

Digital Twin Technology to Achieve High Reliability and Low Cost in Full-Scale Testing of Aircraft



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When developing new aircraft, it is necessary to conduct, at the final stage, static strength testing and fatigue testing for the entire aircraft structure and verify and ensure its strength performance. In fatigue testing, aircraft loads corresponding to multiple flight patterns are repeatedly applied from several thousands to several tens of thousands of times, using more than one hundred different types of loading equipment. Interruptions of the test due to abnormalities caused not only in the test piece, but also the equipment being tested, results in longer lead times for development. This report presents a case of digital twin technology applied to a loading equipment as a system for the early detection of abnormality signs in equipment to minimize delays in testing. Using such systems, it becomes possible to conduct testing with enhanced reliability.

1. Introduction

Aircraft are developed based on the concept of building blocks as shown in **Figure 1**. Specifically, material testing, element testing, component testing and full-scale testing are performed to evaluate and ensure the strength performance of the product that is being developed. In full-scale testing, which comes last, the following two tests are carried out: static strength testing in which the ultimate load, 1.5 times higher than the limit load, is applied to validate the integrity and fatigue testing in which aircraft loads corresponding to multiple flight patterns based on the expected operations are repeatedly applied from several thousands to several tens of thousands of times to verify the fatigue strength. As the period of fatigue testing is long, interruption in the middle of the process owing to test piece or equipment abnormalities significantly affects the lead time for development. Among the equipment used in testing, we focused on the loading equipment, the number of which used in a single test can total more than one hundred. Digital twin technology using physical models was employed to build a system enabling the early detection of abnormality signs in the loading equipment and the identification of their locations and the developed system was actually used in testing. This report presents the results of this application, as well as a monitoring system in which a wireless measurement system is used to detect abnormality signs of the jigs attached to the test piece for load application.

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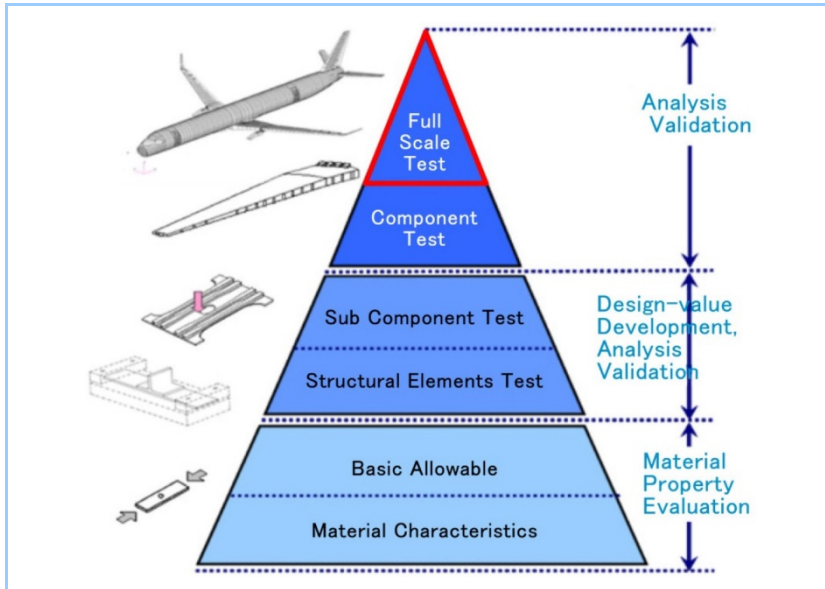


Figure 1 Building blocks for aircraft development

The figure indicates that full-scale testing is conducted as the final verification test.

2. Abnormality sign detection system using digital twin technology

2.1 Digital twin system overview

As shown in **Figure 2**, the digital twin system, the applicability of which is under discussion in this report, represents each of the more than one hundred of loading equipment (actuators) used in full-scale testing. In this system, individual actuators are created by mathematical models (non-linear equations of motion). The internal state of these mathematically-modeled actuators is continuously estimated and the mathematical models used are kept updated in such a way as to minimize the difference between the measured values for a given input command (i.e., measurement data of load and displacement sensors) and the estimated values calculated by the mathematical models (load and displacement). Considered within the mathematical models, the internal state is estimated based on the flow coefficient, which strongly correlates with dysfunctional spool valves of hydraulic actuators and the friction force, which is strongly correlated to cylinder seizure or the deterioration of sealing elements. The internal state, which gradually changes with factors such as time-related changes, can thus be recorded numerically. This enables abnormality signs to be identified by monitoring whether the recorded value exceeds the preset threshold value. An unscented Kalman filter was used to estimate the state in the system, because non-linear problems can be solved without linearizing a non-linear function and it was suitable for online calculation.

