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Automated Wing Drilling System for the A380-GRAWDE

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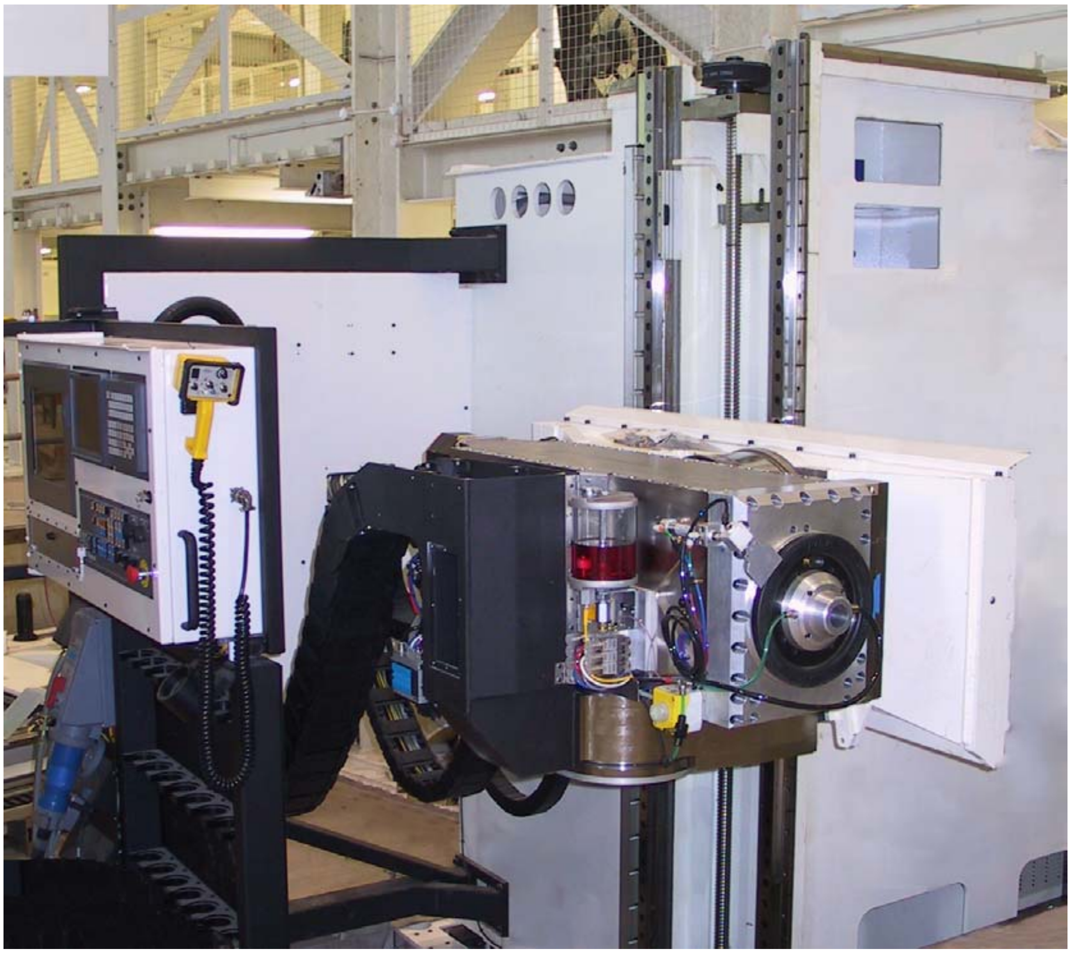

ABSTRACT

On Airbus aircraft, the undercarriage reinforcing is attached through the lower wing skin using bolts up to 1-inch in diameter through as much as a 4-inch stack up. This operation typically takes place in the wing box assembly jigs. Manual hole drilling for these bolts has traditionally required massive drill templates and large positive feed drill motors. In spite of these large tools, the holes must be drilled in multiple steps to reduce the thrust loads, which adds process time.

For the new A380, Airbus UK wanted to explore a more efficient method of drilling these large diameter holes. Introducing automated drilling equipment, which is capable of drilling these holes and still allows for the required manual access within the wing box assembly jig, was a significant challenge. To remain cost effective, the equipment must be flexible and mobile, allowing it to be used on multiple assemblies.

In conjunction with Airbus UK, Electroimpact has developed a mobile automated drilling system for the A380 undercarriage area. The system can drill up to 1.25-inch diameter holes in one shot. Similar in design to a five-axis post mill, the system can be transported to multiple work zones using an adapted stacking crane.

The system has been termed the GRAWDE for Gear Rib Automated Wing Drilling Equipment.

