pHUMS—Prognostic Health and Usage Monitoring of Military Land Systems

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Reading Recommendations

Part I – Anatomy of a HUMS System

Brief executive level description of a HUMS system. It highlights the components involved and presents the benefits of HUMS in military ground vehicles. No engineering knowledge is required.

Part II – The pHUMS Analytical Model

Conceptual overview of the pHUMS analysis and the cause of structural failures. Paper assumes some general engineering background but expertise in durability and vehicle dynamics are not required.

Part III – pHUMS System for a Military Ground Vehicle

Description of a typical pHUMS system suitable for military ground vehicles. Paper assumes an understanding of Part II or a prior understanding of vehicle dynamics, loading and durability.
**pHUMS – Prognostic Health and Usage Monitoring of Military Land Systems**

*Part I – Anatomy of a HUMS System*

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**Abstract**

*pHUMS*, or ‘Prognostic Health and Usage Monitoring Systems’ improve operational capability by providing instantaneous information on the condition of military ground vehicles. This information is used to prioritise the most reliable vehicles for deployment and to ensure supply chains for any replacement components. Asset management is improved and maintenance costs are lowered. These three papers introduce the application of *pHUMS* to military ground vehicles. Part I provides an executive level summary of HUMS in general, Part II describes the *pHUMS* approach in detail, and Part III describes a complete installation suitable for deployment.

**Introduction**

*pHUMS*, or ‘Prognostic Health and Usage Monitoring Systems’ improve operational capability by providing enhanced decision support information on the operational condition of ground vehicles. This information is particularly valuable for:

i. ensuring the most reliable vehicles are prioritised for deployment
ii. establishing supply chains of necessary replacement components to ensure that the vehicles remain fully operational during their deployment
iii. to rapidly identify aging or damaged onboard systems to ensure they do not compromise operational effectiveness

The system can diagnose faults with a vehicle before they become critical and can predict the residual life of various components. This ensures operational effectiveness while reducing maintenance overheads. In this paper we provide an overview of a HUMS system. We introduce the concepts of Diagnostic and Prognostic based HUMS and conclude that a Prognostic approach is preferred for Ground vehicles.

**The Anatomy of a HUMS System**

An effective HUMS system consists of three elements;

i. a network of sensors,
ii. an onboard HUMS processor,
iii. an off-board HUMS server.

These are illustrated in Figure 1.

![Figure 1 Elements of a HUMS System](image)

**Sensors**

Sensors monitor loads on the vehicle and pass this data to the onboard HUMS processor. Some special HUMS sensors might be required as shown in Figure 2, but most of the information will already be available from the existing array of sensors used by the vehicle’s own systems.
management. This mass of operational data is accessible via the vehicle bus. The onboard processor interfaces with the vehicle bus collating data from the required sensors, and analyses it to assess the current health and usage profile of the vehicle.

![Typical HUMS sensor containing a transducer for measuring acceleration, strain, temperatures, etc. along with a microprocessor suitable for onboard analysis and interface to the vehicle bus.](image1)

**Figure 2 Typical HUMS sensor**

**Onboard HUMS Processor**

The onboard HUMS processor is responsible for assessing the cumulative damage seen by critical components. It can communicate with other onboard systems to inform the crew of impending problems. Some vehicles are fitted with a computerised inventory of installed components. The HUMS system can also communicate with this to pass information on the cumulative damage seen by each component. This facilitates the movement of components between vehicles. The onboard HUMS processor can be self contained as shown in Figure 3 or provided as a co-processor card suitable for mounting in the vehicle’s onboard rack.

![The onboard HUMs processor can be self contained or provided as a co-processor card for mounting in the existing vehicle hardware rack.](image2)

**Figure 3 Typical self contained onboard processor**

**Off-board HUMS Server**

When convenient, the onboard processor passes its data to the off-board HUMS Server. This collates health information from a fleet of vehicles. Data is used for operational planning, maintenance management and fleet management. Whereas traditional maintenance systems log usage by time or mileage, pHUMS implicitly accounts for the severity of usage, shortening or lengthening the maintenance periods accordingly. Supply chains of replacement components can be established before failures in-service are seen, thereby minimising maintenance downtime. Measured load profiles can also be used when designing new vehicles in the future.

Fleet management systems also benefit from HUMS data. These track the locations and status of vehicles to optimize deployment. HUMS can augment this with information on the residual life of the components fitted. This ensures the best vehicles are prioritised for active service. Remaining vehicles can be interrogated and aging components quickly identified for replacement. If a vehicle is severely damaged then the system can also be used to assess parts fit for cannibalisation.

