Equipment Health Monitoring in Complex Systems

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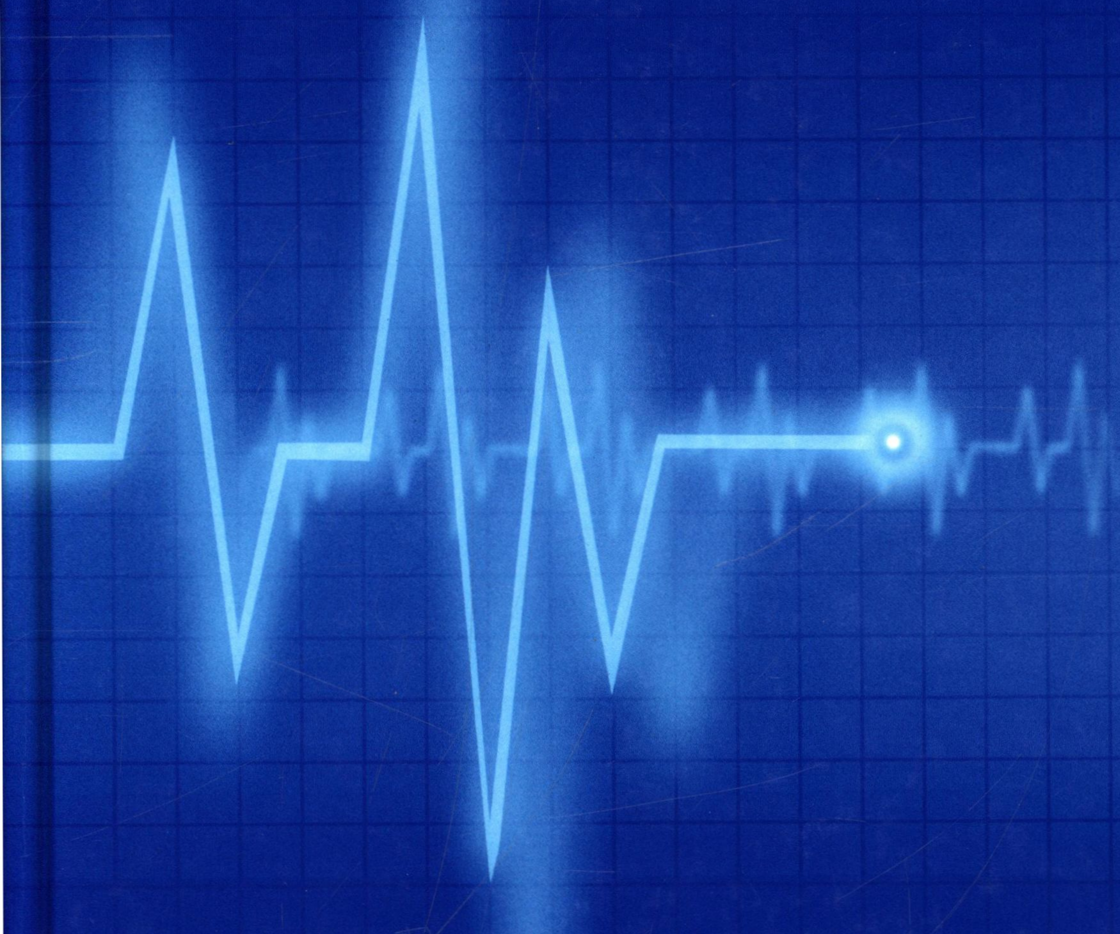

This timely resource provides a practical introduction to equipment health monitoring (EHM) to ensure the cost-effective operation and control of critical systems in defense, industrial, and healthcare applications. This book highlights how to frame health monitoring design applications within a system engineering process to ensure an optimized EHM functional architecture and practical algorithm design.

This book clarifies the need for intelligent diagnostics and proposed health monitoring frameworks. Machine learning for health monitoring, including feature extraction, data visualization, model boundaries, and performance is presented. Details about monitoring aircraft engines and model-based monitoring systems are described in detail. Packed with two full chapters of case studies within industrial and healthcare settings, this book identifies key problems and provides insightful techniques for solving them. This resource provides a look into the future direction of health monitoring and emerging developments within sensing technology, big data analytics, and advanced computing capabilities.

