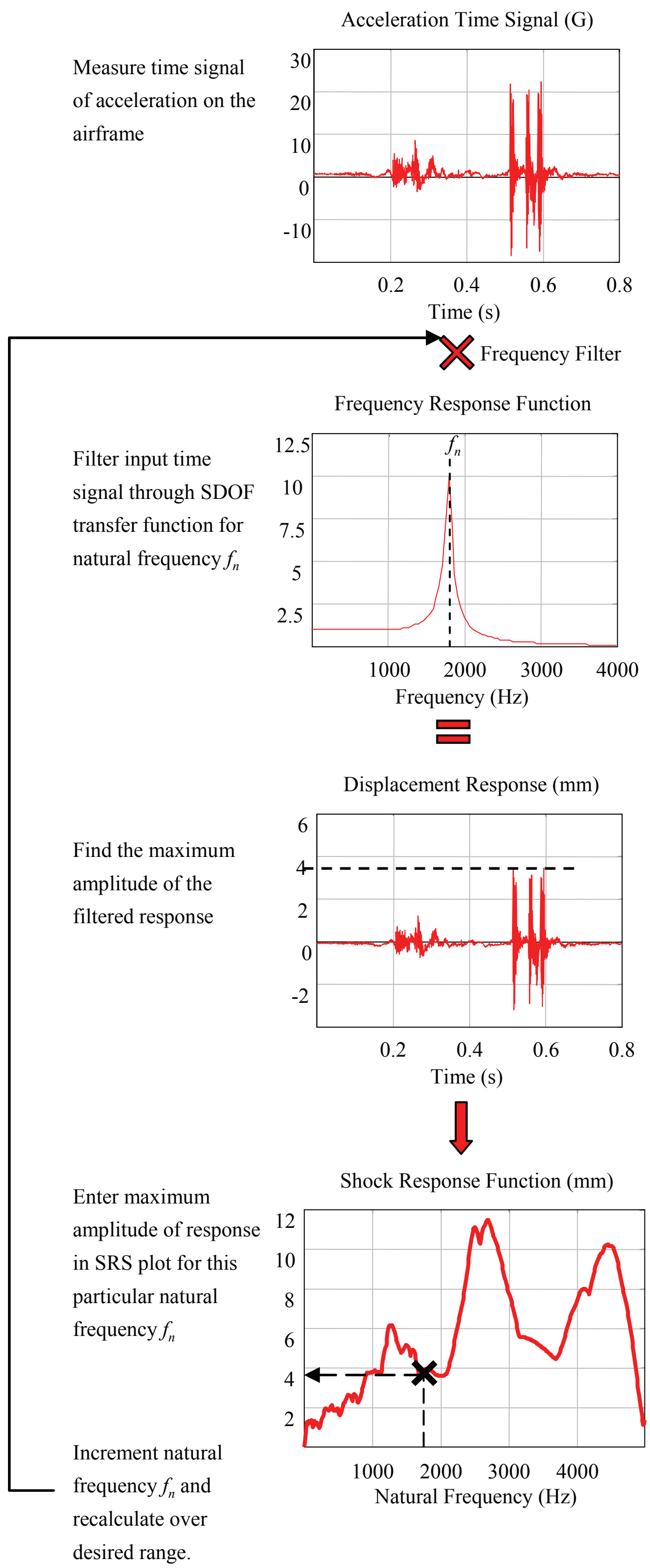


Figure 1 Calculating the Shock Response Spectrum (SRS)

The SDOF response function is dominated by a single spike located at the natural frequency f_n. 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 as illustrated in Figure 1. It is possible to vary the amplification factor Q; however, established procedure assumes a value of Q=10 for comparative analysis. This assumes that we use the same Q value when calculating the SRS in-flight and the SRS from the qualification test.

The Shock Response Spectrum (SRS) can be expressed in terms of acceleration or displacement response depending on the frequency response function used. For fatigue purposes, we are mostly 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 when applied to components with a multi-modal response. Lalanne [7] 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 [8] 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.

THE FATIGUE DAMAGE SPECTRUM (FDS)

Lalanne [9], 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 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 events as well as steady state events. 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 [10] and Downing et al. [11] respectively. An example of the FDS is given in Figure 3.

VIBRATION DAMAGE DOSAGE (VDD) SENSOR

The Vibration Damage Dosage (VDD) sensor 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 severe landings, impact, weapons discharge or nearby explosions. These extreme events can give rise to catastrophic failure as component stresses exceed the 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 over time and lead to eventual fatigue failures. Examples of both spectra are presented in Figure 3.

