Contribution

The Current Situation of Condition Monitoring and Diagnosis of Machine Systems

Tsuyoshi INOUE

Ph.D. Professor, Department of Mechanical Systems Engineering, Graduate School of Engineering, Nagoya University

Recently, condition monitoring and diagnosis technologies for machine systems have been rapidly developing and attracting attention. This paper first reviews the recent trends in condition monitoring and diagnosis of mechanical systems, referring to the standardization activities of ISO/TC 108/SC 5, in which the author has been involved for many years. Subsequently, this paper introduces the recent trends in asset management and condition monitoring, condition monitoring and diagnosis of wind power generation, IoT for predictive maintenance, and condition monitoring and diagnosis using 1DCAE as the latest topics. Finally, some topics regarding condition monitoring and diagnosis of machine systems and bearings at domestic conferences in the past few years have been introduced.

1. Introduction

I have been involved in ISO standardization activities for ISO/TC 108/SC 5 Condition Monitoring and Diagnostics of Mechanical Systems since 2004. I will first briefly review the standardization activities of ISO/TC 108/SC 5 and then give an overview of recent developments in condition monitoring and diagnostics of mechanical systems. The first half of the paper (Chapters 2 and 3) is mainly based on a commentary article1) written and published in the journal “Nondestructive Inspection” in 2020, with an update based on information from the last two years.

The latter half of the paper (Chapters 4 to 7) will cover recent trends in asset management and condition monitoring, condition monitoring and diagnostics for wind power generation, IoT for predictive maintenance, and condition monitoring and diagnostics using 1DCAE. Finally, we will introduce some content from presentations at domestic academic conferences in the past few years that relate to condition monitoring and diagnostics of bearings.

2. International Trends in Condition Monitoring and Diagnostics of Machine Systems1)

2.1 Scope of ISO TC 108/SC 5

ISO/TC 108/SC 5 is officially called “Condition monitoring and diagnostics of machine systems”. The purpose and scope of SC 5 provided on the website2) are as shown below.

Standardization of the procedures, processes and equipment requirements uniquely related to the activity of condition monitoring and diagnostics of machine systems is an important part of all programs with selected physical parameters associated with an operating machine system are periodically or continuously monitored, measured and recorded for the interim purpose of reducing, analyzing, comparing and displaying the data and information obtained to support decisions related to the operation and maintenance of the machine system.

2.2 Working Group for ISO TC 108/SC 5

The working groups (WGs) established in ISO/TC 108/SC 5 as of September 2022 are listed in **Table 1** and introduced individually below.

AG E: This is a working group for discussing the overall strategic plan for SC 5. Here, the overall direction of international standardization of SC 5, how to proceed with the work of each working group, and the establishment and dissolution of working groups are examined and discussed. The initial draft of the preliminary work item (PWI), which assumes that a new working group will be established in the future, is also considered here.

Table 1 Working Group[2)] of ISO/TC 108/SC 5 (as of September 2022)

WG	Technical field
AG E	Strategic planning
WG 7	Training and accreditation in the field of condition monitoring and diagnostics
WG 11	Thermal imaging
WG 16	Condition monitoring and diagnostics of wind turbines
WG 17	Condition monitoring and diagnostics applications
WG 18	Condition monitoring management

WG 7: This working group focuses on the training and certification of condition monitoring technicians. It has developed a series of standards for training and certification. In addition to ISO 18436-1:2021, which covers the entire range, it has published standards for condition monitoring technicians for individual technologies which include ISO 18436-2:2014 Vibration condition monitoring and diagnostics, ISO 18436-4:2014 Field lubricant analysis, ISO 18436-5:2012 Lubricant laboratory technician/analyst, ISO 18436-6:2021 Acoustic emission, ISO 18436-7:2014 Thermography, and ISO 18436-8:2013 Ultrasound. In Japan, certification of machinery condition monitoring technicians based on these 18436 series, has been in previously in place, details of which are described in Chapter 3.

WG 11 Thermal Imaging: This working group focuses on condition monitoring and diagnostic techniques using thermal imaging. It has published ISO standards for general procedures in ISO 18434-1:2008 and for interpretation of images in ISO 18434-2:2019, where images of bearing anomaly detection are also presented. It is currently considering the standardization of optical gas imaging. In addition to WG11, which focuses on thermal imaging, which were previously in many other working groups on condition monitoring and diagnostic techniques (WG3 Performance monitoring and diagnostics, WG4 Tribology, WG10 Condition monitoring and diagnostics of electrical equipment, WG14 Acoustic techniques, WG15 Ultrasound diagnostics, etc.). However, each of these has finished publishing the ISO standards that are currently required and has therefore been disbanded. Information on these disbanded working groups is shown in **Table 2**. If the need arises for a new ISO standard in the same field, or if a major revision of the current ISO standard becomes necessary, we plan to reopen the Working Groups.

WG 16 Wind turbines, WG 17 Applications: These working groups focus on condition monitoring and diagnostics for individual machines. WG16 has completed the standardization of ISO 16079-1: 2017 General Guidelines and ISO 16079-2: 2020 Monitoring the drivetrain. The latter describes the monitoring and diagnosis of bearings and gears for wind turbines. As its name suggests, WG17 covers a wide range of applications. It has published the standard ISO 19283:2020 Hydroelectric generating units and has started the standardization of reciprocating compressors.

WG 18 Asset Management: This is a new working group launched in 2019 that, as of September 2022, is the most active. The condition monitoring and diagnostics of mechanical systems have traditionally been done mainly by the engineers who directly handle machines. However, the need for standardization that also incorporates the perspective of asset management systems, has been raised at SC 5 international meetings (see Section 2.3) for the past 10 years. Now, under the strong leadership of the current SC5 chairman, the working group has begun studying and vigorously promoting the standardization of asset management systems with a specific focus on mechanical systems. The standards being examined are (1) accreditation of condition monitoring managers, (2) accreditation of condition monitoring auditors, and (3) physical asset management.

2.3 International meetings for ISO TC 108/SC 5

In ISO standardization, international meetings play an important role as forums for reviewing and reflecting ballot comments on draft standardization texts and for considering the next standards. The first international meeting of SC 5 was held in 1994, and 23 meetings were held up to 2019. **Table 3** shows the years and venues of the conference. The 24th meeting was originally scheduled to be held in New York in September 2020 but was postponed (and subsequently canceled) for the first time due to global restrictions on international travel arising from the COVID-19 pandemic that began in March 2020. It was held later in May 2022 as the first online meeting. In 2023, with the pandemic now largely under control, Japan will host the meeting in Kyoto, which will be the first in-person meeting in four years.

Table 2 Working groups established in SC 5[1)] [2)]

WG	Technical field
AG A	Vibration condition monitoring procedures and instrumentation used for diagnostics
WG 1	Terminology
WG 2	Data interpretation and diagnostics techniques
WG 3	Performance monitoring and diagnostics
WG 4	Tribology-based monitoring and diagnostics
WG 5	Prognostics
JWG 6	Formats and methods for communicating, presenting and displaying relevant information and data
WG 8	Condition monitoring and diagnostics of machines
WG 10	Condition monitoring and diagnostics of electrical equipment
WG 14	Acoustic techniques (Acoustic emissions)
WG 15	Ultrasound
For these working groups, items to be discussed to consider future projects or new areas of work are included in each year's meeting. These are examined, along with considering the resumption of activities.	

Table 3 List of SC 5 International Conferences[1)]

1st	1994	Swansea	UK
2nd	1995	London	UK
3rd	1996	Sydney	AU
4th	1997	Berlin	DE
5th	1998	Tasmania	AU
6th	1999	Copenhagen	DK
7th	2000	Nanjing	CN
8th	2001	Vienna	AS
9th	2002	Minden, NV	USA
10th	2003	Paris	FR
11th	2004	London	UK
12th	2005	Dania Beach, FL	USA
13th	2007	Prague	CZ
14th	2008	Kyoto	JP
15th	2009	Copenhagen	DK
16th	2010	London	UK
17th	2011	Sydney	AU
18th	2013	Berlin	DE
19th	2014	Paris	FR
20th	2016	Sydney	AU
21st	2017	London	UK
22nd	2018	Helsinki	FI
23rd	2019	Copenhagen	DK
24th	2022	Online	
25th	2023	Kyoto (scheduled)	JP

2.4 ISO TC 108/SC 5: Status of activities and outlook

The latest SC 5 activities can be found on the ISO Website. The current chairman is Mr. L. Hitchcock (SA), the fourth chairman. The secretary is Mr. A. Rashid (SA). As of September 2022, the P-members (Participation members) consisted of 23 countries and regions, while O-members (Observer members) consisted of 12 countries and regions.

Fig. 1 shows the status of SC 5 standards as of September 2022. SC 5 has published 28 international standards. Five standards are in the process of being established or revised.

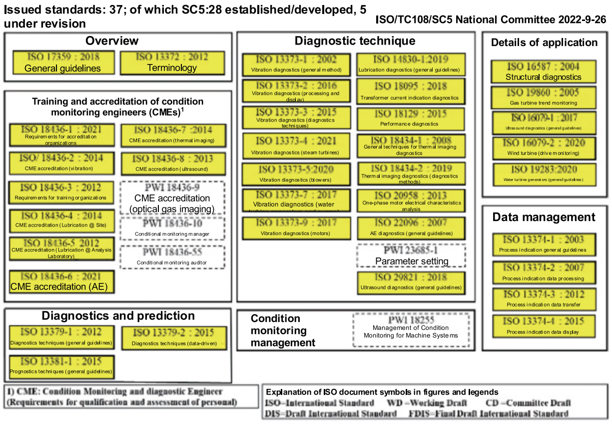


Fig. 1 Standardization Activities as of September 2022

SC 5 began with the concept of "Condition Monitoring and Diagnostics." As the work of standardization progressed from 1994 to around 2011, there was an overall shared recognition among Japan, the United States, Europe, and other countries in terms of the background, needs, and objectives of this concept. However, around 2012, while the original concept was retained, (the background, needs, and objectives of condition monitoring and diagnostics as recognized and advocated by the SC5 members in Europe and the United States) gradually expanded. They have long recognized the need for and value of condition monitoring and diagnostics standards that should be used by engineers and management from an asset management standpoint. Now that the first round of standardization of the basic technologies of SC 5 has been finished, the activities of SC 5 show signs of a shift toward such new standards for condition monitoring and diagnostics.

As of September 2022, as shown in **Table 1**, SC 5 has the following active working groups: Training and Accreditation WG 7, Thermal Imaging WG 11, Wind Turbines WG 16, Applied Technology WG 17, and Asset Management WG 18. As mentioned in the previous section, the WG on foundational technologies (currently WG 11) is to be disbanded after completing standardization. The future activities of SC 5 will mainly take two directions: applied technology (WG16 and 17) and asset management (WG18). In particular, the current chairman of SC 5 has strongly indicated the latter direction based on the aforementioned background. This shift has been clear in the past three international meetings, as SC 5 currently has liaisons with IEC TC 56 Dependability and ISO/TC 251 Asset management in the opposite direction. WG18 is expected to be the center of SC 5 activities shortly. However, TC 108/SC 5 has not yet reached a mutual understanding or recognition concerning the asset management of mechanical systems proposed by TC 108/SC 5 concerning the 55000 series, which is the major ISO standard for asset management. It is also clear that TC 108/SC 5 itself has yet to define the ideal state of condition monitoring management for mechanical systems.

