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Design and Performance Evaluation of Hydraulic Fixing System for Aircraft Skin Milling Flexible Jigs

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ABSTRACT

Manufacturing aircraft skin components requires high precision and structural integrity because of the process complexity. Traditional bolt friction brake fixation methods have resulted in inadequate stiffness, leading to suboptimal machining accuracy and surface finish. To address these issues, this study proposes a hydraulic fixation system to improve the stiffness of flexible jigs in CNC milling of aluminum plates. The hydraulic system's performance was assessed via stiffness tests and repeated precision measurements, demonstrating significant improvements over conventional methods. The horizontal stiffness increased to 11.6 N/μm, marking an 830% improvement over that of bolt friction brakes, and the vertical stiffness reached 190 N/μm. Furthermore, the hydraulic system achieved an axial precision of 1 μm and radial precision of 5 μm under a working pressure of 30 MPa. These results underscore the effectiveness of hydraulic fixation systems for enhancing machining quality and fixture reliability in aerospace manufacturing.

1. Introduction

Manufacturing aircraft skin components demands high precision and structural integrity due to the complexity of the process. In the CNC milling of aluminum plates, the jig's stiffness and positional fixation precision directly impact the machining quality. New fixation methods, such as flexible fixtures, have been proposed to address these issues. Solano and Bella (1994) introduced a 5-axis CNC machine with an integrated multifunctional fixture for the aerospace industry. This system uses vacuum cups on support bars to hold and secure the workpiece during machining, offering improved handling and fixture adaptability for complex shapes[1].

Fuwen (2014) further explored the automation potential of vacuum fixtures by integrating proximity switches near vacuum cups to detect workpieces and connect them to a PLC for CNC control. This method demonstrated the feasibility of automating workpiece mounting, enhancing operational efficiency and precision[2]. Flexible jig systems have been developed to secure aircraft components with complex 3D curved surfaces and are utilized in CRD-waterjet hybrid machining systems. These systems, integrated with large-scale composite equipment, support the precision machining of aerospace parts[3].

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Ra et al. (2014) discussed the challenges in machining thin and wide airfoils, which are prone to deformation during and after machining. Their research highlighted the effectiveness of vacuum fixtures in reducing machining distortion, thus ensuring better dimensional accuracy and surface finish[4]. Yang et al. (2021) proposed a flexible jig for smart factory assembly lines, emphasizing the need for reconfigurable and adaptive fixtures to cope with varying product shapes and sizes. Their study validated the responsiveness of flexible jigs in a smart manufacturing environment, facilitating quick adjustments for different vehicle door trims[5]. Fleischer et al. (2006) examined the technological efficiency of workpiece and tool handling systems in metal cutting machines. Their research provided insights into minimizing secondary processing times by improving handling systems, which are critical for high-performance machining[6].

Kumar et al. (2023) developed a hydraulic clamp system for machining fixtures, using analytical techniques to calculate maximum stress and deformation under various hydraulic pressures. Their study emphasized the importance of precise clamping forces to ensure fixture stability and workpiece accuracy[7]. Payne and Cariapa (2000) introduced the Fixture Repeatability and Reproducibility Measure (FR-R) to evaluate the performance of machining fixtures. This measure quantifies the variability in part dimensions due to fixture performance, enabling pre-production evaluation and real-time monitoring to prevent the production of defective parts[8]. Jiang et al. (2014) investigated the impact of interference fit size on hole deformation and residual stress during hi-lock bolt insertion. Their study showed that increased interference fit size led to non-uniform hole expansion and variations in protuberance, influencing the tensile and compressive stresses on the hole wall[3]. Traditional bolt friction brake fixation methods have shown inadequate stiffness, leading to suboptimal machining accuracy and surface finish.

This research addresses these limitations by proposing a hydraulic fixation system designed to enhance the stiffness of flexible jigs. Unlike previous methods that applied bolt fixing, as shown in Fig. 1, our approach provides uniform pressure distribution, ensuring better fixture stability and machining accuracy. Existing literature offers various solutions to improve fixture adaptability and efficiency. However, they fail to achieve the required stiffness and precision for aerospace manufacturing. This study aims to bridge this gap by introducing a hydraulic fixation system specifically designed for CNC milling aluminum aircraft skins. The proposed system is expected to offer superior performance compared to existing methods, thus improving overall machining quality.

