

Inferential Sensing Techniques to Enable Condition Based Maintenance

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ABSTRACT

Inferential sensing, as it relates to the equipment operator, can be viewed as human intuition [1]. The person operating the equipment can sense there is something wrong while their intuition tells them when and what needs troubleshooting and repair. Attempts have been made to implement this human intuition model to monitor a vehicle operation and detect abnormalities. In many approaches traditional sensors are added to the vehicle which increases cost, complexity, and another failure point. After years of developments and techniques, there are few highly reliable on-board systems that can duplicate the human intuition model since the specific failure cannot be directly measured but must be inferred from a variety of symptoms. This paper describes an engineering approach using Physics of Failure (PoF) for specific subsystems, developing the applicable fatigue models, and then collecting, monitoring, and manipulating the real-time on-vehicle data to complement the "operator intuition".

Conditioned Based Maintenance (CBM) delivers value through cost avoidance of unexpected down time and reduction in life cycle maintenance costs by scheduling repairs on the correct equipment subsystems at the correct times. CBM Solutions can also provide Condition Monitoring, Maintenance Scheduling, Service & Warranty Cost Reduction and Design Life Optimization. These values are delivered by improving

the understanding of the severity of usage for equipment operations. The basic elements to achieve the aforementioned benefits will be reviewed in the context of process steps so the reader's perspective is aligned with the sequence of development activity needed to deliver value through this PoF and fatigue modeling approach.

An on-board electronics hardware and software architecture that can deliver CBM Solutions by using inferential sensing methodologies in a low cost platform is outlined. Through real-time statistical data techniques several months of data can be collected for several subsystems on a platform that is no more complex than a typical Electronic Control Unit.

INTRODUCTION

Condition Based Maintenance, Machine Health, and Prognostics are related terms which have extensive history of development with the overall goal to monitor equipment operation, manage machine maintenance, reduce service, warranty and operating costs, and optimize design life. The term CBM Solution refers to the overall fatigue modeling process and the on-vehicle system used to deliver CBM as well as other values that are further described in this paper.

THE OPERATOR'S CHANGING ROLE

David is out on the back 50 hectares cutting the last field of his hay crop with a Haybine pulled by a tractor. This older open station tractor gives him wide visibility and closeness to the implement behind him. It is a noisy environment with the tractor at full throttle and the Haybine cutting 20 cm tall crop. But he starts to hear an additional sound. He focuses on this sound as he continues to finish the field. Now he also notices an ever so slight additional vibration on the PTO shaft connecting the Haybine to the tractor. As he thinks of the causes for this problem he deduces there is a bearing going bad. Now he starts to consider his options. 'Can he finish the field before the bearing completely fails?', 'If the bearing fails how much other damage might occur?' 'Which bearing is it?' He can't isolate the main source of the noise, but it is coming from the far back of the machine. He finally infers it is probably one of the roller bearings. He also infers the reward of being able to complete the field is worth the risk of the bearing failing. As he has assessed the growing failure and his rate of progress he feels the bearing will last to the end of the field. In this case David's inferential sensing was right and he was able to repair the bearing later in the convenience of his own shop.

The operator's role in off-road equipment has a dual responsibility--safely operate the machine and diagnose problems. In the role of diagnosing problems the operator provides the primary system for monitoring health and condition of a machine. In the past, the operator was closely connected to the machine and had a fundamental understanding of the components to be able to infer the machine's health and condition. Their 'open station' position on the machine gave them an intimate connection to all the machine's noise, smells, vibrations, sights, and sounds. However, as machine design has evolved, the operator is being isolated in comfort controlled cabs and active isolation seats. New systems are needed to replace the operator's monitoring and intuition skills to fill the void for determining the health and condition of the machine.

Today's machines include nearly 100 sensors for onboard electronic controls. Few of them are used primarily for diagnostics. Diagnostic sensors typically require higher accuracy and faster response time than sensors used for control. There are very few ways to directly sense the onset of problems or the conditions leading up to problems. Due to the added "diagnostic only" cost and the limited capability to sense the onset of problems, these electronic diagnostics offerings are seldom offered on standard equipment. The conditions, and potential problems, are best inferred from other direct measurements and data processing methods to

avoid the added cost and complexity of dedicated diagnostic sensors. This is the premise of inferential sensing.

This paper describes the engineering approach using Physics of Failure (PoF) [2] for specific subsystems, collecting, monitoring, and manipulating the real-time on-vehicle data to estimate the same "operator sense" of; "Is there something wrong?"; "What might be wrong?"; "When should it be repaired?". The difference with this approach is that it is based on PoF, fatigue modeling, design life, usage severity, deterioration rates and data collection instead of trying to duplicate the human intuition model.