![HUMS Server Showing Highly Damaging Events on a Supply Route](image3)

**Figure 4 HUMS Server Showing Highly Damaging Events on a Supply Route**

**HUMS Analysis**

There are two methods of addressing HUMS:

i. Diagnostic HUMS – diagnosing the presence of a fault

ii. Prognostic HUMS – predicting the residual life of a component whether or not a fault already exists

These are illustrated in the diagram in Figure 5. In this section we address both approaches in detail.
Diagnostic HUMS

The diagnostic HUMS approach relies on the fundamental principal of damage tolerance. A fault can only be diagnosed once it is present, therefore, the component must tolerate this fault with sufficient residual life to safely fulfil its mission.

A diagnosis, as any medical practitioner will affirm, is determined after careful consideration of the ‘Signs’, ‘Symptoms’, and ‘History’ of the patient. ‘Signs’ represent anything that you, the practitioner can see, feel, hear or smell. ‘Symptoms’ cover the feelings of the patient and what they can tell you of their complaint. ‘History’ provides an account of the events leading to this unfortunate malady. Diagnostic HUMS proceeds in an analogous route.

Diagnostic ‘Signs’

The diagnostic ‘Signs’ are reported by the vehicle’s crew following irregular observations of performance. Mechanical noises from the transmission or clutch slip are examples of this. Other ‘Signs’ are observed during routine servicing. A mechanic will usually make an examination of the vehicle carefully noting evidence of cracks or ‘play’ in the bearings for example. In most cases ‘Signs’ are qualitative features that lead an experienced mechanic to the route of the problem. Being a subjective measure it usually requires some experience and skill; diagnostic ‘Signs’ are therefore an unreliable method of early fault detection in the field.

Diagnostic ‘Symptoms’

Diagnostic ‘Symptoms’ are reported by the vehicle itself. Coolant temperature and oil pressure gauges are examples of this data. Modern engine management systems also provide basic fault logging. This information can be used by a service mechanic to trace the cause of intermittent faults. ‘Symptoms’ are usually quantitative features and are particularly suited to HUMS analysis. Skill is often required to interpret the information given by the vehicle, HUMS is useful as an expert system for interpreting this data for non-expert vehicle operatives.

Diagnostic ‘History’

Diagnostic ‘History’ has traditionally been a qualitative account of the deployment of the vehicle. The vehicle log provides details of where the vehicle has been used and describes any notable events during its life. Examples of air drops and prolonged operation under extreme conditions provide a mechanic with insight into potential problems that could arise. Unfortunately many vehicle operators judiciously omit to include some of the more controversial events that might have arisen so the log must be accepted with some caution.

Diagnostic HUMS System

Modern diagnostic HUMS are concerned with advanced detection of symptoms. Faults are diagnosed by looking for certain characteristics in the measured data. These are usually referred to as the fault’s ‘signature’. The challenge facing any development engineer is to correctly identify the signature and provide a reliable means of detection. This task is often extremely difficult and many attempts are compromised by an excessive number of false positive detections.

Typical methods of diagnosis are based on either an active or passive approach.

Active Fault Detection

An active approach involves transmitting clean signals through a component and measuring the response. Examples include the use of lambda waves for detecting crack propagation through thin sheet structures. The clean input signals make it easier to diagnose changes in the response. This approach requires transducers that emit the active signal as well as sensors to monitor the response. Piezo electrical transducers are particularly useful because they can serve
both roles.

Active methods are rarely used while the vehicle is operational so this method is better suited to those vehicles that return frequently to base and is particularly suitable for aircraft. Much of the computational analysis can be carried out using an off-board unit with little onboard processing requirement.

The approach is limited where heavily loaded components are concerned because it isn’t viable to provide onboard actuators that are capable of significantly stressing large components.

Passive Fault Detection
The passive approach monitors data while the vehicle is operational. Examples include vibration monitoring of gearboxes to identify progressive faults. This approach is more suitable for heavily loaded components that require significant loads in order to measure a response.

As passive monitoring takes place while the vehicle is operational it can be used to provide an instantaneous warning of failures. The computing facility must be installed on the vehicle, however, and cost and space constraints can limit the available CPU power.

Examples of passive algorithms range from simple threshold monitoring of vibration and temperature levels to very complex neural network solutions for gearbox analysis.

Conclusion
Diagnostic techniques all rely on detecting the presence of a fault before it has time to cause serious damage. Components exhibiting this trait are known as ‘damage tolerant’. We see in part 2 of this paper that, aside from a few transmission components, very few components on ground vehicles exhibit this trait and we therefore need to resort to a prognostic type of approach.

Prognostic HUMS
A prognostic HUMS approach is concerned with predicting the residual life of components and doesn’t require a detectable fault. It uses a quantitative record of the historical load on the vehicle and processes this through an analytical model to determine the cumulative damage on each component. This approach is ideal for many ground vehicle components that exhibit few detectable faults prior to catastrophic failure.

