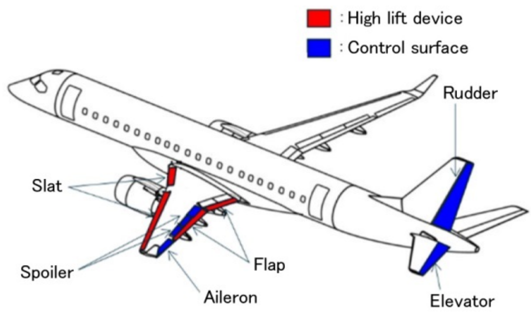
Structure-Mechanism-Control Coupled Large-Scale Analysis for Streamlining of Full-Scale Structural Test



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Aircraft, which are subject to various loads during operation, must fly safely with controllability and redundancy ensured, even under the harshest expected conditions. On the other hand, it takes a significant amount of time and risk to verify by flight tests whether the control surfaces can be operated normally in the presence of a gust and whether the aircraft can continue to fly safely even if a failure occurs during flight. Mitsubishi Heavy Industries, Ltd. (MHI) developed large-scale ground test equipment that can simulate the above conditions and narrowed down the test conditions using the large-scale analysis technology introduced in this report. As a result, we were able to obtain the prospect of completing verification testing in a short period of time. By applying this structure-mechanism-control coupled large-scale analysis technology, it is possible to efficiently evaluate airframe performance in similar developments and to streamline the verification test and accelerate the development process.

1. Introduction

Aircraft must fly with controllability ensured even under various loads caused by steep turns and gusts. Therefore, it is necessary to verify with actual aircrafts that the control surfaces and control system devices can operate normally without interfering with the peripheral structure—while the main wing and airframe are deformed by the maximum aerodynamic load—and that flight safety can be maintained even if a failure occurs, by detecting the failure, notifying the pilot and activating redundant systems. It takes a significant amount of flight time and effort to verify these factors in flight tests. MHI developed full-scale ground test equipment that can evaluate the control surface operating performance and streamlined the test using large-scale analysis technology. As a result, we were able to obtain the prospect of completing actual-aircraft verification in a short period of time. This report introduces this development

2. Full-scale control surface operation test equipment

In order to simulate various movements and flight conditions during flight, we developed the mechanism shown in **Figure 1** that simulates aerodynamic loads according to the angle of the control surface and applies the loads. In order to be able to apply the load to the control surface following the bending deformation of the main wing, the test equipment was configured so that the load-applying jig was not fixed to the ground, but installed on the main wing. In particular, for slats and flaps, which are called high-lift devices and expand the control surface greatly back and forth during takeoff and landing, we developed a mechanism that combines positioning actuators and load-applying actuators so that aerodynamic loads can be simulated according to the load application point and position. Ailerons, spoilers, rudders and elevators used for the control of airframe motion have an around-the-hinge uniaxial rotary motion mechanism and require high operating speed and responsiveness, so we designed their load-applying devices with an emphasis

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on light weight and high responsiveness.