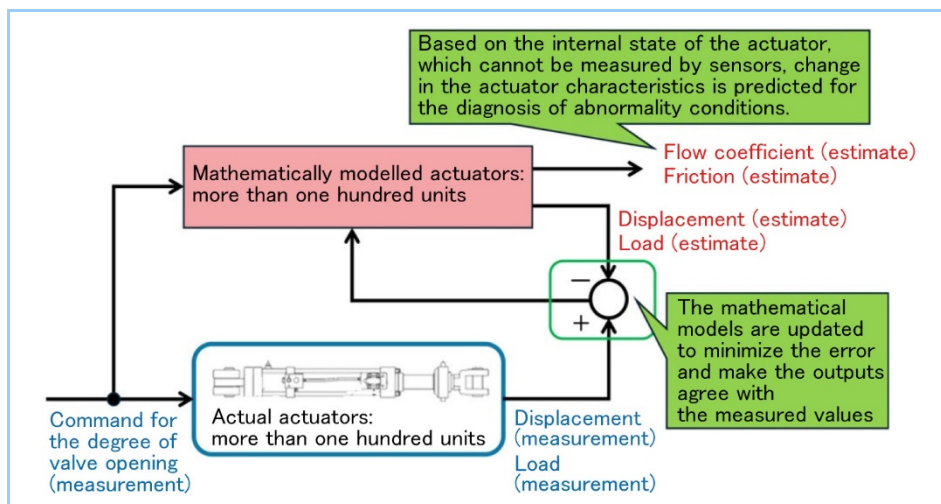


Figure 2 Digital twin system overview

The figure shows the flow of data processing in the digital twin system with regard to actuators (test equipment).

2.2 Configuration of the abnormality sign detection system

Figure 3 shows a system configuration for abnormality sign detection. A full-scale testing network mainly consists of the test equipment, control unit, data collection unit, server and PC for test control. With the addition of a digital twin system-enabled PC for monitoring, data are sent and processed every time one cycle of the test is completed, thereby monitoring whether any abnormality values are observed.

As shown in **Figure 4**, the information displayable on the monitoring screen includes the normal or abnormality status of each actuator installed on the aircraft (e.g., normal: yellow, warning: pink and critical: red), the load being applied, the length of cylinder stroke and the temporal change of estimated values for the internal state of mathematically-modelled actuators. The screen display has been made visually easy to notice abnormality conditions when they occur. In particular, with regard to the estimated values of the internal state, importing past test data makes it possible to check on how it has changed with time, helping to understand the tendency of abnormality occurrence.