The idea of Prognostic HUMS is not new. Several methods have been used in the past to measure the accumulation of fatigue damage. Basic fatigue meters have been used in aircraft for some time to count the number of fatigue cycles, however, these simple devices usually lack the analytical model required to calibrate these readings to the damage on specific onboard components. A number of experiments with ‘fatigue fuses’ have also been attempted on ground vehicles. A fatigue fuse is a sacrificial device that is designed to monitor the same loads as a real component but fail in advance of the component thereby providing prior warning. It is also known as the ‘Canary’ approach, following the analogy with the ill-fated bird used in early mining ventures. These systems can be successful but are often expensive to design and implement and cannot be applied retrospectively to a component midway through its life.

In an ideal system we would monitor the loads going into every critical component on the vehicle and pass these through a dedicated analytical model of that component; however this would prove unfeasibly expensive. A compromise must be sought between the number of measured components and our ability to infer the loading on one component using measured data from elsewhere. The more we reduce the measuring, the more we rely on the analytical model and the more we increase our uncertainty.

This cost compromise creates a clear distinction between aerospace and ground vehicles. Aircraft are employed in low volume with very high unit costs. They frequently operate unsupported deep in hostile territory and the cost of failures in terms of life and equipment are very high. Ground vehicles, on the other hand, are purchased in relatively high numbers with much lower unit costs. They are often deployed in number and with support so when failures occur the crew may be recovered and capital loss is less significant. This reduces the cost benefit of HUMS systems for ground vehicles over aerospace meaning any installation should maximise analytical modelling to minimise the more expensive monitoring process.

The analytical model used for this prognosis has to be simple and reliable. The onboard HUMS
processor has limited CPU power and would be incapable of analysing large models. Measured data is first of all checked for errors and these are corrected before any further analysis is done. The data then passes through a structural model which essentially filters it to determine the effective loads seen on a particular component. This signal is then analysed and its ‘Potential Damage’ calculated. We use the term ‘Potential Damage’ because we rarely calculate the actual damage at this stage. Potential Damage gives a representative measure of the accrued damage that is later calibrated by in-service experience and design models. The process is illustrated in Figure 6.

Fatigue failure is highly statistical in nature. A fleet of apparently identical vehicles deployed on similar missions will all exhibit different fatigue lives. A factor of 2 between the shortest and longest life is typically expected. The analytical models must therefore take account of this statistical distribution to allow field commanders to assess the probability of vehicle failure against the value of the mission objectives, its risk and the consequence of delaying the mission. The analysis model should allow for continual recalibration using in-service observations to improve the statistical confidence.

Conclusion

In this paper we have looked at the anatomy of a HUMS system. The system has been divided into three elements consisting; the Onboard Sensor Network, the Onboard HUMS Processor, and the Off-board HUMS Server. We described the role of these components and introduced two analysis approaches that deal with the diagnosis of a fault and the prognosis using ‘Potential Damage’.

Most ground vehicle components, aside from some transmission components, are not damage tolerant and display few discernable faults prior to catastrophic failure. We concluded that these components are better addressed using a Prognostic type of analysis.

The second paper in this series introduces the analytical damage models required for these prognostic analyses while the third paper discusses a typical HUMS implementation for a ground vehicle.

Figure 6 Flow chart illustrating pHUMS

The Potential Damage models are based on standard fatigue theory. For new vehicle designs calibration of these models is initially based on the Computer Aided Engineering (CAE) design models with refinement from prototype validation and further statistical refinement using in-service records. If HUMS systems are required for existing service vehicles then the original design analysis is seldom available and calibration should be made using instrumented vehicle test along with in-service records.
Abstract

pHUMS, or ‘Prognostic Health and Usage Monitoring Systems’ improve operational capability by providing instantaneous information on the condition of military ground vehicles. This information is used to prioritise the most reliable vehicles for deployment and to ensure supply chains for any replacement components. Asset management is improved and maintenance costs are lowered. These three papers introduce the application of pHUMS to military ground vehicles. Part I provides an executive level summary of HUMS in general, Part II describes the pHUMS approach in detail, and Part III describes a complete installation suitable for deployment.

Introduction

Most ground vehicle components, aside from some transmission components, are not damage tolerant: that is they display few discernable signs of failure prior to catastrophic collapse. In the previous paper of this series we concluded that an approach based on Prognostic HUMS would suit this type of vehicle.

A Prognostic HUMS approach is concerned with predicting the residual life of components and doesn’t require a detectable fault. It uses a quantitative record of the historical load on the vehicle and processes this through an analytical model to determine the cumulative damage on each component. In this paper we discuss the theories used in creating these analytical models.

In many cases it is impractical to derive analytical models for every component in a vehicle so we model only the most critical components or those with a history of failure. Frequently we omit a component that later proves problematic and so the analytical model should be sufficiently versatile to allow us to include additional components as we see fit. The methods discussed here calculate ‘Potential Damage’ on the vehicle due to input loads. These are later calibrated to represent damage on particular components. This post-calibration allows additional components to be added to the damage model and also refinement of the model in light of operational experience.