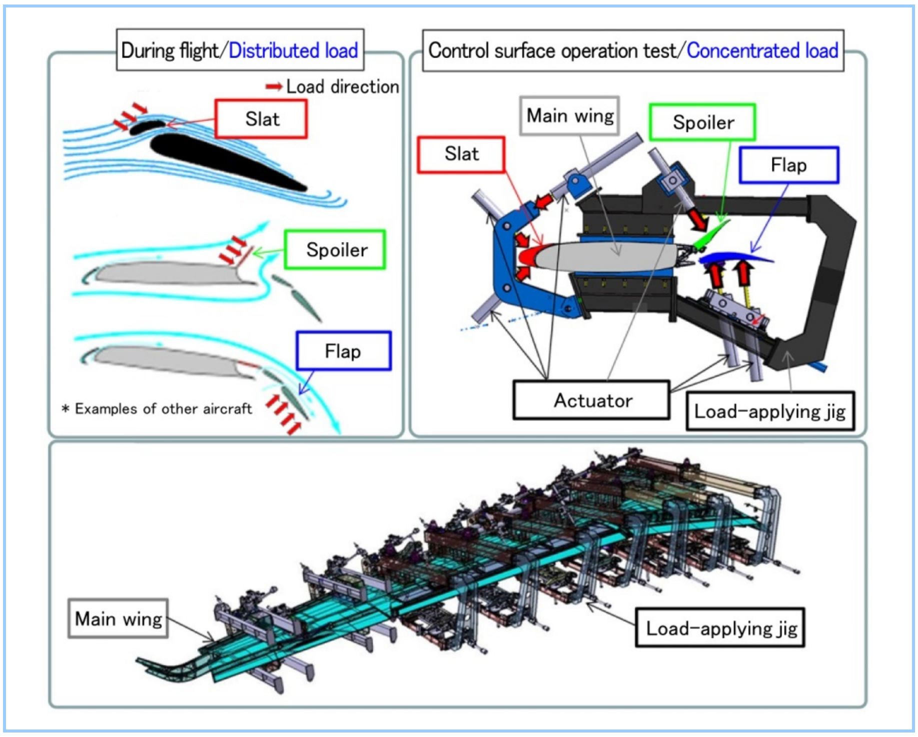

Figure 1　Overview of full-scale structure test equipment
A ground test simulates the distributed load during flight with the concentrated load applied by load-applying actuators. This figure gives an overview of the test equipment developed in consideration of the angle of control surfaces and the link mechanism for applying load appropriately in cases where the main wing is deformed.

3. Structure-mechanism-control coupled large-scale analysis

In order to couple simulations of structure, mechanism and control, we built the system shown in **Figure 2** that uses the Adams mechanism analysis software as a platform to analyze structural deformations using Nastran and to simulate the dynamic characteristics of actuators using MATLAB. We further developed a method to perform simulation considering the effects of mechanical gaps and friction with Adams by using the built system to perform coupling. This made it possible to express the coupled behavior of deformation, motion and control that changes from moment to moment and with the development of calculation environment and analysis technology, calculation and evaluation could be made in a shorter amount of time than before. As a result, the execution of a parameter survey aimed at reducing the number of test cases described later was made possible.

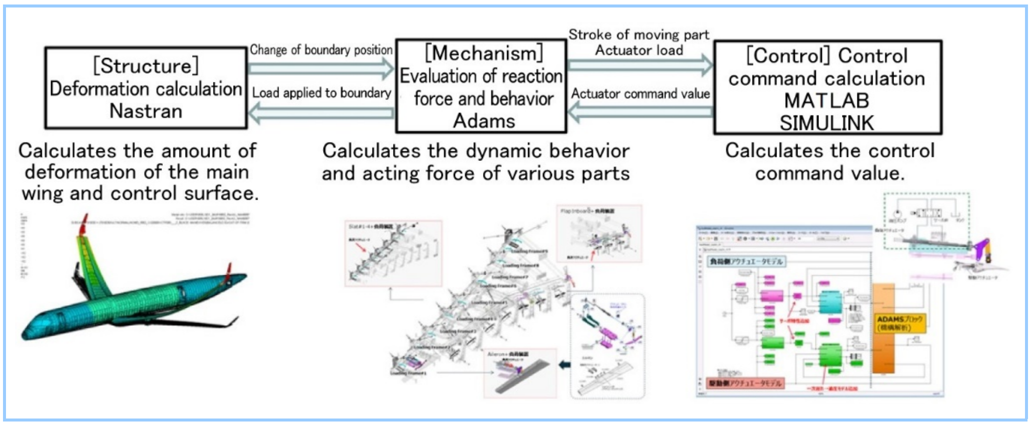

Figure 2　Structure-mechanism-control coupled large-scale analysis
We utilized structure-mechanism-control coupled analysis to develop full-scale ground test equipment.

4. Control surface operation test

We conducted control surface operation tests for the following two purposes and evaluated the performance of the actual aircraft.

(1) Operation test

Demonstrates that the control surfaces operate normally under flight conditions (with the airframe deformed).

(2) Failure mode test

Demonstrates that if a control surface actuator failure occurs, it can be detected and the flight can be kept safe.

The following is an example of the test results of the operation test. **Figure 3** shows the amount of deformation resulting from a test in which a concentrated load was applied to the main wing with a load-applying jig to simulate the behavior of the main wing bending upward due to lift during flight, as well as the analysis results. It can be seen from this figure that the difference is 5% or less, which indicates an accurate match.

