

Next Generation Composite Wing Drilling Machine for Vertical Builds

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ABSTRACT

Growing use of composite materials in aircraft wing construction requires a new generation of drilling machines. Electroimpact developed the LTD machine to address the specific needs posed by large scale composite wing box assembly. The machine maximizes the efficacy of blind access to create a single sided assembly process. Innovative design greatly reduces machine weight and foundation requirements. Optimized processes and automation tools increase the drilling capacity. The mobile machine maximizes plant flexibility by carrying out work on both wing surfaces across multiple assembly jigs. Through thoughtful engineering and thoroughly developed processes the LTD presents a highly capable and cost efficient solution for composite wing box drilling automation.



Figure 1-Lean Technology Drilling Machine (LTD)

INTRODUCTION

The past decade has seen rapid growth in the use of composite materials in airframe structures. Production of carbon fiber cover wing boxes poses unique challenges compared to the traditional construction of aluminum wings.

Primary among these challenges are four problems which design engineers identified when designing the Lean Technology Drilling machine (LTD) for outer wing box assembly on the Bombardier C-Series.

SINGLE SIDED ACCESS

During construction the cover must be progressively doweled in position and clamped to the underlying structure. Traditional wing box assembly methods require large numbers of low clamp force temporary fasteners and in some cases separate clamps and dowels, both are cumbersome and labor intensive processes. Other automated wing assembly systems address this need through the use of two piece temporary fasteners. While these fasteners provide both high clamp forces and accurate doweling, installation relies on man access to both sides of the wing panel and within the cramped confines of the torque box itself.

The LTD automates the entire process by feeding, inserting, and tightening Single Sided Temporary Fasteners (SSTF's). These bolts achieve both the same clamping and doweling performance as two piece fasteners but can be installed, clamped, loosened, and removed from the same side of the structure.

REDUCED WEIGHT AND FOUNDATION REQUIREMENTS

Large wing structures demand machine tools with equally large working envelopes. At the same time, drilling machines must be stiff to meet the close tolerances, clamp loads, and rapid machine moves needed for the assembly process. In the past these two requirements have commanded hulking and heavy automation machines which in turn necessitate thick, costly foundations.

Through radically new machine architecture and a fresh engineering approach, the LTD is 30% lighter than post machines with comparable working envelopes.

INCREASED SIZE RANGE

New aircraft designs have increasingly large fastener diameters through diverse material stacks including CFRP-Titanium. Drilling high quality, large diameter holes in titanium stacks often requires very large spindles. Machine tool infrastructure must increase to accommodate these large spindles, leading to a heavier machine. The LTD takes advantage of new automation processes and a highly tuned drill process to deliver clean, large diameter holes with a spindle size typically employed for smaller fastener sizes. The machine also features new bolt feed technology to automatically insert bolt sizes which are usually reserved for manual installation.

LEAN APPROACH

Large fixed monument machines are historically associated with full wing panel automation. These machines require a massive amount of support infrastructure and deliver little in the way of plant flexibility. The LTD, on the other hand, is specifically designed as a mobile piece of equipment. The machine is capable of being moved from cover surface to surface across multiple assembly jigs.

SINGLE SIDED ACCESS

SINGLE SIDED TEMPORARY FASTENERS

The SSTF used by the LTD feature clamp feet which expand on the back side of a hole to provide high clamp loads without the need for nut running or swaging operations. These fasteners, in tandem with the LTD's one sided post machine design, allow for a fully automated and truly blind assembly process. The feet are optimized with a large clamping area to avoid marking the aircraft components. The SSTF shank is precision ground to provide close tolerance doweling.

