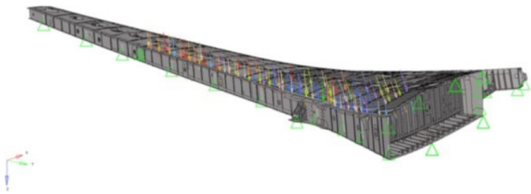
Efficiency Technology for Aircraft Assembly Work Utilizing Numerical Simulation



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In structures consisting of a frame and thin panels such as aircraft, each of the parts is produced with dimensional tolerances. Naturally, there are gaps between the parts when assembled. In the actual work process, the gaps are measured using temporarily assembled parts and based on the results, shims are produced to fill these gaps. It therefore takes a tremendous amount of time until all the shims with proper thickness distribution are prepared. Mitsubishi Heavy Industries, Ltd. (MHI) constructed an FEM model of the actual contours of the parts using three-dimensional (3D) surface measurement results and established a method to estimate the gaps found in the temporarily assembled parts by numerical simulation. The verification results show good agreement between the simulated gaps and those measured at the time of temporary assembly. This enables shims to be produced based on the estimation results by simulation instead of measurement, thereby shortening the time required for shim procurement.

1. Introduction

The first step in the process of assembling the main wing of general aircraft is to build a skeleton, which is a frame consisting of spars and ribs. The next step is to assemble the wing temporarily while adjusting/fitting panels to the skeleton. During this process, the load called correction force is applied in the direction of reducing the gaps between the skeleton and the panels. However, the application of excessive load may result in increased residual force after the assembly, increasing the risk of stress corrosion cracking (SCC) and fatigue damage. The maximum allowable correction force is therefore set for precautionary purposes. In addition to this limitation of applicable load, since the parts have dimensional tolerances and thin-plate panels may be curved or undulate, it is unavoidable to have gaps between the parts when assembled. Therefore, the gaps between the skeleton and panels are measured at the time of temporary assembly and shims with appropriate thickness distribution are produced as gap fillings. The temporary assembly is then dismantled, followed by the final assembly with the produced shims inserted. This series of processes, starting from temporary assembly through gap measurement until shim production, demands a huge amount of labor and time, which is very likely to be a bottleneck in mass production. This report presents a technology that estimates the gaps by numerical simulation, enabling shims to be produced without requiring temporary assembly or gap measurement to improve such situations and streamline assembly processes.

2. Gap estimation method

Figure 1 is a flow chart for the gap estimation method. Each step in the flow chart will be described in order in the following sections.

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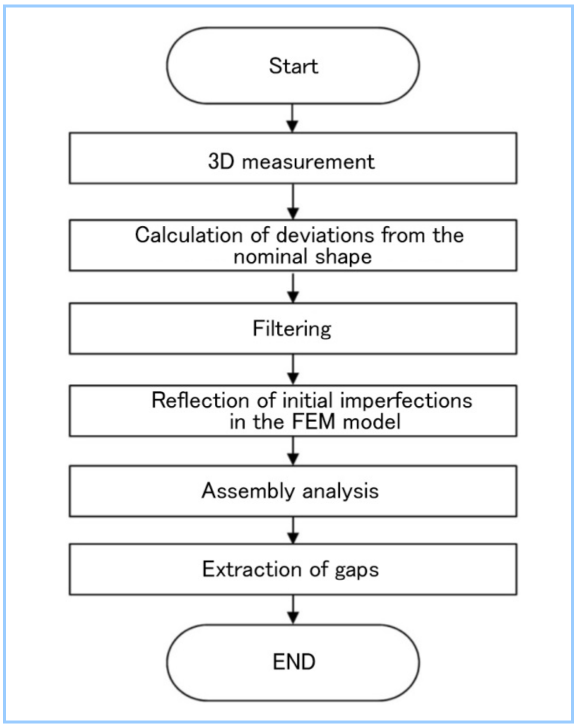

Figure 1 Flow chart for gap estimation method
The figure shows the sequence of measuring the gaps as per the method presented in this report.

2.1 Reading of measurement data

Firstly, devices such as 3D scanners are used to measure the shapes of the skeleton and panels. The surfaces to be measured are the panel's inner mold line (IML) and the skeleton's outer mold line (OML), these are, the surfaces bound together at the time of assembly. The 3D measurement data consist of a point group on the surface of each part. **Figure 2** shows the visualized data. Because the panel is measured while some weights are placed on it for adjustment and fitting, the point group data for some areas of the panel are missing.