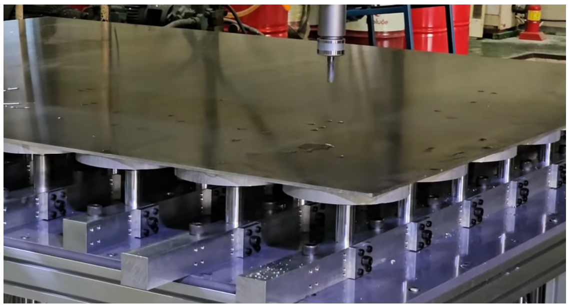


Fig. 1 Flexible jig applied bolt fixing

2. Design Selection and Structural Analysis

2.1 Cylinder Design Selection

The hydraulic cylinder design was chosen for its ability to provide uniform pressure distribution, a critical requirement for high-precision applications in the aerospace industry. The design considerations included material selection, pressure capacity, and compatibility with existing CNC milling systems.

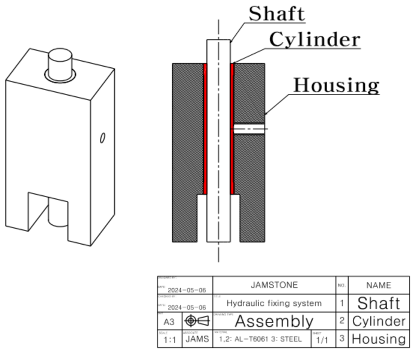
As shown in Fig. 2, the product's structure consists of an inner cylinder that acts as a hydraulic brake and an outer housing that acts as an airtight and support. When hydraulic pressure is applied to the structure, the cylinder shape is designed to apply uniform pressure in all directions of the shaft supporting the aircraft skin.

Since the structure of the aircraft skin and flexible jig is duralumin, the cylinder material was chosen as A6061-T6 to have the same stiffness and coefficient of thermal expansion.

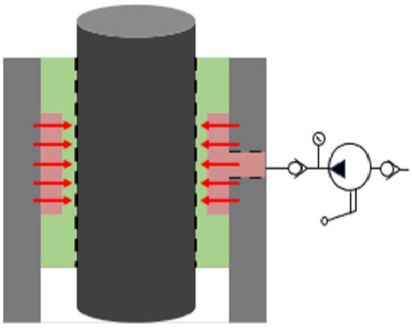
The cylinder is designed to fix the cylindrical shaft by reducing the diameter when hydraulic pressure is applied to the outside. The cylinder is designed of A6061-T6 material, 110 mm long, 24 mm outer diameter, and 2.5 mm thick. If 34.3 MPa, which is half of the maximum pressure of the hydraulic pump, is substituted into Equation (1), the hoop stress is 147.5 MPa, less than the yield stress of A6061-T6 so that it can be used repeatedly.

$$\sigma_t = \frac{Pr}{t} \tag{1}$$

The hoop stress was divided by the modulus of elasticity and multiplied by the average diameter of the cylinder,

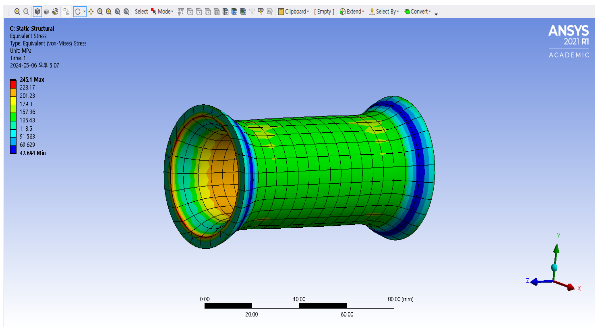


(a) Assembly drawing

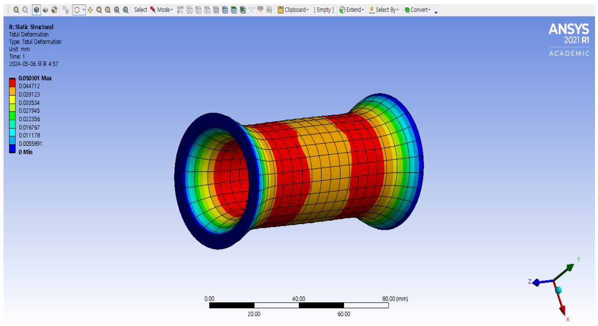


(b) Schematic

Fig. 2 Hydraulic brake drawing and schematic



(a) Stress analysis



(b) Deformation analysis

Fig. 3 Finite element analysis

resulting in a total contraction of 0.046 mm. It is expected to be fixed by hydraulic pressure when the fitting tolerance is half the contraction diameter.

