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Body Join Drilling for One-Up-Assembly

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ABSTRACT

Over 1,200 large diameter holes must be drilled into the side-of-body join on a Boeing commercial aircraft's fuselage. The material stack-ups are multiple layers of primarily titanium and CFRP. Due to assembly constraints, the holes must be drilled for one-up-assembly (no disassembly for deburr).

In order to improve productivity, reduce manual drilling processes and improve first-time hole quality, Boeing set out to automate the drilling process in their Side-of-Body join cell. Implementing an automated solution into existing assembly lines was complicated by the location of the target area, which is over 15 feet (4 meters) above the factory floor.

The Side-of-Body Drilling machines (Figure 1) are capable of locating, drilling, measuring and fastening holes with less than 14 seconds devoted to non-drilling operations. Drilling capabilities provided for holes up to ¾" in diameter through stacks over 4.5" thick in a titanium/CFRP environment. Using high precision servo control, each layer could be customized with specific drill parameters optimized to improve hole quality and decrease drill cycle time. Drill life was improved by tracking depth drilled for each drill bit.

The drilling process is stabilized by rigid support structure which is optimized for both stiffness and natural frequency resulting in deflections no greater than 0.020 inches. Each drilling machine is light-weight and mobile to accommodate multiple work zones in multiple assembly lines. One-up assembly was achieved by using custom doweling/clamping fasteners automatically installed by the machine in strategic locations to provide the proper part clamping.

INTRODUCTION

Over 1,200 large diameter holes must be drilled into the side-of-body join of a Boeing commercial aircraft's fuselage. The thick material stack-ups are multiple layers of primarily titanium and CFRP. Once the fuselage sections are aligned, the holes at the Side-of-Body fitting must be drilled for one-up-assembly.

In order to improve productivity, reduce manual drilling processes and improve first-time hole quality, Boeing set out to automate the drilling process in their Side-of-Body join cell. Implementing an automated solution into existing assembly lines was complicated by the location of the target area, which is over 15 feet (4 meters) above the factory floor.

To automate the drilling operations, the focus was first on stabilizing the drilling process by overcoming the limitations for support structure. The structure needed to be stiff but also needed to have a high a natural frequency for the best stability so there was a trade-off between these two parameters.

To improve hole quality, the drilling process itself needed to be controllable over multiple layers of stack-up to be able to vary and optimize drilling profiles through each layer.

To achieve One-Up-Assembly, a part clamping scheme was developed to provide clamp-up during and after drilling with specialized temporary fasteners developed by Centrix.

Figure 1 Side-of-Body Drilling Machine

SUPPORT STRUCTURE DESIGN

Mobile Machine

The first stage of the structure design process was to design the mobile machine portion of the automated equipment. The mobile machine essentially acts as a mass (m) at the end of a cantilevered beam. This beam (the x-axis beam is supported on two columns shown in ***Figure 2***) had some unknown stiffness (k) that was optimized once the machine was designed.

$$\text{Natural frequency: } f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

For this reason, a lower mobile machine mass is desirable in order to maximize the natural frequency but at the same time, the machine needs to have minimal deflection. The stiffest beam was not the most stable solution in this case. The mobile machine can be seen in ***Figure 2***. The main structure of the mobile machine is a single weldment that integrates all of the machine's axes and electronics and interfaces with a sled on the beam. As a starting point, the existing factory crane limited the target machine weight to less than 11,000 pounds. Also, the machine had to clear existing tooling and work platforms used for accessing the top of the barrel and had to fit within the length of the existing cell. The main machine structure was optimized through many iterations of finite element analysis, adjusting dimensions and plate thicknesses to minimize its weight, while maximizing its stiffness. With a goal of deflection less than 0.010 inches of deflection for the mobile machine portion of the assembly and the length and height constraints, the resulting structure came in at 2,000 pounds and pushed the limits of the dimensional constraints. ***Figure 3*** shows the machine's physical space constraints and how close it came to the existing bridge structure (in yellow). ***Figure 4*** shows the finite element analysis of the mobile machine deflection at the clamp pad with a 1,200 pound clamp force assuming it was attached to a rigid beam. This allows the beam to deflect some to give a total machine deflection of under 0.020 inches. The resulting total machine weight was less than 7,000 pounds which was helpful in increasing the natural frequency of the system and also facilitated shipping the machine and moving it around the factory. Another consideration was the machine tower deflecting under X acceleration moves. This drove the X length of the machine with the addition of triangular gussets that help to resolve some of the X acceleration loads. ***Figure 5*** shows the deflection of the machine tower under an acceleration of 0.1g. This analysis was run in the worst case with the process head at the top of travel. The goal was to minimize this deflection so that the machine would not need to wait for it to settle out while doing pitch moves in X from one hole to the next.

