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An Investigation into the Use of Small, Flexible, Machine Tools to Support the Lean Manufacturing Environment.

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ABSTRACT

Drilling fastener holes in large assemblies is traditionally accomplished through the use of large machine tools in order to obtain the accuracies required for the assembled part. Given recent advances of machine design and machine controller compensation, the accuracy of the motion platform can be corrected if the machine is repeatable. This coupled with the use of a vision system or touch probe to compensate for assembly variations, permit the use of smaller, more portable drilling systems. These smaller, more portable machine tools allow for lean manufacturing techniques to be incorporated into build processes, utilize less floor space, and in many cases are less costly than larger, permanent machine tools.

This paper examines the feasibility of utilizing a small 5-axis, portable, drilling system for drilling the side panel skins on the F/A-18 E/F forward fuselage. The system will have the capability to scan key-locating features on the assembly, correct for any assembly variations, and drill and countersink through various stack-ups of composite, aluminum, and titanium. The drilling system can be easily hoisted on and off of the existing assembly jig to allow for additional utilization of the assembly jig for other manufacturing operations. This paper will examine the technical aspects of the portable machine tool, along with the advantages and disadvantages of small portable drilling machines for the use in assembly processes.

INTRODUCTION

Like many companies, The Boeing Company is embracing lean manufacturing techniques to streamline their manufacturing processes. This paper focuses on utilizing lean manufacturing equipment to drill precision holes in multi-material aerospace structures. Lean manufacturing principles are driving companies like Boeing to utilize more flexible build processes that are easily re-configured when processes are changed or optimized, or when parts are redesigned. This in turn drives equipment manufacturers and procurement organizations towards smaller, more flexible machine tools. Traditionally, there have been two different methods employed to drill precision holes in aerospace structures: 1) manufacturing of drill templates where hand or semi-automated drilling processes are utilized to produce the holes, or 2) using large machine tools to drill precision holes. Typically, these large machine tools require a permanent foundation, and require that the assembly is transported to the drilling equipment. Generally speaking, these two actions are in violation of the lean manufacturing principles of a continuous flow build process. The large machine tools are often not flexible enough to allow for significant changes in the manufacturing process when major design or process changes are implemented. The Boeing Company and Advanced Integration Technology, Inc (AIT) have developed and are implementing a 5-axis numerically controlled drilling machine to drill side panel skins (and associated substructure) on the F/A-18 E/F forward fuselage.

BACKGROUND

The Boeing Company continually monitors its production processes and explores opportunities for new and improved automated assembly initiatives. In the fall of 1999, a team was assembled to study the feasibility of implementing a drill and countersink machine on the F/A-18 E/F forward fuselage (both left and right-hand side panels). After much investigation and proposal reviews, Advanced Integration Technology was chosen to design and build a small, portable 5-axis drilling system to drill and countersink (single step process) the forward fuselage side panels. The 5-axis drilling system is termed the Numerically Controlled Drill Jig (NCDJ) and is slated for production implementation in the second quarter of 2002. The machine is currently in one of Boeing's Advanced Manufacturing Development laboratories for process development and machine optimization purposes. The basic premise of the design is based on a 3-axis NCDJ previously designed by AIT and implemented into the 767-wing assembly line (Williams, et. al., 1999).

The major differences between the 3-axis and the 5-axis concept are the addition of two rotational axes (a and b-axes), the addition of a pressure foot (used for referencing the part surface for countersink depth control, elimination of inter-laminar burrs, and improved drilling dynamic stability), and the addition of a two-dimensional vision system (used for correcting for assembly variations of the parts being drilled).

COMPARISON OF SMALL MACHINE TOOLS

Given the advantages of smaller automated assembly drilling systems, several types of portable, numerically controlled (NC) drilling systems have recently emerged in the aerospace industry. Two main types of equipment have transpired; those machines that attach to the part's assembly jig (AJ), and those that attach directly to the part itself. The machines that attach directly to the part being drilled have the advantage that rigid assembly jigs for mounting of the machine tool are not necessary. However, the work envelope of this particular type of automation is often limited due to weight restrictions of the equipment attaching to the part. This reduced work envelope can result in additional set-ups of the machine to drill a particular part.

In the case of the automated systems that attach directly to the assembly jig, the assembly jigs are normally more rigid than the part, thus, the weight restrictions of the equipment are relaxed. As a result, these types of systems often have larger working envelopes, which result in a reduction in the number of machine set-ups. A disadvantage is that the systems are typically heavier and may require craning of the systems on to the AJ. This paper will focus on a particular automated drilling system that attaches directly to the assembly jig of the part being drilled.