In Japan, the needs and expectations for asset management of mechanical systems are already increasing, and one can sense that interest in the activities of SC 5/WG18 is growing rapidly. On the other hand, the ISO/TC 108/SC 5 National Committee does not yet have a fully shared understanding of the background, needs, and expanding objectives of condition monitoring and diagnostics from an asset management perspective. The start of consideration of several ISO standards in asset management (WG 18) was approved at the 23rd International Conference (Copenhagen) and will be considered at the 25th Kyoto Conference. For the above reasons, the current ISO/TC 108/SC 5 National Committee may not be able to adequately respond to these standardizations. To address this, the ISO/TC 108/SC 5 National Committee has recently started to engage with the Japan Association of Asset Management (JAAM) and is preparing to start mutual participation in committee activities. The committee is also considering adding asset management experts as members if necessary or restructuring the structure of the ISO/TC 108/SC 5 National Committee. We hope that experts from related companies in Japan who are interested in asset management for condition monitoring of mechanical systems will participate in the ISO/TC 108/SC 5 National Committee or international meetings and share their views.

3. Engineer Accreditation Programs and Courses1)

3.1 Machine Condition Monitoring Qualification Accreditation Project

To evaluate the technical competence of individuals in a globally consistent and objective manner, accreditation of machinery condition monitoring and diagnostics technicians is conducted based on the ISO 18436 series (qualification of machinery condition monitoring and diagnostics technicians) developed by ISO/TC 108/SC 5/WG 7.1) In Japan, accreditation has been implemented for vibration, tribology, and thermography.

ISO 18436-2 (vibration) was published first in 2003. The ISO 18436 standard series continued in steady succession with ISO 18436-4 (field lubricant analysis), ISO 18436-6 (acoustic emissions) and ISO 18436-7 (thermography). ISO 18436-5 (laboratory lubricant analysis) followed in 2012 and ISO 18436-8 (ultrasound) was published in 2013. It should be noted that in ISO 18436-2 (vibration) the overall field is divided into categories Ⅰ through Ⅳ (category Ⅳ is recognized as equivalent to a professional engineer or doctor of Engineering), whereas all other fields are divided into categories Ⅰ through Ⅲ. In addition, although the redefinition of vibration as Category Ⅰ to Ⅲ has been proposed and periodically considered at SC 5 international meetings, for the sake of clarity and ease of understanding of the overall categories, the original category system has been maintained due to opposition from countries that have already been implementing the system for nearly 20 years.

The accreditation system for the qualification of technicians who perform condition monitoring and diagnostics of machines (vibration) has been implemented by the Japan Society of Mechanical Engineers (JSME[3)]) since June 2004. A total of 5 472 persons have been certified by the 37th examination to be held in August 2022. In Category Ⅰ, the number of qualified personnel is 819. In Category Ⅱ, it is 4 557. In Category Ⅲ it is 434. On average, around 10 people receive accreditation in Category Ⅰ, 100 in Category Ⅱ, and 20 to 30 in Category Ⅲ. In addition, 41 people have received accreditation in Category Ⅳ, which is positioned as equivalent to a Doctor of Engineering or a professional engineer. This shows the high level of engineers involved in vibration technology in Japan. It is hoped that those who aspire to work internationally as engineers, will take up the challenge of Category Ⅲ and Ⅳ.

The accreditation system for the qualification of technicians who perform condition monitoring and diagnostics of machines (tribology) has been implemented for Categories Ⅰ-Ⅲ since FY2009 through joint certification by JSME[3)] and the Japanese Society of Tribologists (JAST). As of September 2022, a total of 1 421 persons have been certified. (In Category Ⅰ, the number of qualified personnel is 1 176. In Category Ⅱ, it is 234, and in Category Ⅲ it is 11.)

The qualification examinations for technicians who perform condition monitoring and diagnostics of machines (thermography) have been conducted by the Japanese Society for Non-Destructive Inspection (JSNDI) for Category Ⅰ since FY2016 and for Category Ⅱ since FY2018. A total of 206 people (173 and 33 for Categories Ⅰ and Ⅱ, respectively) have passed the examination as of September 2022.

JSNDI (Certification Division for CM Engineers) and JSME (Japan Society for Machine Monitoring Engineers) have formed a partnership for administering the accreditation of condition monitoring[4)]. For example, JSME sponsors meetings of the Condition Monitoring and Vibration Diagnostics Engineer Community. It provides a forum for disseminating information on condition monitoring and for exchange among qualified engineers, including JSNDI's qualified CM engineers and other related parties[4)].

3.2 Workshop on condition monitoring and diagnostics techniques

The ISO/TC 108/SC 5 National Committee organizes and holds a seminar entitled "A Must for Global Engineers! Monitoring and Diagnostics of Mechanical Systems, Fundamentals, Practical Know-How, Application Examples and Standards" (hosted by JSME). The content includes an introduction of the SC5 standards and engineer accreditation for condition monitoring, diagnostics using vibration, lubricant analysis, thermal image analysis, introduction of basic technologies for acoustic emissions (AE), diagnosis of large rotating machinery, diagnosis of wind turbines (mainly bearings), current indication diagnosis (added from 2019), and comprehensive diagnosis (added from 2021). The first seminar was held in Tokyo in October 2007 (30 participants). The second seminar was held in Osaka in October 2007 (15 participants). After a hiatus following the above two seminars, the third seminar was held in Tokyo in September 2016 (29 participants). The fourth seminar was held in September 2018 (44 participants), and the fifth in September 2019 (53 participants).

A book was written based on the contents of the 5th seminar. Entitled "Condition Monitoring and Diagnostic Techniques for Mechanical Systems", it was published in June 2021 (edited by Inoue and Hyodo, Japan Society of Mechanical Engineers, Corona Publishing).[5)] The 6th seminar was held online in November 2021 (150 participants) using this book as the textbook. In fiscal 2022, this workshop was expanded and held in two rounds in November, one for beginners and the other for intermediate-level students. The last three seminars have been fully booked, highlighting the growing need for and interest in this technology with the arrival of the IoT (Internet of Things) era. We will continue to educate people about this field and introduce the activities of the ISO/TC 108/SC 5 National Committee. I hope that through these seminars and publications, people will learn the fundamentals of technology in this field.

4. Condition Monitoring and Asset Management[6)-14)]

4.1 Europe: Trends in IoT and Asset Management

Ten years have passed since IoT and Industry 4.0 were proposed in the 2010s, and these terms and concepts have spread widely. In Europe and the United States, these technologies have evolved through deep integration with equipment diagnostics and asset management. This year, Kawai summarized equipment diagnostics and IoT in Europe in comparison with Japan as follows.[6)] In Japan, discussions tend to focus on the use of data obtained from equipment in a single factory or company. In contrast, in Europe, the European Integrated Data Infrastructure Project GAIA-X represents the European Data Economy Area. In recognition of the strategic utility of data, GAIA-X integrates various cloud services of companies on a single system, enabling interoperability through a standardized authentication mechanism that facilitates data exchange across industries (Data Economy Area).

It is expected that manufacturers will evolve to a model of providing services to customers. Globally, the customer's usage environment will become a complex system environment that includes not only their own products but also those of other companies.[8)] Japan will be no exception to this trend. As a result, manufacturers will be required to manage the entire life cycle of the user's usage environment as they provide services. It is thus expected that manufacturers will need to collect data generated from the entire user's usage environment, including competitors' products. In particular, sharing and utilizing data from the operation and maintenance phases, which have not been visualized until now, will become a new and important area of research and development. It is clear that data collaboration involving users will be key.8)

Let us briefly touch on the report “Applying the Internet of Things (IoT) to Manufacturing” 6) 9) which Siemens has compiled on Industrial IoT (IIoT), the collection and centralization of large amounts of machine data from industrial sites. **Fig. 2** shows the major use cases that manufacturers can implement to maximize the added value and ROI (return on investment) to their businesses, modeled in six levels of IIoT maturity. It is recommended that the IIoT be introduced at the basic level, which is relatively easy to handle, and then gradually expanded to achieve greater value. It is interesting to note that the first asset management and asset maintenance are specifically listed as condition monitoring, asset performance management, and predictive maintenance. We will give an overview of these here.

Asset management condition monitoring uses a centralized IoT system to monitor specific parameters (temperature, vibration, pressure, etc.) and key performance indicators (KPIs). It tracks the operational status of all connected assets and, should a problem occur, takes corrective action before that asset fails, thereby maximizing uptime of critical assets. In this way, condition monitoring ensures transparency into the health and performance of assets at locations around the world.

In asset performance management, KPIs are used to monitor and track the condition and status of machines and identify machines that are not performing adequately in terms of efficiency and productivity. In addition, asset performance management applications using IoT can improve performance by making changes to production lines that deviate from optimal operating conditions. In this way, production is accelerated, and positive effects spill over to resource allocation, time-to-market, and customer satisfaction. In addition, KPIs are fine-tuned each time to identify machine performance more accurately, and machines are continuously adjusted based on real-time data to improve performance. In this way, asset performance management improves overall equipment and corporate profits.

Predictive maintenance in asset maintenance dynamically collects and analyzes machine health and performance data. It then identifies parts that have reached key thresholds, determines when maintenance or replacement is required, and performs maintenance only when necessary. This eliminates the need for scheduled maintenance and significantly reduces unscheduled maintenance. As a result, predictive maintenance can reduce unscheduled downtime, lower maintenance costs, improve quality, productivity, asset uptime, availability, and production, and extend the service life of machines. For more information, including other topics of interest, please refer to the report.

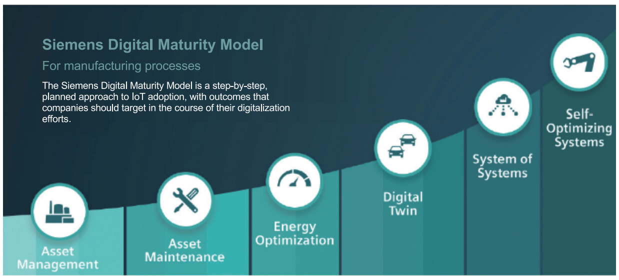


Fig. 2 Siemens Digital Maturity Model6) 9)

Kawai stated that when he attended COMADEM (Condition Monitoring and Diagnostic Engineering Management),10) a traditional international conference in the field of condition monitoring and diagnosis, he noticed that many of the presentations by Asian researchers were on individual diagnostic techniques, while those by Western researchers were mostly about asset management.6) This shows how in Europe and the U.S., research has already expanded in scope to include not only equipment management using diagnostics of anomalies, but also how to realize managerial cost reductions based on such data, taking into consideration the costs of installing diagnostics equipment and conducting diagnostics necessary for that purpose. This point is consistent with the trend of thinking among Western experts, which the author himself has experienced and felt through the standardization activities of ISO/TC 108/SC 5. Japanese engineers and researchers must quickly recognize this global trend so that they can respond appropriately.

4.2 Trends in Japan: Maintenance Optimum Strategic Management System (MOSMS)11)-14)

In Japan, the Japan Institute of Plant Maintenance (JIPM) has been continuously and actively involved in equipment management. **Fig. 3** shows the history of facilities management in Japan, based on the introduction material of the association11). Facilities management technology continues to expand, as can be seen in the background and history of MOSMS, which integrates these technologies and incorporates asset management.