CBM SOLUTION

This paper focuses on 4 key aspects of the CBM Solution which include: 1) Condition Monitoring, 2) Maintenance Scheduling, 3) Service & Warranty Cost Reduction and 4) Design Life Optimization. Each of these CBM elements is further described below:

Figure 1 represents the trends from when the operator performed the condition monitoring function for the machine to the new technology where the machine becomes automated and the human intuition is replaced with the CBM model for complex machines as described by Faulk [1] in "The Human Side of Quality". An important aspect of condition monitoring is the time frame and action required which is greatly enhanced with automated on-vehicle CBM systems.

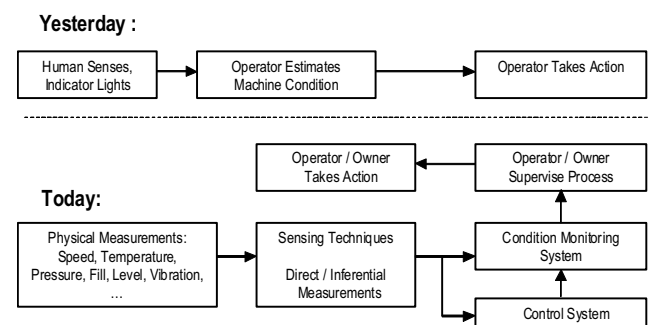


Figure 1 Condition Monitoring Yesterday and Today

The traditional approach for maintenance scheduling used in personal and commercial vehicles is for the OEM (Original Equipment Manufacturer) to determine the maintenance intervals for each subsystem based on a general use profile that itself has varied approaches. Industries such as Aerospace and Rail have advanced the use of monitoring systems and prediction models that predict potential failures and notify equipment maintenance personnel that scheduled maintenance should be performed. These systems have been a key element in delivering the phenomenal safety performance for the aviation industry and have delivered improved up-time for high levels of customer satisfaction and improved productivity. Aerospace and

Rail equipment are relatively small fleets that carry high asset values which have absorbed the cost of the on-board electronics as well as the development and infrastructure costs needed to deliver to this high standard.

A CBM solution reduces Service & Warranty costs by reducing unscheduled maintenance, setting maintenance schedules according to severity of usage, and provides a flexible on vehicle data acquisition and analysis system that minimizes warranty costs by providing a quick response system. The CBM Solution launches a new methodology in investigating and analyzing root cause analysis using real time data of fielded machines. This is a new tool set for service, reliability, and product engineering personnel to quickly respond to potential field issues to minimize costs of handling warranty issues before they can spread further within the fielded population of machines. The fourth key value delivered with CBM systems is design life optimization.

These key benefits are delivered using a combination of on-vehicle analysis and a "back office" that consolidates downloaded information from multiple vehicles. The on-vehicle data that is collected and processed within the CBM Solution and then off loaded to the "back office" provides a wealth of information. This data provides summary information about aspects such as engine usage, component or system deterioration rates comparing between individual vehicles, different vehicle configurations, different operating locations, etc. Comparisons can be made between vehicles and compared to known design specifications, laboratory simulation tests or proving ground tests in terms of deterioration rates to determine if the fielded design life is near the design life goals.

With the continuous improvement in capability and cost of vehicle electronics, the CBM value proposition is crossing the tipping point of cost and ease of delivery for higher valued Commercial Vehicles. Figure 2 illustrates the CBM Systems Elements needed to deliver a solution.

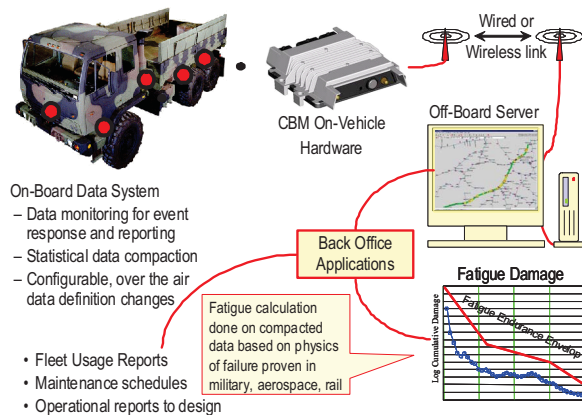


Figure 2 CBM System Elements

THE FATIGUE ANALYSIS MODEL

Using fatigue models of components and systems, the systems engineer can identify the key load inputs to the transfer functions which determine severity of usage. These inputs can then be related to specific individual or combined vehicle data and sensor measurements to support algorithms ("damage correlates") incorporated either in the on-vehicle processing units or in the "back office".