TECHNICAL DESCRIPTION OF THE F/A-18 E/F NCDJ MACHINE

MECHANICAL DESCRIPTION

The NCDJ consists of a large outer frame that determines the machine drilling envelope (see Figure 1). The top and bottom structural members of the frame contain linear rails (x-axis) spanned by the vertical carriage (y-axis). The vertical carriage is driven on these rails in the horizontal, x-direction, by mechanically coupled, dual ball screws. The dual ball screw arrangement is necessitated by the high aspect ratio of the vertical frame. This demands positive x-axis positioning on both ends for stability about the z-axis (feed axis). The carriage is rotated about the y- axis pivot (b-axis rotation) by a linear actuator. This design provides greater stability than a rotary actuator.

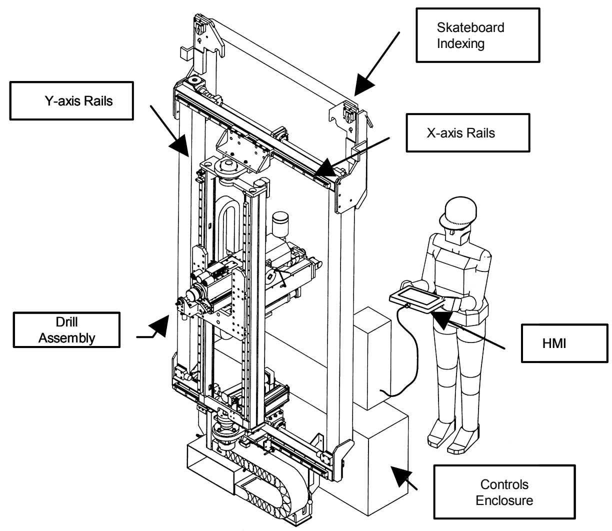

Figure 1: Physical System Layout

The drill assembly (pressure foot and spindle) moves on precision rails inside the y-carriage. The drill assembly can pivot about the x-direction (a-axis rotation), which is driven by a linear actuator (again for greater stability). Both the a-axis and the b-axes are preloaded with counteracting air cylinders to minimize backlash.

SPINDLE

The cartridge spindle is an off-the-shelf component bolted to the z-axis actuator, which is driven by a servo-controlled precision ball screw (see Figure 2). Since there are very few hole sizes in the fuselage assembly, a manual quick-change tool holder is utilized. A direct drive servomotor is used to accurately control the spindle speed through the various material stack-ups.

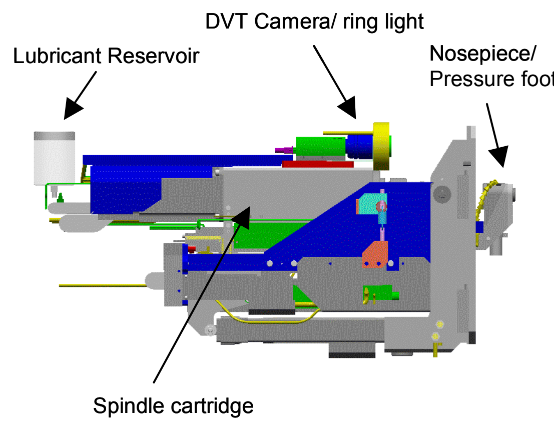

Figure 2: NCDJ Spindle Assembly with Pressure Foot.

PRESSURE FOOT

Since the machine drills outer mold-line fuselage side-panels, precise control of the countersink depth is required. An independently controlled pressure foot (extending from the z-axis actuator via pneumatic cylinders) is used to provide contact with the structure being drilled. A linear scale is then used to provide feedback of the part position to accurately control the countersink depth. The pressure foot contact force is programmable and controlled within 10 pounds. This clamp-up force also helps to eliminate inter-laminar burrs between various materials being drilled. A spherical bearing at the end of the pressure foot is used to provide angular compliance to prevent marking the workpiece. A vacuum shroud encloses the pressure foot allowing for the use of a vacuum system for the removal the carbon fiber dust, cutting chips and mist coolant.

MOVING ZONE TO ZONE

Due to the fact that the x-envelope of the NCDJ is smaller than the fuselage side-panel length, discrete zones along the tool are defined to complete an entire drilling area. To facilitate the ease of zone-to-zone indexing, the NCDJ attaches directly to a set of parallel precision bearing rails along the assembly jig (AJ) of the fuselage. Each rail has a permanently attached 'skateboard' type interface, which acts as a parting plane for attaching the NCDJ to the AJ. Together the rails constrain the NCDJ to the AJ in all but one direction.