The Analytical HUMS Model

The Analytical HUMS model illustrated in Figure 7 comprises 3 analysis stages; these being:

i. Error Detection and Correction
ii. Analytical Structural Model
iii. Analytical Damage Model
The Analytical Model consists a standard set of routines that provide an output in terms of ‘Potential Damage’.

Calibration to the real damage seem by any particular component is based on a separate calibration study.

In an ideal world we would measure the loads going into every component on the vehicle, however this is not practical and so we need to infer the loads on one component based on those measured elsewhere. This stage involves a frequency transfer function approach to modelling the structural gain between the measurement location and the required component. This is discussed later in the paper.

**Damage Model**
The third stage deals with the damage model and is based on fatigue theory also discussed later in the paper.

**Model Calibration**
The analytical model records a ‘Potential Damage’ value that is later calibrated to real damage on a particular component. Calibration can be done using data collected from 3 sources as follows:

i. the original Computer Aided Engineering (CAE) models used for the initial vehicle design,

ii. using measured test results obtained from a fully instrumented vehicle on a proving ground or test rig

iii. using in-field experience of known failures

To appreciate how CAE based design models can be used for this purpose we need to consider the modern durability design methods employed by ground vehicle manufacturers.

**Designing for Durability**
Modern CAE (Computer Aided Engineering) tools are used early in the design of a vehicle to assess its durability and reduce development time and costs. Potential weaknesses are found early when remedial solutions are more effective and economic, while unnecessary over-design is avoided. Component testing can be properly prioritised ensuring the most critical components are always tested, and the test signals can be optimized by removing non-damaging segments thereby accelerating the tests. These techniques improve confidence in the final product and avoid potentially disastrous in-service failures.

In the past, fatigue analysis was largely the domain of the development engineer, who used...
measurements taken from prototype components to predict the fatigue behaviour. This gave rise to the traditional “Build it, Test It, Fix It” approach to fatigue design illustrated in Figure 9. This approach is very costly as an iterative design cycle requires real prototype vehicles. This inhibits the ability to develop new concepts and reduces confidence in the final product due to a low statistical sample of tests. It is also common to find early products released with ‘known’ defects or product release dates being delayed whilst durability issues are addressed.

A more desirable approach is to conduct more testing based on computer simulations. Computational analysis can be performed relatively quickly and much earlier in the design cycle as shown in Figure 10.

Confidence in the product is improved because more usage scenarios can be simulated. However, it is still not recommended that these simulations completely replace prototype testing. Prototype sign-off testing is necessary to validate the analysis performed and improve future modelling techniques.

Knowledge of the failure mechanism gained from the analysis can be used to accelerate the testing program. Fatigue editing methods can be used to reduce the number and length of drive signals required for the rig so tests originally taking months can be completed in days. In the unlikely event that a component fails the test, then the measured results can be fed back to the CAE analysis to replicate the failure mode and revise the model.

The CAE design tools commonly used are illustrated in Figure 11.
The CAE design models can be used to develop the HUMS analytical model discussed previously. Obviously we wouldn’t want to run a real time Finite Element (FE) analysis on a vehicle, but information from the design study can be used to develop very elegant and fast onboard analyses. To understand how these analyses work we must first of all understand the physical nature of fatigue.

The Physics of Fatigue

In this section we review the physical phenomenon of Fatigue to better appreciate how failures develop and the basis of a HUMS analytical model.

Fatigue is defined as ‘Failure under a repeated or otherwise varying load, which never reaches a level sufficient to cause failure in a single application.’ Fatigue cracks always develop as a result of cyclic plastic deformation in a localised area. This plastic deformation often arises, not due to theoretical stresses in a perfect part, but rather due to the presence of a small crack or pre-existing defect on the surface of a component, which is practically undetectable.

Wöhler’s Fatigue Test

August Wöhler was the first to study fatigue and propose an empirical approach. Between 1852 and 1870, Wöhler studied the progressive failure of railway axles. He constructed the test rig shown in Figure 12, which subjected 2 railway axles simultaneously to a rotating bending test. Wöhler plotted the nominal stress versus the number of cycles to failure, which has become known as the SN diagram. Each curve is still referred to as a Wöhler line. The SN method is still the most widely used today and a typical example of the curve is shown in Figure 12.

Several features are notable about the Wöhler line. First, we note that below the transition point (approximately 1000 cycles) the SN curve is not valid because the nominal stresses are now elastic-plastic. We will show later that fatigue is driven by the release of plastic shear strain energy; therefore above yield, stress loses the linear relationship with strain and cannot be used. Between the transition and the endurance limit (approximately $10^7$ cycles), SN based analysis is valid. Beyond the endurance limit the slope of the curve reduces dramatically and as such this is often referred to as the ‘infinite life’ region. In practice, however, this is not really the case. For example, Aluminium alloys do not exhibit infinite life, and even steel does not exhibit infinite life when subjected to variable amplitude loading.

