2014-01-2270

Automated Floor Drilling Equipment for the 767

Jason Rediger
Electroimpact, Inc.

Craig A. Sylvester
Boeing Commercial Airplanes

Abstract

A new portable floor drilling machine, the 767AFDE, has been designed with a focus on increased reach and speed, ease-of-use, and minimal weight. A 13-foot wide drilling span allows consolidation of 767 section 45 floor drilling into a single swath. A custom CNC interface simplifies machine operations and troubleshooting. Four servo-driven, air-cooled spindles allow high rate drilling through titanium and aluminum. An aluminum space frame optimized for high stiffness/weight ratio allows high speed operation while minimizing aircraft floor deflection. Bridge track tooling interfaces between the machine and the aircraft grid. A vacuum system, offline calibration plate, and transportation dolly complete the cell.

Introduction

Boeing Everett required improved automation capabilities to replace aging, unreliable equipment and eliminate hand drilling operations. Lexan templates and machined aluminum drill jigs have been required to drill both the low accuracy floor panel fastener holes and high accuracy galley and lavatory mounting "hardpoint locator" holes in the fuselage floor grid of the 767 aircraft family (767 passenger, 767 freighter and the KC-46A Pegasus tanker shown in Figure 1).

Figure 1: Boeing KC-46A Pegasus tanker, one of the aircraft variants to be drilled by the Electroimpact E3600. Image by Boeing.

To fill this need, Electroimpact developed the 767 Automated Floor Drilling Equipment (AFDE) model E3600 (Figure 2). This is the latest in Electroimpact's line of AFDE machines.

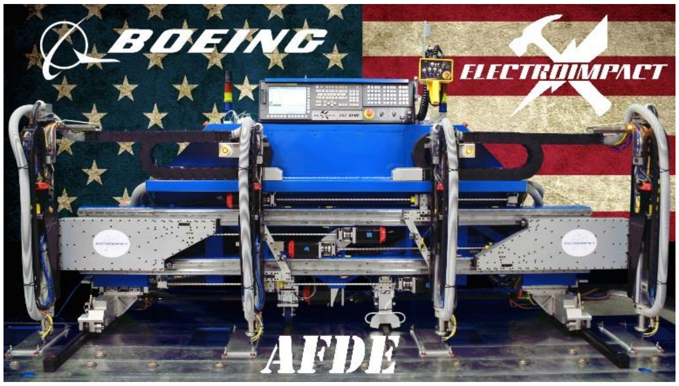

Figure 2: Electroimpact 767AFDE model E3600.

The reintroduction of an automated floor drilling system offers improved process cycle times, more accurate and repeatable hole placement capabilities, and a custom user interface that is safer and more ergonomic compared to hand drilling. The machine's custom user interface was designed using Fanuc Picture and a C-language executable to simplify machine operation and troubleshooting.

The new AFDE has a list of potential process cost savings.

Machine Frame Stiffness and Dimensional Stability

The E3600 was designed to drill the entire width of the 767 floor grid in a single swath, thus cutting in half the operator intervention required compared to traditional two-swath processes used on other widebody AFDEs. This necessitated a machine with a 13 foot transverse drilling span (22% greater than Electroimpact's previous AFDE) that was still light enough to ride on the floor grid without excessive deflections. Electroimpact utilized valuable experience gained from its previous AFDEs including those that drill the 737 aircraft [1, 2]. Additional Finite Element Analysis (FEA) was done to optimize the new machine frame for high stiffness/weight ratio.

Frame FEA

The AFDE main space frame is supported at each end by a machine base, which in turn clamps down to tooling tracks to prevent liftoff of the light machine due to drill thrust force. The limiting load case is where the machine's four drill spindles are clustered near the aircraft centerline and drilling simultaneously. Each spindle is capable of 404 lb max thrust to allow for the customer requirement of aggressive drilling in titanium. This set the limiting load case for FEA, in which 1616 lb of thrust needed to be reacted by a machine which itself has total weight less than 1600 lb due to the need to ride on the aircraft floor grid. The machine's frame weight could only be a fraction of this and was thus monitored closely during FEA iterations.

Acceptable deflection of the new frame was defined based on a successful previous AFDE frame design Electroimpact had in production. Comparison FEA models of expected deflection caused by worst case drilling thrusts were made to ensure the new frame was at least as stiff as the one in production. The final design of the new frame ended up 15% stiffer than this baseline.

As a result of the worst case drill thrust load, the new space frame acts as a torque tube, and the main challenge was limiting the twist it exhibited. Twist on an early frame model is shown in Figure *3*. To reduce this twist, covering the outside frame faces entirely with a "skin" of aluminum was considered but this limited maintenance access to the frame interior where various utilities are run. Frame thickness in X contributed to stiffness but was limited by the proximity of floor grid holes the machine needed to drill relative to the edge of the floor grid (Figure *4*).

In the end, a mixture of vertical braces on two faces combined with an aluminum-skinned rear face (Figure *5*) resulted in minimal frame deflection, acceptable weight, and maintenance access. The final frame design weighs 287 lb, less than 18% of the drill thrust load it needs to react.

