Research Article

Fixture Design for Outer Skin Aircraft Door Manual Drilling Operation with Finite Element Analysis and Ergonomic Consideration

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Fixture design for dedicated aircraft components is very challenging nowadays due to complexity, process capability, and effect on technical worker health conditions. The proposed fixture design for drilling an outer skin aircraft door will accommodate a design principle of fixture and ergonomic aspect of the technical worker. The proposed design will include the comfort drilling posture and finite element analysis (FEA) on the structure. The step required for the drilling process, starting from loading, locating, clamping, frame rotation, and hole drilling was discussed. FEA analysis shows a maximum value for the von Mises stress recorded was 6.373 × 10^5 N/m^2 at the flange between the frame and vertical stand, and acceptable stress distribution results from the loaded weight of the outer skin aircraft door. A fully functional prototype was developed with a scale reduced to a quarter to verify the design. The developed prototype is successfully showing the capability of the fixture design in providing a mechanism of ergonomic consideration in the drilling of the outer skin of the aircraft door.

1. Introduction

Aircraft manufacturing industries consist of various processes, such as machining, assembly, and inspection of various components. For example, aircraft machining and assembly contribute about 40% to 50% of the total working time in aircraft manufacturing. This stage determines the final quality and production cost in aircraft industries. One of the essential tools for successful machining, assembly, and inspection is the perfect design for fixtures [1]. Fixtures are tools used for various operations to establish and secure the position and orientation of the workpiece as guided by design specifications.

Aircraft components are complex, large, thin-wall, and special material parts. As the increased machining difficulty, the types and number of fixtures required increased. Producing various products in small batches and developing a small number of new products parallel to mass production has become the main production characteristic in the aircraft manufacturing industry. In fixture design for the manufacturing of aircraft parts, there are various challenges and serious problems, which influence the quality and efficiency of fixture design [2].

Manufacturing processes of aircraft thin-walled components, the fixture is used to accurately locate and constrain workpieces during manufacturing processes, assembly, and inspection. Fixturing is an essential aspect of the manufacturing process, significant for workpiece productivity and quality. Even under the impact of static and dynamic mechanical loads, a good fixture design will specify the placement of a clamped workpiece in the workspace [3, 4].

Setup planning, fixture planning, and fixture configuration design, according to Biao et al. [1], are the three primary stages of the fixture design process. The number of setups required to complete all production operations, the task for each setup, and the orientation and position of the workpiece in each setup are all determined by setup
Fixturing cost can account for 10–20 percent of the total cost of a manufacturing system. These fixturing and tooling costs rise in short batch manufacturing applications because fixturing is typically unique to each workpiece [9]. However, fixture design frequently relies heavily on the experience and knowledge of fixture design engineers, resulting in inconsistency in fixture design quality [2].

Rivet and bolted connections are commonly used in aircraft construction. A large aircraft contains 1.5 to 2 million rivets and bolts. Therefore, many high-quality holes must be efficiently drilled to assemble an aircraft structure with rivets and bolts [3]. The fatigue life of assembled aircraft structures is heavily influenced by the drilling quality holes, which is the key evaluation index of a drilling system. Position variation, axial direction variation, dimple depth variation, diameter variation, and burr size all contribute to hole quality. As a result, the aircraft structure, fixture, and operator form a closed-loop system that stabilizes the drilling process and ensures diameter and location accuracy. Most aircraft assembly applications require a fastener hole position tolerance of 0.3 mm or less, which is frequently far beyond the assembly variation of the aircraft structures for drilling. Recent work on the fixture for aircraft drilling was done by Calabrese et al. and Biogeny et al. [4, 10].

According to Khan and Muzammil [11], the number of holes drilled on aircraft components by technical workers has an impact on health and safety issues such as repetitive strain injury (RSI) and musculoskeletal disorders (MSDs). Working in an awkward posture will result in MSDs because hands should not be kept above shoulder height for long periods [12, 13]. Khan and Muzammil [11] also found MSDs to be the main occupational health in the industrial world. Technical workers’ uncomfortable posture and repetitive motion can be reduced to a greater extent, if not totally, with ergonomic interventions. Ergonomics is defined as “the design and engineering of human-machine systems to boost human performance;” intervention can be considered ergonomic if it eliminates or considerably decreases fatigue and improves technical worker performance. Ergonomic design reduces stress and utilizes technical worker capacity more effectively, resulting in enhanced output. The main and interactive impacts of tiredness had a considerable effect on performance and muscle activation patterns during the drilling task, according to Ranjana and Michael [14].

