Journal of HyoJeong Academia

Article

Prognostic inspection for proactive maintenance

Junhyong Kim[1], Inho Cho[1], Youngsik Pyun[1] and Auezhan Amanov[2,*]

[1]DesignMecha Co., Ltd, Asan 31460, Korea
[2]Faculty of Engineering and Natural Sciences, Tampere University, Tampere, Finland
*Correspondence: auezhan.amanov@tuni.fi

Abstract: Preventive medicine aims to promote health by investigating and researching the distribution of health and health-related risk factors. The desired life time of the small modular reactor (SMR) being developed as a new energy source is more than 100 years. Improving the problems of key components such as stress corrosion cracking (SCC) and corrosion fatigue of the SMR structures and erosion and fretting fatigue of turbine blades improves the service life of the SMR. Also, in bearings, it improves wear and rolling/sliding contact fatigue. It is necessary to develop a proactive maintenance program prior to design to ensure that the SMR and bearing systems can be shut down after operation within their designed lifespan. Similar to preventive medicine, proactive maintenance programs applied to the SMR and bearing systems must undergo advance inspection. This ensures that the characteristics of key components do not deteriorate or exceed predetermined standards. Additionally, it is necessary to develop and standardize technology that restores the characteristics of key components to their designed performance state. In this paper, we introduce the concept of prognostic inspection and proactive maintenance (PIPM) system with ultrasonic nanocrystal surface modification (UNSM) and suggest a method of applying PIPM to SMR and bearing systems.

Keywords: Prognostics and Health Management (PHM), Prognostic Inspection and Proactive Maintenance (PIPM), Ultrasonic Nanocrystal Surface Modification (UNSM), Small Modular Reactor (SMR), Bearing

Citation: Junhyong Kim, Inho Cho, Youngsik Pyun and Auezhan Amanov. Prognostic inspection for proactive maintenance. *JHJA* 2(2), **2024**.

Received: 4 June 2024
Accepted: 18 September 2024
Published: 22 September 2024

Publisher's Note: JHJA stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

Devices and systems used in various industrial fields are damaged for various reasons even when they are optimally designed. Preventive maintenance is the process of periodically replacing parts to prevent this. However, it requires high costs every year and is not excellent at preventing accidents. Recently, as the use of big data and machine learning has increased, Prognostics and Health Management (PHM), a technology for diagnosing and prognosis fault, is being researched and applied [1-4]. In the medical field, biomarkers have been used for a long time to personalize medicine or health management and analyze the safety of medicines. These biomarkers are produced either by organs affected by the disease or by the body in response to various diseases. They are utilized to monitor the progression of a disease [5, 6]. The population health management requires advanced information technology systems and tools that can collect, store, process, and analyze large amounts of health data, and biomarkers are an important element of the population health management [7]. PHM in the industrial field also identifies and monitors factors that affect the progression of damage, such as biomarkers. After analyzing the values of these factors for the current state using big data-based data, it is decided whether or not to carry out maintenance. The application of big data-based PHM is increasing in bearings, gears, and shafts in the mechanical field, based on a wide range of failure cases [8]. If the Stress Corrosion Cracking (SCC) and corrosion-fatigue problems of the Small Modular Reactor (SMR), which is being developed as a new energy source, are improved through the PHM, the service life of the SMR will increase. SCC and fatigue problems are improved by increasing compressive residual stress rather than reducing surface roughness, and this can be achieved through surface stress improvement technology [9, 10]. In this paper, we introduce the concept of Prognostic Inspection and Proactive Maintenance (PIPM) system with Ultrasonic Nanocrystal Surface Modification (UNSM) and suggest a method of applying PIPM to SMR and bearing systems.