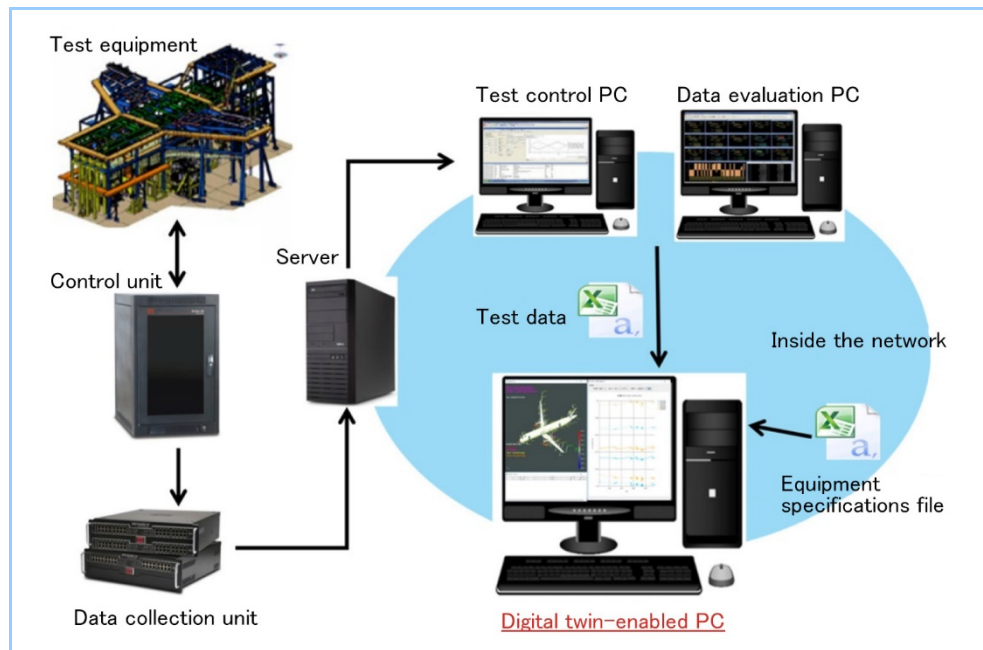


Figure 3 Configuration of the abnormality sign detection system

The figure shows the positioning of digital twin system in the abnormality sign detection system in full-scale testing together with the flow of data processing.

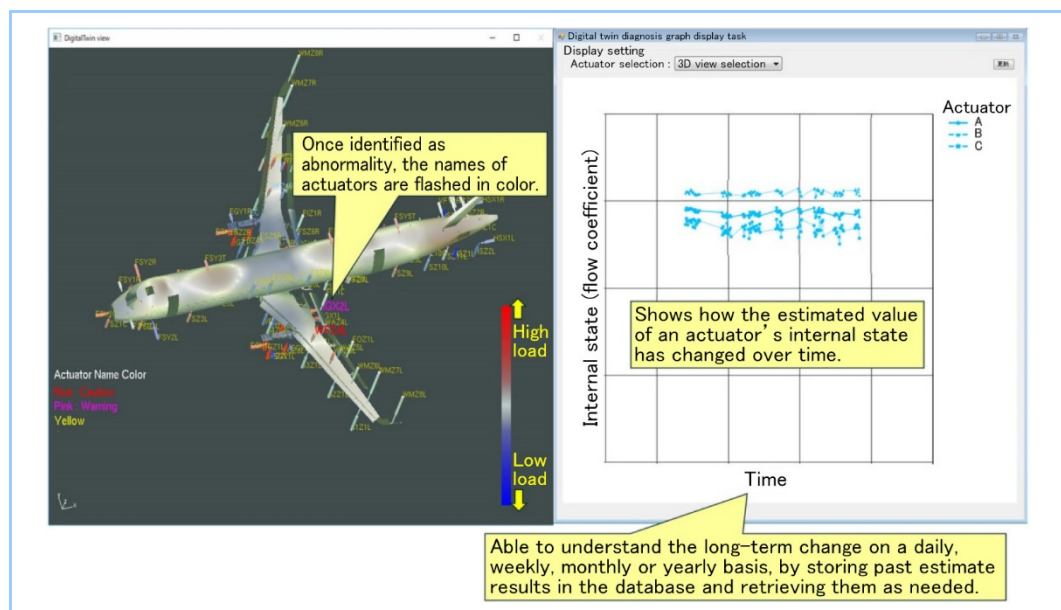


Figure 4 An example screen display of the digital twin system

The figure gives an actual example of the digital twin system showing the display state and the trend of the internal state of an actuator with an abnormality.

2.3 An example of detected abnormality conditions

After the digital twin system was introduced, no abnormality events occurred as a result of the change in the internal state of actuators, as originally anticipated. However, as shown in **Figure 5**, the system identified a temporary failure of a sensor (loosened connectors) as an abnormality condition, thereby demonstrating its capability of detecting abnormality signs at an early stage even if they were not caused by changes over time.