Drilling of aircraft structures can be done by sitting or standing. Drilling involves postures that induce fatigue and pain to the technical worker, such as persistent static neck flexion, shoulder flexion, forearm muscle exertion, severe wrist postures, and prolonged standing. It has been discovered that stationary positions induce more fatigue than nonstationary postures. Standing in a stationary position is thought to reduce blood supply to muscles, speed up exhaustion, and produce pain in the legs, back, and neck muscles. Excessive standing can also induce temporary immobilization or locking of joints in the spine, hips, knees, and feet, leading to MSDs due to degenerative damage to tendons and ligaments [15, 16].

This paper examines the integration of design techniques, including FEA and ergonomic effect, on the drilling fixture design for the outer skin aircraft door. The goal of this project is to quantify the benefits. The proposed fixture design will make drilling on the outer skin of an aircraft door more comfortable for technical workers. The process entails evaluating and simulating potential fixture designs.

2. Outer Skin Aircraft Door Fixture Design

2.1. Outer Skin Aircraft Door. The aircraft door comprises an egg crate assembly of frames and intercostals, upper and lower beams, and an outer and inner skin made of aluminum. The outer and inner skin of the aircraft door will be used for drilling operations. Therefore, a dedicated fixture will be designed to accommodate the outer skin of the aircraft door. The outer skin aircraft door has an outline size of 1910 mm × 800 mm × 250 mm and a thickness of 5 mm, as shown in Figure 1. The outer skin aircraft door is made from aluminum alloy and consists of more than 250 holes located with 4 mm through holes diameter.

2.2. Hand Drilling Operation with Ergonomic Consideration. The process of making holes in the outer skin aircraft door is done by an operator using a hand drill machine. For the drilling operation, the rotating drill bit is fed against the stationary outer skin of the aircraft door, and it is performed in a straight stand or sits horizontal posture. The operator pushes the spinning drill bit into the outer skin of the aircraft door using forward feed force. In the end, to complete the process, the hand slides forward slowly from the shoulder and presses against the outer skin of the aircraft door.
Operators need to apply a minimum feed force at the beginning of the cumulative drilling depth to reach a stable operating point. Furthermore, hand drill vibration will influence the control of the feed force. On the other hand, the weight of the hand drill will contribute to the vertical forces. The weight of the hand drill will alter how the operator handles the instrument by distributing the load within the tool. This was due to the need for a hand to support the tool and the operator’s time to hold the tool during the drilling procedure. The tool’s weight distribution should also allow for comfortable gripping in an orientation that aligns the tool’s center of gravity with the gripping hand’s center of gravity. The center of gravity of the hand drill must also be aligned with the center of the gripping hand. When using a hand tool, mechanical stress or pressure can be conveyed to the palm and fingers, especially when considerable pressures are required.

2.2.1. Drilling Posture/Ergonomic Impact. Using a hand drill for hole making on the outer skin aircraft door should use a neutral posture instead of awkward postures as suggested by Susan et al. [17]. If the operator does drilling in an awkward posture, the fatigue occurs sooner than in a neutral posture. Working in severely uncomfortable postures can also put a lot of strain on muscles and joints. When the muscles are at their resting length and the joint is naturally positioned, you have a neutral posture. In most cases, the neutral posture relates to the joint’s mid-range of motion. Muscles and tendons are either contracted or extended when a joint is not in its neutral position. In neutral postures, the joints have the most control and force production [18]. In neutral postures, muscles, tendons, nerves, and bones are less stressed.

It is deemed awkward when a posture shifts away from neutral and toward the extremes of range of motion. Most of the time, an operator can produce the most force while a joint is in its neutral position. Because some muscle fibers are constricted or elongated as the joint moves away from neutral, the muscles’ amount of force can create diminishes. The tendons of the muscles partially wrap around the carpal bones in the wrist as the operator bends the wrist. The force produced will be reduced since the bones do not operate as a perfect pulley. In addition, friction causes force losses. As a result, an operator’s muscles must work more and use more energy in an awkward stance to create the same force in a neutral posture. Working in an uncomfortable position is thus a risk factor for muscle fatigue and pain, which should be avoided. This is a crucial notion since working at one’s greatest capability, especially without rest, can lead to an earlier onset of weariness and, over time, an increased risk of MSDs [18].

As a result, operators must use the neutral posture of their joints to reduce the amount of effort as a percentage of maximal capacity. However, some joint motion is required because being in a static posture for an extended period has various harmful effects that should be avoided. The prolonged application of a load by the muscles might result in fatigue when an operator is in a static posture. In addition, not moving muscles for an extended period reduces blood flow, which is required to provide oxygen and vital nutrients to muscles and remove metabolic waste products. The fixture should be built to allow operators to employ neutral postures and postures that are close to neutral postures as often as possible [17].