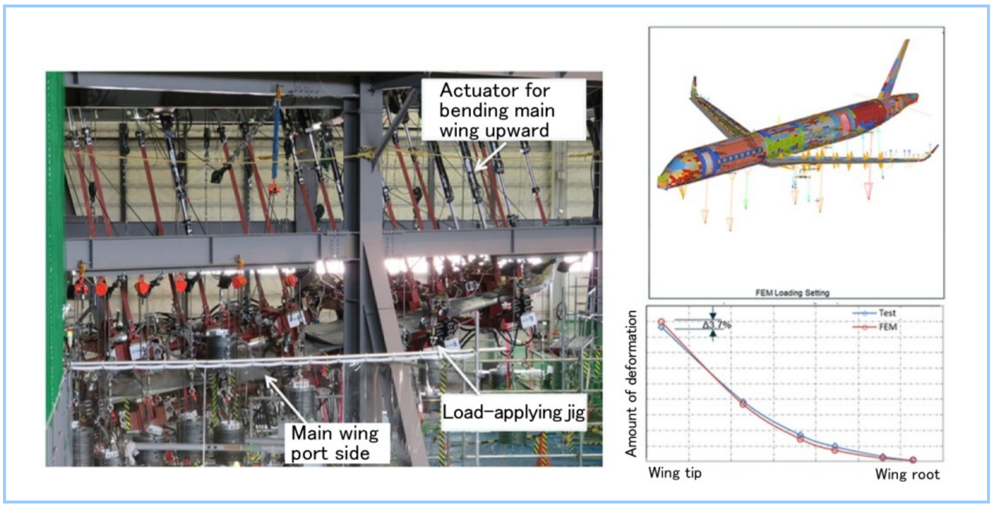

Figure 3 Comparison of test and analysis results of upward bending deformation of main wing

It was confirmed that the test and analysis results of the amount of main wing deformation under the boundary condition where the control surface operation test equipment was mounted on the main wing match with the difference of 5% or less.

Next, the results of the aileron control surface operation test and mechanism analysis are described below. As shown in **Figure 4**, the analysis used the aileron control surface structure modeled with an elastic body, modeled reaction force and frictional force acting on the joint with the main wing and the bearing of the actuator moving part and considered the dynamic characteristics of the actuator for the model. As a result, it was confirmed as shown in **Figure 5** that the analysis can accurately reproduce the deformation of the control surface and the actuator load. From these comparison results, it was confirmed that the behavior of the actual aircraft can be reproduced with high accuracy by the developed analysis method.

It was also demonstrated in the control surface operation test that the control surface operates normally when the main wings and the airframe are deformed under flight conditions. We worked on improving the analysis accuracy by performing careful comparison and accuracy verification of the test data and the structure, mechanism and control analysis results one by one, in order to make it possible to predict how deformation and posture change occur when a load is applied to the airframe, how many seconds it takes for a control surface to reach the target angle after the pilot issues a command, how do the hydraulic pressure, the response of electric equipment, the friction of various bearings and the mechanical loss affect things at that time and how the actuator load and the control surface deformation/response change, etc.