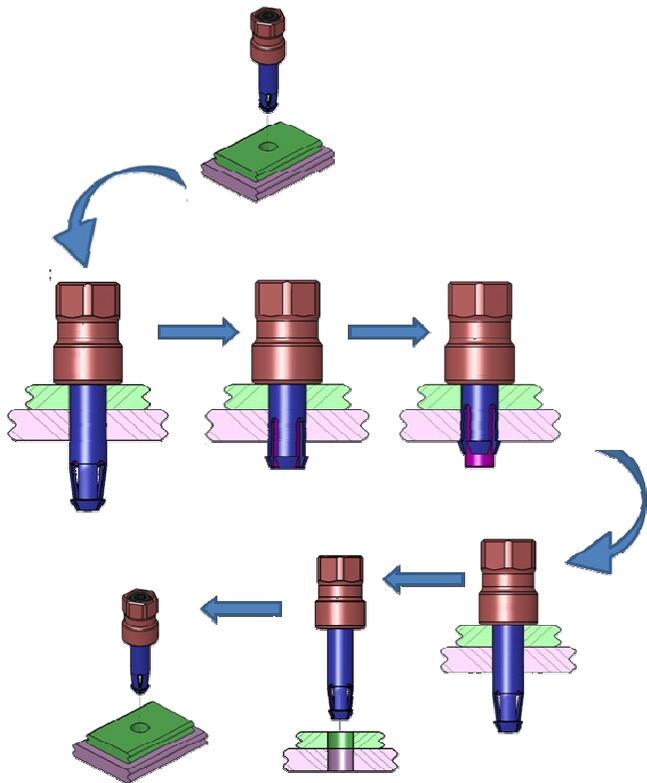


Figure 2-SSTF Clamping and Unclamping

The design of the collapsible mandrel style SSTF was finalized after extensive qualification tests for the LTD bolt process. Each diameter of SSTF ranging from $\frac{3}{16}$ "- $\frac{5}{8}$ " was analyzed to ensure that the tensile strength, shear capacity, and clamp foot fatigue met customer requirements. These tests also determined the optimum applied torque for each fastener size. Torque values were selected to maximize clamp force while ensuring that the fasteners would not damage aircraft components.



Figure 3-Single Sided Temporary Fasteners

BOLT CYCLE

An onboard fastener rack carries quantity and grip range of SSTFs sufficient to assemble an entire wing surface. During a bolt cycle the CNC program calls for the proper size fastener which is transferred from the feed rack to the bolt injector via compressed air. The Bolt Injector receives the fastener, measures grip length and diameter. The LTD automatically discards and refeeds any misfed bolts. Selecting, feeding, and measuring bolts concurrently with the drill cycle maximizes process efficiency. After confirming that the correct SSTF has been fed, the Bolt Injector passes the fastener to the Bolt Inserter which sets the bolt into the cover. The Bolt Inserter then tightens the SSTF to a predetermined torque value to clamp the cover to the underlying structure.

REDUCED WEIGHT AND FOUNDATION REQUIREMENTS

Machine mass has a large effect on performance, machine cost, and foundation costs. For this reason weight savings was a paramount concern for the LTD design team. By reducing internal machine loads and those applied to the foundation the LTD is able to do the same work as comparable machines with a weight reduction of 30%.

INNOVATIVE ARCHITECTURE

The LTD represents a radically different style of post machine meant to efficiently react clamping, drilling, and acceleration loads. Based on designs and principles initially developed for two sided riveting machines, the new architecture removes or minimizes moments and creates redundant load paths allowing for a stiffer, yet lighter machine structure. Most significant is the change from a single tower structure to a central process head flanked by two towers. The LTD's new arrangement creates two direct, symmetrical load paths from the tool point through the A-B pivots, Y-sled, and machine towers into the foundation.