The FDS is seen to rise throughout the life of the aircraft. As vibrations worsen the FDS rises faster. If we knew the exact failure mode of a component and could ascertain the principal frequencies involved we could estimate the failure threshold directly and mark this on the FDS plot. In reality, we seldom have this information and it is much easier to compare the accumulated in-flight damage with the qualification test instead. In this way we obtain a measure of residual life before hitting the certification limit. Thankfully there are established procedures for calculating the FDS and SRS values directly from design standards like MIL-STD-810F. For more information see HBM-nCode GlyphWorks user manual on accelerated testing [12].

The VDD device is transparent to the crew. It calculates and maintains the SRS and FDS. The VDD is designed to work within the context of a CBM system. The CBM server uses the VDD sensor to calculate the FDS and SRS and then uses this information to determine the cumulative damage on each piece of onboard equipment. This 'damage ratio' is maintained within the inventory so equipment can be freely exchanged between aircraft and the damage ratio transferred with the item.

VDD SENSORS ON A HELICOPTER

The vibration environment on a helicopter is characterized as a series of sinusoidal vibrations superimposed on a broad-band random background. The amplitude and frequencies are dependent on the measurement position on the aircraft. Design standards usually divide the aircraft into a number of regions; these are generally referred to as:

1. Fuselage general
2. Vibration isolated mounting racks
3. External stores
4. Tail cone and tail fin
5. On or near drive system elements

The prominent fuselage frequencies are attributable to the rotor frequency and harmonics of the blade passing frequency. The first three blade-passing harmonics are most prominent and the usual frequency range is regarded as 5 – 500Hz. A triaxial VDD sensor can be used but in most cases only the vertical and lateral axes are significant.

Many avionic components are mounted on isolated racks which are designed to reduce the vibration amplitude transmitted to the component. VDD sensors can be mounted to each rack and will quantify the actual vibration levels seem by all items of equipment mounted on that particular rack. Again, the usual frequency range is 5 – 500Hz.

Equipment mounted externally on the aircraft; such as missiles, antennae, external fuel tanks, etc.; can also be instrumented with individual VDD sensors to determine the vibration loads. These vibrations are mostly influenced by the blade-passing harmonics of the main rotor in the frequency range 5 – 500Hz.

For equipment mounted in the tail boom and tail fin, the prominent frequencies are dictated by harmonics of the tail rotor.

Where equipment is mounted close to the engines or gear boxes then high frequency contributions from the engine and gearbox meshing frequencies also become significant. The typical frequencies range here is 5 – 2000Hz but can be higher.

It is not necessary to instrument all equipment with a VDD sensor. Sufficient sensors are located to attain an overall picture of the vibration environment. Of course, if there is a safety critical component or a component of high value then it is possible to use a dedicated VDD sensor and derive more accurate results. A cost-benefit study can be used to identify such cases.

VDD ALGORITHM

A flow chart of the VDD 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

To ensure a reasonable frequency range the first prototype VDD units are set to acquire acceleration data at a continuous 5 kHz sample rate and use an antialiasing filter. The SRS and FDS are calculated over a range of 5–2000Hz with 40 selected frequencies. Research has concluded that the preferred sample rate is 5–10 times the maximum frequency of interest. In this case the prototype becomes less accurate for frequencies in excess of 500Hz.

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 1. For each frequency of interest, the buffered acceleration data is first of all filtered using an IIR filter. The maximum response is used to update the SRS plot while the rainflow cycle count is processed and the resultant fatigue damage accumulated with 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 using a spike detection and correction algorithm.

The VDD 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 aircraft is powered or in transit or during ground handling events. The SRS and FDS outputs are available at any time for use by the CBM system. The

FDS accumulates throughout the life of the aircraft, whereas the SRS can be reset by the CBM administrator.

CASE STUDY

For this case study acceleration measurement data was taken from the AgustaWestland Super Lynx 300 aircraft as shown in Figure 2. It was not possible to mount the real-time VDD device to the aircraft so the VDD analysis was performed using a desktop PC running the HBM-nCode GlyphWorks [12] program. A prototype of the real-time VDD device was built as part of the UK MOD FRES research framework and this is discussed.