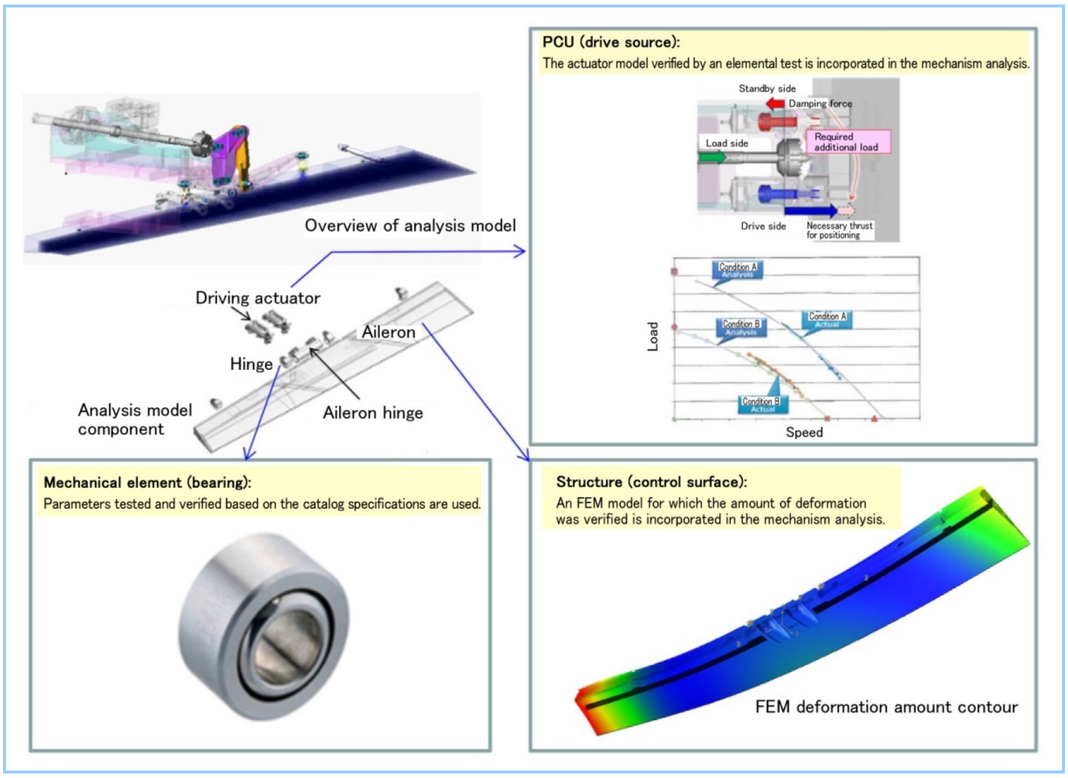

Figure 4 Mechanism analysis model (example: aileron)
For the aileron mechanism analysis model, the control surface structure was taken from FEM as an elastic body and for the hydraulic dynamic characteristics, the basic data and mathematical model of a single unit were taken from MATLAB. The coefficient of friction of the bearing used in the control surface rotating mechanism was repeatedly tested and verified based on the catalog specifications.

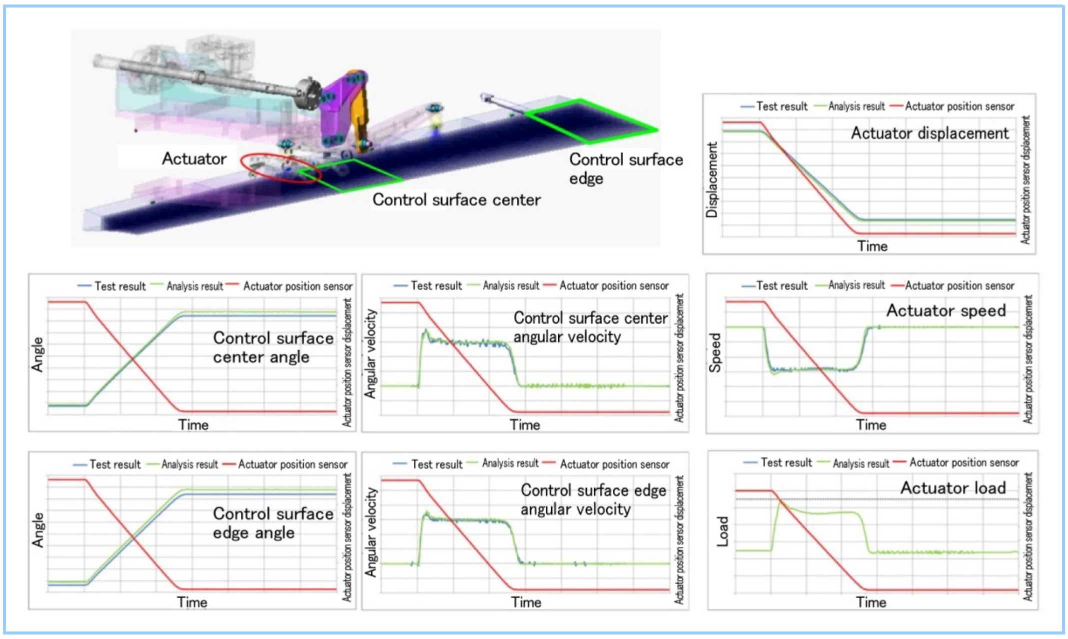

Figure 5 Comparison of results of control surface operation test and analysis (example: aileron)
Indicates the time series data of the aileron control surface operation test. It can be confirmed that the results of analysis and test for the deformation, response and load match with high accuracy.