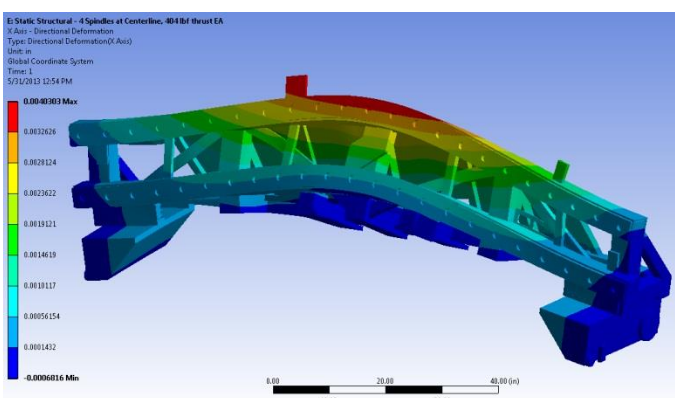

Figure 3: Frame twist on an early frame FEA model.

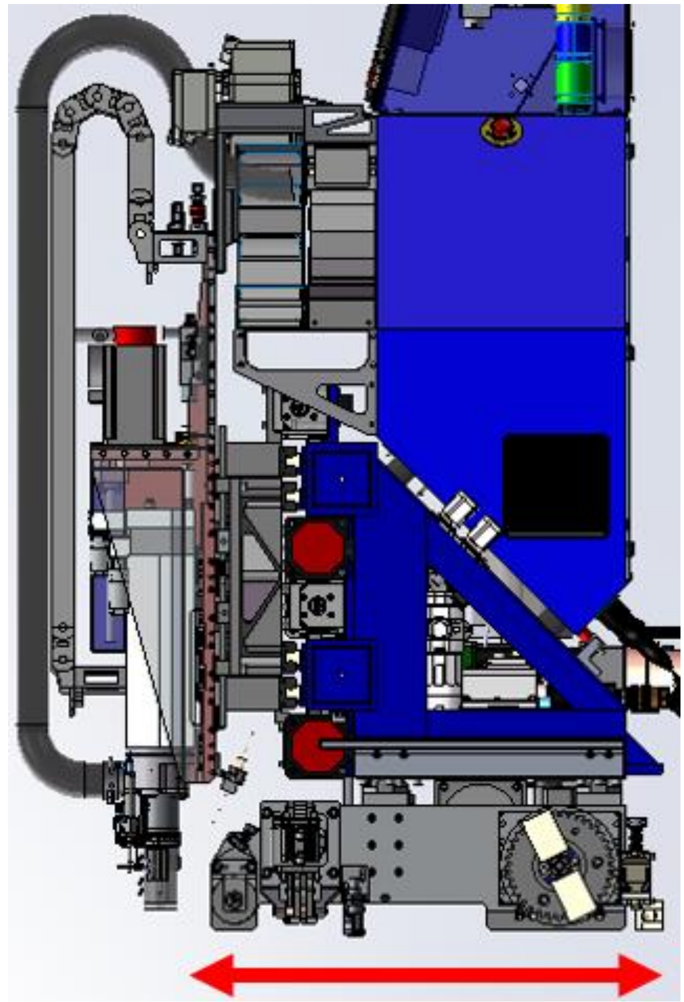

Figure 4: Frame width in X was limited due to proximity of floor grid holes relative to edge of grid.

Figure 5: Machine frame rear face with aluminum "skin" prior to major machine assembly.

Frame Fabrication

Electroimpact had previously acted on lessons learned about long-term dimensional stability from its (now 20-year old) 777AFDEs. This resulted in changes to how the main machine frame was designed and fabricated for its 737AFDEs including the use of multiple stress relieve steps [1]. Since the multiple stress reliefs reduce yield strength of the frame aluminum, the maximum Von Mises stress in the frame was checked and confirmed to be well under (2400 psi) minimum yield strength.

Since the new 767AFDE frame had increased frame length over previous models (to support 156” vs. 128” of transverse spindle travel), extra attention was given to minimizing frame distortion during fabrication including keeping it flat during stress relieve with a jig (Figure *6*).

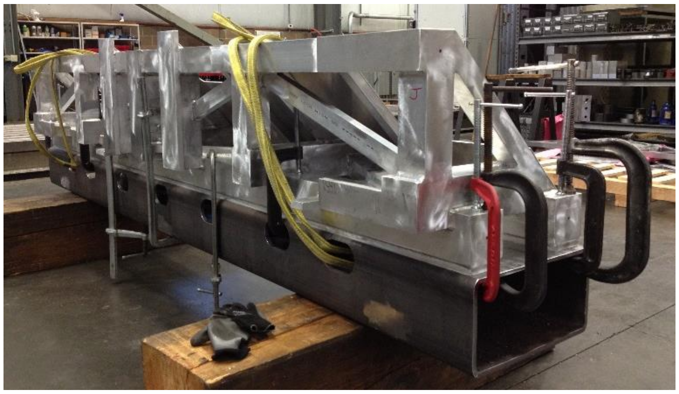

Figure 6: Main machine frame prior to first stress relieve operation.