INTRODUCTION

The GRAWDE is a wing-drilling machine specifically designed for operations in the gear rib area of the A380 wing. The machine drills fastener holes for the purpose of fastening the gear rib reinforcing through the skin into the rib spar structure matrix. Fastener holes in this area of the wing are as large as 1 inch in diameter and 4 inches deep. Manually cutting these large holes is a multi-step process using numerous pneumatic drill motors and drill templates. In the assembly jig, this area of the wing extends just below factory floor level. High fastener density, numerous drill motors and templates, and restricted worker access to the reinforcing area for the workers creates a rate-limiting step in the wing assembly process. The GRAWDE was designed to address these challenges.

The key design features of the GRAWDE are:

1. Reduce labor and decrease production time by replacing the multi step manual drilling process with single step CNC drilling process.

2. Increase hole quality and significantly decrease rework with automated drilling.

3. Maximize machine utilization by providing functionality to move machine into multiple parallel workzones.

4. Machine fits into an envelope, which allows manual work access with or without the machine in place.

5. Adaptive feedback provides real time countersink depth compensation on faceted surfaces.

MANUAL PROCESS

In the wing assembly jig, the A380 wing is fixtured trailing edge down with the gear rib area extending below factory floor level. A permanent reinforcing plate is fastened over the lower wing skin and extends from the aft tip of the wing box up to the rear spar. The 2 meter wide reinforcing plate provide structural support to the main landing gear. The surface area of this region of the wing amounts to approximately four squares meters and contains approximately 250 fasteners; the majority over 0.75 inches in diameter.

DRILL TEMPLATES

Figure 1 - Drill jig on A340 gear rib area

To achieve proper hole placement using manual processes, drill jigs like the one shown in Figure 1 are used. Each manual drill template consists of a machined aluminum plate with various drill and fixture bushings. The templates are located and fastened to the wing skin through backdrilled holes. Due to the area, size of fasteners, and size of the drill motors, the drill templates are large, complex and labor intensive to use.

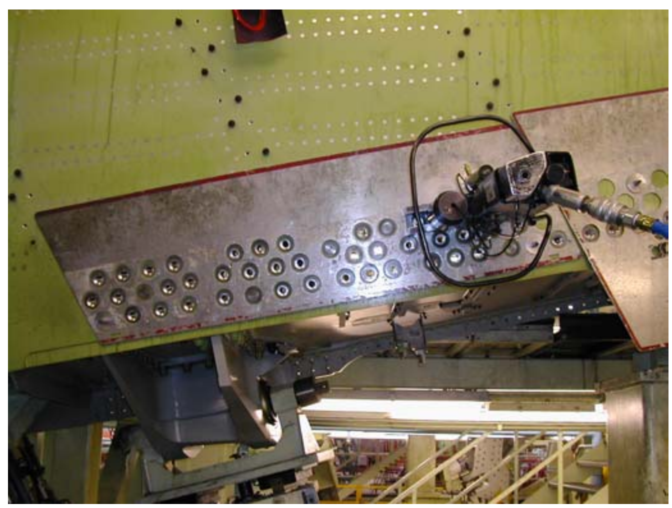

Figure 2 - Pneumatic drill and template

Fastener pitches are too close for the required drill bushing diameters, which results in multiple templates for a given area due to the overlap. These templates are sometimes referred to as half templates as they are used in pairs to place alternating holes.

The manual drilling technology is not suited for accurately and efficiently cutting large holes in a single pass. One hole may require as many as five tool changes. The hole is started with a small pilot and then stepped up to the final size. The hole is finished with a final ream and countersink pass. Table 1, below, shows a sample drill sequence for a .871-inch diameter hole. Each drill size uses a dedicated drill motor, which represents a significant cost element. As shown in the table below, several types of drill motors may be used for a single hole. Figure 2 shows a sample drill motor and template. Drilling these large holes manually can be a time consuming process and may sometimes require rework.

Table 1 Example drill step sequence

	Hole - .871	**Stack - 2.6**
Step	**Tool Description**	**Machine Type**
1	DRILL - NON / PILOTED	Positive Feed
2	CORE DRILL - NON / PILOTED	Positive Feed
3	REAMER - NON / PILOTED	Positive Feed
4	BACK SPOTFACE CUTTER	RACKFEED
4	SPOTFACE ARBOR	
5	COUNTERSINK - FORWARD / PILOTED	RACKFEED
6	COUNTERSINK - FORWARD / PILOTED	Pistol
6	ARBOR - COUNTERSINK CUTTER	
7	GAUGE, PLUG	

WORKER ACCESS

The gear rib area has limited access in the assembly jig. It is located on the first floor with the lowest part of the trailing edge below factory floor level. From an ergonomics perspective, this requires manually lifting jig plates and drill motors into positions, which range from below floor level up to 2 meters above the ground. The ideal working range is approximately 1.1 to 1.3 meters above ground. Work below that range requires workers to be on their hands and knees and above that requires an elevated platform.