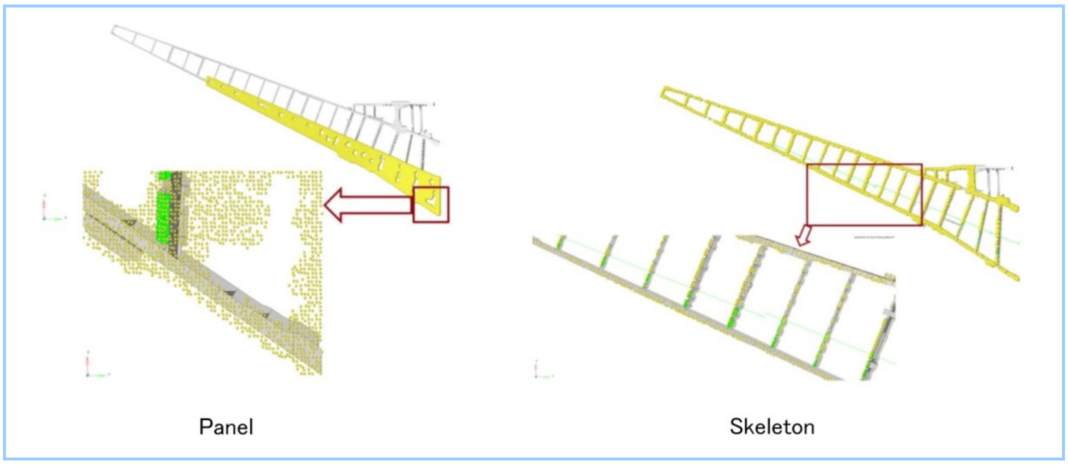

Figure 2 Point group data on surfaces of parts, measured by 3D scanner
The point group data obtained by 3D measurement (plotted by yellow colored circles) are displayed together with CAD data. As the panel is measured while some weights are placed on it, the point group data for some areas of the panel are missing.

2.2 Calculation of deviations from the nominal shape

Secondly, the surface with no initial imperfections (that is, the nominal shape based on CAD data) is linked to the measurement data. By calculating the deviations from the nominal shape, the initial imperfection vector of each measurement point [X, Y, Z, dX, dY, dZ] is calculated. Here, X, Y and Z are spatial coordinates in the aircraft coordinate system and are the coordinates of measurement points on the nominal shape. On the other hand, dX, dY and dZ are initial imperfections and are deviations from the nominal shape. In this report, as shown in **Figure 3**, the measurement points projected to the surface with no initial imperfections are represented by the X, Y, Z coordinates and the magnitude of initial imperfection of the projected point is represented by dX, dY and dZ. In the process of linking the nominal shape to the measurement data, however, if the deviation of the actual shape from the nominal one is large, the error of the initial imperfection vector obtained by the aforementioned simple method becomes large, which adversely affects the accuracy of gap estimation. Therefore, the panel, for which deviation from the nominal shape tends to be large, was first laid on a jig and some weights were placed on the panel for shape adjustment and fitting, before 3D measurement was eventually conducted (as indicated in Figure 2). As there is a limit to the applicable total weight of the weights, it has been confirmed that the force applied to the panel by the maximum allowable weight is sufficiently smaller than the correction force produced by the load at the time of temporary assembly.

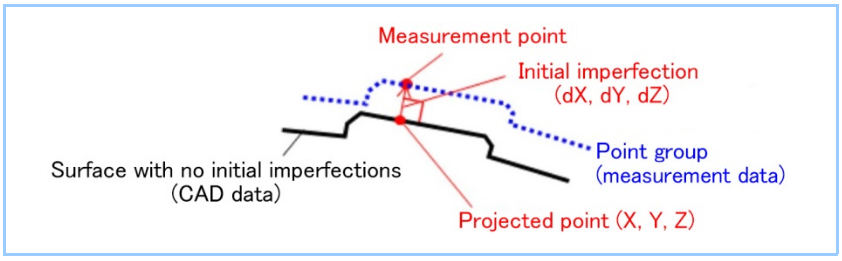

Figure 3 Measurement point, projected point and magnitude of initial imperfection

The figure shows the relationship between the measurement point, the projected point and the initial imperfection.

