ASAT4-Enhanced Flexibility for the C-17

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ABSTRACT

The Automated Spar Assembly Tool or ASAT was originally developed for the Boeing 767 wing spar in the late 1970s. Since then this powerful concept has been further advanced and integrated into nearly all the current Boeing commercial wing lines. A fourth generation system, ASAT4, has been developed for the Boeing C-17 Globemaster III. ASAT4 provides an unprecedented level of flexibility in a minimum amount of floor space. Similar to ASAT3, ASAT4 consists of a vertical traveling yoke machine which straddles the spar fixtures. Two fixtures placed end to end form a system approximately 220 feet in length which is serviced by a single machine. This allows manual operations, e.g. load and unload, to be performed on one spar while the machine works in the adjacent cell. Each fixture can accept any of the six C-17 spars. Fixture reconfiguration between spars is completely automatic. The single three axis yoke machine, the E5000, travels the full system length. The yoke is simply supported on the side of a rigid gantry structure. The E5000 has completely redundant tool heads on both legs of the yoke. This permits drilling and fastener insertion from either side of the spar.

1.0 INTRODUCTION

The wings of the Boeing C-17 Globemaster III are built around three wing spars, front, center and rear. During the initial production ears these parts were completely manually assembled. Twelve different assembly jigs were used to assemble these six spars. Spar caps and stiffeners are located to the web in the first assembly jig (AJ1) with drill templates used to place fastener holes. Once fastened the spars are then transferred to a second assembly jig (AJ2) for precision location of critical components such as the wing rib attachment fittings. With thousands of fasteners per spar the entire process is highly labor intensive.

As part of a program wide effort Boeing engineers were challenged by the US Air Force to develop long term manufacturing cost reduction strategies for the C-17. While automation is recognized as a means to significantly reduce labor costs and improve quality, large-scale automation projects are typically difficult to justify on low rate sustaining programs such as the C-17. An additional hurdle common with many sustaining programs was the introduction of automation to an assembly designed without the benefit of Design For Manufacturing and Assembly (DFMA) initiatives. While the C-17 spars are flat in profile, there are offset fasteners with extremely tight clearances on both sides of the spar.

To prove cost effective in this environment the automation system must provide a high degree of flexibility in a minimum amount of floor space. The ASAT4, a fourth generation spar assembly system, was developed to meet these unique challenges of the C-17 program. ASAT4 is based on the concept of "in jig" assembly with a vertical yoke assembly machine. This ASAT configuration was initially implemented for the Boeing 737 and 757 programs. ASAT4 however offers an unprecedented level of flexibility along with many new features for improved process speed and control.

2.0 SYSTEM OVERVIEW

ASAT4 consists of a vertical traveling yoke assembly machine, which straddles two CNC controlled flexible spar fixtures. The fixtures are placed end to end to form a system approximately 220 feet in length serviced by a single machine. This allows manual operations, e.g. load and unload, to be performed on one spar while the machine works on the adjacent fixture. Each fixture can accept any of the six C-17 spars. Reconfiguration between spars is completely automatic and requires under five minutes. The machine is designed with completely redundant tool heads that permits drilling and fastener installation from either side of the rigidly supported spar.

Since ASAT4 was introduced into a sustaining program the existing AJ1s remain in use for initial location of cap to web. This helped to reduce the over system cost and complexity. The spars are therefore loaded into the fixtures in a tacked condition. This is illustrated in Figure 6. The machine is used to install the bulk of the remaining fasteners. All fastener installation and fixture operation are CNC controlled. The high accuracy of the ASAT4 machines ultimately will allow elimination of the need for the AJ2s and reduce overall spar manufacturing floor space requirements. Components with critical position requirements will be located using machine drilled coordination holes.

2.0 AUTOMATED FASTENING MACHINE - E5000

The requirements being placed on next generation assembly systems demand that the assembly machine be stiffer, faster and significantly more accurate than older systems. These newer machines are actually being designed more as machine tools with the accompanying performance requirements. The ASAT4 automated fastening machine, the E5000, was designed to meet these challenges.

3.0 MAJOR MACHINE STRUCTURE

Figure 1: E5000 Machine with Redundant Operator Stations

The E5000 consists of a rigid yoke mounted to a gantry structure which straddles the spar fixture and rides on parallel sets of precision beds. The system is completely CNC controlled with fifteen servo axes all directly integrated into a single control, the Fanuc 15MBMA. Since the C-17 spars are flat no major rotary axes are required. The E5000 therefore operates as a three axes machine for fastener location.