Figure 2 Mobile Machine

Figure 3 Machine Clearance

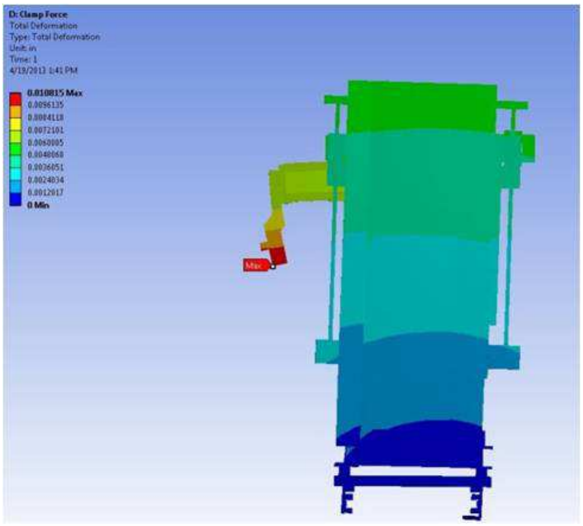

Figure 4 Machine Deflection under 1200# Clamp Force

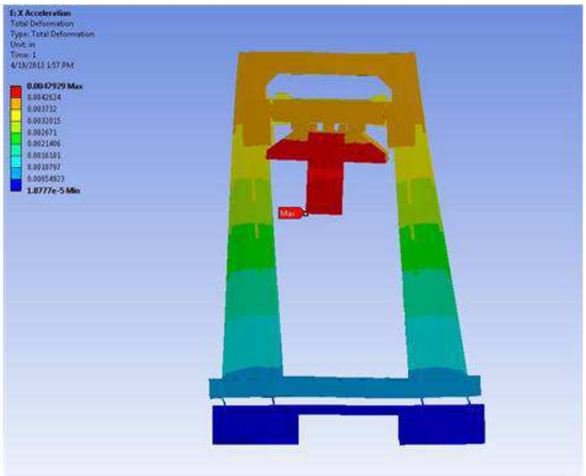

Figure 5 Machine deflection under 0.1g acceleration

Support Structure

With a total weight of less than 7,000 pounds for the machine, the overall stiffness and natural frequency of the system could be analyzed. The torsional rigidity of the x axis beam as well as the stiffness of the columns both contribute to the natural frequency of the system. Boeing allowed three options for the beams and columns: use the existing beams and columns to support the machine, use the existing columns and build new beams or build all new beams and columns. With another round of finite element analysis, it was determined that the existing beams and columns were not stiff enough for the new machine. The existing cell posed some significant space constraints, particularly in the area directly below the machine and this created some issues with achieving the desired stiffness. Electroimpact first started by optimizing the space available for a beam with a new, stiffer beam. ***Figure 6*** shows that the new beam alone did not achieve the desired natural frequency and came in around 8 hertz, well below the goal of reaching 10 hertz. It also shows the shape of the columns that support the beam. The thin area of the column below the beam is to allow for the existing automated guided vehicle used to transport the barrel from cell to cell. ***Figure 7*** shows the same analysis but with new, optimized columns as well. The natural frequency was increased to over 11 hertz. The new columns were designed to use as much of the available space as possible and to be as stiff as possible. This was necessary because a direct load path was not available. The two worst case positions were when the machine was in the middle of the beam between 2 columns and also at the end of a beam. The ends of the beam, however, were less important because they are both over-travel areas. The second natural frequency was also considered. This mode is excited by the X axis acceleration and shuttle moves. The new beams and columns did not have much of an effect on the mode as it was primarily due to the tower as shown in ***Figure 8***. The natural frequency was greatly driven by the weight of the mobile machine and the height of the process heads. All analyses were run with the head at the top of travel to find the worst cases.