As a result of the frame stiffness FEA optimization and care taken during fabrication, all four drills can move within a 0.002” (+/-0.001”) wide line in X while they travel over 156” in the Y direction.

The X Drive System

Bridge Track Tooling

Since the machine operates on the 767 floor grid, its X axis accuracy is heavily dependent on the design and quality of the bridge track tooling (the interface between machine and aircraft which is installed on the floor grid prior to drilling). On previous AFDE jobs, Boeing Tooling had handled fabrication of the bridge track, but for the 767AFDE Electroimpact received both the equipment and tooling contracts. This sourcing allowed Electroimpact to ensure seamless integration of the machine and tooling while utilizing a high quality rack and pinion drive system.

The 767AFDE travels on an AGMA 11 quality gear rack mounted to a supporting base extrusion which tools directly to the airplane floor grid. Beside the rack sits a rail which is ground to match the pitch line height of the rack (Figure *7*). These bridge tracks are mounted on the floor grid prior to drilling.

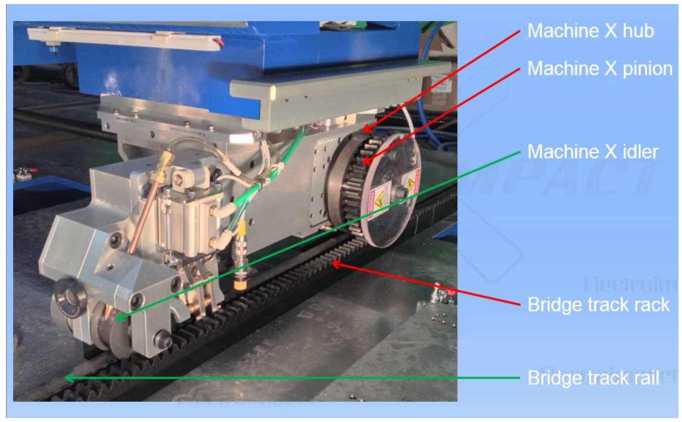

Figure 7: 767AFDE X axis drive system.

Each machine X drive consists of a belt-driven high speed shaft connected to an ultra-low backlash multi-stage planetary gearbox. The output of the gearbox connects directly to an AGMA 14 quality pinion gear and a ground hub at the pitch diameter. The hub rides on the bridge track rail to set correct engagement of the gear into the rack.

Waterline Deviation Compensation

The bridge tracks mounted to the airplane floor act as the machine bed for the AFDE. However, due to airplane build tolerances Boeing could not guarantee the flatness in Z (“waterline deviation”) of the floor to better than 0.100”.

To compensate for X axis inaccuracies caused by this waterline deviation, Electroimpact employed a mechanism originally designed into its 737AFDEs [1]. (Figure *8*). This mechanism, located on each base of the machine, employs a die spring (located at red arrow) to force the X hub down to the bridge track rail (orange arrow), which in turn ensures the X pinion gear remains fully engaged in the bridge track rack (blue arrow). On level tracks, the die springs are compressed to a stop. On out-of-level tracks, both front X idlers (Figure *7*) remain down and one of the X pinion gears is pushed down to meet the rack while the other pinion gear remains on its stop.

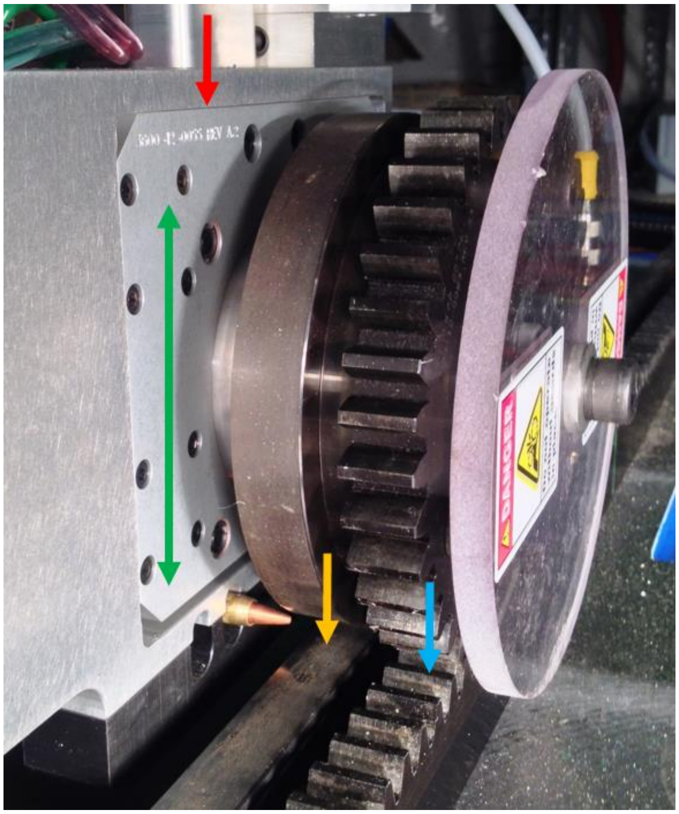

Figure 8: Waterline deviation compensation system.