2. Prognostic Inspection and Proactive Maintenance (PIPM) Systems

2.1. Different types of maintenance

Reactive Maintenance (RM) only repairs or replaces machine parts when an error occurs and they can no longer function. The advantage of this method is that the cost associated with maintenance personnel and maintaining machine operation is low. However, since the machine or parts are used until they break down, the probability of serious failure increases, and the repair cost also increases [11]. Scheduled Maintenance (SM) is a maintenance method performed at regular time intervals. The goal is to perform maintenance activities even while the machine is operating under normal conditions to minimize the possibility of failure and prevent costly unplanned downtime. On the other hand, the SM method requires performing some costly maintenance interventions even when the equipment is still functioning properly [4]. Condition Based Maintenance (CBM) and PHM both focus on maintaining system reliability and reducing system downtime. CBM is a maintenance strategy that uses sensors and data analytics to monitor the real-time performance of assets or equipment. CBM uses real-time data to determine maintenance requirements and perform maintenance, making it a more efficient maintenance method than RM and SM [12]. PHM, on the other hand, is a technology that enables CBM and has the ability to predict the Remaining Useful Life (RUL) of a system while it is in operation. PHM is a new maintenance approach that only handles repairs or replacements for actual damage to components [13]. The most common applications of PHM in the mechanical field are bearings, gears, and shafts. As shown in Table 1, PHM is implemented through algorithm analysis by collecting failure modes, characteristics, and common features [8, 14].

Table 1. Summary of PHM of mechanical components

Component	Failure mode	Characteristic	Common feature	Common algorithms used
Bearing	Outer-race, inner-race, roller, cage failures	Raw data does not contain insightful information; low amplitude; high noise	Vibration characteristic frequency, time domain statistical characteristics, metallic debris shape, size, quantity, sharp pulses and rate of development of stress-waves propagation	Fourier Transform (FT), Short Time Frequency Transform (STFT), Wavelet Transform (WT), etc.
Gear	Manufacturing error, tooth missing, tooth pitting/spall, gear crack, gear fatigue/wear	High noise; high dynamic; signal modulated with other factors (bearing, shaft, transmission path effect); gear specs need to be known	Time domain statistical features, vibration signature frequencies, oil debris quantity and chemical analysis	Fourier Transform (FT), Short Time Frequency Transform (STFT), Wavelet Transform (WT), etc.
Shaft	Unbalance, bend, crack, misalignment, rub	Vibration signal is relatively clean and harmonic frequency components of rotating speed can indicate the defects	Vibration characteristic frequency, time domain statistical characteristics, system modal characteristics	Fourier Transform (FT), Wavelet Transform (WT), etc.

2.2. PIPM systems

The Prognostic Inspection and Proactive Maintenance (PIPM) system is an integration of the prognostic inspection methodology and the proactive maintenance methodology. The proactive maintenance methodology entails the maintenance aspects which should be incorporated at the design stage of a physical asset, whereby all anticipated probable prospective failures are identified and removed, based on the focused historical performance of the asset, with the purpose to prescribe suitable maintenance actions at the right intervals and component parts [15]. So the PIPM system should be developed also from the design phase, especially for the regulator's safety evaluation in Design Certification Application (DCA) [16].