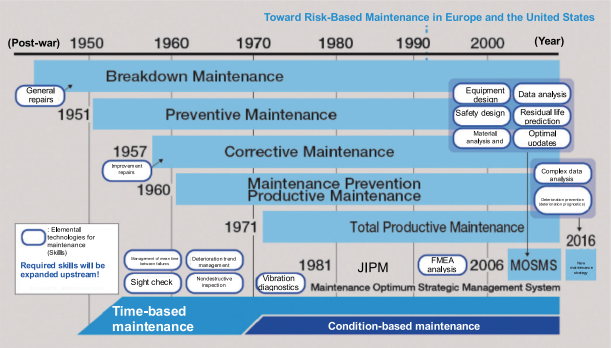


Fig. 3 History of facility maintenance in Japan11)

■ Estimated number of employees (manufacturing and maintenance, thousands)

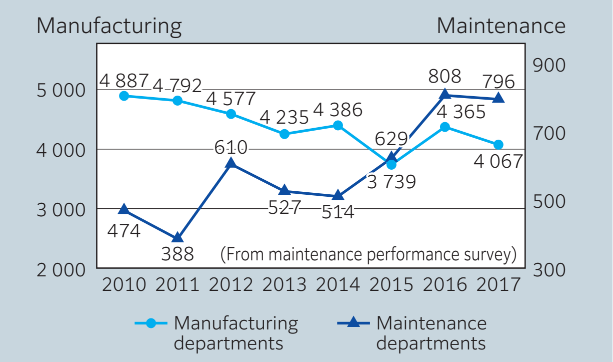


Fig. 4 Number of employees in manufacturing and maintenance departments11)

Fig. 4 shows the number of employees in the manufacturing and maintenance departments.11) The results show that the introduction of new equipment has recently decreased. As this has happened, there has been a growing shift toward maintaining and operating existing equipment as well as possible. Therefore, it can be said we are in the age of maintenance.

Given this trend, in 2006, JIPM proposed and started the Maintenance Optimum Strategic Management System (MOSMS).12) 13) Its aim was to build a maintenance system that matched management theory and technology theory through a consistent concept for dealing both with loss (issues that have already occurred) and risk (possibility that such issues may occur in the future). This system clarifies the relationship between the PDCA cycle of management and the PDCA cycle of maintenance **(Fig. 5)**. In particular, it emphasizes that in order for maintenance to be integrated with management, a plan must be created that is logical from a management perspective and it must be ensured that maintenance follows the plan (maintenance management).13) It is necessary to fully align management and maintenance to create a grand design for maintenance (a maintenance plan offering maximum advantage from a management perspective). MOSMS is a “made in Japan” system that has been developed for this very purpose.

MOSMS lists P (productivity), Q (quality), C (cost), D (delivery time), S (safety), M (motivation), and E (environment) as loss/risk categories, aiming to minimize these loss/risk categories as a result of facility management. The target group is the middle rank (managerial level), which is the same as the target group for asset management in ISO/TC 108/SC 5/WG 18 described in the previous section. To link management and maintenance, as shown in **Fig. 5**, loss/risk management and facility maintenance strategies are incorporated into the P (plan) of the management PDCA cycle. The D (do) of the management PDCA cycle and the P (plan) of the MOSMS PDCA cycle are linked with each other, the C (check) and A (act) of both PDCA cycles are also linked through evaluation of each other.14) In this way, the system aims for to align maintenance management, which aims to balance risk and cost, with planned maintenance using technology for continuous improvement.

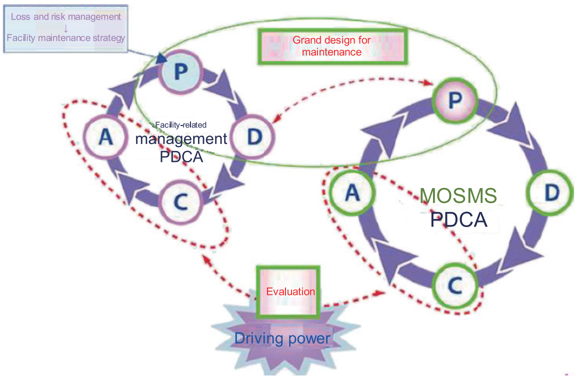


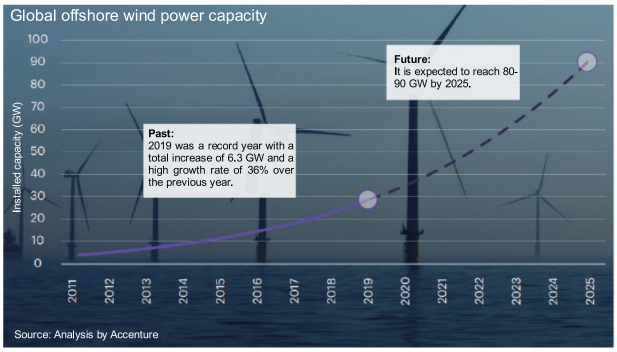
Fig. 5 Linking management and conservation through MOSMS14)

5. Current status of wind power generation and trends in condition monitoring and diagnostics15)-21)

Let us look at wind power generation systems, one of the main systems subject to condition monitoring and diagnostics, and trends in this area.

5.1 Wind power producer trends15) 16)

The following is a summary of a report issued by Accenture15) 16) this fiscal year. Over the past decade, efforts to reduce the Levelized Cost of Electricity (LCOE) of onshore and offshore wind power have expanded and intensified. This has ushered in a digital revolution in the wind power industry. Global onshore wind power generation capacity has risen sharply over the past decade, from 178 GW in 2010 to 594 GW in 2019. Offshore wind power is also growing rapidly, reaching 29 GW of global capacity in 2019. **Fig. 6** shows global offshore wind power capacity and projected short-term growth rates. The power market is investing heavily in offshore wind power, which currently accounts for only about 5 % of global wind power capacity, but with the scale and growth rate of the project, some predict that offshore wind power capacity will nearly triple over the next five years.



Past:
2019 was a record year with a total increase of 6.3 GW and a high growth rate of 36% over the previous year.

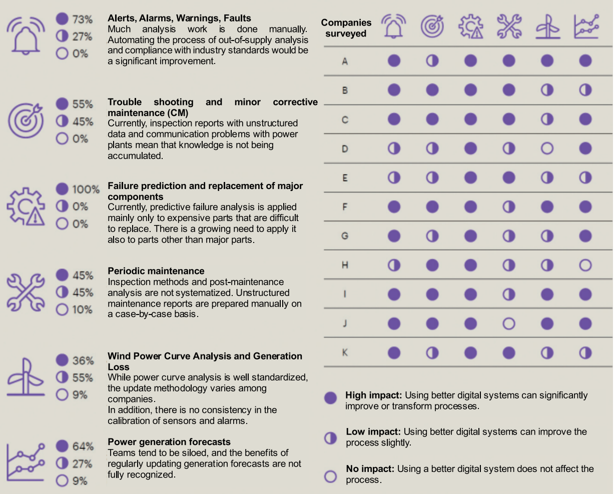
Future:
It is expected to reach 80-90 GW by 2025.

Source: Analysis by Accenture

Fig. 6 Global Offshore Wind Power Capacity and Projected Short-Term Growth15)

5.2 Condition monitoring and diagnostics of wind turbines15) 16)

In the wind power business, LCOE has been improved by increasing turbine size (from 2 MW to 12 MW in 10 years in the UK16)), reducing capital investment per MW, and increasing facility utilization (from 30 % to over 40 % in the UK16)). Accordingly, operation and maintenance (Operation & Maintenance, O&M) costs in the LCOE of wind power plants have gradually increased in relative terms and now exceed one-third of the life cycle costs. As a result, there has recently been a growing interest in achieving productivity gains and cost reductions for O&M processes, and digital technology has been identified as one of the key determinants of its success. Accenture has conducted a survey of 11 leading onshore and offshore wind energy companies and identified six key O&M use cases. The results of the study on the impact of advanced digital tools on process improvement for these six key O&M use cases are shown in **Fig. 7**.



● 73%
◑ 27%
○ 0%
Alerts, Alarms, Warnings, Faults
Much analysis work is done manually. Automating the process of out-of-supply analysis and compliance with industry standards would be a significant improvement.

● 55%
◑ 45%
○ 0%
Trouble shooting and minor corrective maintenance (CM)
Currently, inspection reports with unstructured data and communication problems with power plants mean that knowledge is not being accumulated.

● 100%
◑ 0%
○ 0%
Failure prediction and replacement of major components
Currently, predictive failure analysis is applied mainly only to expensive parts that are difficult to replace. There is a growing need to apply it also to parts other than major parts.

● 45%
◑ 45%
○ 10%
Periodic maintenance
Inspection methods and post-maintenance analysis are not systematized. Unstructured maintenance reports are prepared manually on a case-by-case basis.

● 36%
◑ 55%
○ 9%
Wind Power Curve Analysis and Generation Loss
While power curve analysis is well standardized, the update methodology varies among companies.
In addition, there is no consistency in the calibration of sensors and alarms.

● 64%
◑ 27%
○ 9%
Power generation forecasts
Teams tend to be siloed, and the benefits of regularly updating generation forecasts are not fully recognized.

Companies surveyed						
A	●	◑	●	●	●	●
B	●	●	●	●	◑	◑
C	●	●	●	●	◑	●
D	◑	◑	●	◑	○	●
E	◑	◑	●	●	◑	◑
F	●	●	●	◑	●	●
G	●	◑	●	◑	◑	●
H	◑	●	●	◑	◑	○
I	●	●	●	◑	●	●
J	●	●	●	○	●	●
K	●	◑	●	●	◑	◑

● **High impact:** Using better digital systems can significantly improve or transform processes.

◑ **Low impact:** Using better digital systems can improve the process slightly.

○ **No impact:** Using a better digital system does not affect the process.

Fig. 7 Degree of impact of advanced digital technologies on key O&M use cases and breakdown of surveyed companies' ratings15)

Three of the six major O&M use cases are related to condition monitoring. Applying advanced digital tools to these three cases offers very high potential for improvement. The following sections provide an overview of three of these use cases individually.

- Alerts, Alarms, Warnings, and Faults: Types of alerts and faults are analyzed to identify trends and patterns for equipment condition analysis, work prioritization, etc. These are incorporated into response time guidelines to minimize loss of generation and cost. The control room monitors alarms and warnings and determines the response. The performance engineering team takes charge of the cause and relevance of alarms and faults, while the asset management team and O&M team identify follow-up actions and prioritize responses.
- Troubleshooting and minor corrective maintenance (CM): The process of investigating and repairing incidents remotely or in the field to reduce downtime and increase power generation. An operations team monitors plant performance and remotely investigates reported incidents, coordinates field inspections, and handles subsequent activities based on work instructions.
- Failure prediction and major component replacement: Condition monitoring tools and algorithms are used to understand the risk of major component failure within a pre-specified time frame. Setting up an optimally timed major component replacement process reduces downtime and maintenance activities, resulting in cost savings and increased power generation.