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Introduction

1.1 Maintenance Strategies

The complexity of modern high-value assets, such as aircraft and their major subsystem components, is increasing at a rapid pace. This is occurring against a backdrop of ever-increasing demands on reliability, availability, and performance of the asset in achieving its primary function throughout its service life. By their very nature, such complex systems usually involve large capital investment, and therefore there is an expectation that a profitable financial return can be realized with minimal service disruption and avoidance of expensive outages to the operator. This notion is clearly not unique to high-valued complex systems; indeed any business that is dependent on mechanical equipment as part of its service delivery will always want to see a return on investment with minimum disruption to their service operation. The usual mechanism to deliver a reliable operation is to implement some form of maintenance policy. This will vary depending on the asset type and its application, but typically comes down one of the strategies identified below:

1. Don't bother— exploit any available redundancy and just replace the asset when it becomes defective.
2. Wait until the asset becomes defective then maintain it by performing restoration and/or repair as appropriate.
3. Maintain it at regular intervals even when the asset is still functional (preventative maintenance).

4. Maintain the asset when the need arises (condition based maintenance).
5. Operate a combination of 3 and 4.

There are various factors to consider in deciding which of the above policies are appropriate for the asset owner. This decision is likely to involve a trade-off between asset value (for example, the cost of replacement) and the cost associated with performing maintenance. In the latter case, issues such as impact of outage (i.e., loss of revenue during the outage and its duration), cost of refurbishment, cost associated with inventory (e.g., spare parts and any specialist equipment) will be major items of consideration. Of course from a design perspective, investment costs associated with built-in redundancy may also be considered. Naturally, the operator will consider these factors as a means to mitigate financial and/or safety risks of their service operation, and in certain cases, may choose another party to take on those services as a means to reduce their own financial burden. Indeed, many original equipment manufacturers (OEMs) include such after-sales care as part of their service offering to the point where the asset is considered incidental and becomes a consequence of the functional commodity. For example, the use of a gas compressor in a remote installation for the purpose of pumping gas over a long-distance pipe-line may be sold in the context of guaranteeing volume of gas transferred per hour/day as opposed to the sale of the mechanical compressor.

The circumstances of electing not to perform any maintenance are most likely to occur when the asset value is extremely low (hence affordable to replace) and has minimum disruptive effects on expected operation. In a domestic setting, the author has often been asked when purchasing a kettle (which probably only takes place at a frequency of every 6-7 years) if additional insurance coverage is required in case the kettle fails. Experience indicates this is typically 10% of the purchase price. A quick analysis may lead to the conclusion that such offers are actually financially unattractive. This is based on the product having a 12 month guarantee (will be replaced anyway during that period); a very low risk of failure; being relatively easy to replace after the warranty period, and therefore having an extremely low disruptive impact on its prime functional purpose. It most likely can be replaced at a similar price and is hence affordable.

Electing to perform maintenance that involves repair and/or restoration only when the asset becomes defective can be, in certain applications, very expensive particularly in cases where secondary damage follows the initial failure. One reason for selecting this option, however, may be influenced by the loss of revenue in a continuous operating environment, versus any potential outage cost, such as parts replacement, weighed against an expected low risk of failure. Again using a domestic example, it is unlikely that most people will implement a routine preventative maintenance policy for an electric oven. Should the heating element fail, then obtaining a replacement is relatively easy and quick to obtain. It is also easy to replace using basic tools. This does of course assume that the root cause of failure can be diagnosed by the owner. Even so, if the owner does not have access to the skills or capability, then it is relatively straight forward and relatively low cost to organize the services of a tradesman who can carry out the work on their behalf; hence contracting out the maintenance activity.