2.3 Filtering

In optical 3D measurement using devices such as 3D scanners, local measurement noise may be caused by reflection/diffraction of a laser beam depending on the surface properties of the specimen. **Figure 4** gives an example of initial imperfections and measurement noise. The X and Y coordinates of projected points in the aircraft coordinate system and the magnitude of initial imperfection dZ in the Z direction are presented three-dimensionally. For visualization, the dZ value is amplified by a factor of several hundred, making the occurrence of initial imperfection and measurement noise more easily noticeable. Further observed, apart from the initial imperfections shown as undulation throughout the image of visualized data, are reflection noise generated at the edge and the one isolated appearance of salt-and-pepper noise. These measurement noises lead to local overestimation of initial imperfection, causing the issue of reduced accuracy of gap estimation. To reduce the noise influence, we developed our own programs and filtered the measurement data. In filtering, the averaging filter, which is a widely-used noise removal filter in image processing (i.e., replacement by the average of the neighboring N points) and the median filter (i.e., replacement by the median value of the neighboring N points) were used. After reading the measurement data, one measurement point was selected and the Euclidean distances from the selected point to other points were calculated to extract the neighboring N points. The median filter is effective in removing salt-and-pepper noise, while the averaging filter is effective for smoothing reflection noise. The overall noise of measurement data was removed by filtering all the measurement points in succession. It is possible to improve the noise removal rate by increasing the number of neighboring points or the number of filtering applications. However, as this may cause the removal of initial imperfections inherent to the parts, we tried multiple combinations of different numbers of neighboring points and filtering applications and selected the one that can result in the desirable outcome.

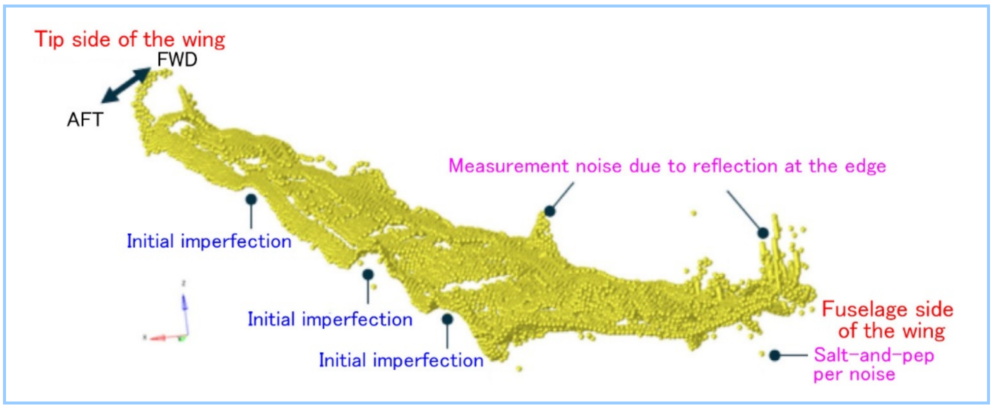

Figure 4 Initial imperfections and measurement noise (the trend is exaggerated)
The deviations in the direction of panel thickness are exaggerated by processing the 3D measurement results of the panel IML.
The data shown herein are not filtered.

2.4 Refection of initial imperfections in analysis model

Figure 5 shows the projected points after filtering, which are plotted on an FEM mesh with no initial imperfections. As the nodes in the FEM model do not coincide with the projected points, linear interpolation is used to determine the magnitude of initial imperfection at each node. When a node in the FEM model with no initial imperfections is represented by the coordinates (X, Y, Z) and the magnitude of initial imperfection at the same node by (dX, dY, dZ), the coordinates of the corresponding node in the FEM model with initial imperfections are regarded as (X + dX, Y + dY, Z + dZ), thereby reflecting the initial imperfections in the FEM model. Strictly speaking, the magnitude of initial imperfection (dX, dY, dZ) is subject to the error between CAD and FEM, as well as the linear interpolation error. However, when compared with the element size, these errors are small enough to have no significant impact on the shim thickness estimation described later.