As a solution, the proposed fixture design will make the following:

(i) Avoid twisting motions, bending motions, and excessive reaching
(ii) Keep the upper arms close to the operator’s body with the elbows slightly bent
(iii) Use both hands instead of one to lift or complete tasks
(iv) Avoid high contact forces and static loading
(v) Use the right tool for the job and the right tool for the operator

Therefore, the proposed fixture design will provide the best solution for locating, positioning, securing, and rotating the aircraft door panel for drilling operation.

2.2.2. Drilling Fatigue Impact. Drilling is a difficult operation that requires a continuous forward push and a shoulder lift, resulting in fatigue. Muscle fatigue and discomfort ensued from the continual repetitive motion of the hand and arm, resulting in decreased efficiency and job unhappiness [19]. Working in an improper position might lead to MSDs as hands should not be held above shoulder height for an extended amount of time [18]. Awkward posture was classified as shoulder elevation greater than 60° during work [20]. When the task was conducted above the elbow height, Lee et al. [12] discovered that the upper limb experienced a lot of tiredness. Farooq and Khan [13] found that exerting forcefully in an uncomfortable position enhanced the risk of MSD prevalence. Awkward working postures have been identified as the leading cause of MSDs and the primary occupational health concern in the industrial world. Khan and Muzammil [11] suggested that the proposed fixture design will accommodate the neutral posture instead of the
awkward posture for the wrist, elbow, shoulder, and back joints. Mehta [14] suggests a general guideline for good horizontal drilling postures, incorporates the fixture design to cater for the awkward position, reduces stretch and ergonomic design, and provides the best solution for locating, positioning, securing, and rotating the outer skin aircraft door for drilling operation.

If not eliminated, factors like uncomfortable posture and repetitive motion can be minimized to a larger extent, using ergonomic interventions. Since ergonomics is defined as “the design and engineering of human-machine systems to boost human performance,” an intervention might be considered ergonomic if it eliminates or considerably reduces fatigue while improving operator performance [11]. In addition to the assumptions made, the factors hammer drill weight, hammer drill power, type of drill bit, and workpiece also have an influence.

Another important consideration was the feed force applied by the operator during drilling. The lateral forces do not change significantly with different feed forces during horizontal drilling. When drilling vertically downwards, the lateral forces also increase significantly when the feed force increases. This could be explained by the fact that in horizontal drilling, the feed force is mainly applied at the main handle, whereas in vertical downwards drilling, the operator leans more on both handles.

Based on this, studies should be carried out which examine the above-mentioned theoretical consideration of fatigue varying the applications and the technical boundary conditions. The proposed fixture design will be considering operator fatigue and discomfort when working with a hand drill over a longer period; higher productivity can be achieved with a lower feed force. It is known that fatigue has a negative impact not just on productivity but also on the health of the worker.

2.3. Fixture Position. In order to avoid the fatigue impact and ergonomic consideration on the operator during the drilling process, the fixture needs to move up and down according to as neutral as possible drilling posture. According to guidelines, the neutral drilling posture is between shoulder to elbow or Shoulder-Waist while the operator is standing or sitting. It measures the length from the middle of the shoulder to the elbow or waistline. According to Izzah et al. [21], for an Asian male operator, the height of the shoulder to the ground is 138.5 cm, and the height of the elbow to the ground is 103.7 cm. Therefore, the working height for drilling should be within this range for a neutral drilling posture. As a result, the aircraft door panel needs to move up and down within this range for the drilling. Then, the operator can drill the hole horizontally from right to left or left to right, whichever is convenient. In order to cooperate with the movement of the frame according to this setting, there is a need to have a motorized actuator that can move the frame to a height of 103.7 cm, as shown in Figure 2.

Considering a work from Izzah et al. [21], the operator will do the drilling job by standing and sitting posture. Considering that the neutral drilling posture is between shoulder to elbow while the operator is standing or sitting, all drilling areas will be covered. Therefore, the drilling process can be done by considering the ergonomic postures, as shown in Figure 2. For an Asian male operator, the sitting shoulder height is 59.3 cm, and the elbow height to the buttock is 23.1 cm. The knee height is 50.4 cm from the ground. The frame needs to move down to 12.26 cm from the ground by operating standing drilling. Then, the operator can do the stand drilling for an area colored in black and then sit to drill an area colored in blue. Finally, while in sitting posture, the frame moves 57.98 cm upward from the ground to drill the remaining holes in the red-colored area. This layout also results in a more ergonomically friendly design because the operator’s reaching distance is significantly decreased, saving time.