Adopting a policy based on routine preventative maintenance is often selected when the asset has high intrinsic value and/or high functional value to the operator such that disruption to normal operation would be unwelcome and potentially costly to remedy. In the case of high-integrity assets, it's likely that certain components will be assigned a hard-life for safety reasons, meaning that such components would be expected to be replaced before they have reached a predetermined age to avoid the risk of hazardous failure. This approach therefore follows a conservative policy and is based on domain knowledge of component/subsystem wear mechanisms. Preventive maintenance activities generally include partial or complete overhauls of the asset at specified time intervals involving different work-scopes depending on service life achieved and future service life ambitions and may entail activities such as oil changes, lubrication, minor adjustments, and replacement of parts, and so on. The ideal preventive maintenance program would preserve equipment function and prevent all equipment failure before it occurs. The main disadvantage with this approach is that following a prescribed maintenance task, based on a subsystems service age, is likely to lead to the replacement of parts that may still have an acceptable service life if additional analysis of component condition does not take place. Unfortunately, this isn't always straight forward as accurate assessment of a component's condition may require use of expensive specialized equipment to fully assess remaining useful life. Such a policy also has the obvious disadvantage of needing to take the asset out of service for the duration of maintenance. Although such events can be planned in advance to minimize the disruptive effect, it does have an inevitable impact on availability and the likely consequence of carrying additional spare inventory. Even in cases where a minimum stock order system is in place, there is likely to be an increase in through-life costs resulting from higher demand of spares. Although there is no requirement to actually perform any form of monitoring to comply with this approach, it is necessary for the maintainer to track life usage.

Condition-based maintenance (CBM) can be regarded as performing maintenance when the need arises. Usually, need is determined when one or more indicators show signs of deterioration or emerging signs of failure. CBM aims to utilize monitored data to assist and direct the optimum use of resource and parts to maintain the system at a level of health that delivers the required functionality. This means that assuming an accurate assessment of health condition can be derived at a system level; action only takes place when maintenance is necessary. To be fully effective, CBM should also support the appropriate level of analysis of health condition so that work-scope activity is optimized ensuring maintenance personnel only perform activities that are essential to preserve function. The obvious benefit of this approach is that CBM minimizes the demand for spare parts, reduces down-time, and increases availability to the operator. There are of course significant challenges with this approach, particularly when implementing CBM on existing installations for the first time. Heavy use of instrumentation will be required and therefore additional sensing capability may need to be installed. Introducing CBM into an existing organization will also have an impact on how maintenance is performed and therefore how personnel perceive its effectiveness against an established traditional approach. Such cultural changes in work practices are not trivial and a successful CBM policy will only be realized if all members of the maintenance organization are fully engaged and buy-in to the strategy. There are also significant technical challenges with this approach since investment will be required to translate simple measured values (such as vibration and pressure temperature.) into actionable information related to the current health state of the system which may be nontrivial. Use of CBM therefore tends to be in application areas where increased reliability and safety are required; an example of which is the U.S. Army who have developed a robust approach to CBM through the introduction of guidance and reference standards [1] that apply to systems, subsystems, and components of U.S. Army aircraft.

For high-integrity assets, particularly in applications where operational safety is paramount (as in the case of the aviation industry), there is clearly a need to track the age and condition of life-limited parts. As mentioned before, life-limited parts are cleared for safe operations with a predetermined age limitation. This is established using conservative operational assumptions as it is not always known how the equipment will actually be used. When the actual asset utilization is known, there is opportunity to review and adjust the life limitation and still achieve the design intent. For example, the life limit for some components of an aero gas turbine engine may be influenced by the maximum shaft speed of the low-pressure shaft during take-off. Engines operating on aircraft which tend to use relatively lower thrust at take-off (and hence lower shaft speed) will consume less life than those operating at higher take-off thrust levels for the same engine type. Such a difference can be significant enough to alter the interval between shop visits and hence aircraft availability.

CBM can also reduce the conservatism inherent in a purely preventative maintenance policy by mitigating the risk of disruption from unexpected equipment wear out and failures. Clearly disruption to service still needs to be minimized and hence for noncritical components (where safety of operation is not hazarded by their failure) the option to include a more condition-based