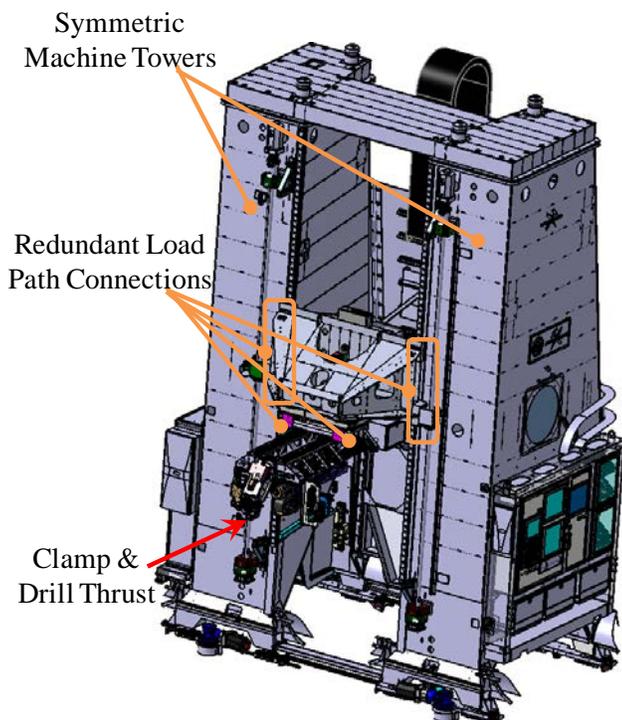


Figure 4-Machine Load Paths

Optimizing the load path in this manner enabled LTD engineers to build the machine structure from thin walled, light weight material. This design offers a significant weight savings over most post drilling machines which are arranged with the drill center line offset from the center of the machine structure and which rely on the torsional stiffness of large, thick walled structures to resolve drill thrust and machine clamp loads. In addition, the entire LTD structure underwent extensive finite element analysis to minimize material use and optimize machine characteristics including stiffness, harmonic response, and ease of construction.

WIDE STANCE

The two tower construction also creates a broad support to react forces from Shuttle Table motion and X-axis acceleration. Likewise, moving the X-bearing cars apart from each other imparts less force on each car from acceleration loads.

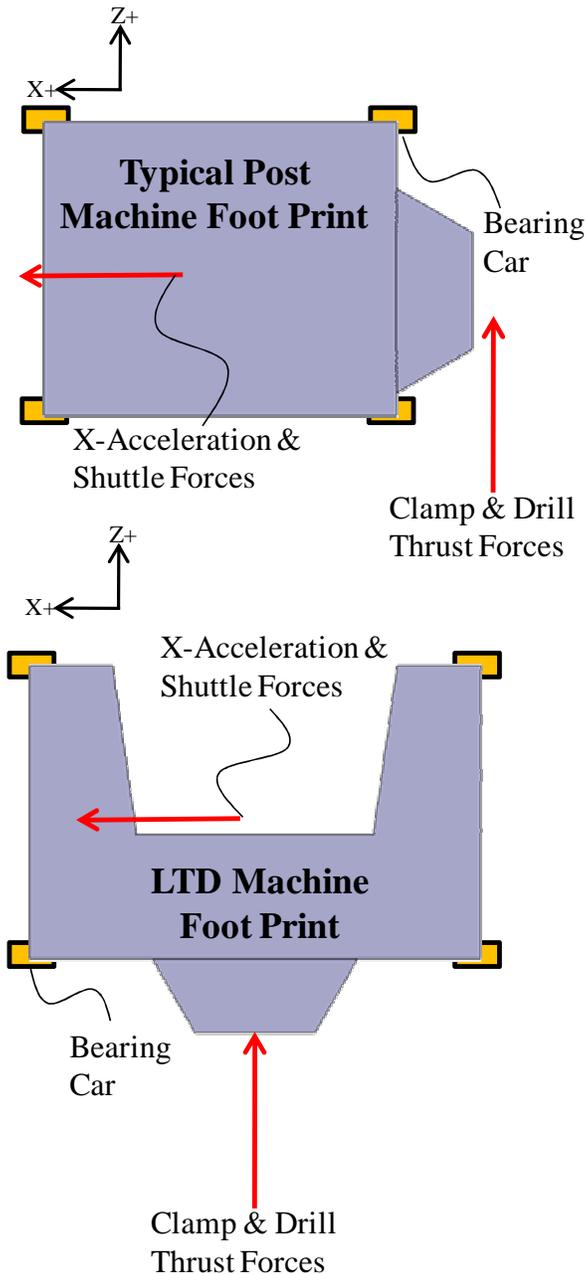


Figure 5-Comparison of Acceleration and Thrust Force Vectors

MONOLITHIC BED

The LTD is supported by monolithic machine beds which were designed concurrently with the machine structure. These beds are relatively light weight and work in tandem with the lower bearing car loads to reduce foundation requirements and costs. Precision machined reference edges for each rail greatly reduce installation. Reference edges also make it possible to reliably set the X-rails parallel to each other to within 0.004". Holding this tolerance ensures long life from the bearing cars and eliminates downtime due to

car replacement. The machine's innovative "Stiletto Heal" feature represents a further step to protect X-rails and cars. The machine towers are optimized for up to 0.010 inches of passive compliance to account for potential misalignment between X-rails.