High precision and stiffness is required along the X-axis to allow for fast, stable and accurate positioning. The E5000 is driven in X by four motors in a synchronous tandem configuration, a unique feature provided by the Fanuc control. A Rennishaw RG2 tape scale is used for secondary feedback. This arrangement provides active electronic anti-backlash control which does not vary over time, as is the case with most mechanical anti-backlash mechanisms. Active temperature compensation using macro calls within the Fanuc CNC is used to maintain absolute positional accuracy throughout the large thermal swings present in the Long Beach factory. These features insure the high accuracy required over the 100 foot working envelopes for precise CNC fastener and detail part location.

Servo positioned tool tables are mounted to the bottom of the yoke legs. See Figure 2. A rigid yoke provides the most reliable arrangement to maintain alignment between opposing heads. Precision alignment of the tool points is critical to the fastening process especially for the installation of collars onto interference bolts. The yoke is simply supported on the gantry legs with a minimal constraint design. This insures that in the event the machine beds should settle differentially the yoke will not see any torsional loading transmitted through the gantry which could cause the tool point to move out of alignment. These features provide the optimal configuration for long-term process reliability.

The yoke is positioned vertically by one Y-axis motor which drives Y carriages on either yoke leg through a pair of right angle gearboxes. Secondary feedback for the Y-axis is provided with a Heidenhain glass scale linear encoder which guarantees high precision over the 72-inch vertical working envelope. The entire Y-axis is counterbalanced with a 300-psi pneumatic counterbalance system. Air was chosen over more a more conventional nitrogen charged hydraulic system since pneumatic systems are less costly and more easily maintained. Functionally the pneumatic system has proven equal in performance to the older hydraulic systems.

3.2 PROCESS HEADS</B> </A>

While the C-17 spars are flat in profile, there are offset fasteners with extremely tight clearances on both sides of the spar. The E5000 was therefore designed with completely redundant tool heads mounted on both legs of the yoke. This permits drilling and fastener insertion from either side of the spar. The spar remains fixed throughout the assembly process. Redundant operator stations allow the operator to monitor the process from the most appropriate side with no loss of control. These are illustrated in Figure 1.

Two CNC controlled clamp tables are mounted to bottom of the yoke legs. Clamp up on a rigidly held part without part movement is critical to the success of the "in jig" assembly process. Clamping is accomplished without imparting a differential load to the spar by driving one table forward and actively sensing the spar surface with a non-contact panel probe. The opposing table then drives into the part under load cell feedback to complete the clamping cycle. Clamping is maintained throughout the installation process by continual closing of the clamp table servoloops around the loadcell. This enabling operation is described in detail in Hartmann [1].

The fastener installation tools are mounted to redundant shuttle tables which ride on the underside of the clamp tables. See Figure 2. The tools consist of a servo driven spindle, a feedernose servo EMR, a "smart" pneumatic bolt inserter, a hole probe, a fastener ejection tool and a resynchronization camera. The shuttle table axis is the most critical axis to cycle rate. For each one-inch machine move between fasteners the tool shuttle table must move approximately three feet between the various tools. Linear motors drive the shuttle tables with 1G acceleration to a maximum velocity of over 40 in/s. The integration of the linear motor shuttle table alone has reduced process cycle times by 15%-20%.

Figure 2: Clamp Table with Process Tools

A number of features have been integrated into the process tools to enhanced the speed and verification of the fastening process. These include:

1. The 15,000 RPM DC servo controlled spindle is provided with water cooling for increased heat dissipation required at higher power levels, The spindle is configured with an Ott Jacob powered drawbar which allows for quick change of the appropriate cutters. Cutters can be preset with their set up parameters stored in the CNC to reduce downtime during tool changes.

2. Past electromagnetic riveting heads (EMR) have been positioned using air cylinders. One disadvantage of this method is that since material stacks vary infinitely and slug rivets only come in 1/16" increments it is difficult to properly set the rivet protrusion height. Servo control of the EMR forming die's axial position by the CNC however permits precise balancing of the slug rivet protrusion on both sides of the spar. The desired protrusion is calculated by the CNC using the stack thickness and selected rivet grip. The EMR is then servoed to the calculated position for exact protrusion balancing. This feature provides more repeatable and higher quality fastener installation results.

3. The axial position of the pneumatic bolt inserter is controlled by an air cylinder which has a linear encoder grating etched directly

on its rod. This powerful feature allows continual monitoring and verification of the bolt insertion process. Bolt length, orientation, diameter, installation speed and bolt/hole interference levels all can be checked real time with this feedback device.

4. A servo driven hole probe based on precision ball gages is used to validate hole diameter in process and prior to fastener installation. Hole diameter is one parameter which cannot be measured after the fastener installation cycle is completed. A record of the hole diameter is critical to the long term goal of reduction or elimination of test coupons.

5. A fastener ejection tool allows automatic recovery in the event that a bad fastener is detected prior to forming. This tool increases the efficiency and safety of the system as it eliminates the need for operator intervention to clear unwanted fasteners.