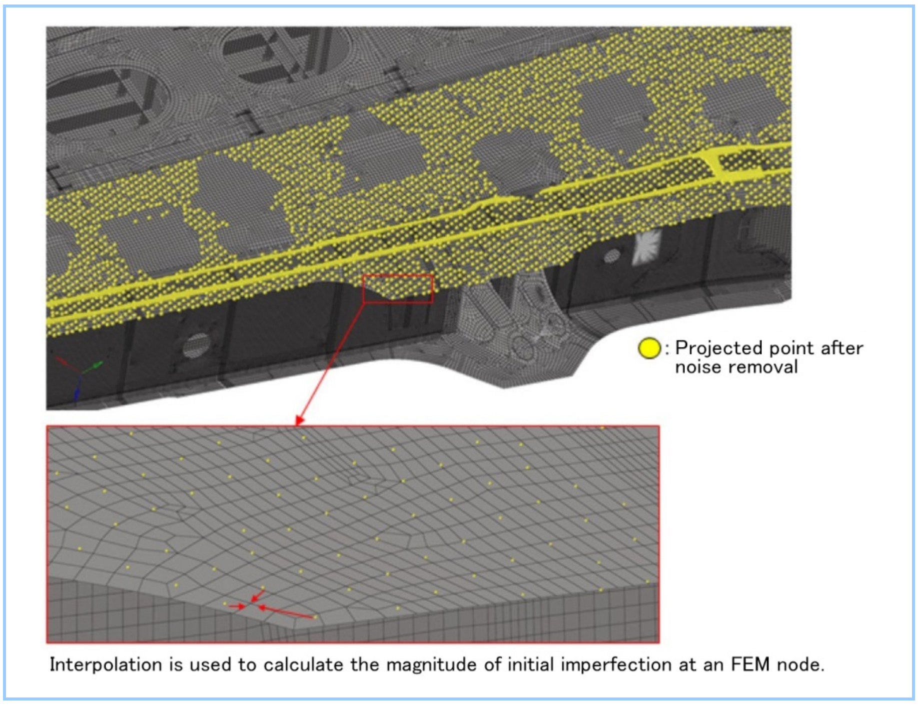

Figure 5 FEM mesh and projected points after noise removal
After the initial imperfection vectors obtained from the 3D measurement data of the panel IML (X, Y, Z, dX, dY, sZ) were filtered, the projected points (X, Y, Z) were plotted on the FEM mesh. As the projected points do not coincide with the nodes, the magnitude of initial imperfection at each node is interpolated based on the three neighboring points.

2.5 Assembly analysis

Figure 6 is an FEM model for the assembly analysis. Being modeled with shell elements, the contact and friction were defined at the joint interface between the skeleton and panel. As the load boundary conditions, the correction force applied at the time of temporary assembly was simulated under the conditions of the load being concentratedly applied in directions opposite to the panel's normal OML and the skeleton's IML. When it comes to the displacement boundary conditions, fixation using the jigs was simulated while constraining the translation of each part of the skeleton. The constraint of the panel's movement along the OML by the jig called the locator that determines the positioning was also included in the simulation.

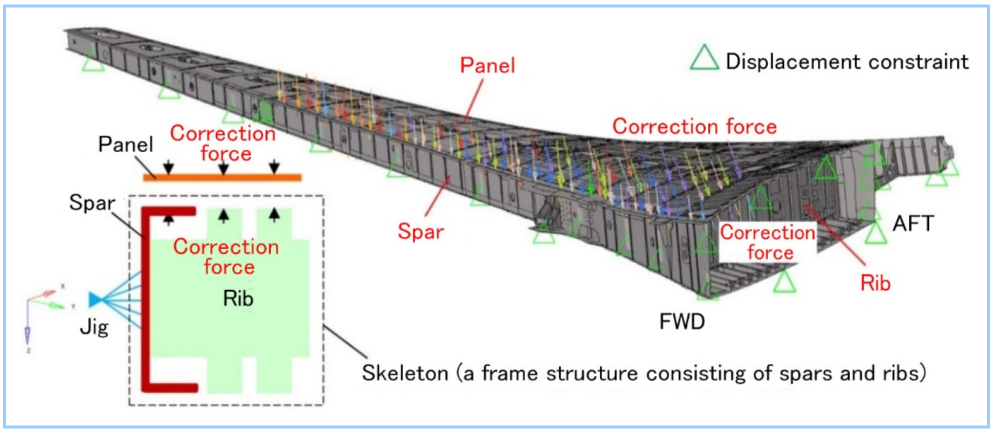

Figure 6 FEM model for assembly analysis
The figure illustrates an FEM model for assembly analysis.

2.6 Extraction of gaps

The analysis results were post-processed to output the gap between the panel's IML and the skeleton's OML. An example of the results is shown in **Figure 7**, which indicates that the gap is uneven yielding a large interspace in some areas.