Machine X axis repeatability on the test plate was measured to be less than 0.0001”. Total system accuracy is a function of the bridge track gear rack.

Process Heads

Spindles

The AFDE had to support drilling of both titanium and aluminum. Electroimpact worked with GMN USA to develop a compact and lightweight (37 lb) spindle cartridge, capable of 64 in-lb constant torque at speeds from 0-7000 RPM and 5.34kW power under an S6-40% duty cycle. The spindles are air-cooled to eliminate the extra weight and complexity of liquid cooling. An HSK 40C toolholder was incorporated for maximum tool retention and rigidity. Tribos toolholders were used to allow access in tight spaces around airplane geometry while retaining room for spindle chip shrouds.

Chip Shrouds and Vacuum

The previous 767 process utilized open drill bits which left 100% of drill swarf on the floor grid structure. The 767AFDE incorporates a vacuum and encloses the drill bits in spindle chip shrouds to collect the vast majority of swarf and improve operator safety. Tight aircraft and bridge track tooling geometry constraints combined with sufficient chip flow area and toolchange access requirements made for a challenging design task. These were solved with a telescoping shroud combined with a long nosepiece (Figure 9). The nosepiece has feeder lines for drilling fluid and air blasts to break up chips, and is easily removed by hand for tool change access.

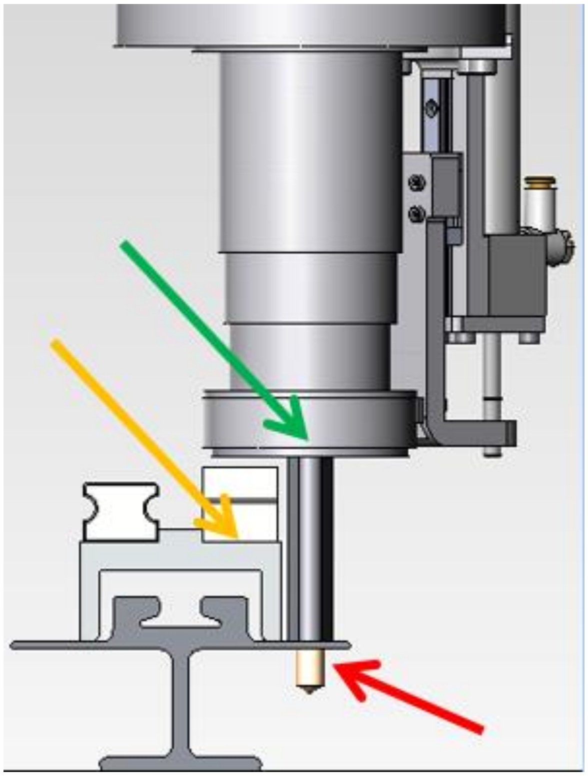

Figure 9: Chip shroud (green arrow) next to bridge track tooling (orange) while drilling the seat track (red).

Different shroud geometries and replacement air blasts were tested in an effort to maximize swarf collection. One efficiency test resulted in 99.6% chip collection (Figure 10) by mass. The result is a dramatically cleaner floor grid and machine.

Figure 10: Chips captured in vacuum (left) versus chips left on floor (right).

Left Butt Line 11 (LBL11) Tracer

LBL11 is used as the datum for all other buttlines; therefore, the AFDE, which rides on LBL54.75 and RBL54.75, needed a way to follow LBL11 and place holes accordingly. Adding a third hard mechanical contact point at LBL11 was rejected due to the extra weight and possibility of over constraining the machine in Y. Non-contact laser sensors were chosen from the same line that Electroimpact uses for normality sensing on wing machines [3].

Two sensors observe the Y position of both sides of LBL11 (*Figure 11*). As the buttline position deviates relative to the machine, the readings from the sensors are used to adjust the coordinate system of the CNC accordingly. The transverse (Y, W, U, and V) axes are physically moved to their adjusted positions after every X move.

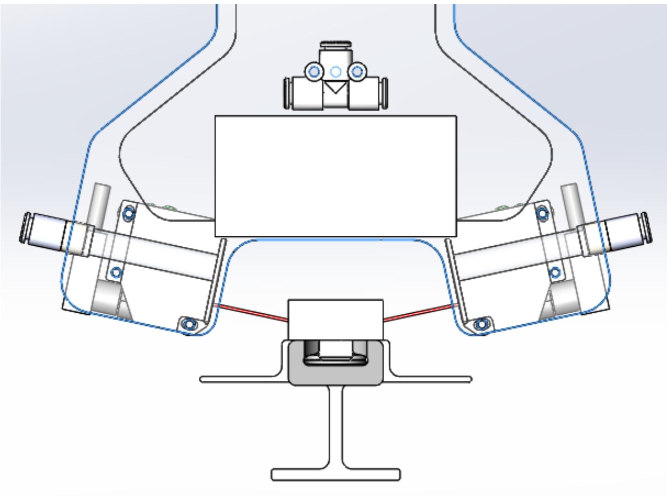

Figure 11: LBL11 Laser Tracers.