6. The resynchronization camera is used to reference the machine to the appropriate fixture. In additional it is used to verify the location of parts which were manually installed in the initial tacking stage. This tool thereby allows the E5000 to function as a very large CMM for verification of part and fastener locations.

The requirement to fasten six different spars with one machine is by itself not a significant challenge in today's DFMA design environment. The C-17 however was not designed with this philosophy and therefore access to the fasteners varies considerably across the different spars and even with a single spar. The E5000 system is designed to install two diameters of slug rivets as well as three diameters and two types of interference bolts. There is an assortment of different clearance requirements for each fastener size and type. To meet these requirements a variety of front end or clampnose configurations were developed. One offset configuration is illustrated in Figure 3. To avoid collisions and potential damage to the spars it is imperative that the correct clampnose is installed for the appropriate part program. Each nosepiece assembly has therefore been provided with an identification tag realized through a series of dip switches and a D shell connector. This connector and all other utility connections are fully integrated into the headstone and the appropriate nosepiece for quick change convenience. This greatly simplifies the tool change process for the operators.

Figure 3: Offset Clampnose

The large number of fasteners which must be supported requires a compact fastener feed system. Fasteners are stored in coiled tube cartridges which are approximately the size of a small briefcase. Each cartridge holds around five hundred fasteners. The narrow cartridge cross section permits a large number of cartridges to be carried on the gantry in a relatively small area. The sixty point system easily fits onto one side of the gantry. (Figure 4) The individual escapements are pneumatically controlled through a PLC which resides on the Fanuc fiber optic ring. The cartridges are multiplexed through a series of laterals located below the main storage racks. A second routing station located on top of the gantry directs the requested fastener to the appropriate side of the machine. For low fastener counts drops tubes are provided at the operator stations upstream of the main fastener feed station to permit manually feeding. The cartridges are automatically loaded off line with vibratory bowl feeders. This removes all inherent problems of dealing with bulk fasteners off line and away from the production environment. For a further discussion of these feed systems see, Rink [2].

Figure 4: Fastener Feed System

4.0 FLEXIBLE FIXTURES

Jigs are typically used in the aircraft industry to provide faster, simpler and more repeatable location of detail parts than could be accomplished by repeated manual layouts. In the past large component jigs have been designed for high rigidity and precision to meet the tight tolerances required for integration with other aircraft components in final assembly. Drill blankets are used to locate holes and locating jigs index subcomponents relative to the nearest available reference. Over the first few shipsets jigs are typically modified to correct unforeseen problems encountered in the downstream assembly process.

The result is typically the development of dedicated inflexible fixtures for each major aircraft component. For lower rate programs this inflexibility can prove costly. The large number of jigs are expensive to maintain and routine. Floor space requirements are high and cannot be as easily amortized over low production rates. The lack of jig flexibility can also hamper the design of derivative aircraft modifications. With conventional jigs changeover time between variants can significantly reduce efficiency and drive up costs. Assembly jig flexibility is therefore key to the commercial success of low rate programs.

The ASAT4 system contains two flexible fixtures which are situated end to end to form one automated cell. The two fixtures are identical and each can accept any of the six C-17 wing spars. Since the C-17 is a relatively low rate program the decision was made to keep the original dedicated AJ1s for use as tack fixtures only. Unlike previous ASATs the spar is therefore provided to the ASAT4 cell in the tacked configuration. ASAT4 is then utilized to install the bulk of the fasteners and to ultimately locate and install critical components such as the rib attachments. This revised job description allowed a significant reduction in the number of indices required relative to previous ASATs and thereby reduced the overall system cost. Despite the reduced number of indices the fixtures still must maintain the spars in precise and repeatable locations relative to the machine coordinate system since all fastening is performed under complete CNC control.

Figure 5: Flexible Fixture Unloaded

Figure 6: Loading Spar into Fixture

Figure 7: Spar Loaded in Fixture

Each fixture consists of sixteen upper index assemblies, sixteen lower index assemblies and one primary index assembly. These assemblies are mounted to a series of rigid steel based modules which are placed between the two X-axis machine beds. The sixteen lower index assemblies provide the anchor for the spar fixture and are used to clock the spars' X-axis parallel to that of the machine. Each lower index consists of three unique index nests which correspond to the cap geometry of the front, center and rear spars at that particular station value. The nests are spaced 120 degrees apart on a pneumatic rotary indexer as shown in Figure 8. The indexer operates using a Geneva mechanism which provides .001-inch true position repeatability. Pneumatically controlled toggle clamps retain the spar in the lower nests. The clamps move on a vertical slide and index off each individual nest to insure proper orientation of the clamp body to the respective spar cap as the spar heights vary between the three spars. Belleville washer stacks provide the clamp arms with sufficient compliance to accommodate the gage changes between the three spars at each station.