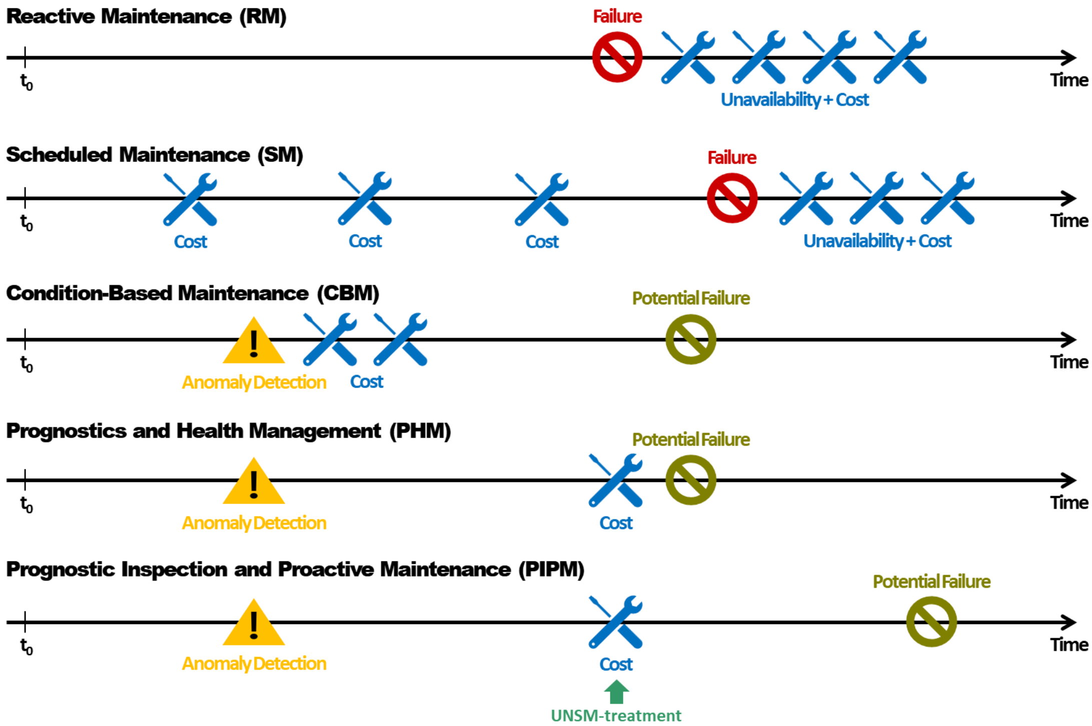

Figure 1. Scheme of the behavior of the different type maintenance approaches [4].

The concept of prognostic inspection is similar to that of CBM, which is an advanced form of preventive maintenance [1, 2]. However, an important difference lies in the measurement focus. Instead of measuring crack growth conditions, the PIPM system focuses on crack initiation conditions. To implement this, a method for measuring the condition of components at the onset of failure mode, for example, the condition of crack initiation, needs to be developed. In CBM and PHM, crack growth conditions are already measured using analysis algorithms through changes in vibration, noise, etc. Measuring crack initiation conditions is difficult, but if possible, the potential failure interval can be significantly increased. The purpose of the PIPM system is to determine crack initiation conditions and delay crack initiation with a proactive maintenance method using UNSM technology, thereby increasing the potential failure interval and service life of the product. Consideration should be given to new sensor technologies integrated with Artificial Intelligence (AI), which could be available in the future, for the development of prognostic inspection methodology. Furthermore, the remaining service life until the beginning of crack initiation should be estimated based on the results of these measurements by the analyzing function.

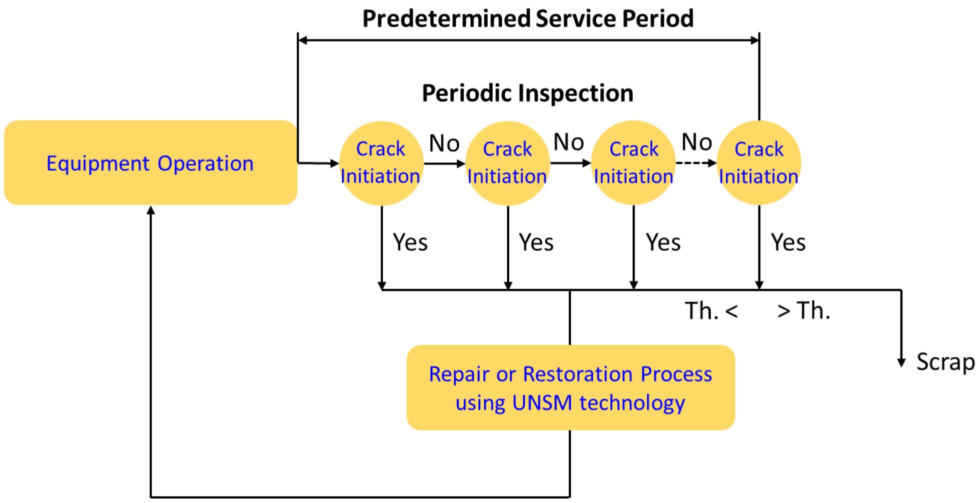

Figure 2. Flow of the PIPM system.