Figure 2 AgustaWestland Super Lynx 300 Helicopter

SUPER LYNX 300 VDD ANALYSIS

Acceleration data was taken from a Super Lynx 300 aircraft similar to that shown in Figure 2. Measurements were taken over a number of flights and were digitized at a rate of 6 kHz with an antialiasing filter fitted. Data was collected at many locations on the aircraft; however, this study is primarily concerned with equipment mounted in the general fuselage area with particular emphasis on the newly designed control rods sited in the main cabin area. The analysis therefore uses 2 sets of accelerometers sited in the cabin. The SRS and FDS are calculated for both sets of accelerometers and the envelope is used in this study. The SRS and FDS were calculated over a range 5–2000Hz and the frequency points for the calculation are biased to known excitation frequencies, principally: harmonics of the main rotor frequency, harmonics of the tail rotor frequency and meshing frequencies of the intermediate and tail rotor gearboxes. A comparison of the measured SRS and FDS is given in Figure 3. The calibrated certification limit is also shown on the plots and this is discussed later.

From Figure 3 we see that the peak shock loading experienced in-flight was significantly less than the certified limit. From this plot it is clear that failure due to overload is very unlikely as the original certification tests were based on much greater amplitudes than those experienced during these particular flights. In this case the most severe shock is less than 30% of the level seen during the certification tests. Of course the peak values might increase in the case of a hard landing, evasive maneuvers or missile launch. In this case the in-flight curve might approach or even exceed the limit. The maintainers must then decide on a course of action. Often times this might involve replacement of some critical components along with a simple inspection of some of the less critical components. Operational experience will feed into the CBM system to guide maintainers on a course of action depending on the shock levels recorded. After each inspection the SRS would be logged by the CBM server and the onboard SRS reset. CBM analysts can use this data for various trending analyses to monitor fleet life consumption and offer recommendations to the ground crew.

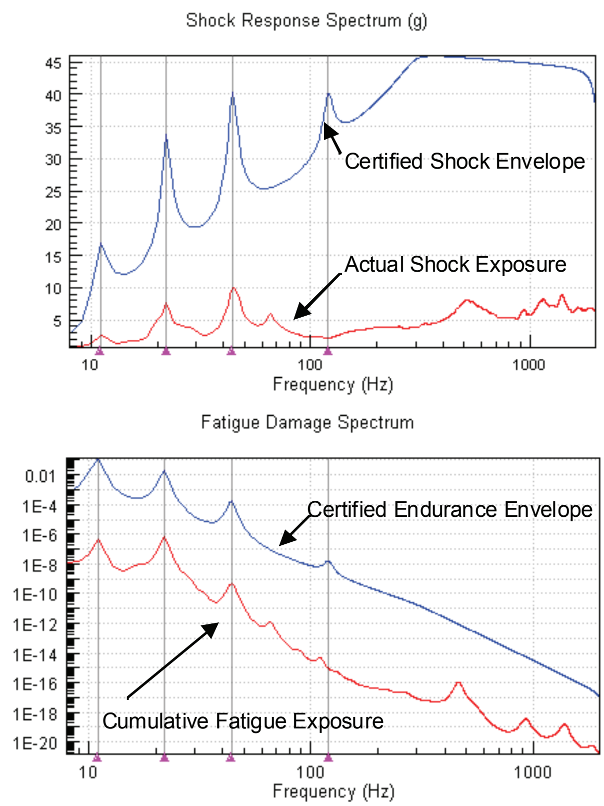


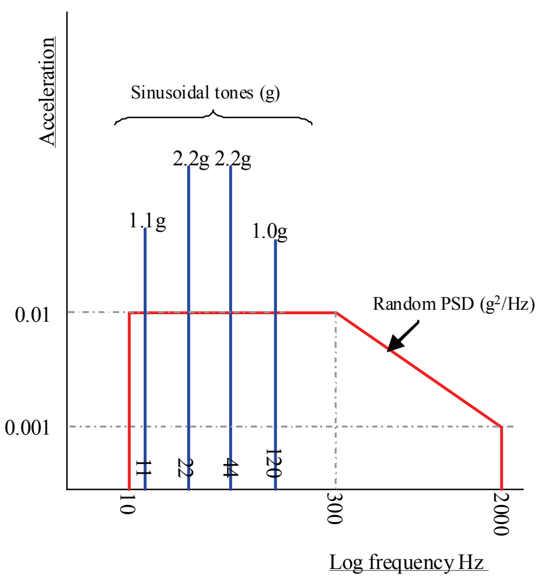
Figure 3 Comparison of in-flight vibration exposure to calibrated limits

From Figure 3 we also see that the cumulative in-flight fatigue exposure is less than the certified limit. It is customary to plot fatigue damage on log axes for clarity. The in-flight FDS curve will rise throughout the life of the aircraft. As the vibrations worsen then the FDS rises faster. The difference between the current level and the certification level can be used to estimate the residual life of components. In this case study the limiting factor appears to be the tail rotor gearbox meshing frequency. The cumulative damage ratio amounts to 5.5E-4. The cumulative flight time is only 6 hours so the residual life is approximately 6 / 5.5E-4 = 10,000 hours based on the current mix of flying.