2.2 Structural Analysis

ANSYS structural analysis was performed to verify that the stress and diameter reduction generated when hydraulic pressure was applied to the outer surface of the cylinder were the same as the design. The boundary conditions were set to simulate real-world operational scenarios, ensuring the accuracy of the analysis. Since both sides of the cylinder are joined by welding, it was set as complete fixing conditions in all directions. A uniform pressure condition was applied to the outer surface of the cylinder, and a pressure of 34.3 MPa was applied to analyze the static stress and deformation. As shown in Fig. 3(a), the maximum stress of the middle part, excluding the support part, is about 145 MPa, the same as the value calculated by hoop stress. Both sides of the cylinder are connected to the housing. Still, since it is assumed to be a completely fixed condition for convenience of analysis, the maximum stress of 245 MPa is generated in the part where the stress concentration occurs. Since the stress and strain generated in the center of the cylinder are of interest in this study, the stress concentration of the completely fixed part was not considered. In Fig. 3(b), considering all deformation directions, the maximum deformation amount was 0.05 mm, more significant than the result of calculating only the diameter direction with hoop stress.

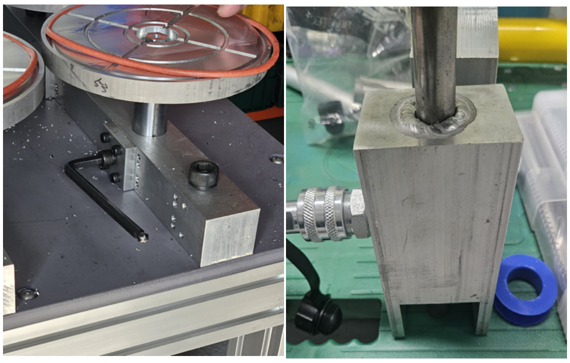
3. Methodology

3.1 Fabrication and Assembly

The Hydraulic-fixing method was newly produced to improve the limitations of the previously developed Bolt- fixing method. The bolt fixing method in Fig. 4(a) is fixing the shaft by tightening the bolt from one side of the housing. It has a limitation in that the fixing force varies depending on the number of revolutions of the bolt and cannot apply uniform pressure to the entire shaft. The hydraulic fixing system in Fig. 4(b) can apply constant pressure in all directions, improving the limitations of the bolt-fixing method. The components of the hydraulic fixation system were fabricated using high-precision machining techniques. The assembly process involved welding both ends of the cylinder.

3.2 Repeated Precision

As shown in Fig. 5, the main body was firmly fixed to the



(a) Bolt fixing (b) Hydraulic fixing

Fig. 4 Fabricated fixing system

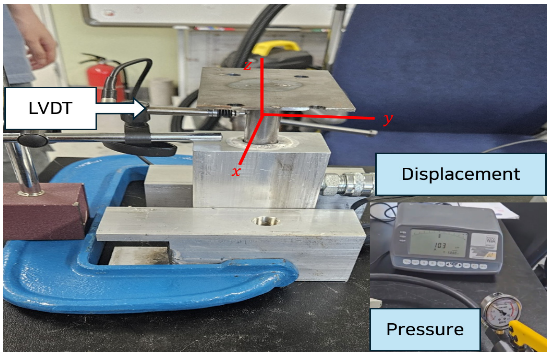
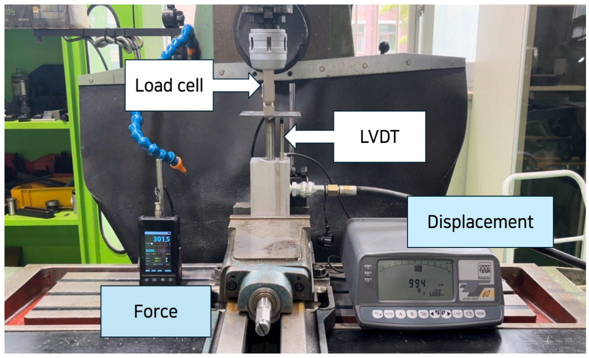