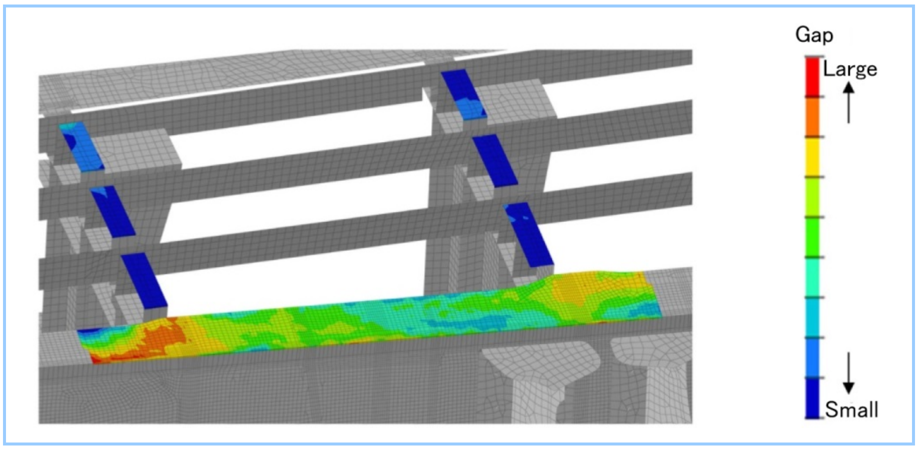

Figure 7 Example of gap distribution
The figure diagrams the contours of the gap obtained by the assembly analysis.

3. Gap estimation results

We assessed the accuracy of the gap estimation method described in the previous chapter by comparing the analysis values and the measurement values. As shown in **Figure 8**, the gaps were measured using a gap gauge installed approximately every 100 mm along the toe edge of the spar flange (tip of the flange). For the analysis values, the gaps at the measurement points were calculated by linear interpolation of the gaps at the nodes. The results of comparison between the analysis values and the measurement values are given in **Figure 9**. Normally, the maximum allowable gap (i.e., the value below which no shims need to be inserted) is predetermined at the site of assembly. Based on the maximum allowable gap for a certain model, the analysis values are plotted by different symbols: ▲ in the case of the difference between the analysis value and the measurement value being equal to or greater than the maximum allowable gap and ◆ in the case of the difference being smaller than the maximum allowable gap. The measurement values are also plotted by the symbol ○. As a general trend, the analysis values are almost in agreement with the measurement values. However, the figure also indicates the low accuracy of estimation in the area marked by the red dashed-line. In this area, the removal of measurement noise by filtering was presumably considered insufficient, leading to the increased difference between the analysis values and the measurement values.

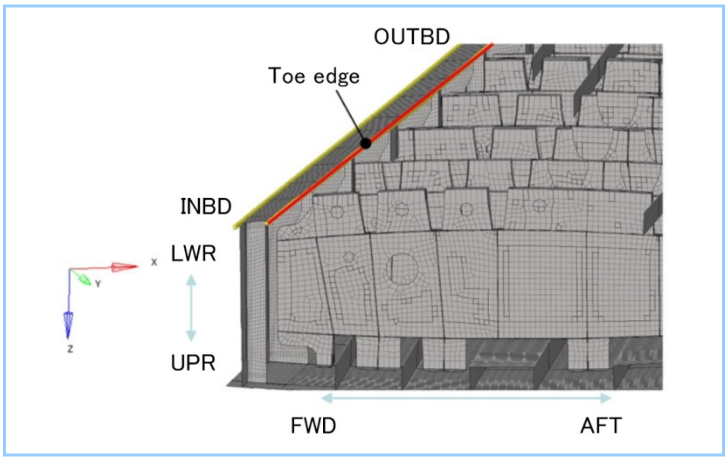

Figure 8 Toe edge of the spar flange (gap measurement area)
The toe edge is indicated in the figure. In this area, the analysis values of the gap and the measurement values are compared in Figure 9.