3. Outer Skin Aircraft Door Fixture Design

Fixture design to accommodate the outer skin aircraft door hole drilling comprises locating, orientating, supporting, and clamping/holding the workpieces as a rigid unit during the whole process of drilling. The important considerations for fixture design are accuracy and rigidity, ease of handling, quick interchangeability, and competitive cost in construction. The proposed fixture design is made from stainless steel to avoid frequent damage and resist wear. It must possess enough rigidity and robustness to avoid unwanted outer skin aircraft door movement during drilling. It should remain perfectly rigid and stable during operation.

3.1. Locating. For locating, the outer skin aircraft door must be easily loaded and quickly unloaded from the fixture so that no time is wasted while placing the workpiece in position to perform drilling operations. The design of fixtures should be such that it would not permit the outer skin aircraft door to be inserted in any position other than the correct one. The outer skin aircraft door is not located on more than 4 points to avoid rocking. The locations of supporting pin/surfaces of outer skin aircraft door inside surface were properly chosen to locate the clamp by ensuring equal distribution of forces throughout all sequence of operation. It also is used to locate cylindrical holes provided in the outer skin of the aircraft door. In a horizontal plane, such locators can give constraints in two directions. All locating and supporting pad surfaces are made from hardened materials as conditions permit so that they are not worn out, and accuracy is retained for a long time.

3.2. Clamping. Clamping holds and locks the outer skin aircraft door after being securely positioned/located accurately. It should be as simple as possible without sacrificing effectiveness or rigidity. The strength of the clamp should not only hold the outer skin aircraft door firmly in place without causing any distortion but also resist the pressure during the drilling operation. The clamp positions are located directly above the points supporting the aircraft door outer skin to avoid distortion and springing. The quick-acting clamps with minimum movement are used to be
sufficiently robust to prevent any bending on the outer skin aircraft door. Clamping procedures must be used to deploy sufficient forces without harming the aircraft door’s outer skin. The proposed fixture design will accommodate the quick-acting latch clamp. The movement of the aircraft door after being clamped should be restricted.

3.3. Aircraft Panel Fixture Design. The proposed size of the fixture design was 1800 mm × 1200 mm with a 4-inch square tube. The maximum supporting angle was 180°, and the swivel radius was 600 mm. The exterior skin of the aircraft door measures 1910 mm × 800 mm × 250 mm and is 5 mm thick. There were more than 250 holes on the workpiece to be drilled. The fixture design for outer skin aircraft door drilling is shown in Figure 3. The fixture design consists of a frame (holding, securing, and clamping an aircraft door’s outer skin) and a vertical stand with an actuator and swivel motor (used to hold and rotate the shift up and down the frame). The frame has four locators for location and a quick-acting latch clamp for clamping. The vertical structure consists of a base structure made from solid steel square bars. On top of the base structure, a heavy-duty, high-force electric Rod Style Actuator (RSA) is attached. The RSA is used to move the frame up and down according to the neutral posture of the operator during drilling, either neutral standing or sitting, as discussed in Section 2.2. Also, on the top of the RSA, a bracket is used to accommodate the motor and RSA. The motor is attached to the frame and used to rotate the frame.

3.4. Step of the Outer Skin Aircraft Door. With the design of the fixture, the following are the steps for aircraft door outer skin drilling operation:

1. First, the factory floor’s rail system directs the movement of the outer skin aircraft door from the store
2. The frame is rotated horizontally to receive the outer skin aircraft door. The outer skin aircraft door is positioned over frames, fully into contact, and secured with four latch clamps
3. An axis rotation of the frame is rotated to a horizontal 90° position bringing the outer skin aircraft door to a vertical position facing the operator. In this

Figure 2: Standing and sitting position of operator for drilling with vertical movement of the fixture.

Figure 3: The design for fixtures for aircraft outer skin door drilling.
4.1. Finite Element Analysis (FEA) Simulation. The overall fixture design will be simplified to conduct a finite element analysis (FEA) in SOLIDWORKS analysis to evaluate the strength of the fixture structure [22, 23]. The mesh for fixture design models was created by a 4-node tetrahedral blended curvature-based mesh. The total number of nodes and elements created for the FE model was 17256 and 8608, respectively. Only 1 set size was selected for the FE model due to the lowest computational cost. For a boundary condition, a fixed, nonrotational boundary element was set at the flange between the frame and vertical stand. Although this component is relatively strong on the upper and lower frame parts, the strength-generating flanges do not affect the bend. According to the analysis, the fixture frame can also support the motor’s maximum thrust output. Based on the current FEA assessment, the strength of fixture components was identified as appropriate under self-weight and assembly stresses.