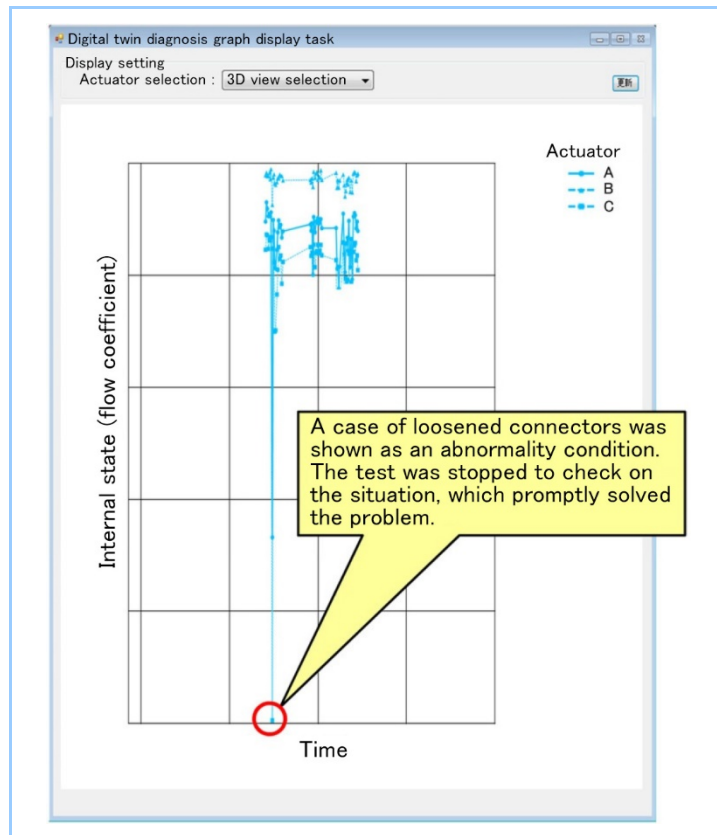


Figure 5 An example of detection of abnormality conditions

The figure shows a case in which the digital twin system detected abnormality conditions resulting from loosened connectors, instead of changes in the internal state.

3. Wireless measurement monitoring system

3.1 Wireless measurement system overview

The main purpose of the aforementioned digital twin system is to detect abnormality signs based on the estimated internal state of actuators. As shown in **Figure 6**, in the case of load application in full-scale testing, the loading jigs are attached to the test piece to transfer load on to it and the load is induced by actuators that are connected to these jigs. As it is not possible to directly bolt the jigs to the test piece, a rubber pad is adhered and sandwiched between the test piece and a mounting plate to which a jig is connected using mounting bolts. Long-term testing has the risk of causing issues such as the degradation of adhesion strength, as well as the loosening of mounting bolts. The monitoring system described in this section, therefore, aims to detect such abnormality signs (based on the change in the displacement).

While the stroke of an actuator can be used to monitor the overall displacement of a loading jig, it is not sensitive enough to measure extremely small changes caused in the aforementioned adhered parts and bolted joints. Therefore, a clip gauge was introduced as shown in **Figure 7**, thereby enabling the detection of minute changes on the order of several tenths of millimeters. To make it possible to install wherever monitoring is considered necessary, a wireless measurement system with a wireless logger as shown in **Figure 8** is employed for data collection. This eliminates the necessity of work for cable connection between a sensor and the measurement device, which is otherwise necessary for every installation. Prompt start of monitoring has thus become possible.

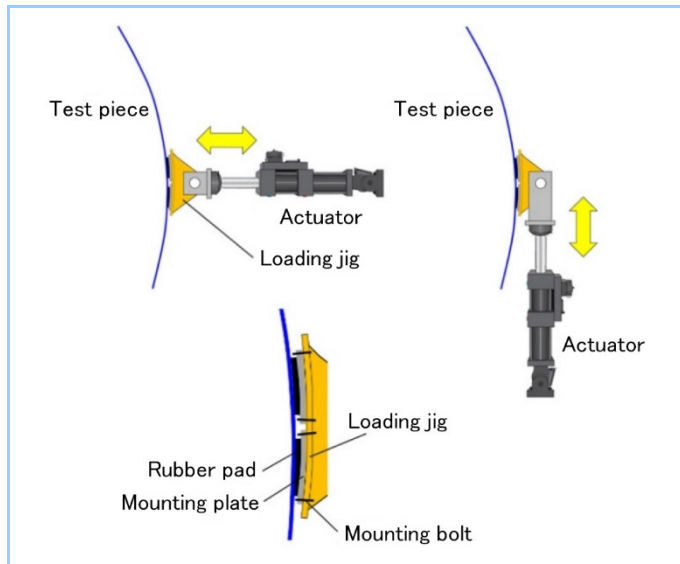


Figure 6 Illustration of the structure of load application to the test piece

The figure shows the mechanism of transferring load on to the test piece via the loading jig and a rubber pad from the actuator.