In addition, this study comprehensively analyzes the cases above and clarifies the following key findings related to the current role, potential and challenges of digital technology in O&M.15) 16)

Most of the companies surveyed see digital technology as having an important role in fault prediction, alerts and warnings, and trouble shooting. All companies have implemented appropriate custom-built solutions, and many of them would like to develop further functionality. In this regard, a business opportunity has arisen for third-party companies to provide O&M insight services that power producers can implement in their current environments.

- Integrating data of all types throughout the O&M process enables the addition of rich contexts to analytics to create added value. However, because of the low quality of data and the lack of data engineering skills, few companies have achieved this.
- Many companies are willing to improve their O&M processes by learning from past activities and information, such as alert responses and service records. In reality, however, the lack of time and of easy-to-use digital tools makes this difficult to do.
- As for data, data owners, such as owners, power generators, and OEMs (or O&M service providers), are reluctant to share the data and the insights derived from it. Therefore, third-party companies need to clearly define the ownership of the data and consider and provide a partnership model for jointly developing software and tools.

Going forward, based on the abovementioned recognition, advanced digital technologies will be used to devise and build mechanisms for successful data sharing. There will be a rapid global shift to achieve increased productivity and cost reduction for the O&M process of wind power generation. In this regard, condition monitoring and diagnostics will play an important role.

5.3 Wind Power Condition Monitoring and Diagnostics Trends in Japan (from the NEDO Report)[17)]

In Japan, a few years ago, NEDO summarized its research results in "R&D of Technologies for Wind Power and Other Natural Energies, R&D for Advanced Practical Use of Wind Turbine, smart maintenance technology R&D (analysis) (fatigue prediction, etc.)."[17)] The following is a brief overview of the research results.

Fig. 8 shows an example of a basic wind turbine component configuration. In this report, to contribute to the development of maintenance methods for highly efficient rotating (drive train, control equipment) and non-rotating (tower, etc.) systems, data was collected on wind turbine failures and accidents, the circumstances and causes of their occurrence was analyzed, along with analyzing maintenance methods. The report also summarizes the maintenance methods of existing wind turbines in Japan and overseas, as well as the measures taken in response to failure accidents.

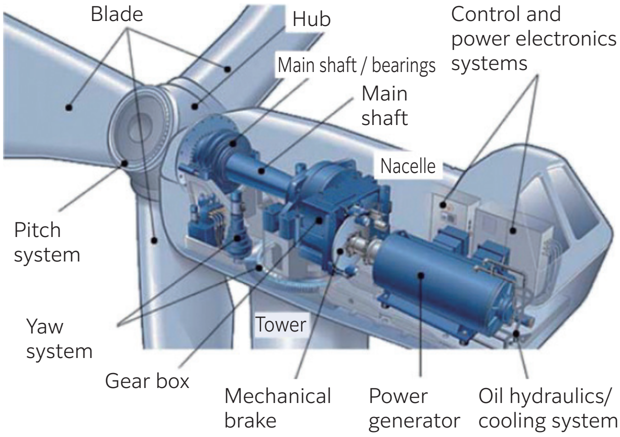


Fig. 8 Example of windmill equipment configuration[17)]

Fig. 9 shows the trends in the failure and accident rates for the wind turbines cooperating with the survey (the same survey method has been in place since around 2012, and the rates have remained almost constant.)[17)] **Table 4** shows a breakdown of the causes of failures and accidents in fiscal 2016. Among the factors related to condition monitoring and diagnosis, "inadequate maintenance" (6.1 %), a "human factor", was relatively common. Compared to past surveys, the "Other" category in the "Cause unknown/other" category, which is related to condition monitoring and diagnosis, has increased significantly. This "Other" category was mainly reported as long-term deterioration. The same trend has continued in recent years, indicating an increase in the number of failures and accidents due to the deterioration of wind turbines after a certain number of years.

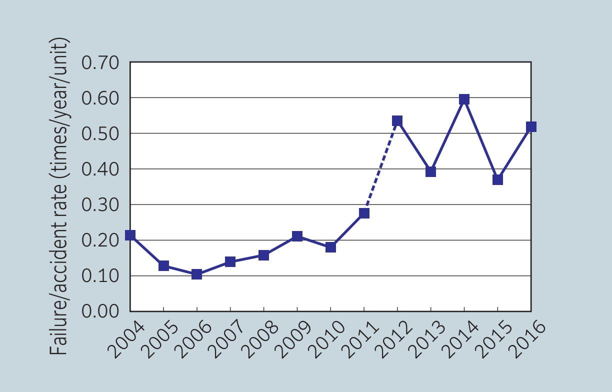


Fig. 9 Trends in wind turbine failure and accident rates[17)]

Table 4 Breakdown of Failure and Accident Factors (FY 2016)[17)]

Failure and accident factors	Breakdown of factors	Number of occurrences	Percentage of total
Natural phenomenon	Strong winds	0	0.0 %
	Lightning	34	9.1 %
	Air turbulence	19	5.1 %
	Low temperatures/ freezing	0	0.0 %
	Flooding	7	1.9 %
	Other	12	3.2 %
Failure in wind turbine	Design flaw	3	0.8 %
	Manufacturing flaw	17	4.5 %
	Construction flaw	13	3.5 %
Human factor	Inadequate maintenance	23	6.1 %
System failure	System failure	17	4.5 %
Unknown cause/Other	Under investigation	6	1.6 %
	Unable to identify	108	28.9 %
	Other*	115	30.7 %
Total		374	100 %

* "Other" of "Cause unknown/other" is mainly reported as "long-term deterioration"

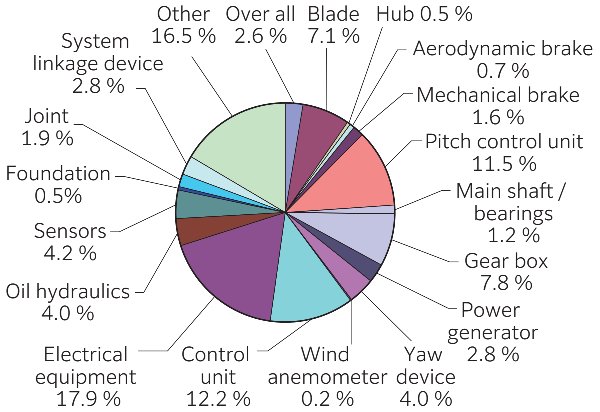


Fig. 10 Summary of wind turbine failures and accidents by site of occurrence (FY2016)[17)]

Fig. 10 shows a summary of wind turbine failures and accidents by site (FY2016). The most common failure/accident categories were “electrical unit” (17.9 %), “other” (16.5 %), “control unit” (12.2 %), and “pitch control unit” (11.5 %). In the evaluation by operation period, “blades”, “pitch control unit”, “gearbox”, “control unit”, and “electrical unit” accounted for a relatively high number of failures of wind turbines that had been in operation for “10 years or longer”. In most cases, the longer the operation period, the greater the number of failures. In the past survey results, the number of failures and accidents tended to increase with the length of operation period for parts with mechanical drive mechanisms such as the pitch control device, gearbox, and yaw device. In contrast, the number of failures and accidents tended to be higher for blades, generators, electrical devices, and control devices regardless of the length of operation period. This is because the former are mechanical devices, while the latter are electrical devices. Mechanical fatigue (including the effect of turbulence) is thought to be the main cause of the former failures, while lightning strikes are often the cause of the latter. The NEDO report also mentions that the data owners are not willing to share their data. The same trend can be seen in the situation in Europe described in the previous section. In addition, a serious shortage of engineers who can work on O&M of wind turbines has been reported worldwide.

5.4 Condition monitoring technology for wind turbines[17)]

5.4.1 SCADA and wind turbine CMS

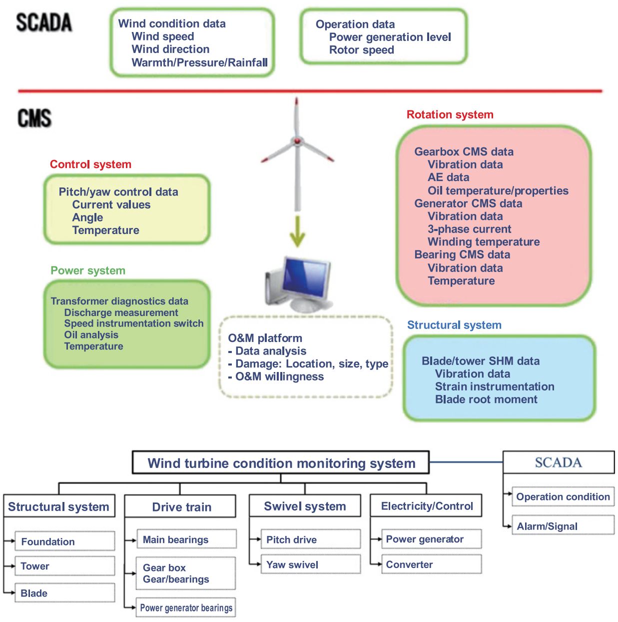


Fig. 11 SCADA and condition monitoring (CMS) system for wind turbines[17)]

Fig. 11 shows the supervisory control and data acquisition (SCADA) system and condition monitoring system (CMS), which are the core systems for wind turbine operation and control. The actual relationship between CMS and SCADA is organized as an integrated image. Together with the operational status data of each device collected by the CMS, Operational data obtained by the SCADA system is indispensable for evaluating the condition of wind turbine components and equipment. As for the necessity of CMS for wind turbines, the failure rate of gearboxes, generators, and converters, which are major components of wind turbines, is reported to be higher than those of the same type and capacity used in other industries. As the output of a wind turbine fluctuates with wind conditions, the load constantly changes due to turbulence and blade position and deformation. In addition to these load fluctuations, wind turbines with higher output and larger sizes tend to have lighter equipment components, which can increase the probability of failure and accelerate fatigue. It is therefore important to constantly monitor the equipment condition (load and response values) to detect and address anomalies as early as possible (application of condition-based maintenance). It is also important to use digital technology to evaluate and predict the impact of load fluctuations on the equipment and to take measures for operation and maintenance in advance (remaining service life evaluation).

5.4.2 CMS technology for wind turbines

The failure modes of wind turbines and diagnostic techniques are shown in **Fig. 12**. Most of the monitoring technologies applied to wind turbine CMS are based on existing condition monitoring technologies. The CMS of wind turbines is characterized by the high need for online monitoring because the operation and maintenance of many wind turbines must be performed at a distance from the site. **Table 5** shows the results of a survey of detection technologies in the current wind turbine CMS in terms of online monitoring and diagnostic effectiveness. While the development and application of new CMS technology specifically for wind turbines is not necessary, given the shortage of real-world examples there are major obstacles to wind turbine CMS in terms of providing qualified failure diagnosis through online monitoring.