DERIVATION OF THE CERTIFICATION CURVES

These certification curves are based on a tailored implementation of the MIL-STD-810F [1] design standard. In this case the test generated is specific to the yaw control rods as they pass through the fuselage section. The test comprises the following steps:

1. Initial resonance search at a sweep rate not exceeding 1 oct/min in accordance with in-house specifications
2. 16 hour sine-on-random test in accordance with Figure 4
3. Final resonance search as per step 1
4. Repeat all above steps for each axis (x, y, z)



PSD random

Freq.	PSD g^2/Hz
10	0.01
300	0.01
2000	0.001

Table 1

Sine tones

Freq.	Amp. g
2R = 11 Hz	1.1 g
4R = 22 Hz	2.2 g
8R = 44 Hz	2.2 g
4T = 210 Hz	1.0 g

Table 2

Figure 4 Tailored MIL-STD_810F vibration test

This test is designed for clearance of up to 10,000 hours. It is based on the MIL-STD-810F standard for 'General' locations on the helicopter; however, the acceleration amplitude levels have been tailored to account for measured observations. This analysis was performed using the accelerated testing package in the HBM-nCode GlyphWorks [12] program.

The test tailoring approach starts by using the MIL-STD-810F recommended test values as base-line values. Flight trials of the aircraft are then analyzed and vibration levels are recorded under a succession of flight events which together comprise the usage spectrum. The SRS and FDS are then calculated for each event and the design SRS is obtained from the envelope of all the individual event SRS. The design FDS is based on a weighted sum of the individual event FDS where each event is weighted by the time given in the design usage spectrum. This analysis is discussed by Halfpenny [13]. Using this approach it is possible to tailor the vibration test for specific aircraft and specific components. It allows fine control over the safety margin and also allows for comparisons between the severities of different test specifications. This is very useful when equipment certified for one aircraft is required for use on another and expensive testing can be avoided.

THE ONBOARD VDD SYSTEM

The case study discussed above describes analysis performed on a desktop computer. For the VDD system to function as part of a CBM system it is necessary that the algorithm should work onboard in real-time. It is therefore a requirement that the algorithm be capable of running on small low-powered processors such as DSP's (Digital Signal Processors) and FPGA's (Field Programmable Gate Arrays). It is also desirable that the algorithms work on third party hardware devices so the VDD can be integrated within existing CBM solutions.

A recent study was performed under the UK MOD FRES research framework to port the VDD algorithm to a third party onboard control unit based on a low-powered processor. The demonstration unit was programmed to acquire drive-line data as well as accelerometer and vehicle bus data. A suite of CBM algorithms were written for the unit including the VDD algorithms. In this case the VDD algorithms were implemented on 4 accelerometers over a frequency range of 0-5000 Hz using 40 analysis frequencies. The unit performed this analysis along with the other CBM tasks with residual processing capacity.

For production VDD sensors it is proposed that the accelerometer, VDD processor and communications system be incorporated into a single module. This will reduce data bandwidth requirement over the CBM communication bus and will simplify installation.

CONCLUSION

This paper has described an algorithm for the real-time analysis of Vibration Damage Dosage (VDD). The algorithm can be used to calculate the cumulative fatigue damage for components mounted on a helicopter platform. The algorithm can be used as part of a CBM system to determine component residual life and is ideal for condition-based maintenance assessment as well as aircraft relifing. It can also be used to assess the severity of different missions and provide data for creating tailored vibration certification tests in accordance with MIL-STD-810F, Annex A [1].

The paper presented a review of the background technology and described a case study of how the algorithms have been used to define new qualification tests for the Super Lynx 300 helicopter by AgustaWestland in the UK. A prototype unit has been developed using a third-party electronic control unit which is capable of calculating the VDD in real-time.