Modern Concept of Fatigue

With the advent of modern magnification
techniques, fatigue cracks have been investigated in more detail. We now know that a fatigue crack initiates and grows in a two-stage process. In the early stages a crack is seen to grow at approximately 45° to the direction of applied load (following the line of maximum shear stress). After traversing two or three grain boundaries its direction changes and then propagates at approximately 90° to the direction of the applied load. These are known as Stage I and Stage II cracks and are illustrated in Figure 13.

If we observe the development of a Stage I crack at high magnification we see the alternating stress leads to persistent slip bands forming along the planes of maximum shear. These bands slip back and forth, much like a deck of cards, and give rise to surface extrusions and intrusions. The surface intrusions essentially form an ‘embryonic’ crack and are illustrated in Figure 14. The Stage I crack propagates in this mode until it encounters the grain boundary, at which point it briefly stops until sufficient energy has been applied to the adjacent grain and the process continues.

After traversing two or three grain boundaries the direction of crack propagation now changes into a Stage II mode. In this stage the physical nature of the crack growth is seen to change. The crack itself now forms a macroscopic obstruction to the flow of stress that gives rise to a high plastic stress concentration at the crack tip. This is illustrated in Figure 15. It should be noted that not all Stage I cracks evolve to Stage II. Many find insufficient energy to traverse the grain boundaries and so arrest. This gives rise to the very statistical nature of fatigue.

To appreciate the Stage II growth mechanism we need to consider what happens at the cross section of a crack tip during a stress cycle. This is illustrated in Figure 16.

The fatigue cycle starts when the nominal stress is at point ‘a’. As the stress increases in tension through point ‘b’ we notice the crack tip now opening giving rise to local plastic shear deformation while the crack extends into the
virgin metal at point ‘c’. As the tensile stress now decreases through ‘d’ we observe the crack tip closing and the permanent plastic deformation gives rise to a distinctive saw tooth profile known as a ‘striation’. On completion of the cycle at point ‘e’, we observe that our crack has now advanced through length $\Delta a$, and has formed an additional striation. We can also appreciate that the extent of crack growth is proportional to the range of elastic-plastic crack tip strain applied. Higher cycle ranges give rise to greater $\Delta a$.

Figure 16 Illustration of Stage II crack growth

**The Effect of Stress or Strain Cycles**

From the previous description we notice that in both Stage I and Stage II growth, crack development arises through plastic shear strain on a microscopic scale. To appreciate how these strains contribute to the damage let’s consider the plastic shear strain forming along the Stage I slip planes or at the tip of a Stage II crack as a result of the nominal stress time history shown in Figure 17.

In Figure 17a, we see the nominal stress rise with time. On a microscopic level, in the presence of a crack or pre-existing defect, the stress and strain become plastic and can be plotted in the stress versus strain diagram shown. Figure 17b now shows what happens when the nominal stress is reduced and then raised again by a smaller amount. Again the local stress versus strain can be plotted showing the effect of local yielding. Finally Figure 17c shows another reduction in the nominal stress. From the stress versus strain plot we now see the formation of a hysteresis loop. A loop in the stress versus strain plot indicates release of strain energy where the total energy released is equal to the area of the loop. Essentially we have released a quantity of shear strain energy and this has been expended in sliding the slip planes or advancing the Stage II crack.

Figure 17 Elastic-plastic stress and strain along a slip plane and at the root of a crack

From this illustration we therefore see that a ‘quantum’ of shear strain energy is released when the nominal stress is cycled into tension and then back again. Also, the larger the cycle, the greater the energy released. From the SN curve shown in Figure 12, we see that fatigue life drops exponentially as the cycle range increases. A mathematical algorithm known as ‘Rainflow Cycle Counting’ is used to process a time signal and extract these fatigue damaging cycles.

The mean stress (residual stress) will also affect the rate of fatigue damage. Viewed conceptually, if a mean tensile stress is applied to a Stage II crack then the crack is being forced open and any stress cycles applied will therefore have a more pronounced affect. Conversely, if a mean compressive stress is applied then the crack will be forced shut and any stress cycle would first of all have to overcome the pre-compression before any growth could ensue. A similar concept applies for a Stage I crack. Rainflow Cycle
Counting is also able to extract the mean stress of the cycles.

Fatigue is affected by other factors as well as stress cycles but these are less significant and are beyond the scope of this document.

### Analytical Damage Model

Because fatigue cracks develop and grow in this two stage process, engineers use different analysis approaches to quantify the damage accrued at each stage. Wöhler’s SN (Stress Life) method along with the more modern EN (Strain Life) method is usually employed for Stage I cracking. A Fracture Mechanics approach is used for Stage II. Both approaches use the Rainflow technique to extract the fatigue cycles from the time signal data.

Engineers seldom analyse both crack stages. In practice we find that most components spend much longer in one stage than the other and we therefore ignore the stage with the shorter duration.