The thickness of the buttline is consistent enough to use for parity checking between the two sensors. This check prevents spurious readings from inducing large errors in Y position. For example, if a chip has obstructed the path of a tracer, it may show a large change in position. However, the software will recognize that the thickness is incorrect and ignore the readings. The previous offset is maintained until parity is recovered.

Brief parity check failures are expected. In the event of a prolonged failure (i.e. sensor malfunction/obstruction, problem with LBL11), the software will stop automatic operation and alert the operator.

Custom User Interface

A custom user interface was designed for ease of control, testing, and troubleshooting. During automatic operation (MEM mode), the display provides the operator with tool point position, distance-to-go, current and subsequent program lines, spindle speed, and other useful data (*Figure 12*).

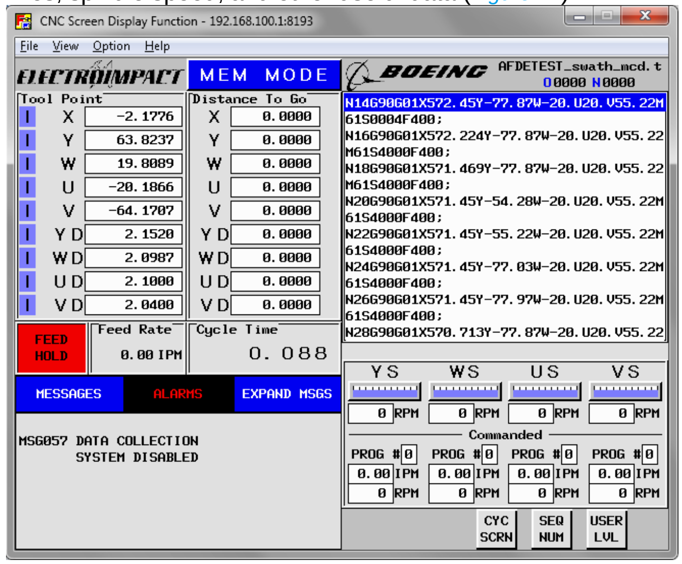

Figure 12: MEM screen.

A cycle supervisor screen helps when troubleshooting (*Figure 13*). If something is holding up a drill cycle, the supervisor screen shows the current state of each sequence involved in the cycle.

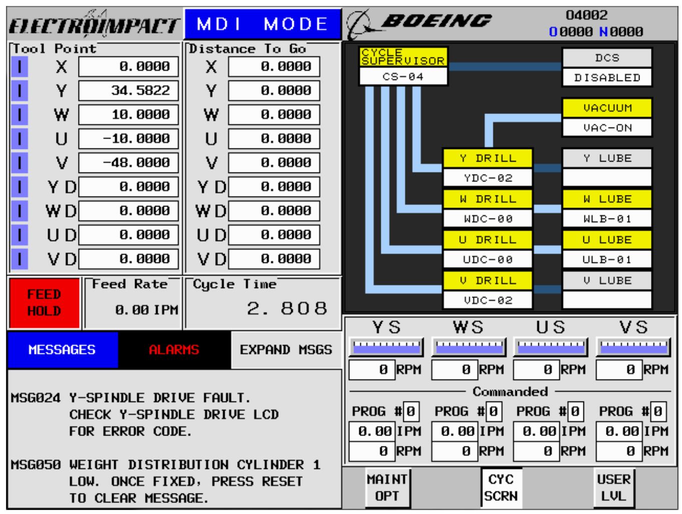

Figure 13. Cycle supervisor screen.

Three levels of user privileges have been set up using a password system (*Figure 14*). This prevents unqualified operators from modifying critical parameters which may cause undesirable machine performance. The basic user level is OPERATOR, which allows control for nominal machine operation. One level higher is MAINTENANCE, which allows for process data adjustment as well as contingency operations such as no-lube and CADO (ink marking) mode. The highest level is ADMINISTRATOR, which allows full control.

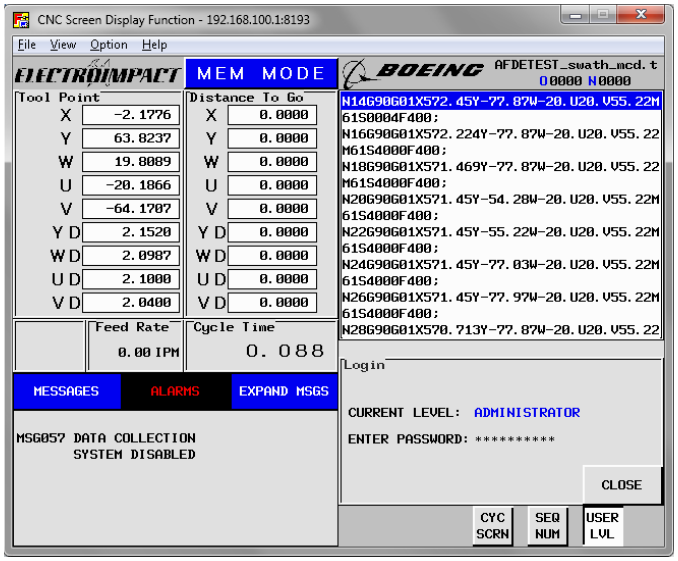

Figure 14. User level password validation in bottom right corner.