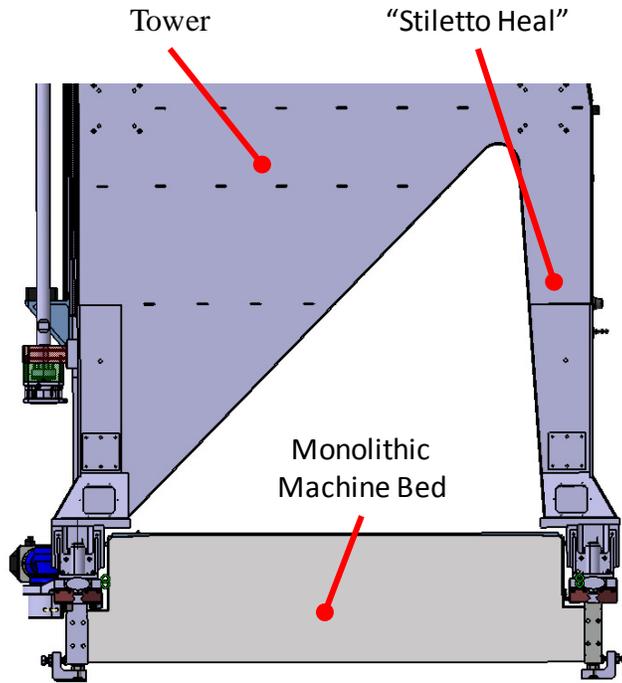


Figure 6-Tower on Monolithic Machine Bed

INCREASED SIZE RANGE

Performance of automated drilling machines can be hampered by large diameter holes and challenging materials including titanium and stainless steel. Often times the solution for these problems is a larger spindle and more manual interaction. In contrast, the LTD carries drill diameters up to one inch with a spindle typically sized for smaller holes. The machine also automatically inserts fastener diameters typically installed by hand.

SPINDLE

Drilling is carried out by a 173mm water-cooled spindle with 10,000 RPM capacity and an HSK 63 tool holder. This spindle package has been used with success to drill $\frac{1}{4}$ "- $\frac{3}{4}$ " countersunk holes on previous machines. To justify using this spindle package on the extended hole range $\frac{3}{16}$ "-1", Electroimpact conducted extensive testing with a variety of cutters and drill processes to optimize the spindle performance for larger holes. Cutter qualification demonstrated that by closely controlling the ream process the smaller spindle was capable of producing large holes with quality comparable to more powerful cartridges. This development paid off by allowing the LTD to drill holes with the smaller 173mm cartridge that normally would require a larger, 205mm spindle. The result is an estimated weight savings of 200 lbs on the process head. This weight reduction benefits all components which support and position the spindle by reducing the required size of drives, bearings, and structural components.

AUTOMATIC TOOL SWAPPER

Central to the LTD's controlled ream process is the Automatic Tool Swapper (ATS). The ATS allows the machine to change cutting tools in process, without unclamping from the wing cover. The tool swapper features a robust design with only three degrees of motion and minimal control requirements, the upshot of which is a complete tool change in less than 20 seconds. With a two tool capacity the ATS was built specifically for drill/ream cycles though it can also be used to increase the efficiency of multi-diameter programs. Integrated proximity sensors together with the machine's tool ID reader allow the ATS to accurately track the tools in both positions.