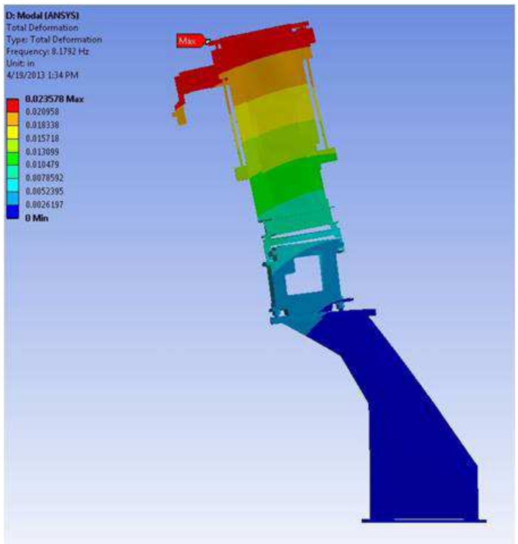

Figure 6 Modal Analysis of New Beam on Old Columns

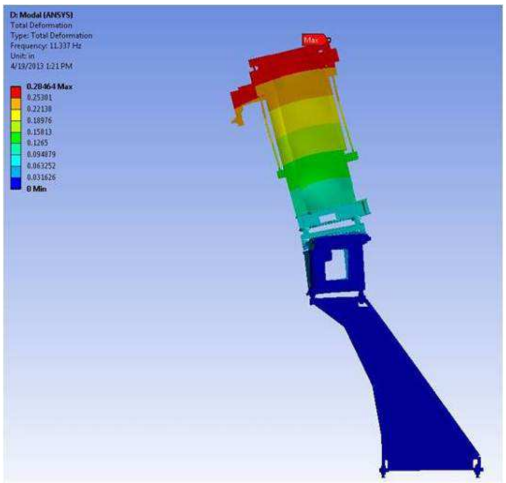

Figure 7 Modal Analysis of New Beam and Columns

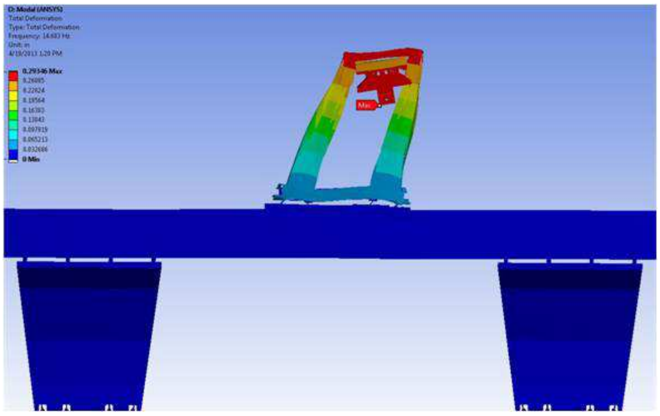

Figure 8 Second Mode of New Beam and Columns

With the individual components of the system stiff enough and the natural frequency improved, the system as a whole needed to be analyzed for deflections. Finite element analyses were run for many different scenarios. All analyses were performed at both the middle of the beam and the end of the beam and with the process head all the way up in both which were the 2 worst cases. Both the clamp force and the acceleration of the clamp table were analyzed. These two forces look similar and excite the first mode of the natural frequency. The clamp force was a greater force and therefore was the worst case scenario. Total deflection was found to be 0.017 inches in the middle of the beam and 0.022 inches at the end of the beam. ***Figure 9*** shows this deflection with the process head up, the machine at the end of the beam, and a 1,200 pound clamp load. Another analysis run was the load imparted by shuttling the process tools. This is a similar load to the X axis moves except that it can occur during a process and could affect the process if too significant. The shuttle move deflects the machine 0.006" if the clamp pad is allowed to slip freely as shown in ***Figure 10***. All of the numbers were now within Electroimpact's acceptable range for compensating out error. The lightweight tower combined with a stiff beam and support columns allowed for an extremely stiff overall system that fit within the existing cell with minimal modifications and allowed the machine to hold a precise position while performing the drilling process.