Machine parameter adjustment and troubleshooting tools can be found on the Maintenance screen (*Figure 15*).

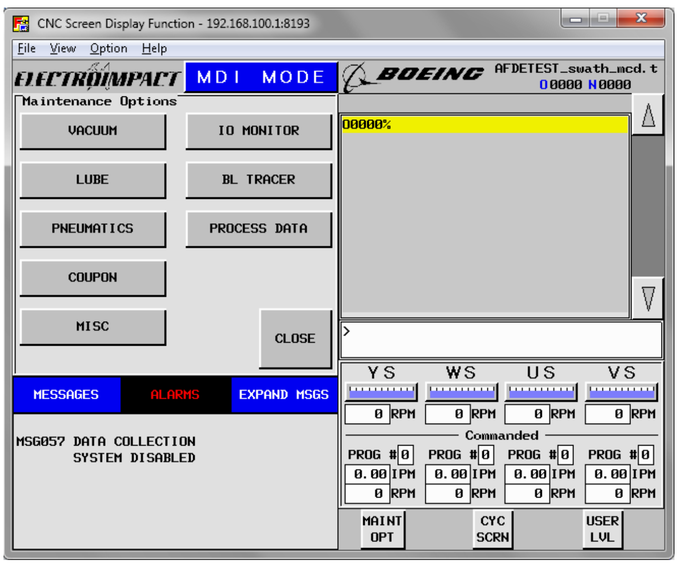

Figure 15. Maintenance base screen.

As an example, the Vacuum maintenance screen displays the health of the filters, level of material in the chip collector, and inlet pressure (*Figure 16*). The vacuum can be turned on and off manually from this screen for troubleshooting. Users with maintenance level access can adjust the vacuum alarm thresholds via Alarm Settings in the bottom left.

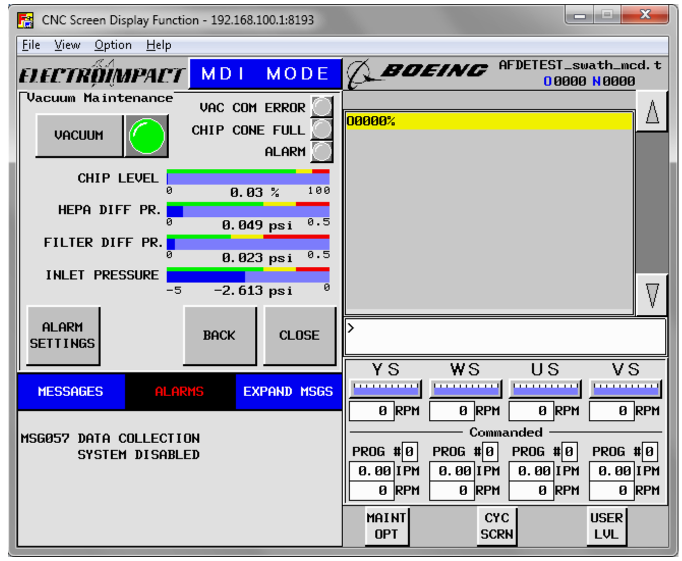

Figure 16. Vacuum maintenance screen.

Drill process data can be modified via the Process Data screen (*Figure 17*). Nine processes can be configured here with maintenance level access. For example, titanium and aluminum holes each have their own process due to different feeds/speeds. Available parameters include spindle speed, spindle feedrate, standby offset, stack thickness, breakthrough distance, lube type, and chip blast.

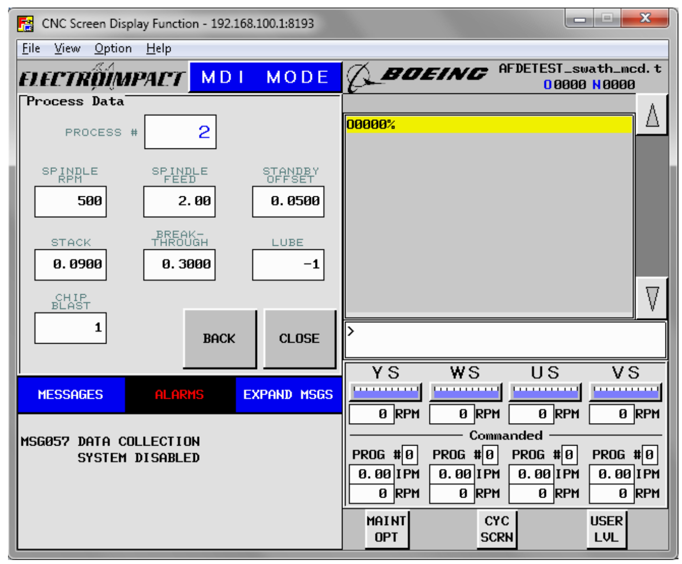

Figure 17. Process Data screen.