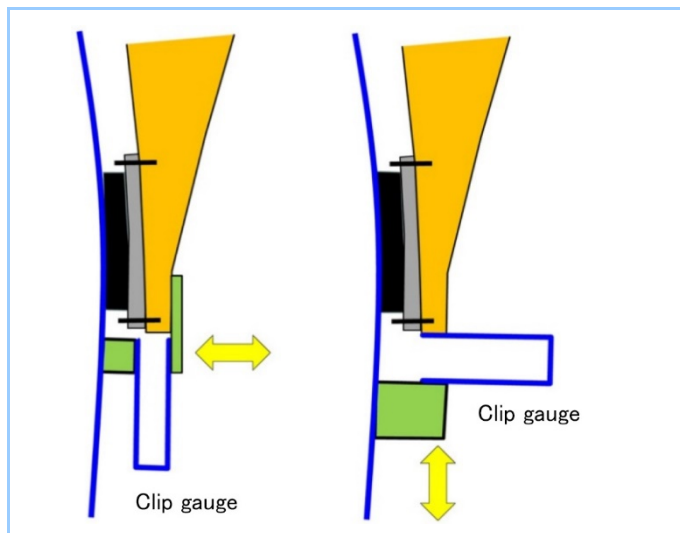


Figure 7 How to install a clip gauge

The figure shows an example of how to install a clip gauge for the measurement of minute changes in different directions.

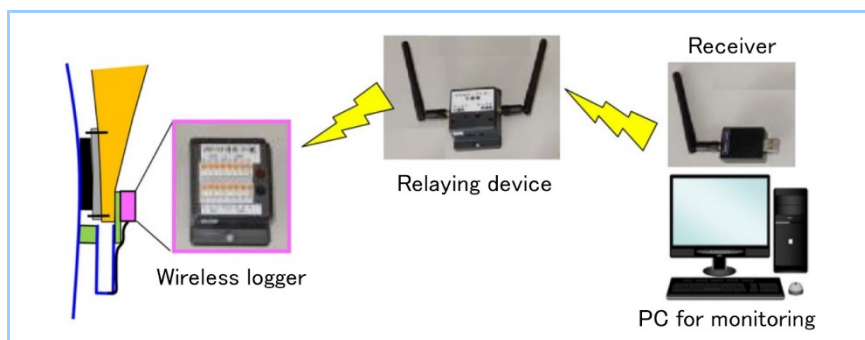


Figure 8 Monitoring system configuration with a wireless logger

The figure illustrates a monitoring system consisting of the wireless logger, relaying device and receiver.

3.2 Abnormality sign detection method by the monitoring system

In full-scale testing, aircraft loads corresponding to multiple flight patterns are repeatedly applied from several thousands to several tens of thousands of times. Monitoring was conducted regarding the flight patterns for which the loads were frequently applied in testing. For this purpose, we adopted a system in which abnormality signs are detected by monitoring the rate of

change in displacement as shown in **Figure 9**. Compared with the unaffected starting state at the initial stage of testing, a series of displacement changes during the first application of load are used to calculate the difference between the maximum and minimum values (i.e., amplitude) and the obtained amplitude is set as the reference value. Whenever load is applied for the Nth time, the amplitude is calculated and the rate of its deviation from the reference value is assessed to examine the conditions for abnormalities. Setting a threshold value for the rate of deviation enables the alarm to sound automatically when abnormality signs are detected.

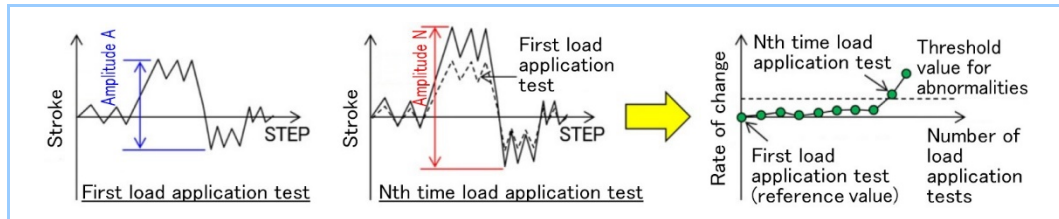


Figure 9 Conceptual diagram of how to detect abnormality signs based on the change in displacement

The figure shows how abnormality signs are detected based on the change in the amplitude of displacement using the test results of repeated applications of the same load pattern.