A key decision is to identify where data analysis takes place: on board the vehicle or in the "back office". The former helps reduce the amount of information that needs to be transferred from the vehicle with the associated cost benefits. Various analysis methods can be incorporated that range from potential Fatigue Damage Spectra (FDS) that identify "damage" caused at different input frequency ranges to "rainflow histograms" illustrating drive train torque cycles in particular gears during service operation. This information can be calibrated using similar analyses of measured data originating from specified proving ground tests, laboratory simulation tests or actual in-service failures.

The "back office" combines multiple vehicle information to deliver reports to the "stakeholders" that summarize usage in terms of engineering information - comparing locations, fleets, drivers, potential remaining life, etc. Traditional telematics provides discrete data about basic vehicle characteristics such as location, fuel consumption, speed, etc. to define current vehicle status and diagnostic information. Limitations of telematics may include bandwidth, cost of data transfer, interpretation of the data in terms of prognostics and on-board analysis capability to understand engineering performance information linked to operational characteristics (e.g. impact of driver actions on engineering integrity).

This system is used by service personnel to improve maintenance effectiveness, warranty specialists to monitor field performance, systems engineers for usage data, and reliability engineers to validate models.

OVERVIEW OF PROCESS STEPS

Each of the process steps needed to deliver a high value CBM Solution is outlined below. This paper is intended to convey how specific data needed for a component or system fatigue model that may not be available within a vehicle network can be derived from existing vehicle data. This section provides background so the reader gains a broader perspective on how derived data makes these solutions feasible using today's technology.

STEP # 1 – CHARACTERIZE THE POTENTIAL FAILURE AND THE OPERATING ENVIRONMENT, DEFINE THE POTENTIAL FAILURE MECHANISM -

Characterizing the potential failure mechanism is the starting point. Before we can monitor the conditions for basing our maintenance decisions, we need to target the vehicle subsystems that will deliver the highest value for the implementation of CBM Solutions. Vehicle systems engineers may begin by looking at critical scheduled maintenance items such as periodic changing of lubricants. Another approach of the systems engineer is to look at the top contributors to warranty costs or problem areas that drive unscheduled maintenance.

A comprehensive understanding of the operating environment of the equipment is an integral part of CBM. On-vehicle CBM systems provide data collection which accumulates to provide actual operating environment specifics. This accumulated operating condition data is not only used to adjust maintenance schedules but is fed back to specifications and standards so equipment designs can more closely match actual use and warranty cost can be reduced.

The vehicle is conveniently divided into 3 sub-systems which are defined and further described below:

- Body Mounted Components (sprung mass)
- Drive Train Components (engine and transmission)
- Suspension and Chassis Components (including steering components)

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 drive train 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 can 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. Notwithstanding the above, unexpected failures are frequently reported during normal road use. These failures can arise through excessive lateral loads on the suspension components, frame twist, etc.

STEP # 2 – DEFINE THE FATIGUE MODEL DATA REQUIREMENTS - Body Mounted Components - Ground vibrations typically occur 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. One approach is to compute the potential Fatigue Damage Spectrum (FDS) that transforms the measured data into stress at a particular location assuming this is largely dominated by a single vibration mode [3,4] as illustrated in Figure 3. Once we can identify the frequency of this mode, we can read the Potential Damage from the FDS 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.

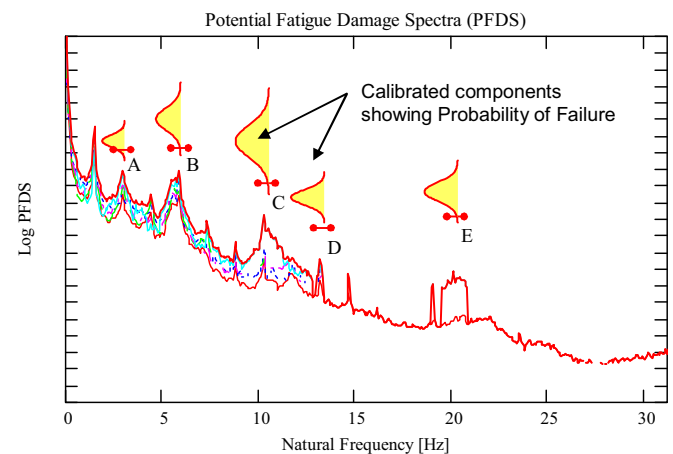


Figure 3 Fatigue Damage Spectrum

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. Any rigid body possesses 6 degrees of freedom about 3 axes in 3 dimensional space. 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. We can measure the accelerations in all 6 degrees of freedom along with a coordinate transformation matrix to bring these relative to the centre of gravity.

Coordinate transformations like these 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. While these are sufficient for assessing the damage from road induced acceleration, additional data may be required to adequately account for other vibrations and loads incurred.