Fig. 5 Repeated precision experiment setup

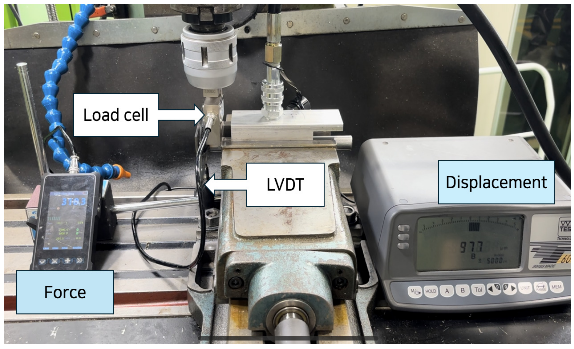
vise, and the displacement, when pressurized to 30 MPa at a preload of 20 MPa, was measured by LVDT. After setting the reference position in the preload state, the pressure was gradually increased and pressurized to 30 MPa. During the pressurization process, LVDT detected and recorded the subtle displacement of the cylindrical shaft. In the bolt fixing method, the shaft was weakly fixed (preload state) with bolts, and the displacement was measured by rotating an additional 60°. Each experiment was repeated five times.

3.3 Stiffness Testing

Horizontal and vertical stiffness measurements were performed using precision instruments to evaluate the performance improvement of the bolt friction brake. The stiffness of the cylindrical shaft was tested under controlled conditions within a flexible jig equipped with a hydraulic fixing system. In the experimental setup, a force of 250 N was measured with a load cell, and the displacement was measured with an LVDT, as shown in Fig. 6. For the vertical stiffness test, the load was applied vertically, and the corresponding displacement was recorded as shown in Fig. 6(a). The load was applied horizontally for the horizontal stiffness test, and the resulting displacement was measured as shown in Fig. 6(b).



(a) Vertical stiffness experiment



(b) Horizontal stiffness experiment

Fig. 6 Stiffness experiment setup

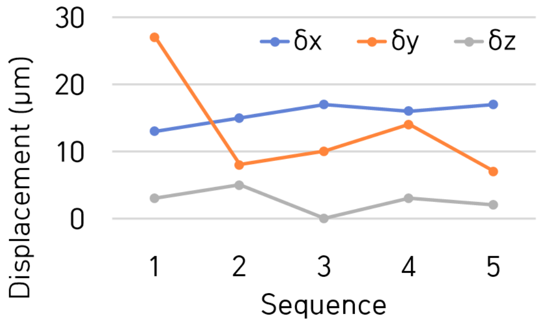
4. Results and Discussion

4.1 Repeated Precision

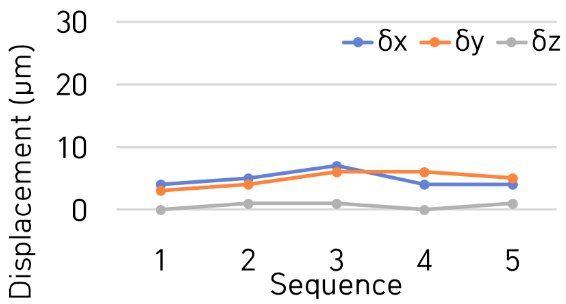
The repeated precision of the cylinder was compared between bolt fixation and hydraulic fixation methods, as shown in Fig. 7. In the bolt fixation method, as shown in Fig. 7(a), the repeated precision of the cylinder changed by 3 μm axially and 16 μm radially before and after tightening the bolts. In the hydraulic fixation method, as shown in Fig. 7(b), the repeated precision improved to 1 μm axially and 5 μm radially under pre-pressure of 20 MPa and working pressure of 30 MPa. The hydraulic fixing method reduced the repeated fixing error in axial and radial directions by about 67%.

4.2 Stiffness Performance

As a result of the stiffness test, the vertical stiffness was sufficient in both cases, and the horizontal stiffness of the hydraulic fixing system was significantly improved compared to the bolt fixing method.