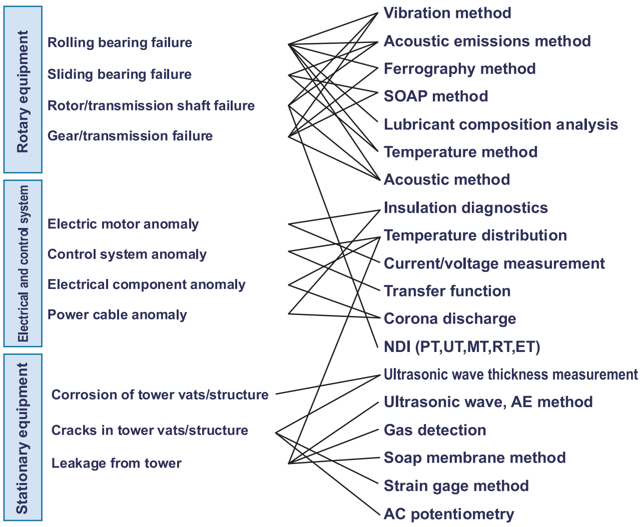


Fig. 12 Failure modes at general plants and applied condition monitoring techniques used for wind turbine CMS[17)]

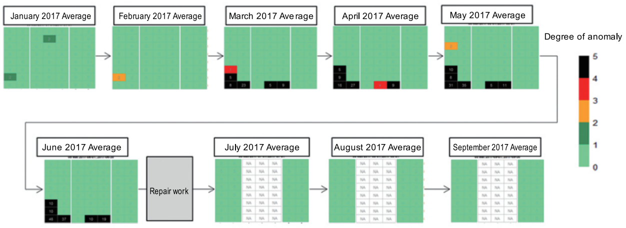
5.4.3 Condition monitoring and prediction of main bearings for wind turbines

As the main bearings of wind turbines are used under low-speed conditions, vibration caused by damage is itself small. In laboratory tests, it is possible to detect changes in vibration levels even in the very early stages of damage. In actual wind turbines, however, peripheral equipment generates vibration at a level that can bring severe damage to the main bearings. Transmission of this vibration from the periphery hinders the detection of damage to the main bearings. A key task in detecting damage to the main bearing is to improve the signal-to-noise ratio by suppressing this vibrational disturbance. To address this issue, this report[17)] develops a detection method that highly integrates frequency band splitting, a physical method, and machine learning algorithms, a statistical method. As shown in **Fig. 13**, we have demonstrated that the method can be used to properly detect and diagnose initial damage to the main bearing.

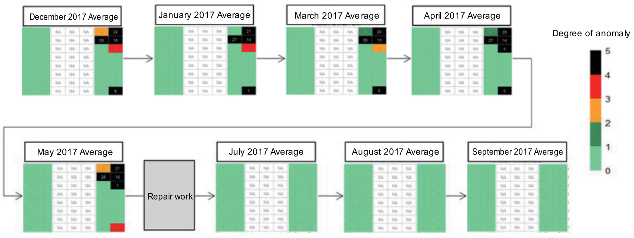
Table 5 Anomaly detection technologies, target sites, and characteristics of wind turbines[17)]

No	CM technology	cost	online commercial	failure diagnosis	track record	wind turbine components
1	thermocouple	low	○	×	in use	bearing generators converter nacelle transformer
2	particle counter method	low	○	×	in use	gearbox bearing
3	vibration analysis	low	○	○	in use	main shaft main shaft bearings gearbox generator nacelle tower foundation
4	ultrasonic exploration	low to medium	○	×	under testing	tower blade
5	electrical signal (e.g., discharge measurement)	low	○	×	in use	power generator
6	vibroacoustic analysis	medium	○	×	×	blade shaft bearing gearbox generator
7	lubricating oil component analysis method	medium to high	×	○	×	gearbox bearing
8	acoustic emission	high	○	×	×	blade shaft bearing gearbox generator tower
9	twisting vibration (encoder based)	low	○	×	under testing	shaft gearbox
10	optical fiber strain gages	extremely high	○	×	in use	blade
11	thermography	extremely high	○	×	×	blade shaft main shaft bearings gearbox generator converter nacelle transformer
12	shaft torque measurement	extremely high	○	×	under testing	blade shaft main shaft bearings
13	shock pulse method	low	○	×	×	bearing gearbox

The same report[17)] also attempted to construct a method for predicting the residual life of wind turbine main bearings. By proposing an equation relating the equivalent distance between wind turbines and the load coefficient that reflects the effect of wakes (areas of lower velocity than the main flow that occur downstream of objects placed in the flow), it is possible to evaluate the bearing-rated life as shown in **Table 6**.



(a) Diagnostic results for Unit 5 on the Unit 20 model.



(b) Diagnostic results for Unit 4 on the Unit 5 model.

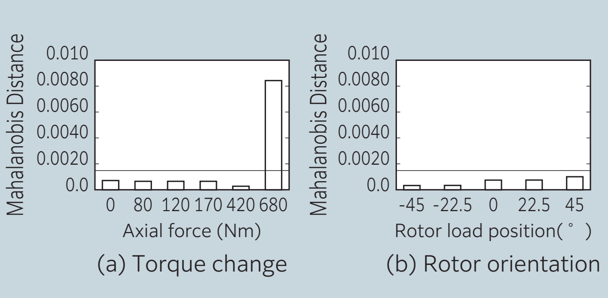
Fig. 13 Damage detection of the main bearing of a wind turbine17)

Table 6 Predicted and actual comparison of rated life17)

Wind turbine	Actual rated life (years)	Distance between equivalent wind turbines (km)	Load coefficient	Predicted rated life (years)
Unit 4	16	0.3	1.55	14
Unit 5	17	0.3	1.51	16
Unit 19	10	0.2	1.72	9
Unit 20	8	0.2	1.75	8

5.4.4 Wind Turbine Tower Anomaly Detection

On March 12, 2013, a wind turbine nacelle fell from the top of the wind turbine support tower at wind turbine No. 3 on the Taikoyama wind farm in Japan. This was due to a fatigue fracture of the tower casing just below the flange. Investigation of the accident revealed that the cause of the fatigue fracture was a stress concentration in the tower casing due to damage to the tower top bolt installed in the flange at the top of the tower. Similar past accidents occurring as anomalies characteristic of wind turbines include: a blade fallout in Falkenberg, Sweden, in 2009; an accident at the Lemnhult wind farm south of Vetlanda, Sweden, in December 2015; and an accident at the Auwahi wind farm on Ulupalakua Ranch on the south coast of Maui, Hawaii, USA in October 2016. In the case of the collapse accident at the Taikoyama wind farm, no anomalies were detected during routine inspections before the accident, and fatigue fracture occurred in a short period. In response to this accident, a method was developed for detecting anomalies in tower top bolts at an early stage and evaluating axial force.17) The MT system (Maharonobis-Taguchi) T method (3), a type of multivariate analysis method, was used to detect abnormal bolts. The results of the analysis using the second-order derivative of the strain variation are shown in **Fig. 14**. When the torque was 680 N-m, the value exceeded the threshold value, indicating that it was possible to determine whether the bolt was abnormal or normal, and the accuracy of the determination could be maintained even when the rotor orientation changed (from -45˚ to 45˚).



(a) Torque change (b) Rotor orientation

Fig. 14 Early anomaly detection method for wind turbine tower top bolts by Mahalanobis distance17)

5.4.5 Example of standard for wind turbine CMS17) 18)

Here we will introduce the standard for wind turbine CMS using the Guideline for the Certification of Condition Monitoring Systems for Wind Turbines Edition 201318) published by GL (Germanischer Lloyd) as an example. The scope and objects of application of the CMS for wind turbines are mainly the drive train, main bearings, gearboxes, and generators. In addition to these, the CMS also covers the tower, blades, main bearings, gearbox lubrication oil, foundations, and other parts of the wind turbine. Monitoring data for wind power generation equipment include load (power generation or torque), shaft speed, temperature in the nacelle, bearing temperature, generator winding temperature, oil temperature, and oil pressure. Other environmental data, such as wind speed, wind direction, and outside temperature, are also required to be measured when available.

Table 4.1 Ref.18) shows the number of sensors required for a wind turbine CMS. It states that at least six sensors are required to monitor the vibration state of the drive train of a wind turbine equipped with a gearbox. The required frequency bandwidth starts from fairly low speeds and has a wide range. Table 4.2 in Ref.18) shows a list of methods for using the signals acquired from each sensor in a wind turbine CMS. It requires the application of various analysis methods for each site in order to deal with frequencies, vibration modes, and corresponding anomaly modes.

6. Predictive Maintenance and IoT[19)]

This is a citation from the article “IoT for Predictive Maintenance” compiled by Mr. Sako, a long-time member of the ISO/TC 108/SC 5 National Committee, in 2020[19)].

6.1 Key Points for Building a Predictive Maintenance IoT System

Predictive maintenance is also called condition-based maintenance or condition monitoring maintenance. It is a maintenance method that uses diagnostics techniques to measure and monitor the condition of facilities and equipment to understand or predict the degree of deterioration and take appropriate maintenance measures. The key points of IoT include:

- selection of sensors for detecting anomalies,
- selection of optimal signal processing methods and analysis methods,
- determination of information collection methods,
- determination of monitoring methods,
- and automation of analysis and diagnosis.

Several development items are needed to promote IoT for predictive maintenance. Here, we take “visualization of equipment conditions (as quantitative values)” as an example. Technological development for visualization of facility conditions (as quantitative values) includes expansion of target facilities for anomaly detection, improvement of detection accuracy, and more efficient and easier detection. To this end, it is important to first clarify the equipment to be monitored, the failure mode, the required prediction level (lead time), the difficulty of stopping the equipment, and the time when the equipment can be stopped. At the same time, it is necessary to clarify the measurement location and available sensor types.

The procedure includes identifying a sensing method capable of detecting anomalies through laboratory testing and determining evaluation indices and threshold values for good or bad judgment through field testing using the same method. **Table 7** shows the application status of the diagnostic techniques developed by Sako et al. for rotating equipment[19)]. The diagnostic techniques have been comprehensively applied to a wide range of objects.

In his contribution[19)], Sako further describes in detail the diagnostic technologies for rolling bearings, plain bearings, and motor current symptom analysis (MCSA) for the IoT of predictive maintenance. Here, we will focus on “diagnostic technology for rolling bearings”.

6.2 Diagnostics techniques for rolling bearings for predictive maintenance

As shown in **Fig. 15**, rolling bearing anomalies generate vibration and sound in various frequency ranges[19)]. These can be roughly classified into two categories: structure-borne, such as vibration and AE (acoustic emission), and airborne, such as acoustic. Sound is further divided into audible sounds and inaudible sounds above 20 kHz.

6.2.1 Diagnostics using the vibration method[19)]

One of the signals used to diagnose anomalies in rolling bearings is vibration acceleration. This acceleration is further divided into two main categories: acceleration in the high-frequency range of 10 k to 30 kHz and acceleration in the low-frequency range of 1 k to 10 kHz.

Fig. 16 shows an example of bearing diagnostic results from the field. This is the acceleration spectrum of a 6310 deep groove ball bearing when false brinelling occurred in the inner ring due to propagating vibration from adjacent equipment. As shown in **Fig. 15**, a frequency of 14 KHz was generated in the zone indicated as high-frequency acceleration. This is an example of how even a small flaw could be detected by acceleration in the high-frequency range.

Fig. 17 compares the trends of acceleration values in the high-frequency range for the six cases that resulted in bearing failure. The average value in the normal state is set to 1.0. The vertical axis shows the ratio of the acceleration to the normal value, and the horizontal axis shows the time elapsed from the time when the condition began to change. Each bearing shows an exponential upward curve. It took three to six months to reach the relative standard of caution (4.0 times), and about six months for the anomaly to arise (8.0 times). When the bearings were replaced after about six months, small defects were observed. It is explained that the variations in the degradation speed of each bearing relates to differences in lubrication conditions and bearing load.