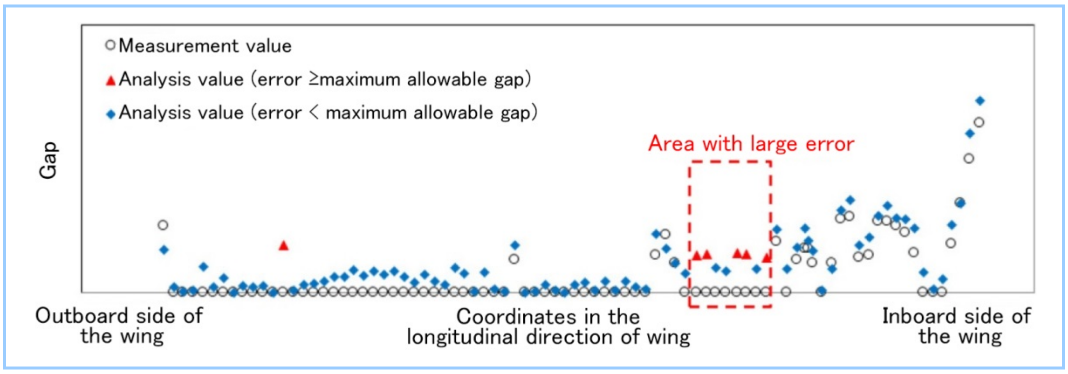

Figure 9 Comparison between analysis values and measurement values of gap
The figure compares the gaps obtained by the assembly analysis and those measured by a gap gauge. The gap distribution along the toe edge, as shown in Figure 8, was graphed.

4. Future development of an integrated system

To considerably shorten the time required for shim production, it is necessary to systematize the series of processes from FEM model construction based on 3D measurement data through gap calculation until NC data generation for shim production using the calculated gaps. **Figure 10** presents a design plan for the integrated system. Firstly, the contours of panels and the skeleton are measured and the obtained data are sent to the simulator. The simulator performs, as described in chapter 2, filtering, reflection of initial imperfections in the FEM model and assembly analysis to calculate gap distribution. Secondly, CAD is used to produce data of shim shapes by following the logic to determine the shim thickness distribution for a given gap distribution and the data are converted to NC data by CAM. Lastly, based on the NC data, shims are produced by machining.

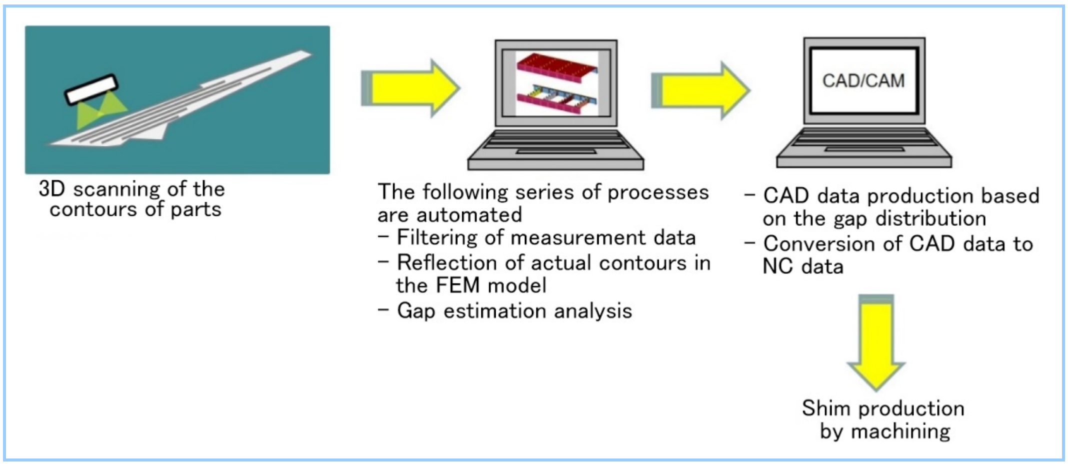

Figure 10 Design plan of integrated system for shim production
The figure gives a brief description of the design plan of the integrated system for shim production, which is to be developed in the future.

5. Conclusion

This report presented a method to streamline the laborious work related to the main wings of aircraft, involving measuring the gaps between the parts at the time of temporary assembly, producing shims to fill these gaps and final assembly. Specifically, the improvement of efficiency was made possible by performing the analysis using an FEM model in which actual initial imperfections of parts were reflected. The evaluation results of the method were also presented. As one of its application cases, the gaps obtained by the analysis and the measurement values were compared. The results show that the differences between them are below the maximum allowable gap at many of the measurement points. This indicates the suitability of using the analysis values when determining the shim thickness distribution for shim production. Although there are still some issues of noise removal from 3D measurement data, it is possible to further improve the efficiency by introducing our method to systematize the series of processes starting from FEM model construction based on 3D measurement data through gap calculation until NC data generation for shim production using the calculated gaps. Our method is expected to be applicable when assembling products with a similar structure consisting of a frame and thin panels, as addressed in this report. For the application to other products, we will continue to develop technologies with improved accuracy.