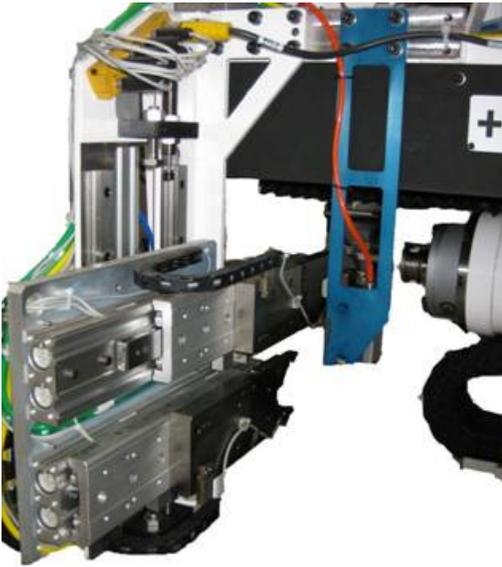


Figure 7-Automatic Tool Swapper

Drill/Ream Cycle

The ATS helps guarantee fast, accurate two shot drill processes with excellent hole quality. Fundamental to this is that the machine maintains position and clamp pressure during a tool change. While drill/ream cycles on most machines consist of: *Clamp-Drill-Unclamp-Tool Change-Resync on Drilled Hole-Clamp-Ream-Unclamp* the same process on the LTD looks like: *Clamp-Drill-Tool Swap-Ream-Unclamp*. On previous machines the optical resync operation required that the hole be drilled 1/32" below net, by eliminating this process the LTD is able to drill 1/64" undersized holes. Removing more material initially allows for a more controlled, precise ream operation. The result is tighter tolerances and greater repeatability.

Multi-Diameter Programs

Although designed specifically for drill-ream cycles, the ATS can also increase efficiency by swapping between two different drill sizes. To maximize this utility, LTD engineers matched other process dependant tooling (nose pieces, probe tips, etc) across the most common hole diameters. As a result, manufacturing teams have the freedom to run cycles of adjacent hole sizes concurrently.

BIG BOLT FEEDER

While smaller bolts are easily pneumatically fed, diameters above $\frac{5}{8}$ " pose several problems for this method of delivery. Among these are:

- The bend radius associated with large diameter feed tubes is too large for the routing path
- The size and weight of large diameter bolts require high pressure and flow rate of compressed air for feeding
- The kinetic energy of a pneumatically fed large diameter bolt risks damage to both the Bolt Injector and the bolt itself.

To address these issues, the LTD is equipped with new Revolver Feed Cartridges to deliver $\frac{3}{4}$ " and 1" diameter fasteners.

Revolver Feed Cartridges

Preloaded cartridges are stored on board the machine and are attached to the Clamp Table only during large bolt cycles. Each cartridge carries five bolts which is ample capacity to tack the Main Landing Gear and Pylon Support brackets which require these larger diameter fasteners. Integrated sensors confirm bolt diameter and position. When in place on the machine, the revolvers bypass the Bolt Injector and deliver the fasteners directly to the Bolt Inserter.



Figure 8-Revolver Feed Cartridge

Revolver Feed Cycle

Revolver Feed Cartridges are simple assemblies with no integrated automation components. The entire large diameter bolt cycle is completed via only the feed axis of the Bolt Inserter and the lateral motion of the Shuttle Table.

The bolt cycle begins as the Bolt Inserter moves forward to engage the fastener head.

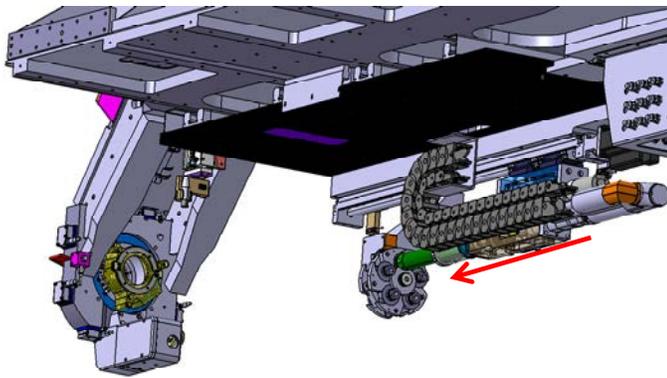


Figure 9-Bolt Inserter Engages Fastener

As the Bolt Inserter shuttles towards the tool center line, the motion of the Bolt Inserter draws the bolt out of the cartridge and advances the revolver to the next position.

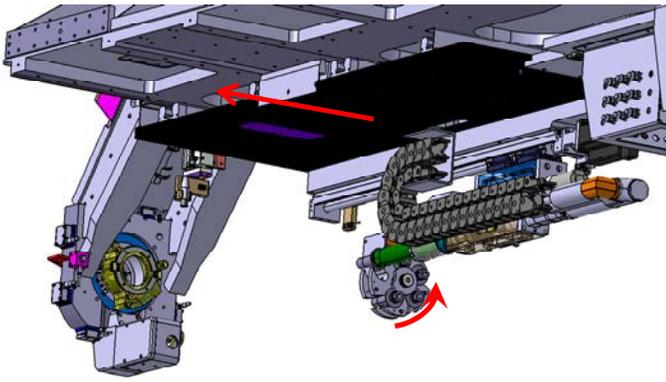


Figure 10-Bolt Inserter Advances Revolver

With the fastener fully released from the revolver the Shuttle Table positions the Bolt Inserter to drive the bolt into the panel.