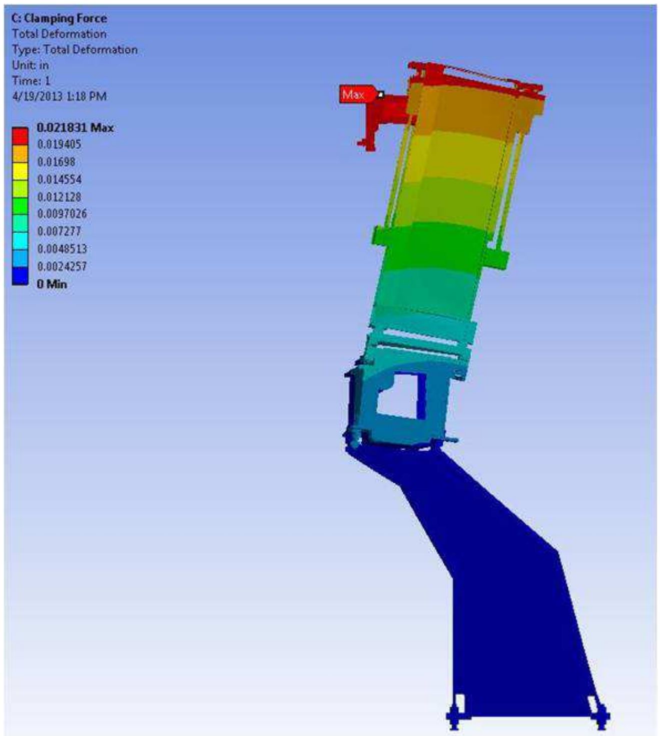

Figure 9 Machine Deflection under 1200# Clamp Load

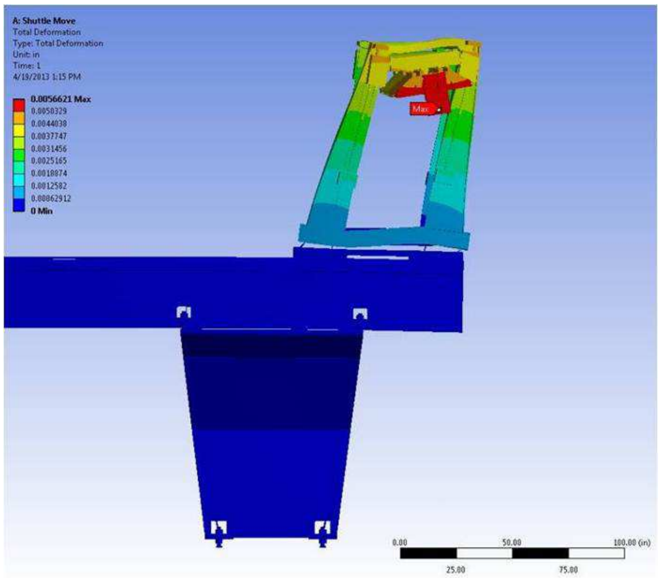

Figure 10 Machine Deflection under Shuttle Load

PROCESS FUNCTIONALITY

Process Development

Development of the drill process began with a high precision servo-spindle assembly which allowed for drill process customization of each stack-up layer. A custom Fischer-Precise spindle cartridge delivered high torque and fast response times with stable operating temperatures. Feed accuracy was achieved with an absolute Heidenhain scale that provided 0.0001 inches secondary feedback to a servo driven precision ground ball screw. Together these allowed for holes up to 3/4 inches in diameter to be drilled in titanium stacks over 4.5 inches thick.

Software was written to control and store hundreds of drill processes by layer, that were unique to the material, cutter, allowed tolerances and preceding layers. Each process allowed for custom feed rates and spindle speeds along with pecking features including start depth, frequency and retract distance. Transition features were also defined and crucial to hole quality. To ensure that parameters were switched appropriately, drill depth was determined from either the tip or from the full diameter. This was extremely important when entering or exiting titanium which would destroy cutters if CFRP parameters were used. An offset allowed further bias of the transition point in layers with large stack depth variability. Also, alarm limits were defined for drill thrust and torque along with wear rates by layer.

To create a complete hole profile, up to five layer processes could be referenced along with additional processes for breakthrough and countersink operations. Generic cycle parameters were also specified and included clamp force, lubrication type, dimensional tolerances and fastener torques. Together this greatly reduced the NC program complexity with all parameters referenced by a single hole profile. All parameters were accessed on a CNC screen (***Figure 11***) listing the hole variables in the middle and layer variables on the bottom.

Speeds and feeds were matched to optimize cycle time against hole quality and effects such as erosion of CFRP by titanium chips were mitigated. Inter-laminar and exit burrs were also minimized while ensuring that cutter longevity was maintained between layer transitions. In the end Boeing was able to maintain an acceptable hole diameter tolerance in production while one-pass drilling large holes in even the thickest stacks of CFRP over titanium. Additionally, all parameters were maintained in an efficient data management system that was maintained across multiple machines.