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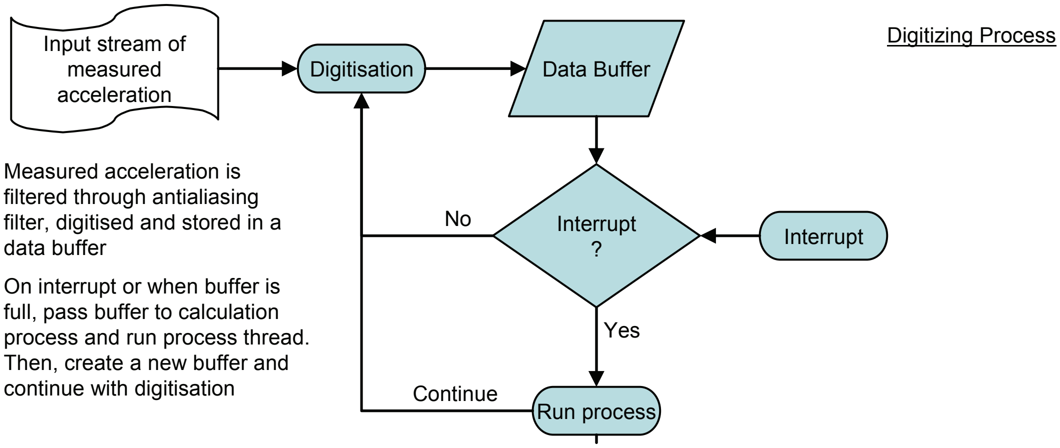
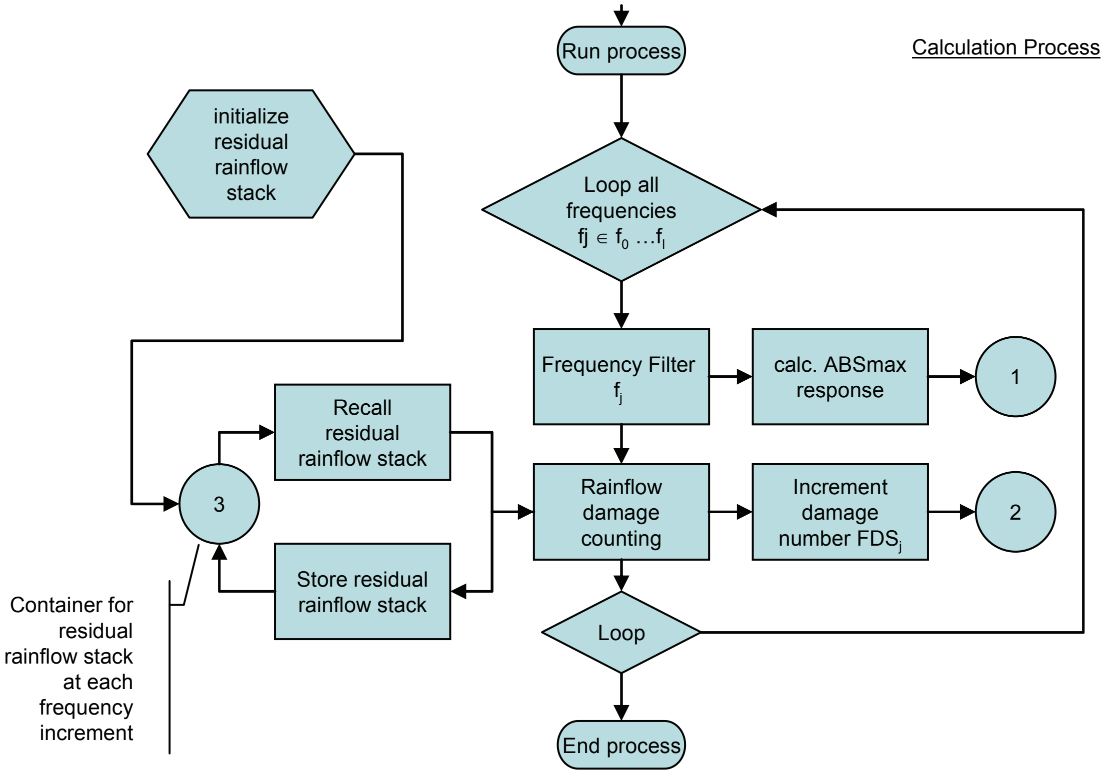
DEFINITIONS, ACRONYMS, ABBREVIATIONS

CBM: Condition Based Maintenance
DSP: Digital Signal Processor
FDS: Fatigue Damage Spectrum
FPGA: Field Programmable Gate Array
FRES: Future Rapid Effect System
HUMS: Health and Usage Monitoring System
IIR filter: Infinite Impulse Response filter
MOD: United Kingdom Ministry of Defence
RMS: Root Mean Square
SDOF: Single Degree of Freedom System
SRS: Shock Response Spectrum
VDD: Vibration Damage Dosage

APPENDIX: VIBRATION DAMAGE DOSAGE (VDD) 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