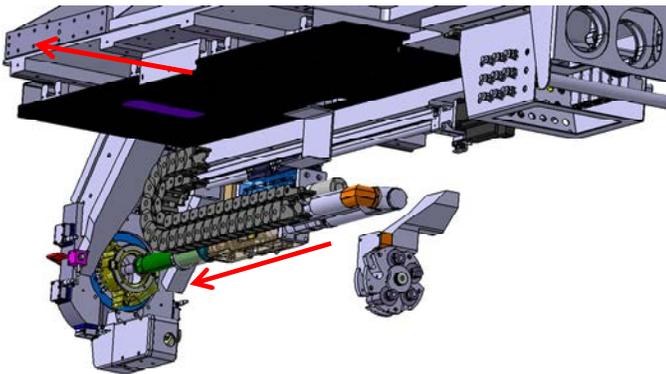


Figure 11-Bolt Delivered to Panel

LEAN APPROACH

Automated drilling greatly reduces the time, costs, and labor associated with wing box assembly. As these machines become more efficient, drilling operations account for a smaller percentage of overall time in jig. To maximize the value of automated equipment it is incumbent on aircraft manufacturers to develop assembly methods where one drilling machine can work across several manufacturing jigs. Flow lines can be one method to share automation work with several assemblies, though this production method is costly and presents several other risks and challenges involved in moving the work piece. In contrast, the mobile LTD machine is easily moved from one wing surface to another across many assembly jigs.

MACHINE TRANSPORTER

The LTD machine is paired with a machine transporter, a modified stacker crane. The transporter is capable of lifting the machine, rotating it from one wing surface orientation to another and carrying it to any other machine line. The transport cycle is largely automated and can easily be completed by the machine operator. The transporter sits above a dedicated transfer aisle beyond the outboard end of the jig. In addition to providing a clear passage to move the machine from one jig to another, the transfer aisle serves as a convenient parking area for machine maintenance or to clear the jig for other manual operations.

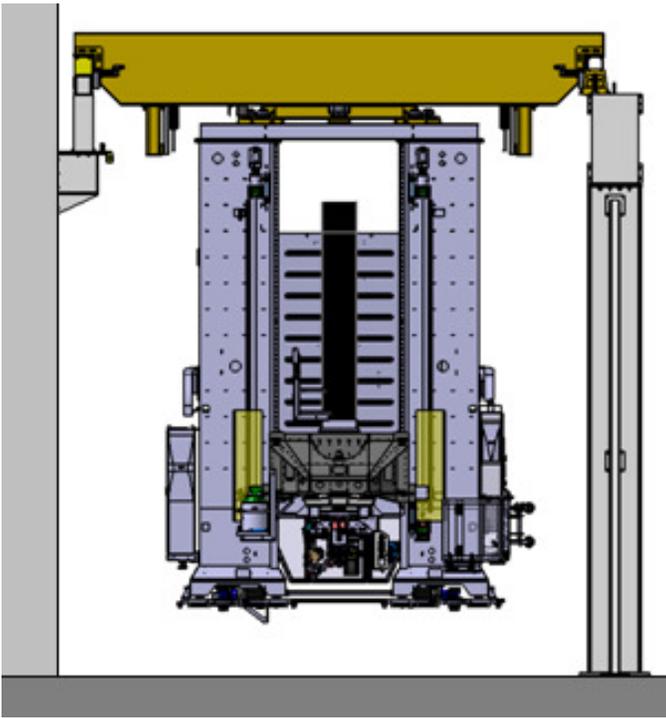


Figure 12-Transporter Moving machine

MACHINE BASE INFRASTRUCTURE

Each machine line is equipped with its own X-base. When the machine is transported it disengages from the base on one line and joins the base on the next. On their bottom surface, the bases integrate to the machine beds via the X-drives and rail cars. On the top side the bases include rough alignment pins to guide the machine during lifting and lowering, and a set of clamping cups and cones to final locate and secure the machine to the base. Machine bases also hold facilities to easily decouple machine services.