Zone indexes with known locations are utilized to establish a repeatable reference station along the travel of the NCDJ. Slotted bushings, along with high tolerance jig pins, establish a firm connection between the NCDJ and AJ. A sensor is used to confirm proper indexing. Additionally, each location is tagged with a unique array of sensor cams. Once indexed, the NCDJ verifies the current position and side of the fuselage side-panel by a series of proximity switches.

CONTROLS AND SOFTWARE

A critical component of the mobile NCDJ technology is a compact, self-contained, control system. A PC-based NC controller is used to control the NCDJ. The controller is housed along with the motors, amplifiers and other various components in a small enclosure (see Figure 1). Since power, air and vacuum are the only connections which are required to operate the machine, the machine can be used virtually anywhere without the use of extensive, tethered equipment.

The human-machine-interface (HMI) of the machine controller presents process information in both NC and graphical formats. Therefore, specialized production personnel with NC experience are not required. Part programs are downloaded only when they are required over a wireless local area network (LAN) from a part program server. This scheme ensures that all current part programs only need to be located in one area on the server. If there are design changes that cause part program changes, they only need to be updated on the server.

The vision system is programmed to recognize several fiducials including part edges, holes and fasteners. The controller is capable of performing four unique transformations based on the different fiducials that are available in each zone. The transformation algorithm is set in the NC program.

NCDJ METHOD OF OPERATION

The machine set up process begins in a design facility tool (DFT). The DFT, shown in Figure 3, is used for a multitude of tasks including, an off line countersink set up bench, a platform for process development activities, and a platform for performing machine calibration for preventive maintenance purposes. After the machine has been calibrated and the cutting tools have been preset for the correct countersink depth, the NCDJ is hoisted from the DFT on to the transport mechanical equipment (TME) cart (see Figure 4).

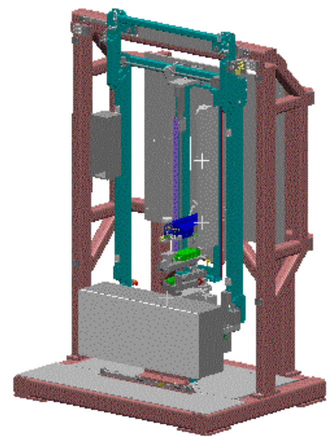

Figure 3: Design Facility Tool (DFT) with 5-axis Numerically Controlled Drill Jig (NCDJ).

The TME is utilized to transport the NCDJ from the off-line location of the DFT to any of the various assembly jig positions located on the F/A-18 E/F forward fuselage line. When the TME/NCDJ machine is in the correct location, an overhead crane is utilized to hoist the NCDJ from the TME to the aircraft assembly jig (AJ). It should be noted that the use of the TME is not necessary when hoisting provisions can be made directly from the DFT to the aircraft AJ.

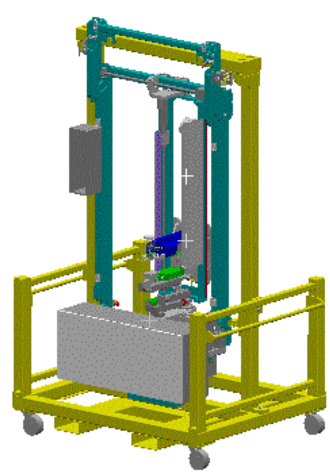

Figure 4: Transport Mechanical Equipment (TME) with 5-axis Numerically Controlled Drill Jig (NCDJ).

Figure 5 shows the NCDJ integrated with the assembly jig. The AJ is equipped with precision rails and bearing cars that allow the NCDJ to move transversely to various zones on the assembly jig. Once the NCDJ has been craned onto the assembly jig and attached to the bearing cars, the machine is pinned into a specific zone. A series of proximity switches are used to identify the specific zone location on the AJ. Power and air is then connected to the NCDJ, the machine is powered up, all drives homed, and the spindle is allowed to warm up to minimize thermal growth errors. During the machine warm up period, the NC programs for that job are downloaded from a "cell controller" (local networked personal computer (PC)) to the on-board NCDJ controller via a radio frequency network interface. (Note all programs for a job will be downloaded at one time. The job will cover an entire fuselage side panel. The operator is restricted to run only the NC programs valid for the current zone of operation.) The NCDJ then scans key locating features on the fuselage within that zone. The scanning is performed by a commercially available, two-dimensional, 'smart' vision system that is mounted on the NCDJ spindle housing. After the key-features are located on the fuselage structure the controller performs the necessary part transformations to correct for assembly variability and to improve the hole location accuracy.