Status information for various sensors is displayed on the I/O Monitor screen (*Figure 18*). This provides a useful debugging tool by eliminating the need to navigate through multiple screens to observe sensor states directly.

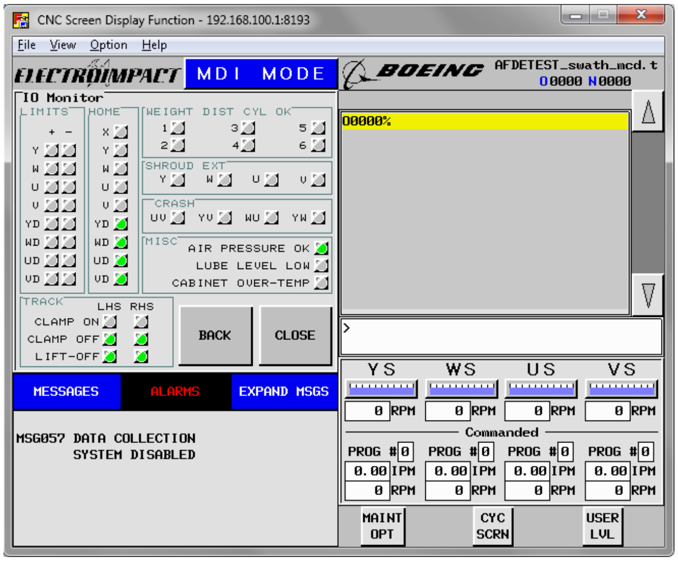

Figure 18. I/O Monitor screen.

The Coupon screen (*Figure 19*) provides a simple interface for coupon drilling on the alignment plate. Spacing, process number, tool diameter, and starting hole are provided by the operator. The interface evaluates the settings and automatically lays out a pattern with the maximum number of holes within a configurable edge margin. The Show Pattern button displays the result for user confirmation. Once satisfied, the operator can load and run the coupon drilling program to drill the holes.

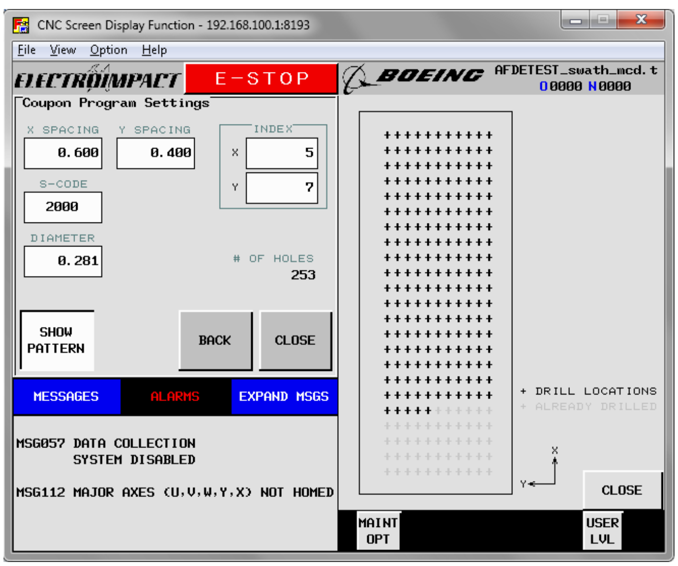

Figure 19. Coupon drilling setup screen.

Machine Setup

Alignment and Calibration Plate

Since the AFDE drills relative to the LBL11 seat track installed in the airplane, machine setup is critical. The accuracy of the X and four Y sled home positions determines the accuracy of the machine and the holes it places. A previous AFDE in the 767 cell used a thin aluminum "test plate" bolted to the scaffolding structure. Electroimpact convinced Boeing Everett than an accurate machine needed an accurate reference from which to set axis positions.

The result is a 5" thick steel alignment plate that rests on three leveling feet. Reference bushings are tightly located on the test plate. Their actual positions were measured with a calibration laser (with the machine mass in place) and the locations recorded directly on the test plate (Figure *20*) for future machine calibration use.

Figure 20: Laser tracking alignment plate bushings with machine mass positioned on plate.

The test plate also houses a calibration bar for the LBL11 tracer, and coupon holders for each of the four spindles to facilitate offline drill testing.

Machine Dolly

Electroimpact supplied a dolly to transport the AFDE machine (Figure *21*). The main use is to move the machine between the test plate and the bridge tracks (aircraft floor); however this also allows transport of the machine around the factory as needed. The dolly has casters and can easily be moved by two people; it also has crane lift points.

Dolly raise/lower is accomplished with a jack screw driven by an air motor. No operator hand cranking is required.