The entire lower index assembly is mounted to the fixture base modules though a second pneumatically controlled rotary indexer. This second indexer provides 180 degrees of motion. By placing the center of the indexer's rotation coincident with the spar datum plane the same assembly is able to locate an opposite hand spar by reversing the orientation of the nest. The second indexer and all required utilities are mounted in a covered trench.

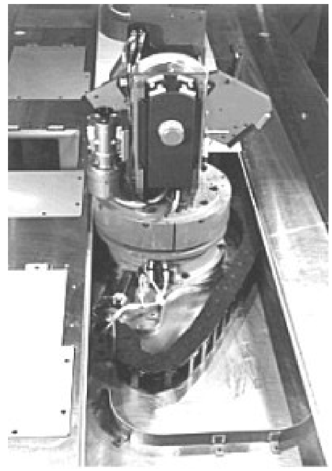

Figure 8: Lower Index Assembly

The upper index assemblies hold the spar vertical by grabbing onto the upper spar cap and thereby maintain the spar plane perpendicular to the machine drill axis. These components are mounted to vertical posts which are provided with sufficient vertical motion to sink into the floor and completely out of the machine path. Servomotors are used to position the upper index both vertically and horizontally under CNC control. Upper index positions are therefore all programmed positions which are easily changed in software. A swing clamp with ample compliance to accommodate the different cap widths draws the upper cap into the index.

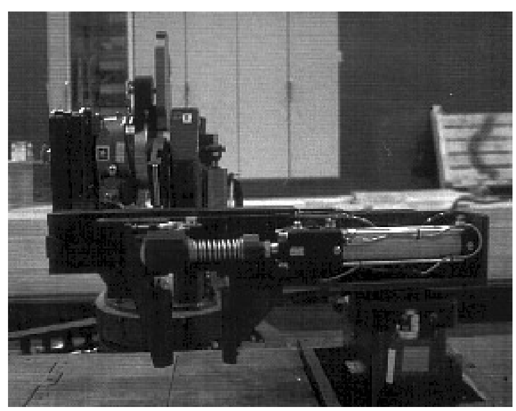

Figure 9: Upper Index Assembly with Post Fully Down

The spars are indexed in the X-axis through a single tooling hole in the web designated as the primary index. The primary index is shown in Figure 10. The tooling holes in the spars webs have been placed such that a single index location can be used for all six spars. The AJ bases sit on conventional jig feet and are fixated to the foundation in X at one point which coincides with the primary index. This insures that all growth due to temperature for both the fixture and the spar originate from the same point. A single primary index provides a fixed origin point to which the machine can synchronize. This is important to insure proper functioning of the machine temperature compensation which is critical to provide the accuracy required for precision jigless component location.

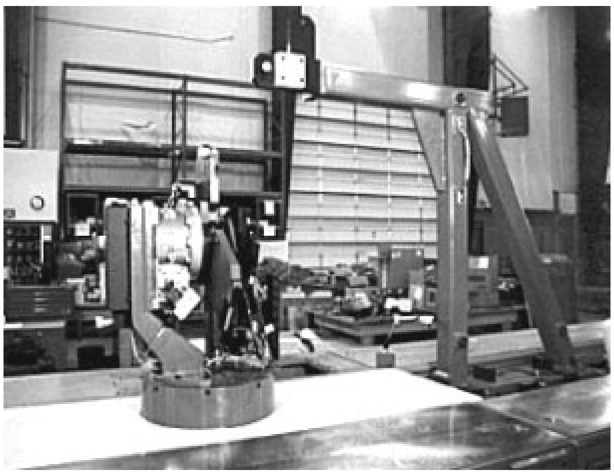

Figure 10: Primary Index with First Lower Index

The two flexible fixtures are completely automated for both their set up and operation. The fixtures are directly controlled by GE PLCs which reside on the fiber optic ring of main system brain, the Fanuc 15MBMA CNC. Each fixture has thirty-two servomotors in addition to pneumatically controlled actuators. Changeover between one spar configuration to another requires under five minutes and is controlled either from the machine button panel or remotely from the fixture junction boxes. No manual intervention is required. Once running under part program control all operation of the fixture is controlled through M-codes for complete CNC operation.

5.0 Conclusion

The ASAT4 system has been designed to meet the specified requirements of low rate production requirements of the Boeing C-17. A high degree of flexibility has been integrated into the spar fixtures and the E5000 automated assembly machine to allow one system to meet the production requirements for all six C-17 wing spars.

ACKNOWLEDGMENTS

The authors wish to thank the ASAT4 team both within Electroimpact and Boeing for all the hard work that made this project a success.

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