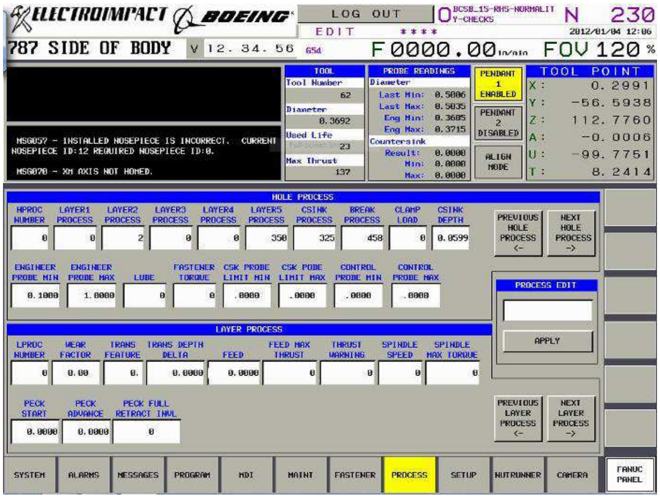

Figure 11 Drill Process Screen

Drill-bit Management

With individual cutters shared across multiple machines, proper drill management was a top priority. Schunk tool holders were chosen with a HSK63A taper for their low profile, high accuracy and unique Tribos clamping which allowed for rapid tool setting. Additionally, each tool holder was fitted with a passive RFID chip (***Figure 12***).

Each chip was capable of storing all relevant dimensional data as well the tool number and serial number for identification. Dimensions were measured and loaded autonomously with the use of a Parlec Tool PreSetter. When loaded on a machine, the drill's gauge length was confirmed against the Parlec's measurement to ensure that the cutter matched the chip's data. The tool number was also confirmed against the NC program to ensure that the correct tool was loaded. When removed, both the drill life and countersink adjustments were written to the chip, allowing each side-of-body driller to utilize the remaining life on other lines.

Due to high tool wear from CFRP and increased likelihood of small cutting edge fractures from titanium, cutters had significantly reduced life and monitoring wear was a major concern. In addition to the theoretical calculations based on wear rates, the side-of-body machines checked drill thrust with a load cell on the spindle ball screw. Operators were alerted when this value reached unsafe levels and provided the option to expire the tool's life.

Each machine was also fitted with a hole probe that accurately measured diameters and countersinks. This probe functioned as a supplementary check on drill life and provided the choice to expire the tool when values approached the engineering tolerances. It also provided the ability to measure and adjust the countersink diameter in process while providing a measurement profile of every hole directly to the quality control team

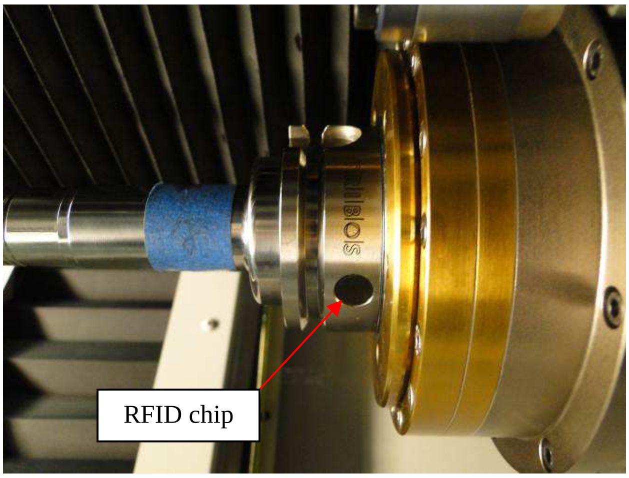

Figure 12 RFID Chip

One-Up Assembly

In order to achieve one-up assembly, part clamping was required by the machine directly and locally with fasteners in adjacent holes. Together these clamp forces maintained the stack-up arrangements and minimized inter-laminar burrs.

For machine clamping, a servo-clamp table provided force to an interchangeable pressure foot which contacted the aircraft (***Figure 13***). A load cell behind the pressure foot provided feedback and allowed for clamp load accuracy within a few pounds. After careful analysis, five pressure feet were designed to clear all brackets, pockets, and obstructions. However an additional nosepiece was required to minimize the effect of local normality deviations while on the CFRP barrel. This compliant pressure foot utilized a rotating clamp pad that centered on the tool point and maintained normality tolerances on variable surfaces. To detect the panel and allow for rapid moves, a trigger switch was installed that could extend through the nosepiece. On clamp-up, this leading edge allowed the machine to simultaneously rapid advance within 0.050" of the panel while detecting if a bolt or obstruction was in the way.