As deterioration progresses from this state, a low-frequency acceleration spectrum in the 2 k to 3 kHz range is generated in addition to the high-frequency acceleration. This is the natural frequency of the bearing outer ring. The explanation for this is that the progressive deterioration of the bearing results in a higher excitation force, which vibrates the entire bearing and generates natural frequencies. The trend of acceleration values in the low-frequency range was also investigated in four cases.[19)] As with the high-frequency range shown in **Fig. 17**, an exponential upward curve was drawn, leading to bearing replacement within approximately one to three months after the change was observed.

Furthermore, as bearing deterioration progresses, changes in vibration velocity also occur. A comparison of velocity trends in seven cases of bearing failure due to increased velocity shows an exponential increase curve similar to that in the high-frequency range. The change in velocity value is so rapid, however, about one or two weeks after the vibration velocity begins to increase, the bearing can be said to have reached a terminally degraded state that requires it to be replaced.[19)]

The conclusion is that although the residual life of bearings can be predicted in several frequency ranges, monitoring using acceleration in the high-frequency range may be essential for critical facilities where continuous operation must not be interrupted.

Table 7 Application of Diagnostic Techniques to Rotating Equipment[19)]

machine element		type of anomaly (example.)	vibration		lubricant analysis	temperature	AE	acoustics		electric current (MCSA)	applicable equipment
			vibration velocity	vibration acceleration				audible range	ultrasound		
rolling bearing	medium and high speed rotation	fatigue spalling	×	○	○	△	○	○	○	○	blowers, pumps, compressors, motors, etc.
		poor lubrication	×	○	○	○	○	○	○	○	
		wear	×	○	○	○	○	○	○	○	
		looseness/ rattle	×	○	○	×	○	○	○	○	
		seizing	×	○	○	○	○	○	○	○	
	low speed rotation (several hundred rpm or less)	fatigue spalling	×	×	○	×	○	×	○		agitators, extruders, rolls, paper machines, etc.
		poor lubrication	×	×	○	△	○	×	○		
		wear	×	×	○	×	○	×	○		
		looseness/ rattle	×	×	×	×	○	×	○		
		seizing	×	×	○	△	○	×	○		
sliding bearing		seizing	×	○ : Kepstrum	○	○	△				turbines, compressors, diesel engines, etc.
		rubbing	×	○ : Kepstrum	○	○	△				
		fatigue	×	○ : Kepstrum	○	×	△				
		contamination by foreign matter	×	○ : Kepstrum	○	×	△				
		oil whirl	○	×	×	×	×	×	×		
		oil whip	○	×	×	×	×	×	×		
gear		pitching	△	○	○	○	○	○	○	○	reduction gears, speed increasers, etc.
		spalling	△	○	○	○	○	○	○	○	
		scratching	△	○	○	○	○	○	○	○	
		meshing anomaly	△	○	×	×	○	○	○	○	
coupling		misalignment	○	×	×	×	×	×	×	○	
belt		slack	○	×	×	×	×	×	×	○	
		overstretching	×	×	×	△	×	×	×	○	
blade		imbalance	○	×	×	×	×	×	×	○	blowers, pumps, etc.
		rotating stall	○	×	×	×	×	×	×		ventilator
		surging	○	×	×	×	×	×	×		ventilator
		cavitation	×	○	×	×	○	○		○	pump
		contact	×	○ : Kepstrum	×	×	○	○	○	×	screw compressor
axis		bend	○	×	×	×	×	×	×		
		eccentricity	○	×	×	×	×	×	×		
Remarks			• AMD speed criteria	• AMD rolling bearing criteria • Noise reduction method for inverter motors	• SOAP method, ferrography method • Light transmission method (MD-410L: currently discontinued)	• Thermal imaging camera		• Non-contact measurement • Operation for moving equipment (LM Guide, etc.)		• Application to equipment for which vibration is difficult to measure (canned pumps, axial flow fans, etc.) • Measurement at power supply panels	

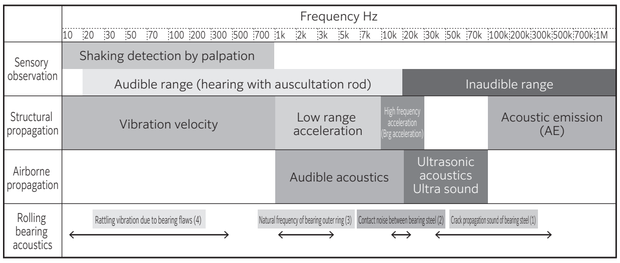


Fig. 15 Vibration and acoustics generated by rolling bearings[19)]

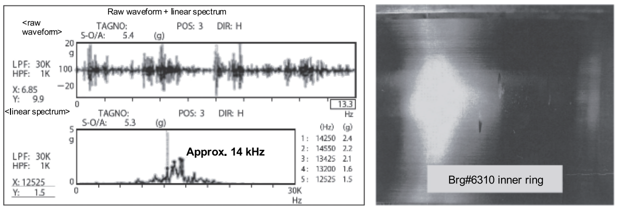


Fig. 16 Acceleration spectrum during false brinelling[19)]

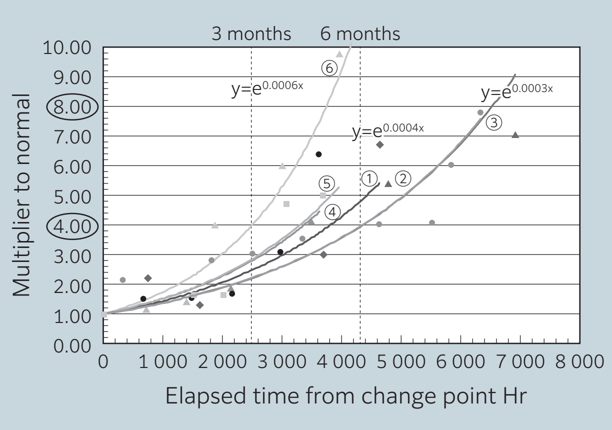


Fig. 17 Bearing degradation curve at high frequency range acceleration[19)]

6.2.2 Diagnosis by AE method[19)]

The AE method is the method that enables the earliest detection of anomalies in rolling bearings. **Fig. 18** shows the results of an accelerated life test at 750 rpm. The horizontal axis shows the test time, and the vertical axis shows the event rate for both AE and acceleration of vibration (ACC). AE captures rolling bearing anomalies earlier than the high-frequency accelerations shown in **Fig. 17**. The explanation given[19)] for this is that fatigue causes spalling on the bearing steel from its internal starting point, and as it progresses to the surface of the raceway, AE occurs at the time of the spalling occurring whereas acceleration occurs after the rolling elements have begun to collide with the spalling on the orbital plane surface. In the case of spalling with a surface cause such as that due to oil film rupture or indentation, the two occur almost simultaneously.

Fig. 19 compares the AE spectra of the exfoliation propagation and slit cracks. The AE spectrum of the exfoliation propagation has a prominent frequency component between 100 k and 500 kHz, whereas the AE spectrum of the slit flaw has almost no component above 100 kHz. Thus, AE can also capture the difference in anomaly modes of rolling bearings in the early stage.

The AE method is also superior in the low-speed speed range. In the low-speed range, where the product of bearing bore diameter d (mm) and rotational speed N (rpm) (dN value) is less than 2.0×10^4, the shock signal level of vibration acceleration decreases and is buried in the noise level, making it generally difficult to distinguish between normal and abnormal conditions. In contrast, the AE method is an effective measurement method because it is independent of rotation speed.

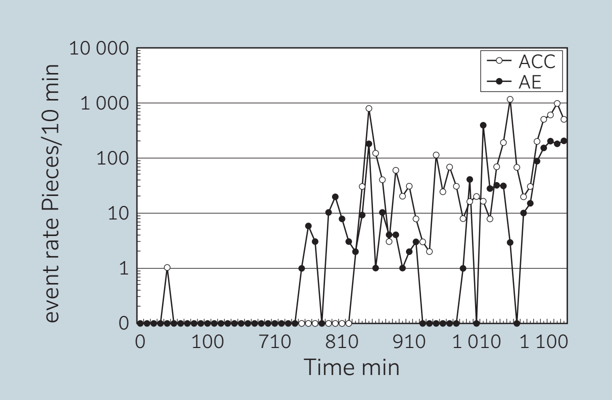


Fig. 18 Accelerated life test results and diagnosis by AE[19]

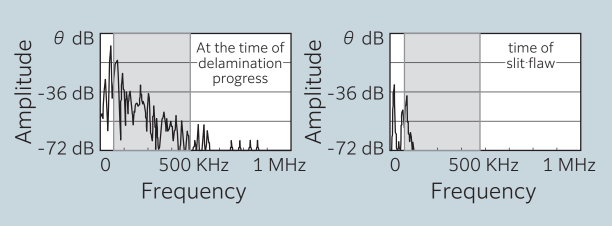


Fig. 19 AE spectra during exfoliation propagation and slit flaw[19]

6.2.3 Other[19]

The AE method requires a couplant to be applied between the equipment surface and the sensor surface. It is difficult to obtain a stable signal in cases where this is strongly affected by unevenness or curvature of the installation surface. For equipment that has conventionally been difficult to diagnose due to such drawbacks, the authors have developed a non-contact detection method using ultrasonic microphones. Using 20 k to 100 kHz ultrasonic acoustics, it has been shown that bearing separation anomalies can be detected in the same way as with the AE method, even at low rotational speeds of 65 rpm. The ultrasonic acoustic method was applied to detect rolling contact fatigue exfoliation of roll support bearings in a solvent gas environment where AE could not be used due to couplant leakage. In addition, AE is also used to diagnose abnormalities in low-speed rotating equipment, such as contact with the extruder body, pitching of reduction gear gears, and bearing rattling in agitators[19].

7. Trends in Condition Monitoring and Diagnostics Using 1DCAE

Kawai, a leading domestic expert who has been engaged in condition monitoring and diagnosis of machinery for many years in Japan, provides an introduction “On Diagnostic Methods for Equipment Using Physical Models – Application to Digital Twins”[21] in the opening article of the 2022 JSME Dynamics, Measurement and Control Division Newsletter. In this article, Mr. Kawai summarizes the process of incorporating 1DCAE software into the equipment diagnosis that he has been working on for many years. 1DCAE is a generic term for CAE methods and tools that have been rapidly spreading and developing in recent years and their design support concepts.[22] It can be applied from the upstream stage of product development because it accurately captures the fundamental nature of the target. It can be expressed in a simple and clear format and can be used for evaluation and analysis. The article explains how modeling the target system with 1DCAE software (in the case of this data, Modelica is used) is useful for equipment diagnosis, and shows examples of system and anomaly modeling **(Table 8)** that Mr. Kawai has been working on.

As a concrete example, the model of an electromagnetic brake is shown. It is explained that a system such as an electromagnetic brake, which combines complex physical phenomena consisting of dynamics, magnetic circuits, and electric circuits, can be easily modeled by the 1DCAE software **(Fig. 20)**. Here, it is explained that the wear of the armature increases the clearance between it and the plate, and that the resulting effects on other physical quantities can be simulated in a variety of simple ways. **Fig. 21** shows the effect of the clearance on the time variation of the current at the start of energization. In the same example, he states that the simulation and experimental results align very well. Thus, he argues, modeling the system and anomalies with 1DCAE software makes it easy to analyze the system behavior when anomalies occur in the system. The interested reader is advised to view the material, which is available free of charge from the department’s website.

