Simulation and Experiment on the Dimensional Error for the Large-Scale Assembly Linked by Abundant Solid Rivets

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Abstract. Large-scale antenna reflector that is sheet-metals linked by abundant solid rivets requires a conversion from the lying to standing state after the riveting. To predict the final dimensional error according to the assembly process, this paper presents a numerical method that gathers the locating and riveting distortions into the global dimensional error. Then experiment finishes the locating, riveting and state conversion of sheet-metals and tests the relative deviations and dimensional errors for the key points at the end of each state or stage for the test sample. Substitution of the experimental locating errors and riveting process parameters into the proposed method yields global dimensional errors which are agreeable with the experimental global dimensional errors.

Introduction

The dimensional precision control plays a crucial role in the assembly operations for the double-curved reflector which is made up of sheet-metals linked by abundant solid rivets. Generally, the assembly operations belong to two states, that is the lying and standing states. The lying state includes the locating and the riveting of sheet metals, which can be identified by locating stage and the riveting stage. The standing state is the working attitude of the riveted assembly. The worker measures the coordinates of the key points on the reflector surface at the end of each stage or state. The Root Mean Square (RMS) of the coordinate deviations should be less than a value relating to the antenna wavelength. A rapider process response requires an effective method to find the process parameters which target to the appropriate RMS after the riveting and state conversion.

Dimensional error sources for the large-scale assembly with abundant solid rivets comprise the geometric error of the part machining, the locating error between part and part, the local riveting distortion, the deformation caused by gravity and the state conversion, etc. The antenna RMS adjustment is mainly supported by coordinate tests using the large-scale metrology [1]. The adjustment seldom directly deals with the error sources in the specific riveted assembly process except for the part geometric and locating errors.

The geometric and locating errors are mainly controlled by engineering drawings for the machining of parts and the position adjustments of fixtures and parts, which are driven by the rigid or flexible tolerance analysis over decades [2]. Meanwhile dimensional errors that relate to locating and joining positions and the state conversions have also been studied by the extension of the stream of variation methods [3, 4]. These analyses are in the forms of probability calculations based on matrix operations and support the advances in the fixture layout designs [5, 6].

To get more comprehensive dimensional error caused by joining distortions, a rivet equivalent unit that considers the deviation induced by different riveting sequences is combined with Finite Element (FE) analysis [7, 8]. And the results of the numerical dynamic FE analyses for both the self-piecing riveting and the solid riveting are interpolated to global static FE analyses [9]. Then experiments validate the precision of the combination of the local-to-global dimensional error calculation and the
three-dimensional precision analysis based on the assembly logic in the single series-parallel mode [9, 10]. Because the local-to-global dimensional error calculation method has an advantage in loading the inherent strain data into the global numerical FE calculations for the sequence modelling of solid riveting, the assembly process optimization method, the specified rivet upsetting direction optimization method and assembly sequence optimization method for the design of the detailed process parameters have been proposed for the assembly with abundant solid rivets [11-13]. But the aforementioned methods do not take the effect of locating errors into the detailed dimensional error calculations for the sheet-metal assembly with abundant solid rivets.

Hence this paper uses the numerical method to interpolate the actual locating errors and the inherent strain data for riveting into the global dimensional error calculation referring to the experimental data.

The Numerical Method for RMS Calculation

The Calculation of RMS Caused by Riveting and State Conversion

The previous dimensional error calculation method based on the inherent strain data for the riveting process [11] is extended by setting the boundary conditions for the FE analyses are according to the constraint and the direction of gravity for the lying or standing state and taking the locating-related RMS into account. The main flowchart is shown in Figure 1.

Steps for the Numerical Interpolation of Locating-Related RMS

The locating errors at the mating surfaces deviate the key points at the contour of the test sample from the ideal positions. To make an accurate accumulation of the locating and riveting-induced RMS, a numerical interpolation method is proposed.

Given the locating and riveting-related coordinates, the accumulation of the two groups of coordinates satisfies the following steps.

Step. 1: Summarize the coordinates for the four endpoints for m groups of experimental X, Y and Z, and summarize that for n groups of x, y and z of the key points in simulation.

Step. 2: Unify the coordinate labels for the key point coordinates of the experiment and simulation to meet that their extreme value is gradually reduced as the coordinate label takes from x to y and to z.

Step. 3: Use the coordinates for the eight endpoints to calculate the middle centers for the key point coordinates of the experiment and simulation, the middle centers of which respectively obey the following vectors, \( \vec{R}_{\text{center1}} \) and \( \vec{R}_{\text{center2}} \).