Almost half of aerospace components are designed for Stage II growth. These include fuselage and wing components which are very flexible and usually made from very ductile materials. This enables them to absorb the plastic crack tip stresses. These components are referred to as ‘Damage Tolerant’ because they are designed to have small cracks present and inspection intervals are scheduled to ensure the cracks do not grow beyond a safe limit. Aerospace engineers usually ignore the Stage I crack growth stage because it is safer to assume that the cracks already exist if they are simply too small to see.

Nearly all structural components in ground vehicles however, spend their time developing Stage I cracks. The Stage II process occurs almost instantaneously because the components are very stiff and usually made from relatively brittle materials that are unable to cope with the high crack tip stresses encountered.

In conclusion, for ground vehicles we would usually use an SN (stress life) fatigue analysis technique along with Rainflow Cycle counting to determine the damage on most ground vehicle components. The EN (strain life) is preferred where components undergo frequent plastic load cycles. Mean stress (or residual stress) correction should be applied to the fatigue model. The process is illustrated in Figure 18. For aerospace components we would augment these with fracture mechanics based techniques.

![Analytical Damage Model](image)

Figure 18 Analytical Damage Model

### Analytical Structural Model

The purpose of the structural model is to infer the stresses on several components based on only a few measurements taken elsewhere on the vehicle. We usually prefer to measure acceleration on the vehicle platform and use this to infer the critical stresses on the various components; this is discussed in Part I.

The relationship between measured acceleration and stress at some remote component is proportional to the frequency of the applied
acceleration and the natural frequency of the component. This relationship is known as the ‘Transfer Function’ and is illustrated in Figure 19. The transfer function can be used to ‘filter’ the measured acceleration input and thus determine the stress at the component. The transfer function can be obtained using Finite Element (FE) analysis or from measurements taken simultaneously at both the input and output locations.

**Figure 19 Illustration of component response versus frequency**

There are three types of structural model used depending on the type of component being considered; these being:

i. Critical Quasi-static component
ii. General resonating component
iii. Critical resonating component

**Critical Quasi-Static Component**

This model is used for any component that is critical to the operation but behaves in a Quasi-Static fashion. Typical components include suspension, steering, chassis and many transmission components. These components are designed to withstand very high loads and are therefore very stiff with a first mode natural frequency typically exceeding 3 times the maximum input frequency. The transfer function in this case reduces to a simple scalar coefficient. The structural model involves a simple Rainflow Cycle count of input acceleration with damage being determined from a scaled SN curve.

**General Resonating Component**

This model is used for most of the components mounted on the vehicle body. At the failure location we usually observe that the transfer function is dominated by a single natural frequency as illustrated in Figure 19; this is known as a ‘Single Degree of Freedom (SDOF) system. Furthermore, the damping is usually small resulting in the steep dynamic amplification curve shown. The structural model involves filtering the input acceleration signal to account for a number of SDOF systems and assessing the damage for each. This is usually plotted in a Potential Damage Spectrum (PDS) as shown in Figure 21. This shows Potential Damage versus natural frequency and also shows how each successive mission has contributed to the total damage to date.

**Figure 20 Analytical Model for Quasi-static Component**

1. Measure acceleration into vehicle
2. Rainflow Cycle Count the acceleration time signal to obtain potential damage cycles
3. Calculate damage caused by each cycle using a scaled SN curve accounting for the constant relationship between acceleration and stress
4. Add damage from each cycle to the cumulative total for the particular component. Probability of failure can be deduced.

**Repeat continually**
The Potential Damage seen by any component is determined from the PDS by finding its dominant natural frequency and observing the value of the plot. The benefit of this approach is that Potential Damage can be calibrated to the failure of a component at any stage of operation thus allowing for the retrospective analysis of components that were possibly overlooked during the initial design.

The PDS can be calculated in either the time or frequency domains. The time domain method involves filtering the acceleration for each natural frequency of interest. Potential damage is assessed by Rainflow Cycle counting the filtered signals using an SN curve to assess the actual damage accumulated. In practice this stage should be repeated for SN curves of different gradient to account for failure of various materials. The process is illustrated in Figure 22.

A more rapid analysis is possible in the frequency domain where filtering is made considerably quicker and Rainflow Cycle counting is replaced with more simplified assumptions. This approach however assumes that the input accelerations are stochastic. In most cases this assumption is true provided we analyse the data in relatively short time buffers. Sharp deterministic shocks are usually sufficiently damped by the suspension.