To automate local clamp-up, side-of-body machines were fitted to insert and torque specialized temporary fasteners (***Figure 14***). Locations were customizable through the NC program and able to support Boeing's one-up assembly requirements. Specifically, these fasteners were capable of doweling an entire stack-up with precisely controlled diameters while applying clamp force with extendable feet. Because of the small pressure area (***Figure 15***), torque values were constrained, especially with CFRP as the exit material. This resulted in multiple adjacent fasteners in critical areas. To improve up-time, each machine was capable of storing 600 fasteners in 24 bays with a wide range of diameters and grip lengths. Real time on-line checks for diameter and torque to ensure that each fastener functioned properly.

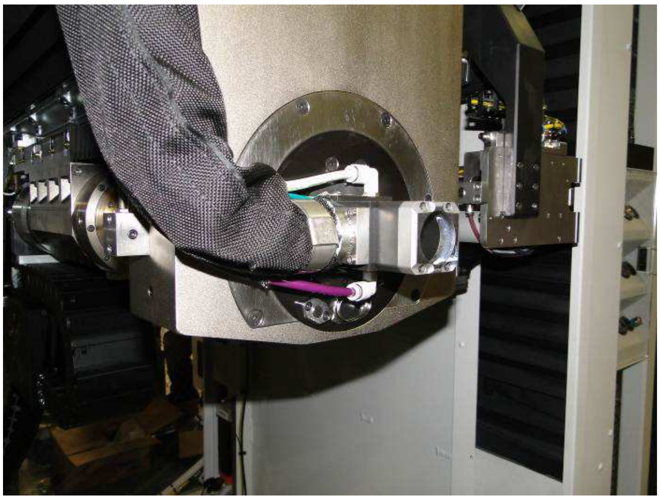

Figure 13 Pressure Foot Nosepiece

Figure 14 One-Up-Assembly Fastener

Figure 15 One-Up-Assembly Fastener

Lubrication

Primary lubrication for the side-of-body driller was delivered through the cutter as a minimum-quantity mist. A custom air atomizer allowed for fine-tuning of the mist quality and a peristaltic pump provided positive displacement output. The flow rate was controlled through the CNC and could range from 35 to 110 mL/min. Flood lubrication was supplied through the nosepiece to improve panel cleanliness and chip evacuation. To minimize lubricant within the barrel both systems could be shut off at the moment of breakthrough by monitoring drill thrust.

All lubricant was recirculated which required additional steps to reduce wear from abrasive carbon dust. Lines were kept unobstructed with pinch valves and restriction lines instead of solenoid valves. Sensors were placed in-line to monitor flow rates and detect clogs from carbon buildup. Strategic purge points allowed the lines to be easily cleared when necessary.

SUMMARY/CONCLUSIONS

Drilling CFRP/Titanium material stacks with a manual drilling process yielded varying quality, provided obstacles to drill-bit management and inefficient drilling templates. The manual drilling process could not be optimized for the different material layers of each hole drilled.

With the ability to locate, drill, measure and fasten a hole with a non-drilling cycle time of less than 14 seconds, the Side-Of-Body drilling machine (***FIGURE 16***) greatly improved hole quality and consistency of quality over the manual process.

Precision servo control provided the opportunity for extensive optimization of process variables including individual drill processes by layer, drill-bit design and clamp-up forces.

Providing a stable platform structure to support the drilling process is paramount to maintaining hole quality. Stiffness alone does not offer the most stable platform due to the vibrations produced during the drilling process and natural frequency drove the final design as much as stiffness. The structure is also independent from the aircraft, requiring no operator set-up and eliminating the opportunity for operator errors in providing the proper clamp loads for one-up-assembly.

Drill-bit management, including part tracking and life tracking greatly maximized drill-bit life. This was especially beneficial when drilling CFRP/titanium stack-up due to the already limited life expectancy.

Automatic hole probing was used to supplement hole quality tracking and creates inspection reports for each hole drilled in the aircraft. Elimination for the many drill plates (or templates) required for manual drilling processes reduced set-up and software in the form of part programs would have to be written for future variants, eliminating drill plate maintenance.

Figure 16 Side-of-Body Drilling Machine

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