Proactive Maintenance involves a variety of approaches and technologies aimed at significantly reducing reactive maintenance in practice. The defining characteristic of proactive maintenance is the exploration of failure origins. Repair or restoration processes delay potential failures by eliminating the cause of the failure. The technology to be used in this process is UNSM technology that can improve surface stress. The UNSM is a surface modification/treatment technology that causes surface severe plastic deformation at the surface region to generate a gradient nanostructured surface layer along with a modified surface [17]. This technology has already been proven to improve the service life of industrial parts such as knives and bearings, and with the approval of ASME Code & Case N931, it is highly likely to be applied to nuclear power plant components. Proactive maintenance is highlighted as an innovative strategic maintenance approach that aims to significantly improve the reliability and availability of components throughout their service life [18]. A proactive maintenance methodology should be developed that can be applied to components during refueling outages and could restore the fatigue strength of components to the condition of new components. Consideration should also be given to new and advanced technologies that could be available in the future as potential candidates for the proactive maintenance methodology.

Table 2. Typical examples of the PIPM system

Prognostic Inspection and Proactive Maintenance (PIPM) system		
Component	**Prognostic Inspection Methodology**	**Proactive Maintenance Methodology**
Bearing	· Sensing and Monitoring of Vibration, oil debris, Acoustic emission, Energy, Temperature, etc.: usually continuous monitoring [14] · Measuring and Monitoring of Surface roughness, Micro-cracks, Hardness, Residual stress, Grain size, etc.: usually inspecting during the refueling outage [19] · Analyzing the remaining service life till the beginning of crack initiation based on the measuring results · Deciding whether sustaining till next or next nth refueling outage or applying the proactive maintenance	· Exchanging with the new bearings or the remanufactured bearings whose service life is equivalent to new bearing during the refueling outage [22] · Restoring the bearings using UNSM (Ultrasonic Nanocrystal Surface Modification) technology during the refueling outage
SMR Component	· Visual inspection of discontinuities and imperfections on the CISCC (Chloride Induced Stress Corrosion Cracking) susceptible surfaces; usually measuring during the in-service inspection period [20] · Measuring and Monitoring of Surface roughness, Residual stress, etc.: usually measuring during the in-service inspection period [21] · Analyzing the remaining service life till the beginning of crack initiation based on the measuring results · Deciding whether sustaining till next or next nth in-service periods or applying the proactive maintenance	· Restoring the necessary surface condition by cold splay technology or advanced surface stress improvement technology such as UNSM, Laser Peening, etc. in ASME Code & Case N931 [23]

3. Conclusions

The PIPM system is a concept that integrates prognostic inspection methodology and proactive maintenance methodology. The key point of the PIPM system is to determine crack initiation conditions and combine repair or restoration processes to improve the service life of the product. This is a model pursued in the circular economy system and an eco-friendly system model to be used in the fields of steel, nuclear power plant and transportation. However, the development of prognostic inspection technology that determines crack initiation conditions must be modeled through the development will and necessity of the main organization. In addition, the PIPM system should be advanced by securing reliable verification of fatigue and life restoration of UNSM technology, the most representative surface stress improvement technology. It is expected that the advanced PIPM system will be applied as a technology required for SMR and bearing system preventive maintenance in the future.