**Critical Resonating Component**

This model is used for components critical to the mission whose first mode natural frequency is less than 3 times the maximum input frequency and whose response cannot be approximated to a SDOF system. Such components are quite rare but may include certain onboard weapons systems. In this case dynamic amplification becomes important. The structural model involves filtering the input acceleration signal to derive the critical stresses along with Rainflow Cycle counting as illustrated in Figure 18. These components should be identified early in the design stage because it is very difficult to retrospectively ascertain the cumulative damage on such components midway through their life.
Conclusion

In this paper we have briefly reviewed the underlying theory of Prognostic HUMS and discussed the role of the analytical and damage models. We discussed the mechanism of fatigue failure of components on the vehicle and concluded that an SN based technique coupled with Rainflow Cycle counting offers the most appropriate route for most analyses. We introduced the concept of ‘Potential Damage’ to measure the damage potential of the input loads on a vehicle and talked about how this could be calibrated later to represent the real damage on a number of components. We concluded by proposing three types of Structural model suitable for transforming measured acceleration to stress on different types of component.

Paper III in this series describes a typical application onboard a military ground vehicle.
Abstract

\textit{pHUMS}, or ‘Prognostic Health and Usage Monitoring Systems’ improve operational capability by providing instantaneous information on the condition of military ground vehicles. This information is used to prioritise the most reliable vehicles for deployment and to ensure supply chains for any replacement components. Asset management is improved and maintenance costs are lowered. These three papers introduce the application of pHUMS to military ground vehicles. Part I provides an executive level summary of HUMS in general, Part II describes the pHUMS approach in detail, and Part III describes a complete installation suitable for deployment.

Introduction

This paper describes a minimal pHUMS system suitable for deploying for military ground vehicles. Ground vehicles warrant special consideration apart from aerospace and naval vessels on grounds of economics and their differing failure mechanisms.

The effect of operational loads seen on a typical ground vehicle are dominated by high impact shock loads as the vehicles transverse rough terrain or negotiate sharp turns at high speeds. These loads necessitate components that are capable of high strength and stiffness. Materials chosen are usually medium to high strength steels that are quite brittle when compared with those used in aerospace. This combination of increased geometrical stiffness with the brittle nature of the material results in components which are seldom damage tolerant. Therefore, complete failure of critical components often occurs suddenly with no prior warning. This failure mechanism renders the damage tolerant diagnostic HUMS approach quite useless and the prognostic approach is preferable.

In this paper we discuss methods that are appropriately suited to the failure mechanisms observed on ground vehicles with consideration of the economic constraints.

Overview of the Approach

A ground vehicle can be conveniently subdivided into three component groups, these being:

i. Body mounted components (sprung mass)
ii. Drive train components (engine and transmission)
iii. Suspension and chassis components (including the steering components)

Each group of components typically share the same type of input loads and exhibit similar failure modes.

Body Mounted Components

Many body mounted components, such as radios, instrumentation, electronic circuit boards and brackets, etc. fail as a result of vibration loads passing through the body shell. These loads can
arise from high frequency transmission induced vibration or, more frequently, ground induced shocks and resonance.

**Drive Train Components**
Critical drive train loads are typically dominated by engine torque and speed, while factors of maintenance, neglect and operator abuse also play significant roles. Other ancillary engine components also suffer from high frequency vibration and resonance in response to the many engine orders being emitted.

**Suspension and Chassis Components**
Loads on the chassis and suspension components are largely dominated by extreme shocks and the components are usually sufficiently stiff that low frequency ground induced loads rarely excite resonance. Not withstanding the above, unexpected failures are frequently reported during normal road use. These failures generally arise through excessive lateral loads on the suspension components. Components are typically designed for high vertical loading caused by negotiating extreme terrain at low speeds. Requirements for ground clearance, ride comfort and having all wheels in contact with the ground, result in a very compliant suspension in the vertical sense. Most shock loads are effectively damped by the suspension with much smaller forces being transmitted to the chassis and vehicle body. The crew are also fairly intolerant to heavy shocks and consequently drive with measured respect for the terrain conditions.

Lateral compliance of the suspension, however, is very slight. The vehicle needs to be very stiff in this direction to achieve high speed stability and steering precision. Therefore lateral forces are lightly damped and result in high component stresses. Failures often result from high lateral loads like lateral wheel impacts over extreme terrain and high lateral forces due to high speed cornering when driven along the public highway. These lateral forces seldom cause discomfort for the crew and are often overlooked.

**Body Mounted Components**
Most body mounted components fail as a result of vibration induced loading. This can arise from high frequency transmission derived loads but more often through ground induced shock and vibration. Ground vibration typically occurs over a low range of frequencies between about 0 – 20 Hz. while shock and impact loads give a broader range of response. Many body mounted components suffer resonance as a result of these loads and this gives rise to dynamic amplification.

Two types of analytical model are appropriate for body mounted components. For critical components whose transfer function is known, we can employ a filter to transform the measured acceleration into stress at the critical failure location. Alternatively we can compute the Potential Damage Spectrum (PDS) discussed in Part II and illustrated in Figure 24.
The PDS assumes the transfer function is largely dominated by a single vibration mode. Once we can identify the frequency of this mode, we can read the Potential Damage from the PDS plot. The Potential Damage can be calibrated to real damage on the component using the original CAE (Computer Aided Engineering) design models or from test based measurements on the component during prototype testing. An additional benefit of this approach is that it can be applied retrospectively to components on the body that were not originally covered by the model.