After the NC program transformation is performed, the machine drills and countersinks the holes in the desired locations. (It should be noted that the vision scanning and drilling processes can be interleaved. The correction step is done real time and is transparent to the user.) When the machine has completed the drilling operations within that zone, the spindle and pressure foot are retracted to a safe location, then the NCDJ is manually rolled along guide rails to the adjacent zone where the process is repeated. This process is performed four more times until the entire side panel skin and associated substructure are successfully drilled and countersunk. After all drilling processes are complete, the air, vacuum and power hook ups are detached, the NCDJ is unpinned from the zone indicator blocks, and can then be hoisted onto the TME or another AJ.

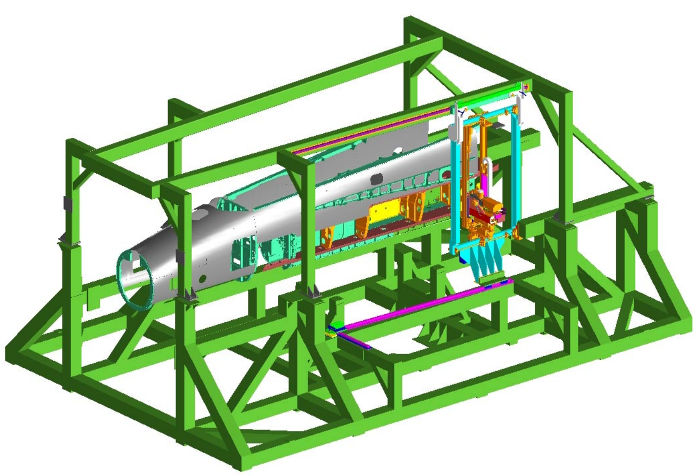

Figure 5: Numerically Controlled Drill Jig (NCDJ) shown Attached to the Assembly Jig (AJ) of the F/A-18 E/F Forward Fuselage.

BENEFITS OF SMALL MACHINE TOOLS

Flexible- Since the NCDJ does not require a foundation and is portable in nature, the machine is able to easily react to redesigns and modifications in the build process or shop floor flow. Since the machine is numerically controlled, the programs can be re-written quickly to respond to an engineering change in hole pattern or changes in hole and countersink diameter. Traditionally, drill plates would have to be sent out for rework or re-manufacture to respond to an engineering change.

Reduced Cycle Time and Increased Quality- Compared to semi-automated drilling processes, the NCDJ has consistent hole to hole moves, resulting in a reduced, consistent cycle time, with little variation in hole quality and countersink depth. Compared to dedicated, permanent machine tools, a disadvantage of a portable NC machine is that an increase in cycle time can result from having to crane and locate the systems to the part or assembly jig.

Ergonomic Improvement - The NCDJ eliminates the need for the movement of heavy power feed drills from hole to hole. Set up and movement of drill plates is also eliminated.

Lower Investment Costs - With the NCDJ, assembly capacity can be added in small increments rather than in large steps, which allows the capacity to be added incrementally, and only when needed (Williams, et. al., 1999).

Feasibility – The NCDJ has made it feasible to automate this particular assembly. Given the current constraints of the assembly, it would not be possible to move the fuselage to a conventional machine tool to perform the drilling process. A portable machine tool is the only viable option for automation.

CONCLUSION

This paper focused on the use of a portable, 5-axis drilling machine for the F/A-18 E/F forward fuselage. This type of automated equipment has been deemed well suited for the lean manufacturing objectives of the aerospace industry. This type of automation has all the advantages of a large, permanent machine tool without having to utilize a permanent machine foundation. Indeed, the existing assembly jigs are used for the drilling operation. This type of automation is also well suited for changes in the production environment such as design and process changes.

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CONTACT

For more information on the NCDJ machine please contact Ed Chalupa at echalupa@aint.com or Gary Williams at garyw@aint.com (972-423-8354).

DEFINITIONS, ACRONYMS, ABBREVIATIONS

NCDJ- (Numerically Controlled Drill Jig) A small, portable gantry style drilling machine used to drill precision holes.

DFT- (Design Facility Tool) A calibration/test station for the NCDJ machine. Can also be used as a tool set up platform.

TME - (Transport Mechanical Equipment) A simple cart designed to safely hold and transport the NCDJ.

AJ – (Assembly Jig) A structure used to locate and hold components during an assembly process.

GUI- (GRAPHICAL USER INTERFACE) A computer environment or program that displays, or facilitates the display of, on-screen options, usually in the form of icons (pictorial symbols) or menus (lists of alphanumeric characters) by means of which users may enter commands. (per ANSI.523-2001)