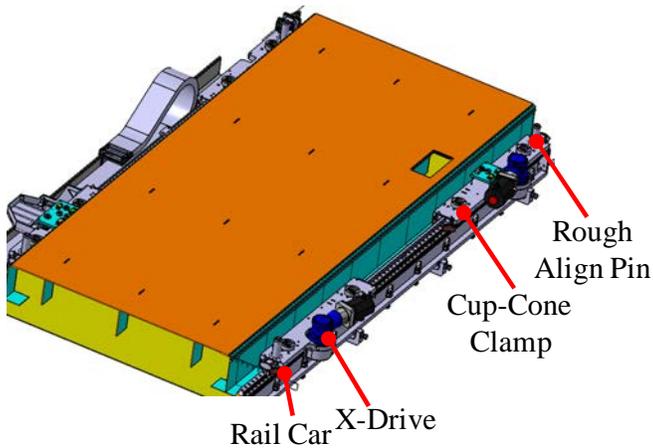


Figure 13-X-Base Layout

Machine base assemblies are contained entirely below floor level. Fixed infill flooring and movable “flip floors” cover all X axis infrastructure. The result is a clean, flat, and trip free floor. With a rated wheel load of 1,000 pounds, the flooring is accessible to carts, work platforms and small lifts.



Figure 14-Flush Flooring Setup

CONCLUSIONS

By addressing the challenges associated with large scale composite wing box assembly the LTD machine makes automated drilling more efficient and cost effective.

One sided post machine architecture combined with SSTF technology enables blind manufacturing. This process is based on in depth fastener qualification and is supported by an efficient automation cycle.

Bold new machine construction creates simplified, redundant load paths. This elegant arrangement yields a much lighter machine. Not only does the optimized layout result in lower internal machine loads, but it also imposes lower forces onto the machine bed. Consequently, the LTD requires a foundation which is significantly less substantial and less costly.

Extensive spindle and cutter development yielded a more controlled ream process which allows the machine to drill a larger range of holes with a light weight spindle. An in process tool swapper facilitates this procedure by removing the need to optically resync on pre-drilled holes. Revolver Feed Cartridges bypass pitfalls common to feeding large diameter bolts. As a result, the LTD brings process automation to a range of holes common in today's composite airplanes.

With lean manufacturing principles in mind the LTD was designed as a flexible machine tool. The machine is easily and repeatably relocated from one line to another. Low profile machine bases help produce a clean factory floor in the absence of the machine.

The LTD machine is currently installed and qualified in the C-Series wing production factory in Belfast, Northern Ireland.

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DEFINITIONS/ABBREVIATIONS

ATS	Automatic Tool Swapper
CFRP	Carbon-Fiber Reinforced Plastic
CNC	Computer Numerical Control
LTD	Lean Technology Drilling Machine
SSTF	Single-Sided Temporary Fastener
Y-Sled	Welded support which carries A-B Pivot and machine head in the Y-direction.
A-B Pivot	Assembly which rotates machine head about A and B axes.
Clamp Table	Welded chassis which moves along the U-axis to apply pressure to the wing cover.
Shuttle Table	Support for the majority of process tools. Shuttle table provides motion perpendicular to the U axis to align tools with the tool center point

APPENDIX

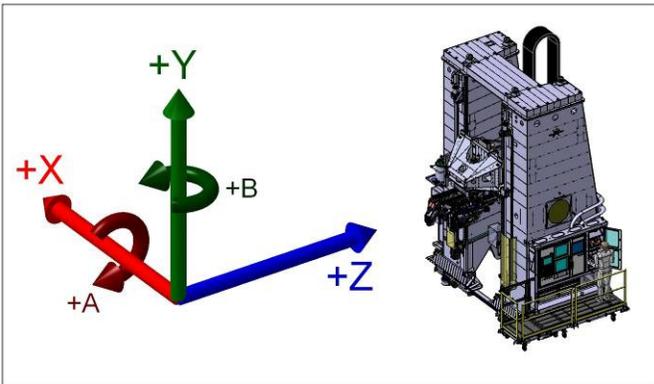


Figure 15-LTD Machine Shown With Axis Compass