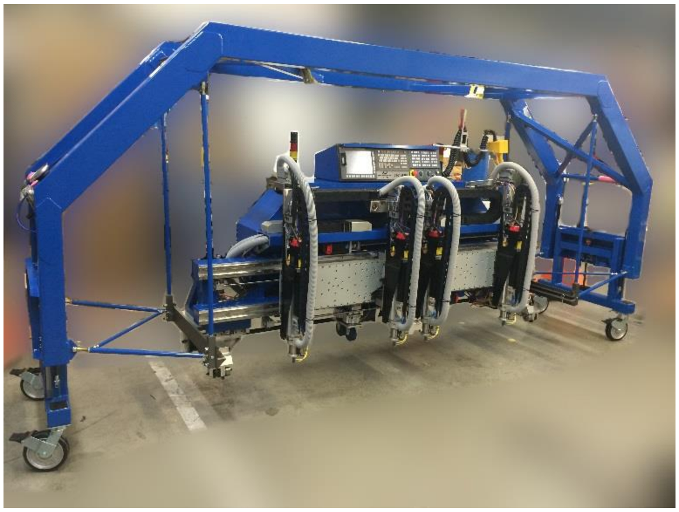

Figure 21: AFDE crawler on transport dolly.

Summary/Conclusions

Automated Floor Drilling Equipment have provided support to various Boeing aircraft programs for more than two decades. The design of Electroimpact's latest generation AFDE draws on a track record of thousands of hours of factory use and improved technology to increase efficiency and reduce costs. The capability to now complete the 767 cell's floor drilling operation in a single pass, coupled with the AFDE's faster cycle time, both offer a measurable cost savings opportunity. The foundation for improved process cycle times include Fanuc-based control and drive systems, a stiff machine frame, and an integrated chip collection vacuum to nearly eliminate the need for post drill cleanup.

References

1. Bankston, W. and Vogeli, P., "Automated Floor Drilling Equipment for the Next Generation 737," SAE Technical Paper 972809, 1997, doi:10.4271/972809.
2. Vogeli, P., Dong, M., Zieve, P., Assadi, M. et al., "Self Contained Portable AFDE With On-Board CNC, Custom Operator Interface and RF Network," SAE Technical Paper 2000-01-3011, 2000, doi:10.4271/2000-01-3011.
3. Remley, D., Rediger, J., Haworth, P., and Holden, R., "Slug Rivet Machine Installs 16 Rivets Per Minute Drill-Rivet-Shave," SAE Technical Paper 2009-01-3155, 2009, doi:10.4271/2009-01-3155.

Contact Information

Craig A. Sylvester, MSME, PE
Equipment Engineer
Boeing Commercial Airplanes
Production Equipment & Automated Tooling Group
craig.a.sylvester@boeing.com

Jason Rediger, BSME, PE
Project Manager
Electroimpact, Inc.
jasonr@electroimpact.com

Joe Malcomb, MSME
Controls Engineer
Electroimpact, Inc.
joem@Electroimpact.com

Acknowledgments

The authors wish to acknowledge the contributions and effort of:

1. The Boeing floors group: who developed the system requirements, implemented the floor drilling process, and managed the system to its completion.
2. The Electroimpact 767AFDE team: who designed, built, installed and started up the system (Figure *22*).

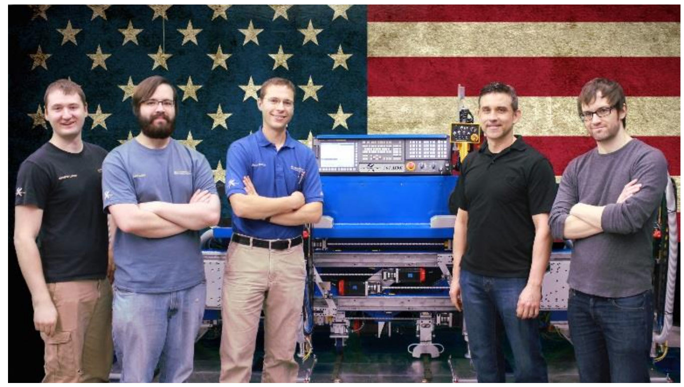

Figure 22: 767AFDE design team. Left to right: Jon Larsen (Electroimpact technician), John Walsh (Electroimpact electrical engineer), Jason Rediger (Electroimpact project manager), Craig Sylvester (Boeing project manager), Joe Malcomb (Electroimpact controls engineer). Not shown: Paul Rousseau (Electroimpact mechanical engineer).

Definitions/Abbreviations

AFDE	Automated Floor Drilling Equipment
CADO	Spring-loaded ink-marking device that fits in a tool holder. Used to mark hole positions, under CNC part program control, on the structure to be drilled.
CNC	Computer Numerical Control
FEA	Finite Element Analysis
LBL11	Left Butt Line, 11 inches left of aircraft centerline
LBL54.75	Left Butt Line, 54.75 inches left of aircraft centerline
RBL54.75	Right Butt Line, 54.75 inches right of aircraft centerline
RPM	Revolutions Per Minute