References

1. Vogl, G. W., Weiss, B. A. and Donmez, M. A. Standards Related to Prognostics and Health Management (PHM) for Manufacturing. In *NIST Interagency/Internal Report – 8012* (NIST, 2014).
2. Soualhi, A., Lamraoui, M., Elyousfi, B. and Razik, H. PHM SURVEY: Implementation of Prognostic Methods for Monitoring Industrial Systems. *Energies 15*, 6909 (2022).
3. Hofmeister, J. P. *Prognostic Health Monitoring Overview & Theory of Operation* (Ridgetop Group, 2019).
4. Biggio, L. and Kastanis, I. Prognostics and Health Management of Industrial Assets: Current Progress and Road Ahead. *Front. Artif. Intell. 3*, 578613 (2020).
5. Bodaghi, A., Fattahi, N. and Ramazani, A. Biomarkers: Promising and valuable tools towards diagnosis, prognosis and treatment of Covid-19 and other diseases. *Heliyon 9*(2), e13323 (2023).
6. Sandø, A. et al. Introduction of a prognostic biomarker to strengthen risk stratification of acutely admitted patients: rationale and design of the TRIAGE III cluster randomized interventional trial. *Scand J Trauma Resusc Emerg Med 24*, 100 (2016).
7. *Global Population Health Management Market 2023-2030* (DataM Intelligence, 2023).
8. Kumar, P., Raouf, I. and Kim, H. S. Review on prognostics and health management in smart factory: From conventional to deep learning perspectives. *Engineering Applications of Artificial Intelligence 126*, 107126 (2023).
9. Zhang, H. et al. The effects of ultrasonic nanocrystal surface modification on the fatigue performance of 3D-printed Ti64. *International Journal of Fatigue 103*, 136-146 (2017).
10. Zhang, R. et al. Fatigue performance rejuvenation of corroded 7075-T651 aluminum alloy through ultrasonic nanocrystal surface modification. *International Journal of Fatigue 153*, 106463 (2021).
11. Swanson, L. Linking maintenance strategies to performance. *Int. J. Prod. Econ. 70*, 237-244 (2001).
12. Kim, S., Choi, J.-H. and Kim, N.H. Challenges and Opportunities of System-Level Prognostics. *Sensors 21*, 7655 (2021).
13. Wesendrup, K. and Hellingrath, B. A Process-based Review of Post-Prognostics Decision-Making. *PHM Society European Conference 5*(1), 12 (2020).
14. Lee, J. et al. Prognostics and health management design for rotary machinery systems—Reviews, methodology and applications. *Mechanical Systems and Signal Processing 42*, 314-334 (2014).
15. Chaïb, R. et al. Failure: a source of progress in maintenance and design. *Physics Procedia 55*, 185-191 (2014).
16. https://www.nrc.gov/docs/ML1919/ML19191A196.html (accessed on 4 December 2019).
17. Pyoun, Y. S. et al. A Study on the Ultrasonic Nano Crystal Surface Modification (UNSM) Technology and It's Application. *Transactions of The Korean Society of Mechanical Engineers A 33*, 190-195 (2009).
18. Papic, L., Aronov, J. and Pantelic, M. Safety Based Maintenance Concept. *International Journal of Reliability, Quality and Safety Engineering 16*(6), 533–549 (2009).
19. Kim, J., Cho, I. and Pyun, Y. A Prognostic Inspection and Proactive Maintenance System (PIPM) to Bring Snowball Effects on the Transition to the Circular Economy and a Carbon-Neutral Society. *The journal of Hyojeong Academia 1*, 8-12 (2023).
20. ASME Code Case N-860. *Inspection Requirements and Evaluation Standards for Spent Nuclear Fuel Storage and Transportation Containment Systems* (The American Society of Mechanical Engineers, 2020).
21. Broussard, J. E. Technical Basis Summary for Code Case N-860: Inspection Requirements and Evaluation Standards for Spent Nuclear Fuel Storage and Transportation Containment Systems. In ASME 2021 Pressure Vessels & Piping Conference, Online (13-15 July 2021).
22. Darisuren, S. et al. Remanufacturing process and improvement in fatigue life of spherical roller bearings. *Journal of KSTLE 30*(6), 350-355 (2014).
23. Kim, J., Cho, I., Pyun, Y. and Amanov, A. Code Case N-931 and UNSM Technology for the Improving Service Life and Safety of Nuclear Power Plant. In Proceedings of the 2nd International Conference of Hyojeong Academy, Asan, Korea (31 Aug. - 2 Sep. 2023).