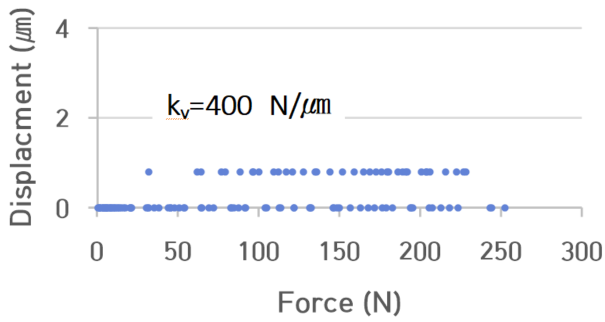


(a) Bolt repeated precision

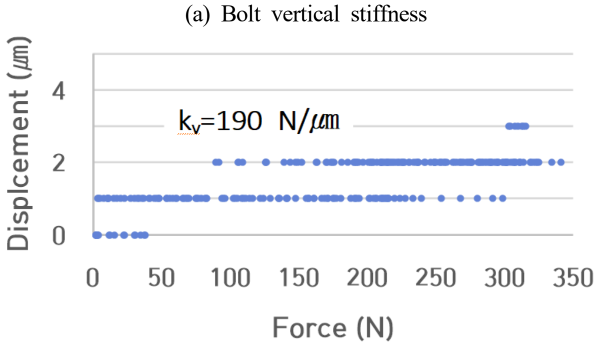


(b) Hydraulic repeated precision

Fig. 7 Repeated precision



(a) Bolt vertical stiffness

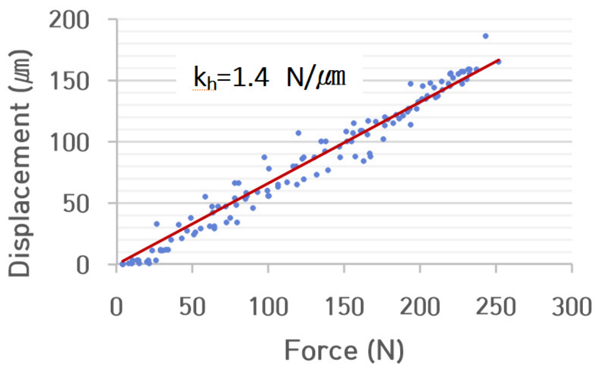


(b) Hydraulic vertical stiffness

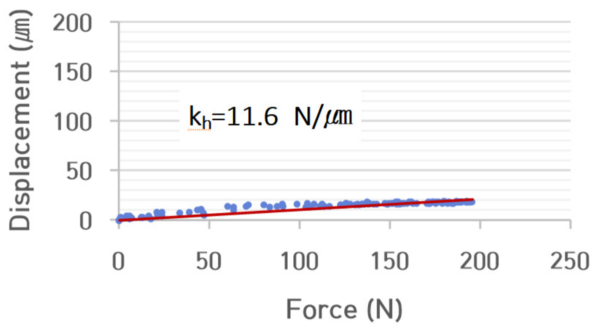
Fig. 8 Vertical stiffness compare

Fig. 8 shows the vertical displacement for the vertical load, Fig. 8(a) is the bolt fixing method, and Fig. 8(b) is the hydraulic fixing method. The maximum displacement at 250N was measured as 1 μm in the bolt fixing method and 2 μm in the hydraulic fixing method. As a result of calculating the stiffness by regression analysis in the graph confirmed that the bolt fixing method was 400 N/μm and the hydraulic fixing method was 190 N/μm, which were sufficient rigidity to satisfy the precision required for processing[10].

Fig. 9 shows the horizontal displacement of the horizontal load, Fig. 9(a) is the bolt fixing method, and Fig. 9(b) is the hydraulic pressure fixing method. At 200 N, the bolt fixing method was measured at a maximum displacement of 135 μm and the hydraulic pressure fixing method at a maximum displacement of 18 μm. As a result of calculating the stiffness of the graph by regression analysis, it was found that the bolt fixing method showed 1.4 N/μm and the hydraulic pressure fixing method 11.6 N/μm, indicating that the horizontal stiffness increased by about 830% compared to the bolt friction brake, proving the effectiveness of the hydraulic fixing system in improving the jig stiffness.



(a) Bolt horizontal stiffness



(b) Hydraulic horizontal stiffness

Fig. 9 Horizontal stiffness compare

5. Conclusion

This study successfully designed and evaluated the hydraulic fixing system for flexible jigs used for CNC milling aluminum sheeting for aircraft skin parts. The hydraulic system significantly improved the jig stiffness and repeated precision, improving machining accuracy. The horizontal stiffness measured 11.6 N/μm, and the vertical stiffness measured 190 N/μm, showing significant improvement over conventional bolt friction brake methods. In addition, the hydraulic system showed good repetition precision, such as minimizing axial and radial displacements under high-pressure conditions. These advancements confirm the hydraulic fixation system's potential to improve machining quality and fixture reliability in aerospace manufacturing.

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