3.3 An example of detected abnormality conditions

After the displacement monitoring system was introduced, no abnormality events occurred as a result of the change in the displacement of actuator stroke or clip gauge. As a reference, **Figure 10** gives an example of a case in which abnormality signs were detected, when loosening of the adhered parts and bolted joints between the test piece and the loading jig was intentionally induced prior to the official introduction of the system. This has demonstrated that testing can be effectively stopped by the monitoring system, when the rate of deviation exceeds the preset threshold after being increased slightly by gradually-increasing degree of loosening of the joints by judging the test result as abnormality.

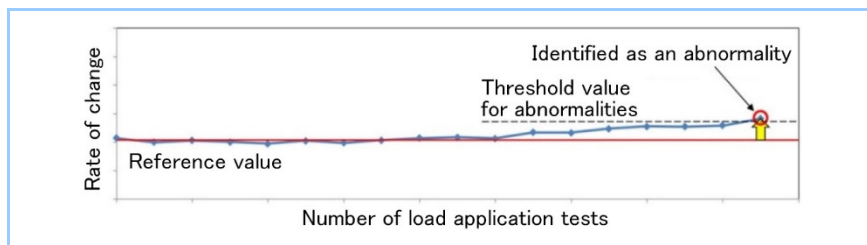


Figure 10 An example of detection of abnormality signs by the monitoring system

The figure shows the results of a case conducted to assess the accuracy of detection under the intentionally induced abnormality conditions, before the system was officially introduced.

4. Estimation of the effect of test process shortening

After the aforementioned abnormality sign detection system was introduced in actual full-scale testing, no serious events were detected. However, it has been indicated that the early detection of abnormality signs by the system can shorten the process of full-scale testing by nearly 10% within the test period covered by this test, when compared with the entire process containing the interrupted periods which were referred to estimation based on past cases, as shown in **Figure 11**. When the scheduled test period is longer, the probability of the occurrence of equipment abnormality is expected to increase and as a result the effect can be greater.

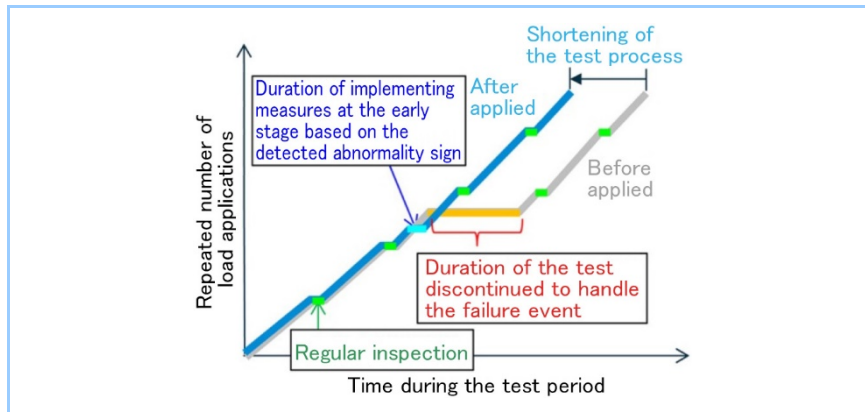


Figure 11 Shortening effect on the test process by application of abnormality sign detection system.

The figure illustrates a shortening effect of the system on the test process, when compared based on past cases. In the case of the full-scale testing in this report, it has been indicated that the use of the system can shorten the test process by nearly 10% within the test period covered by this test.

5. Conclusion

This report summarizes the abnormality sign detection systems for the long, continuously operating test equipment in full-scale fatigue testing conducted in the process of developing aircraft. Their demonstrated effectiveness for the detection of abnormality signs by this system was also presented. The two systems described in this report are the digital twin system to detect abnormality signs shown by the internal state of actuators and the wireless measurement monitoring system to identify an extremely small, but abnormality change in the displacement of loading jigs. The digital twin system can be deployed with the actuator information, load and stroke measurement data. The wireless measurement monitoring system is applicable without cabling work, if sensor installment is spatially allowable.

In this testing, in addition to these two systems, various other types of monitoring systems such as hydraulic power unit monitoring and actuator hydraulic valve monitoring are also employed as precautions for long-term continuous operation, in order to execute testing in a stable manner. While promoting the adoption of these systems for similar tests, we will further improve the reliability and cost effectiveness, as well as continue to develop technologies to help realize a shorter lead time for development.