Some examples of modeling of mechanical systems using 1DCAE software are shown below. Kashiwase et al.[23] modeled a capacitor motor using the magnetic circuit method and conducted an analysis using 1DCAE software (Modelica). A coupled system **(Fig. 22)** connecting an electric motor model and a rotating shaft model was used to perform a coupled simulation **(Fig. 23)** relating the vibration of the rotating shaft and the current of the power supply. This is expected to enable more detailed diagnosis of the electric motor.

Furthermore, Kashiwase et al. constructed a basic model for three-phase induction motors, which are widely used in plants, based on the magnetic circuit method, which consists of a stator, rotor, air gap, and other components, and a model that can be coupled with a rotating shaft[24]. The validity of the model using 1DCAE software was verified by comparing its electromagnetic behavior with FEM analysis, and the results showed promise for simulation application to electric motor diagnosis. **Fig. 24** shows the winding currents in each phase. Although the pulsation of the 1DCAE model (Modelica) is larger, it was confirmed that the overall behavior can be reproduced, according to the report.

Table 8 System and Anomaly Modeling Examples[21)]

target system	anomaly
control valve	biting, sensor offset
compressor	leakage
cogeneration system	decrease in efficiency, clogging, and heat transfer coefficient due to debris
crankshaft	bearing rattling
rotational axis system	rotor disproportion, bearing flaw, bearing rattling
coupling	misalignment, miscoupling
journal bearings	wear and its evolution (residual life estimation)
screw compressor	bearing rattling, leakage
electromagnetic brake	wear
gear mechanism	gear wear
3D printer	failure of fan for cooling (control in case of anomaly)

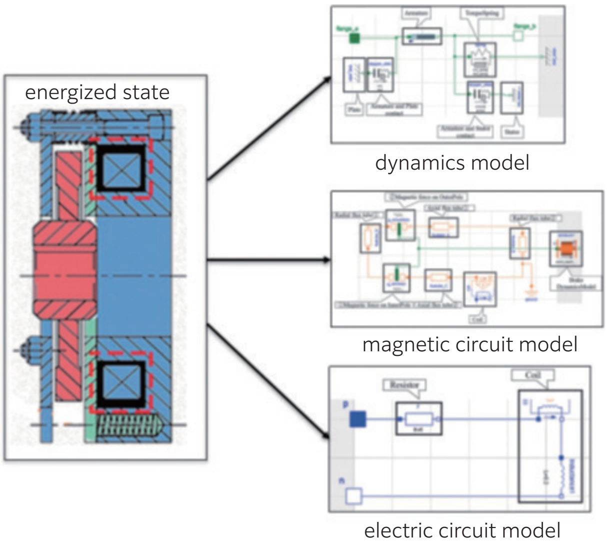


Fig. 20 Electromagnetic brake model[21)]

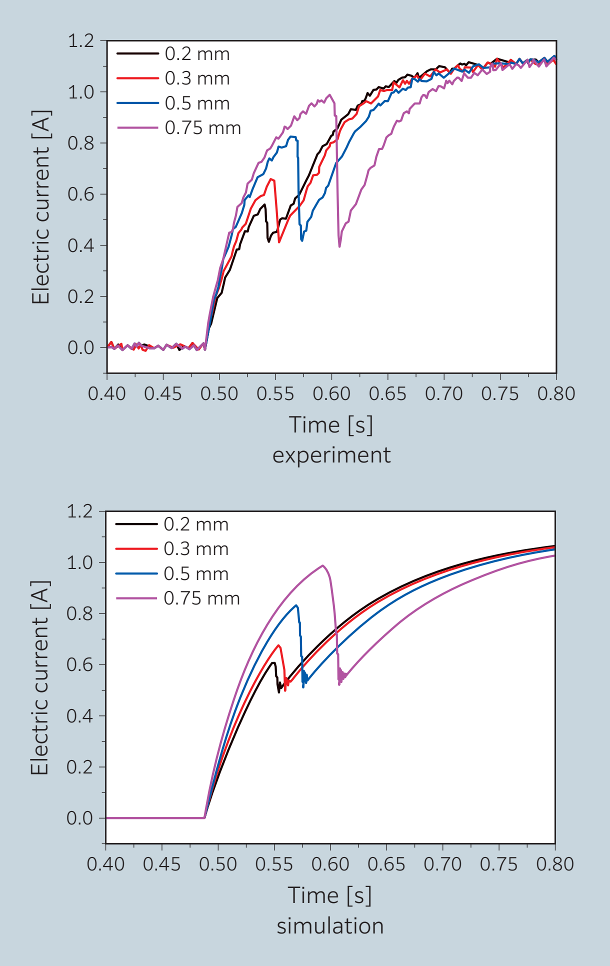


Fig. 21 Current change at the start of energization (effect of clearance)[21)]

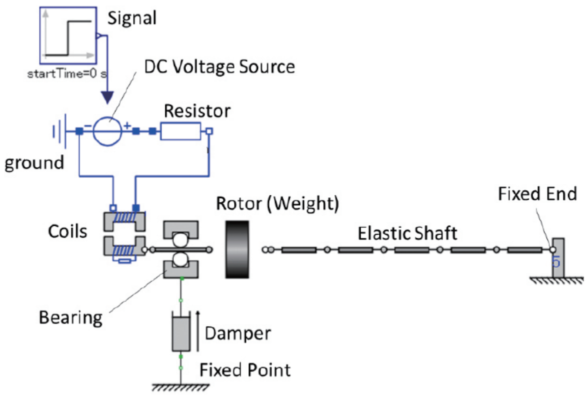


Fig. 22 Modelica model of motor and shaft system[23)]

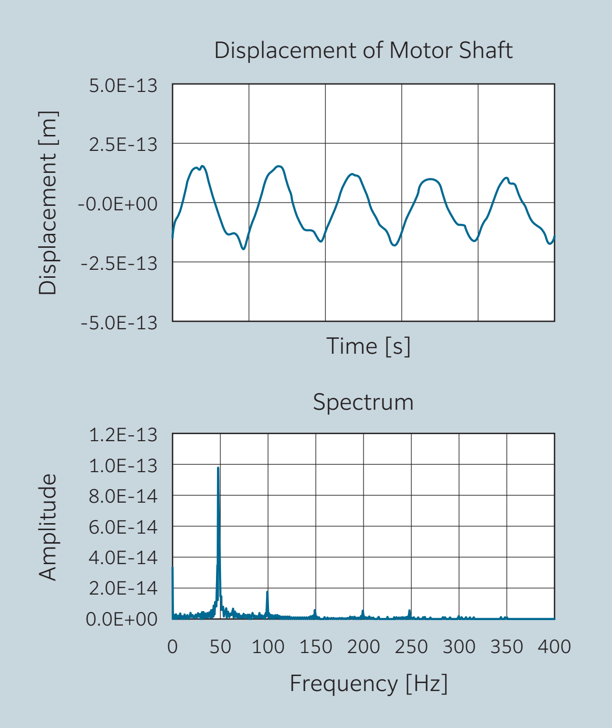


Fig. 23 Vibration analysis results of motor and shaft system[23)]

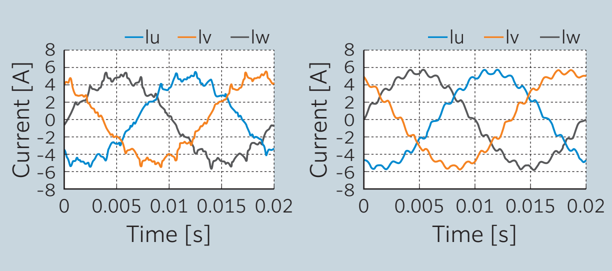


Fig. 24 Stator current (unsteady) (1DCAE and FEM)[24)]

Another study[25)] modeled gear pairs and gear tooth wear, which are typical power transmission mechanisms, using 1DCAE software (Modelica). The model was used to estimate how the vibration characteristics of the gear pair changed due to wear on the tooth flanks, and also to verify the results using actual equipment.

In this regard, modeling of mechanical systems using 1DCAE software has been used extensively in recent years. The results of 1DCAE modeling of various mechanical systems were presented in a cross-divisional OS organized at the 2022 annual conference of the Japan Society of Mechanical Engineers (JSME). As mentioned above, the use of 1DCAE software as a modeling method for condition monitoring and diagnosis of mechanical systems is expected to advance further.

8. Research Trends in Condition Monitoring and Diagnosis of Bearings in Japan

8.1 National Scientific Conference on Condition Monitoring and Diagnosis

Finally, I would like to review research trends in this field in Japan. In Japan, the representative academic societies for this field are the Japan Society of Mechanical Engineers, the Japanese Society for Non-Destructive Inspection, the Society of Plant Engineers Japan, and the Japanese Society of Tribologists. Among the conferences held by these academic societies are the Dynamics and Design Conference of the Dynamics, Measurement and Control Division of the Japan Society of Mechanical Engineers[20)] and the Symposium on Evaluation and Diagnosis, which is held jointly by the Dynamics, Measurement and Control Division of the Japan Society of Mechanical Engineers, the Society of Plant Engineers Japan, and the Japanese Society of Tribologists. Numerous condition monitoring and diagnostics research results are published every year.

The following is a list of articles and papers presented at these conferences over the past year or two, focusing on bearing-related topics.

8.2 Examples of AI-based diagnostic techniques

In the field of bearing anomaly diagnosis, there have been recent studies on the use of AI technology for intelligent and automated diagnostics techniques. Deep learning, with its high feature extraction capability has been garnering attention in the equipment diagnosis field in particular. In Japan, Maeda et al. have been working on AI-based bearing diagnosis. In one recent example, after removing noise from vibration signals measured for bearing diagnostics using a statistical information filter, the spectrum of the vibration signal was converted into a quadratic array (equivalent to image information). The method automatically performed feature extraction and state classification using a convolutional neural network (CNN), which is a type of deep learning[26)]. The results of various validation tests showed that the proposed method can achieve highly accurate automatic diagnostics of bearings even in noisy environments.

8.3 Examples of lubricant film evaluation techniques

Takeda et al. have verified the effect of differences in lubricant composition on bearing life by using a thrust ball bearing operating life test machine. The test observed the lifetime until the thrust ball bearing actually failed as a test piece. In addition, the effect of lubricant degradation on bearing life has also been verified by observing the thickness of the lubricant film after bearing failure in new oil and life tests using a lubricant film visualization system. Recently, as a new oil film evaluation method, an ECR (Electrical Contact Resistance) observation circuit was attached to the lubricant film visualization system **(Fig. 25)** to electrically evaluate and observe the oil film condition, and the observation principle and results were reported[27].