**Potential Damage Measurement**

If we assume that the body of a vehicle acts as a solid body we can measure the accelerations of the body and assume that these act on all the components mounted on the body. In practice this assumption is not strictly true because local dynamic modes of the body panels themselves will affect the loads seen by the individual components, however these are accounted for implicitly in the calibration of the Potential Damage model 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 25. 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.

In theory we can measure the accelerations in all 6 degrees of freedom using 6 accelerometers located as per Figure 26 along with a coordinate transformation matrix to bring these relative to the centre of gravity.

![Figure 26 Ideal configurations for accelerometers to determine the rigid body motions of a ground vehicle](image)

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 Potential Damage. This is because the Potential Damage Spectrum lacks phase information. For road 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 quarter as illustrated in Figure 27. While these are sufficient for assessing the damage from road induced acceleration, additional accelerometers may be required to adequately account for other loads incurred from weapon firing, etc.

![Figure 27 Preferred configuration of accelerometers](image)
The effect of mechanical shock

To this point we have considered failure through an accumulation of fairly low amplitude fatigue cycles. However failure could also arise due to a severe mechanical shock passing through the body. It is beneficial to address these discrete shocks separate from the above fatigue loads. An analogous analysis to the PDS can be undertaken called the Shock Response Spectrum (SRS). This considers the high acceleration event and again filters it to consider its effect on components with a range of natural frequencies. In this analysis we are only interested in the maximum and minimum acceleration results. These can be calibrated with components to determine whether the stresses exceed the Ultimate Tensile Strength (UTS) of the component. The HUMS system can then warn the vehicle crew that they should test the equipment before relying on its effective operation. These analyses need only be performed after extreme events are detected.

Drive Train Components

These are potentially the most complicated chain of components to analyse and design. The mechanical behaviour is very complex with a broad range of excited frequencies arising from engine orders, gear meshing frequencies, etc. All components are susceptible to wear and this can lead to eventual failures.

The load from many critical components is directly related to the torque from the engine, while the number of cycles is related to the engine speed. A measure of Potential Damage is therefore available based on these parameters. Of course, the speed of various shafts and gears and hence the number of cycles is also proportional to the gear selected so the Potential Damage model should also account for this. The most popular damage model is therefore obtained from the statistical joint probability distribution of torque versus gear versus number of engine revolutions. This plot is derived using measurements of engine torque and speed along with the axle speed. All these measurements are available on the vehicle bus.

Calibration of this damage model is notoriously complicated using CAE based analysis. It is therefore desired to use prototype testing as a means of calibrating failures of critical components. These tests are usually performed using dynamometer test rigs. Further statistical calibration can be obtained using records of in-service failures.

Many transmission failures are quite progressive with warning signs detectable prior to failure. Excessive bearing and gearbox wear can be detected from the amount of debris collected in the oil, furthermore acoustic emission devices can diagnose high frequency ‘hum’ emanating from a worn bearing or the gearbox. These diagnostic techniques can be applied to a sample of operational vehicles to help diagnose early signs of failure and provide statistical calibration data for prognostic analysis.

The broad range of engine vibrations can also induce failure in ancillary components through resonant vibration. The Potential Damage model used here is identical to that discussed for body mounted components. As engine vibrations tend to be Gaussian, a rapid frequency domain approach is most suitable for this calculation.

Other contributing factors to drive train wear and failure include cold starting and operator abuse. Information such as the number of cold starts, excessive coolant temperature and engine over speed are useful parameters to log.

Suspension and Chassis Components

These components are designed for extreme loading and are consequently very stiff and strong. Low frequency ground loads rarely cause resonance and therefore components are assumed to respond quasi-statically to input loading. Not withstanding the above, the stress state in many components is highly multiaxial and this adds a degree of complexity to the fatigue damage analysis.

In practice the suspension of most ground vehicles is designed to be compliant in the vertical direction; this effectively dampens shock loading and therefore improves ride comfort. Conversely, the design ensures high stiffness in the lateral direction which improves high speed
stability and handling. This high stiffness, however, leads to significant transmission of shock loads through the chassis and steering components. The Potential Damage model therefore Rainflow Cycle counts the lateral loading cycles.

Calibration of the damage model can be accomplished using CAE design models, instrumented prototype vehicles with strain gauges located at the critical regions and with further statistical refinement based on in-service experience.

**Conclusion**

In this paper we have discussed a basic pHUMS implementation for military ground vehicles. Methods are proposed for body mounted components, transmission components, and chassis and suspension components. The techniques account for ground and transmission induced loads so additional provisions should be considered to account for the effect of weapon firing, etc.