The positioning and drilling of the outer skin aircraft door take a long time. This eliminates the requirement for an additional support element on the fixture to allow for faster positioning of the aircraft door outer skin on the panel frame while retaining existing positional precision. The outer skin surface must be supported rigidly by a reasonably thick backing plate on the fixture during the outer skin door drilling to meet the flatness tolerance necessary for the fixture and uplock assembly. When held by its edges, the deflection under its weight is substantially

Table 1: Material properties of Stainless Steel 304.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (GPa)</td>
<td>203</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.275</td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>215</td>
</tr>
<tr>
<td>UTS (MPa)</td>
<td>505</td>
</tr>
</tbody>
</table>

Figure 4: Stress distribution on the frame and vertical structure loaded with outer skin aircraft door.

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larger than the acceptable flatness tolerance, despite the comparatively moderate stress levels on the skin. This supported the fixture’s usage of rather heavy backing plates and stiffening elements, demonstrating that there would be no material savings in this area.

4.2. Prototype Development and Testing. Since the proposed fixture design is very costly, a prototype was fabricated to evaluate the performance of the fixture system, as shown in Figure 6. The size of the fixture prototype is a quarter of the originally proposed size. The prototype fixture has a function of location, securing, clamping, translation, and rotation motion as actual fixture design. Also, a scale-down outer skin aircraft door was prepared. The prototype fixture will locate, secure, and clamp the down-scaled outer skin aircraft door panel on the frame, as shown in Figures 7 and 8. Figure 9 shows the frame will rotate 90° facing the operator once it is secure. Then, Figure 10 shows the frame containing the outer skin aircraft door will move upward and downward according to the drilling location.

4.3. Discussion. In order to improve the performance of the outer skin aircraft door drilling process, a combination of fixture design with a drilling ergonomic approach, FEA assessment, prototype fabrication, and animated sequences were used. This method had the advantage of combining process and fixture design operations, which were previously done in a nonhealthy and safe manner for the operator while drilling. The savings are mostly due to the better handling qualities of the outer skin aircraft door drilling.

Protecting the safety, health, and welfare of those engaged in work is what health and safety are all about. Improved fixture design can help researchers better understand how operators interact with their surroundings. In order to perform a drilling activity, the fixture is constructed so that no overreaching or sustained abnormal body postures are required. Designing an ergocentric fixture aims to create a lean environment where the operator only moves a short distance, saving wasted movement and time. Drilling the outer skin aircraft door gets leaner as needless nonvalue added time is minimized by using an ergocentric fixture like the one depicted in Figure 6. Although only minor
improvements were made to the ergocentric fixture for the drilling operation, the overall drilling time was reduced significantly.

Since the proposed fixture design is very costly, a prototype was fabricated to evaluate the performance of the fixture system. The size of the fixture prototype is a quarter of the originally proposed size. The prototype fixture has a function of location, securing, clamping, translation, and rotation motion as actual fixture design. Also, a scale-down outer skin aircraft door was prepared. The prototype fixture will perform location, securing, and clamping of scale-down outer skin aircraft door panel on the frame. Once it is secure, the frame will rotate 90° facing the operator. Then, the frame containing the outer skin aircraft door will move upward and downward according to the drilling location.

5. Conclusions

This project aimed to create a specific fixture for drilling outer skin aircraft doors while considering ergonomics and FEA. The proposed design incorporates the drilling holes location, drill tool position, and operator applied lateral and feed forces and reduces fatigue due to repeatability tasks. The proposed fixture design changes the drill hole position by moving the drill location vertically considering the standing and sitting position of the operator. The FEA result shows that the maximum value for the von Mises stress recorded was $6.373 \times 10^5$ N/m$^2$ at the flange between the frame and vertical stand, which is able to withstand any deformation. A prototype was developed to locate, position, clamp, and manipulate the fixture as actual motion. From this study, the fixture for the outer skin aircraft door has been improved by introducing the ergonomic aspect during drilling, improving health issues, and reducing drilling time.

5. Data Availability

The aircraft door design and dimensional data used to support the findings of this study have not been made available because of confidentiality reasons set by the company/manufacturer due to safety reasons.

5. Conflicts of Interest

The authors declare that they have no conflicts of interest.

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