5. Reduction of test cases by large-scale analysis

There are various possible causes of slat and flap failure, such as jamming of the operating mechanism and damaged/missing support mechanisms. Evaluation of the operating performance of the control surface with regard to all these accidental failures requires verification of a huge number of combinations. We therefore evaluated the actuator load, control surface deformation and failure detectability using the developed coupled simulation method. As an example, this chapter describes the results of slat skew analysis. A slat is a control surface that is located on the leading edge of the main wing and is designed so that it develops during takeoff and landing in order to generate high lift in the low speed range. Normally, the control surface is operated by multiple actuators and rails, but if a failure such as sticking at any one point occurs, the skew of the control surface occurs. As a result, the control surface becomes asymmetrical, which causes the aerodynamic force acting on the airframe to become imbalanced and stability to deteriorate. In order to maintain stable flight even in this state, it is necessary to detect such a failure and maintain the control surface angle. The operating method of a slat is shown in **Figure 6**. The slat is operated to the target position by driving force transmitted from the rotary actuator through the pinion gear to the rail installed on the control surface. The mechanism analysis was conducted by modeling each of these parts and considering the clearance and contact conditions between the roller and the rail as shown in **Figure 7**. To detect skew, skew sensors installed between adjacent slat control surfaces as shown in Figure 6 are used. An increase in the relative distance between the control surfaces beyond the threshold is detected by this sensor. When the rotary actuator rotates with any one operating mechanism stuck, another rail develop, but the slat cannot operate due to being stuck. If this continues, skew of the control surface occurs as shown in **Figure 8** and will be detected by the skew sensor. Through this analysis, all of the various possible failure causes such as the sticking of a rail and roller were predicted and narrowed down to the harshest conditions. As a result, we were able to obtain the prospect of shortening the time period required for verification.

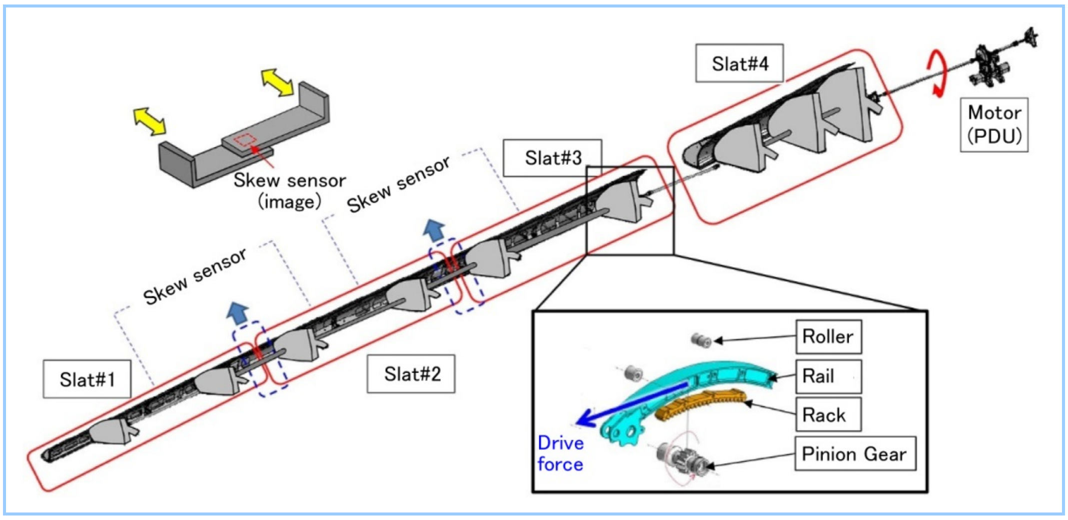

Figure 6　Slat structure and operating method
The slat control surface mechanism transmits driving force from the rotary actuator through the pinion gear to the rail installed on the control surface to develop the control surface.