Step. 4: Translate the key point coordinates in experiment by adding vector, \( \vec{R}_{\text{center2}} - \vec{R}_{\text{center1}} \).

Step. 5: Normalize the coefficient for the coordinate that has the least extreme value for the planar equation of key point coordinates, thus we have \( ax + by + c = z \).

The coefficient vector satisfies the Eq. (2).
\[ \begin{bmatrix} a & b & c \end{bmatrix}^T = \begin{bmatrix} u & v & 1 \end{bmatrix}^T w. \]  
\tag{2}

Where \( u, v, w \) are respectively the vectors which represent the deviated key point coordinates, \( x, y \) and \( z \) in experiment or simulation.

Step. 6: Calculate the coefficients for the data planes of experiment and simulation by Eq. (2). Denote them respectively by the following vectors,

\[ \begin{bmatrix} a_{\text{test}} & b_{\text{test}} & c_{\text{test}} \end{bmatrix}^T \]  
and  
\[ \begin{bmatrix} a_{\text{sim}} & b_{\text{sim}} & c_{\text{sim}} \end{bmatrix}^T. \]

Step. 7: Rotate the data planes to make the plane of experiment coincide with that of simulation and modify the deviated key point coordinates of experiment by the following points:

- Use the normal vectors of data planes to determine the unit direction vector for the common line and angle between the two planes by Eq. (3) and Eq. (4).

\[ n_{(0)} = \frac{\begin{bmatrix} a_{\text{test}} & b_{\text{test}} & -1 \end{bmatrix} \times \begin{bmatrix} a_{\text{sim}} & b_{\text{sim}} & -1 \end{bmatrix}}{\left\| \begin{bmatrix} a_{\text{test}} & b_{\text{test}} & -1 \end{bmatrix} \right\| \left\| \begin{bmatrix} a_{\text{sim}} & b_{\text{sim}} & -1 \end{bmatrix} \right\|}, \]  
\tag{3}

\[ \theta = \arccos \frac{\begin{bmatrix} a_{\text{test}} & b_{\text{test}} & -1 \end{bmatrix} \cdot \begin{bmatrix} a_{\text{sim}} & b_{\text{sim}} & -1 \end{bmatrix}}{\left\| \begin{bmatrix} a_{\text{test}} & b_{\text{test}} & -1 \end{bmatrix} \right\| \left\| \begin{bmatrix} a_{\text{sim}} & b_{\text{sim}} & -1 \end{bmatrix} \right\|}. \]  
\tag{4}

- To reduce the numerical error, substitute the third component \( z_{\text{center}2} \) in \( \hat{R}_{\text{center}2} \) to the common line of the data planes of experiment and simulation and find the other two coordinate components, which are shown in Eq. (5) and Eq. (6).

\[ \begin{cases} a_1 x + b_1 y - z_{\text{center}2} + c_1 = 0 \\ a_2 x + b_2 y - z_{\text{center}2} + c_2 = 0. \end{cases} \]  
\tag{5}

\[ \begin{bmatrix} x_{\text{m2}} \\ y_{\text{m2}} \\ z_{\text{center}2} \end{bmatrix} = \begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \end{bmatrix} \begin{bmatrix} -c_1 + z_{\text{center}2} \\ -c_2 + z_{\text{center}2} \end{bmatrix}. \]  
\tag{6}

- For the vector of each key point \( A \) of experiment, the relative point \( A' \) in data plane of simulation obeys Eq. (7).

\[ r_A = \begin{bmatrix} x_{\text{center}2} \\ y_{\text{center}2} \\ z_{\text{center}2} \end{bmatrix} + Q \begin{bmatrix} r_A - \begin{bmatrix} x_{\text{center}1} \\ y_{\text{center}1} \\ z_{\text{center}1} \end{bmatrix} \end{bmatrix}, \]  
\tag{7}

where
\[ Q = \begin{bmatrix} x_{n0} y_{n0} (1 - \cos \theta) + z_{n0} \sin \theta & y_{n0}^2 (1 - \cos \theta) + \cos \theta & y_{n0} z_{n0} (1 - \cos \theta) - x_{n0} \sin \theta \\ x_{n0}^2 y_{n0} (1 - \cos \theta) - y_{n0} \sin \theta & y_{n0} z_{n0} (1 - \cos \theta) + x_{n0} \sin \theta & z_{n0}^2 (1 - \cos \theta) + \cos \theta \end{bmatrix}, \]

and \( x_{n0}, y_{n0}, z_{n0} \) are the components in \( n_{(0)} \).

- Convert the key points in the data of experiment into the data plane of simulation according to the process from \( A \) to \( A' \).