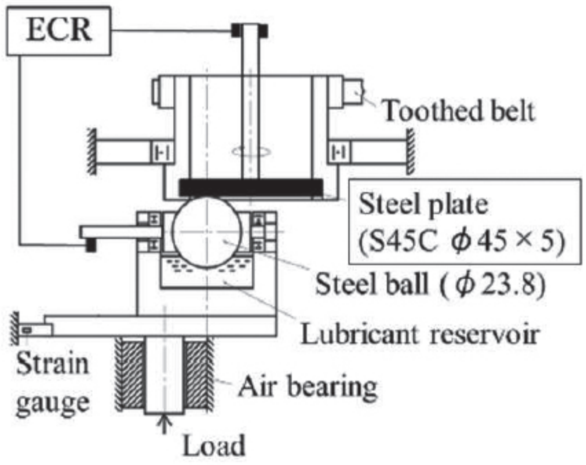


Fig. 25 Equipment for electrical evaluation and observation of bearing oil film condition[27]

8.4 Examples of diagnostic techniques using ultrasound and acoustics

Wakabayashi et al. reported the efficacy of the ultrasonic echo method for condition monitoring of bearings. They studied the early detection of anomalies in oil-lubricated bearings by applying autocorrelation analysis to the time variation of ultrasonic reflection intensity (URI). The higher the periodicity of the URI waveform, the better the rolling behavior of the bearing. Research has also been conducted recently into the applicability of the ultrasonic echo method to a grease-lubricated bearing (6210 deep groove ball bearing). It was shown that the method can detect rolling behavior inside the bearing during operation and grease removal and replenishment on the orbital plane in the actual working condition by performing two analyses based on autocorrelation for the time variation of the URI. In addition, methods were investigated for extracting periodicity of rolling behavior in URIs with low signal-to-noise ratio (S/N ratio), which is often obtained when diagnosing abnormalities in grease-lubricated bearings by ultrasonic echo method. A comprehensive method and a simplified method were developed as methods to improve multiple analyses by autocorrelation, and it was clarified that they were effective **(Fig. 26)**[28].

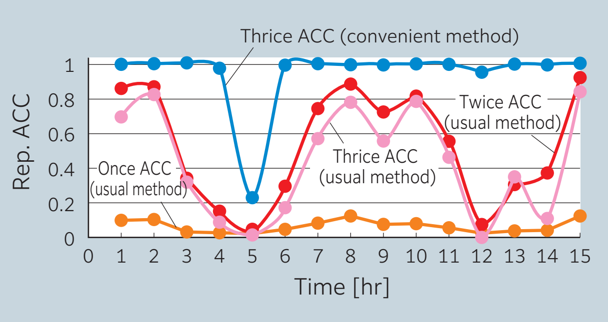


Fig. 26 Analysis of URIs with low signal-to-noise ratios using a simplified method to improve periodicity extraction of rolling behavior[28]

For highly accurate acoustic diagnosis of bearings, Takada has proposed a new method for improving the signal-to-noise ratio. Recently, he applied this method to failure detection of rolling bearings and confirmed its effectiveness.[29] In particular, the effectiveness of this method was demonstrated by applying it to operating conditions with low dN values, which are generally considered difficult to diagnose **(Fig. 27)**. Furthermore, the S/N ratio improvement method using an adaptive line enhancer, which is one of the adaptive signal processing methods, was used as a subject for comparison, which shows that the proposed method was effective.

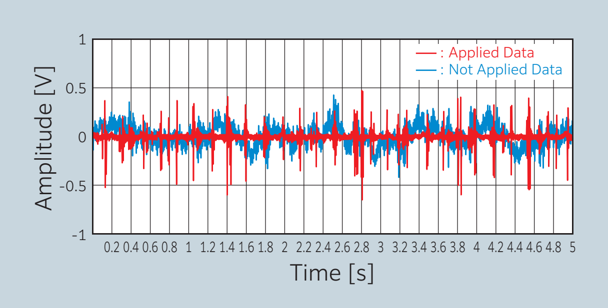


Fig. 27 Time series data obtained by applying the proposed method and an anti-aliasing filter (low-pass filter with a cutoff frequency of 40 [kHz]) to the measured rotating noise of a bearing with outer ring failure[29]

8.5 Examples of data collection techniques for initial failure processes

Conventional research into the diagnostics of bearings often involves scratching the inner or outer rings beforehand. In actual bearing condition diagnostics, however, it is necessary to detect the earliest signs of any anomalies that could eventually lead to failure. Inoue et al. focused on this point. With the aim of collecting bearing data from the normal state to the occurrence of failure in a time-efficient manner, they created a rotating device with a vibratory mechanism that can apply displacement of any frequency to the rotating shaft. They conducted vibration experiments on deep groove ball bearings as the targets for inducing failure[30]. Failure progression was evaluated using acceleration data from the normal state to the occurrence of initial defects **(Fig. 28)**. The degree of failure to the actual bearing was then confirmed by cut-off disassembly inspection.

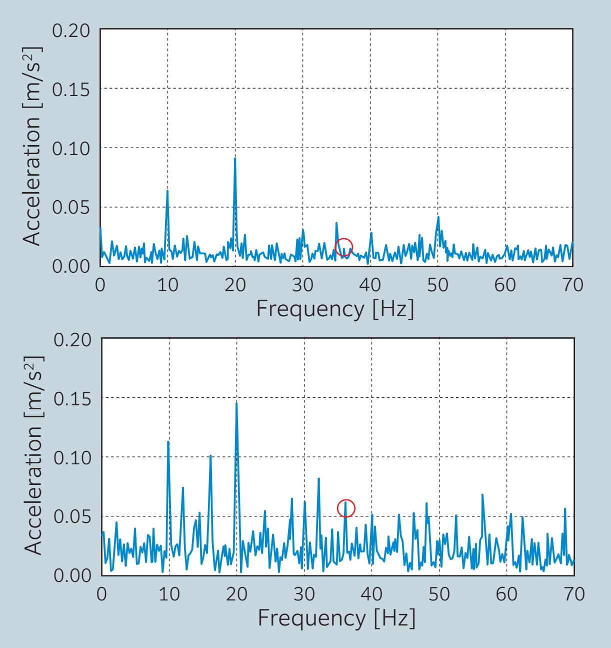


Fig. 28 Envelope spectrum of acceleration signal (upper) before vibration, (lower) after vibration[30)]

9. Conclusion

In this article, entitled “Trends in Condition Monitoring and Diagnosis of Mechanical Systems”, the author first describes the recent activities and trends in ISO/TC 108/SC 5 condition monitoring and diagnosis of mechanical systems with which he is involved[1)]. Those interested to know more about the historical background to this subject may refer to the series of documents [31)-34)] compiled by the TC 108/ SC 5 National Committee Chairman at that time. Going forward, the international standardization of condition monitoring and diagnosis of bearings is expected to continue. It will develop along with the standardization of condition monitoring asset management in connection with the standardization of individual machines. We look forward to continued cooperation from all parties concerned.

Next, the status of condition monitoring and asset management in Japan and overseas is described, with a focus on the IoT. This field is expected to be one of the biggest areas of development globally in the field of condition monitoring and diagnosis. The paper describes IoT-based condition monitoring and diagnostics and predictive maintenance in wind power generation projects. With the wind power generation business undergoing full-fledged development in Japan with the installation of large floating offshore wind turbines, condition monitoring techniques that involve linkage to a digital twin are being developed. We look forward to seeing the development of these fields in Japan.

In addition, the author also focuses on the trend of condition monitoring and diagnosis using 1DCAE modeling of target machines in relation to the condition monitoring technology using the digital twin described above. This field is also being actively researched in Japan, and its future trends will be worth watching.

Finally, the research and publication trends in the field of bearing condition monitoring and diagnostics in Japan are described. Recently, the published proceedings of academic conferences have tended to be extremely short. This makes it necessary to actually visit the conference and listen to live presentations. In the wake of social distancing measures adopted during the COVID-19 pandemic, academic conferences are adopting hybrid formats of online and face-to-face meetings. I hope that there will be a resumption in people visiting academic conferences, exploring the latest trends, and engaging in lively exchanges with researchers and technicians in various fields.

The above is an introduction to the trends in condition monitoring and diagnostics of mechanical systems in the direction of this author’s interest and concern, which it is hoped may be of some reference. The author wishes to thank the Japanese Society for Non-Destructive Inspection for granting permission to include the citation in the first half of this paper[1)]. For providing information in the latter part of this paper, I would like to express my gratitude to Mr. Hitoshi Sakakida, ISO/TC 108/SC 5 committee member and formerly of Toshiba Corporation, Mr. Keita Ishimitsu of JERA Co., Inc, Mr. Takashi Sako, formerly of Asahi Kasei Corporation, to the Japan Institute of Plant Maintenance, and to Professor Tadao Kawai of Osaka Metropolitan University.

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Author Profile

Tsuyoshi Inoue

Ph.D. Professor, Department of Mechanical Systems Engineering, Graduate School of Engineering, Nagoya University

Academic and professional background

1993	Completed master’s program in Electronic and Mechanical Engineering, Graduate School of Engineering, Nagoya University
1993-1995	Okuma Corporation
1995-2001	Assistant Professor, Faculty of Engineering, Nagoya University
2000	Doctor of Engineering (Nagoya University)
2001-2005	Lecturer, Graduate School of Engineering, Nagoya University
2004-2012	ISO / TC108 / SC5 National Committee Secretary
2005-2012	Assistant Professor, Graduate School of Engineering, Nagoya University (renamed Associate Professor in 2007)
2012 - Present	Professor, Graduate School of Engineering, Nagoya University
2012 - Present	Chair, ISO / TC108 / SC5 National Committee
2013 - Present	Chairman, Multibody Dynamics Council
2017 - Present	ASME Journal of Computational and Nonlinear Dynamics Associate Editor
2018 - Present	Director, Creation Plaza, School of Engineering, Nagoya University
2018 - Present	Delegate, Turbomachinery Society of Japan
2021 - Present	Vice-Chairman, Standard Project Committee, Japan Society of Mechanical Engineers
2022	Head of the Dynamics, Measurement and Control Division, Japan Society of Mechanical Engineers

Specialties

- Mechanical mechanics, vibration engineering, nonlinear dynamics, vibration control
- Explanation and use of vibration phenomena, in particular those caused by nonlinearity

Academic societies

Japan Society of Mechanical Engineers, Turbomachinery Society of Japan, Japan Society for Design Engineering
The Japanese Society of Tribologists, ASME

Major awards and commendations

Fiscal 2000	Japan Society of Mechanical Engineers Japan Society of Mechanical Engineers Award for Encouragement of Research
Fiscal 2006	The Japan Society of Mechanical Engineers, Dynamics, Measurement and Control Division, Division Contribution Award
Fiscal 2013	Turbomachinery Society of Japan Award (Technology Award)
Fiscal 2016	Turbomachinery Society of Japan Award (Best Paper Award)
Fiscal 2018	Project Award, Tokai Branch, Japan Society of Mechanical Engineers
Fiscal 2019	Turbomachinery Society of Japan Award (Best Paper Award)
Fiscal 2020	Tokai Branch Distinguished Service Award, Japan Society of Mechanical Engineers
Fiscal 2020	25th Engineering Education Award, Japan Society for Engineering Education
Fiscal 2021	Turbomachinery Society of Japan Award (Best Paper Award)
Fiscal 2022	Japan Society of Mechanical Engineers (JSME) Medal for Outstanding Paper (2 papers)
Fiscal 2022	The Japan Society of Mechanical Engineers (JSME) Standard Project Award Contribution Award