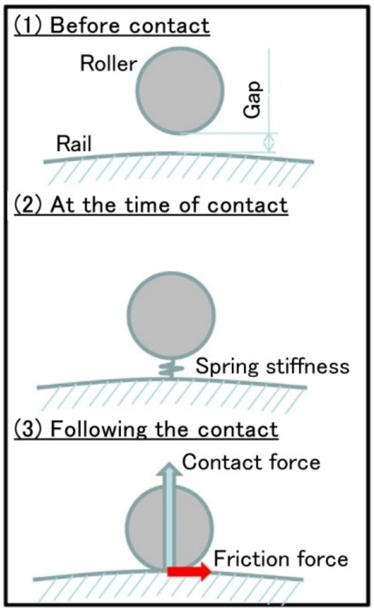

Figure 7　Contact boundary conditions between slat roller and rail
There is clearance between the roller and the rail and the restraint changes depending on the presence or absence of contact. The mechanism analysis was performed in consideration of the above three types of contact conditions.

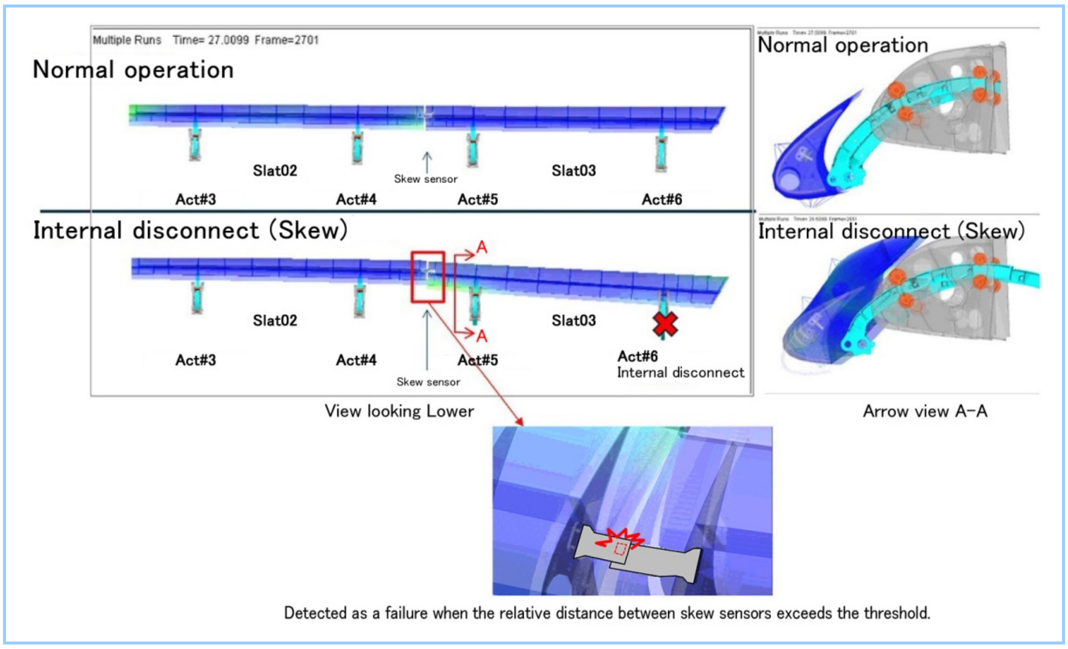

Figure 8 Result of simulation analysis of slat control surface failure
Shows the mechanism analysis results of the behavior of the slat control surface during normal operation and in a failure state (internal disconnect). It can be seen that at the time of failure, the control surface is deformed so as to be twisted and the skew pin contacts the sensor, which results in failure detection.

6. Conclusion

In the past, large-scale coupled analysis had problems with the enormous computer load and complicated analysis work, but with the improvement of computing power and the development of analysis technology, the analysis method has become able to perform evaluation in a short period of time and at low cost. Against this background, the simulation method presented in this report—one that focuses on mechanism analysis technology and also coupled with structure and control—can predict and evaluate the performance and functionality of the mechanism to be operated in a short period of time. In addition, this simulation method can evaluate the behavior against accidental failures, which makes it possible to supplement the work that had to be verified with the actual aircraft by using analysis in advance. We will continue to apply the coupled analysis method presented in this report to contribute to accelerating the development of various products and preventing rework.