Step. 8: Re-calculate the coefficients for the data plane of experiment and the vector for middle center of the modified key point coordinates, \( \hat{R}_{\text{center}1} \).

Step. 9: Unitize the normal vector of the data plane of simulation by Eq. (8).

\[ n_0 = \frac{\begin{bmatrix} a_{\text{sim}} & b_{\text{sim}} & -1 \end{bmatrix}^T}{\left\| \begin{bmatrix} a_{\text{sim}} & b_{\text{sim}} & -1 \end{bmatrix} \right\|}. \]  
\tag{8}

Step. 10: Compute the angle \( \alpha \) between the distributions of key points in experiment and simulation by comparing the vectors of the eight endpoints.
Step. 11: Re-translate the key point coordinates in experiment by adding the following vector,
\[ \vec{R}_{center2} - \vec{R}_{center1} \].

Step. 12: Given \( n_0, \alpha \) and \( \vec{R}_{center2} \), the above points for the rotation of data plane of experiment to that of simulation finishes the rotation in the data plane of simulation.

Step. 13: Put the modified \( u, v, w \) and Eq. (2) into Eq. (1). Then the subtraction of \( z \) from \( w \) leaves the deviations along the normal direction of the data plane, which is shown in Eq. (9).

\[ \text{deviation} = w - [u \ v \ 1][u \ v \ 1]^T w \]. \hspace{1cm} (9)

Step. 14: Because that deviations include key point coordinates representing the ideal assembly contour from the data plane, let \( u, v, w \) be vectors representing the coordinates of the key points on ideal assembly contour and then Eq. (9) yields the ideal deviations.

Step. 15: The Subtraction of ideal deviations yields the actual key point coordinate deviations of experiment in the data plane of the simulation.

Step. 16: For each key point of experiment, find the nearest key point of simulation and linearly add the relative coordinate deviation in simulation into that of experiment. Subtract the ideal deviations again and calculate the RMS.

The Experiment for RMS Test

The test sample is a scaled reflector whose dimension is about 1879mm \( \times \) 2267mm \( \times \) 1050mm and it contains 1093 rivets. The locating and riveting are performed to the test sample at the lying state. After the assembly, the test sample is set to the standing state according to the work condition.

Briefly Figure 2 (a), (b) and (c) shows these stages or states in the lying-to-standing conversion. Key points are selected from the reflector surface. And the RMS of the coordinate deviations for these points is tested at the end of each stage or state. The process parameters is shown in Figure 2(d) and (e).

The coordinate measurement system for the RMS calculation comprises an INCA3 camera, an auto bar, a series of targets and the V-STARS software. Before the experiment, the targets are distributed on the test sample surface. During the experiment, a large number of photos are taken for the targets at the end of each stage. The coordinates of the target positions can be determined by the photos. Then the RMS is yielded from the comparison between the tested and theoretical coordinates.

Figure 2. The test sample information: (a) locating; (b) riveting; (c) standing; (e) upsetting directions; (e) sequence.

Figure 3. Deformation: (a) lying and gravity; (b) standing and gravity; (c) lying and riveting; (d) standing and riveting.
Results

According to Figure 1, the boundary conditions for the lying or standing states, and the involvement of gravity or riveting yield the deformations in Figure 3. The 4 groups of relative RMS are respectively 0.0047mm, 0.2331mm, 0.4227mm and 0.4177mm. The linear accumulation between the deformations related to the gravity and riveting yields the sum of X, Y or Z componential deformations for the key points. Then the X, Y or Z componential deformations determine the RMS related to both the gravity and riveting, 0.4226mm and 0.5009mm.

Given the tested key point deviations, the steps in section 2.2 add the locating errors into the above simulation result. For clarity, Table 1 includes all the RMS and the data sources.

Table 1. RMS sources and results.

<table>
<thead>
<tr>
<th>Data source</th>
<th>Locating</th>
<th>Locating and riveting</th>
<th>Standing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>0.58[mm]</td>
<td>0.546[mm]</td>
<td>0.781[mm]</td>
</tr>
<tr>
<td>Simulation</td>
<td>0.62[mm]</td>
<td>0.58[mm]</td>
<td>0.82[mm]</td>
</tr>
</tbody>
</table>

Summary

Comparison between line 2 and line 3 in Table 1 indicates the proposed method gives a prediction for the RMS within a 7% deviation. Due to the test and involvement of the locating errors at every mating surfaces are quite time-consuming, the proposed method is an accurate and effective method to take the key point deviations caused by locating into the detailed dimensional error calculations.

References