AUTOMATED PROCESS

The GRAWDE is a CNC controlled five-axis, precision drilling machine designed to replace the manual drilling process. The head consists of a single spindle with an integrated pressure foot. The 22kw spindle spins at up to 8000 RPM. It uses HSK 80 hydraulic holders complete with through-bit starvation lubrication. The spindle provides sufficient stability and power to accomplish one shot drilling and countersinking of the large diameter holes present in the A380 gear rib area.

The headstone or pressure foot on the GRAWDE is fitted with a spherical nosepiece with integral normality sensors. This permits the GRAWDE to be driven to a precise location on the wing skin, sense and adjust to the local normal vector by rotating the drill about the tool point. The Z-axis drive (parallel the spindle axial feed axis) is fitted with a force sensing load cell. Allows the GRAWDE to clamp or press up against wing skin with as much as 2000 lbs of force for added process stability and rigidity.

DRILLING

The drilling process starts with CNC programs or tapes. Airbus programmers develop programs, which define nearly all aspects of the drilling process. The machine runs under five-axis CNC control in each the wing surface zones. The machine operator calibrates the machine using test coupons, synchs the machine to the proper zone using a camera target and runs the CNC tape.

Coupon stands are located in the inboard area of the assembly jig. Multiple coupons, representative of the wings skin are used for setup. The coupon stands also have a re-synch target used for establishing machine position and calibrating for normality. The re-synch target consists of a flat plate with a precision hole whose position and orientation in the coordinate system are known. Calibrating involves using the re-synch camera to establish the machine position and then clamping up to calibrate the normality sensors.

Holes are usually drilled in the coupon prior to drilling the wing in order to prove the cutting tool and establish plunge depth for the counter sink. Once the machine is calibrated, the tape will drive the head to a position easy for the operator to access the drill head and prompt the operator to install the appropriate cutting tool. A Balluff tool identification system is used to verify that the proper cutter is loaded into the machine. The NC tape drives the machine to the appropriate position and rotates the U-axis to the theoretical normal vector. The machine head then drives along the theoretical normal vector in force sensing mode.

When the pressure foot engages the wings skin with the programmed force, the program verifies the actual normal vector, as measured with real time sensors, is within a set tolerance of the theoretical vector. If not, the machine will unclamp, rotate about the tool point, re-clamp, recheck for normality before drilling the hole.

DRILLING FACETED SURFACES

The above example illustrates drilling holes on non-faceted surfaces on the wing, i.e. where the fastener's axis is normal to the wing surface. The GRAWDE also has the capability to drill holes on faceted surfaces. For these areas, the fastener is inserted normal to the wing skin, but not normal to the exterior surface of the reinforcing plate.

The rotating clamp nose on the GRAWDE makes it possible to drill off normal on faceted surfaces with full clamp load. As mentioned above, the clamp nose is mounted on a spherical bearing. Because the clamp nose pivots in a spherical bearing as it contacts the wing skin, it will rotate normal to the exterior surface while the drill axis is coincident with the wing skin normal vector. The integrated normality sensors can be used to verify that the theoretical facet angle agrees with the actual facet angle.

INK MARKING

To aid in debugging programs and ensure proper hole position, the GRAWDE has the functionality to ink mark the part. This functionality is typically used for part program try out. This allows the operator replace the cutting tool with a marking pen and run the drilling program while inhibiting drill feed. This paints dots on the wing panel, which can be visually verified for position prior to actual drilling.

JIG INTEGRATION

One of the greatest challenges of this project was the integration of a precision CNC controlled drilling machine into a wing assembly jig, while maintaining access for manual assembly operations. To meet this challenge, the GRAWDE was designed concurrently with the assembly jig. Each jig is a 4 story steel structure and is about 50 meters long. Manual worker access is required from both sides of the wing in all areas for fitting and fastening processes.

JIG CONSIDERATIONS

The jig was designed to provide a stiff structure for supporting precision CNC machines, while maintaining maximum manual access. Continuous floors are required on each of four levels to extend to the surface of the wing. The floors are moveable for part loading and to provide machine access. The automatic drilling machines need services such as air, power, communications, and position feedback, all of which had to be well integrated into the jig structure.

GRAWDE CONSIDERATIONS

Floor heights dictated by manual access requirements determined the size of the GRAWDE working envelope. To be a cost effective investment it is crucial that the machine be portable and be able to move between multiple wing surface zones. The tight working envelope represents a challenge to provide a safe working environment due to potential obstacles and tight clearances between the machine parts and the jig, creating shear points.

ACCESS

When operating the GRAWDE, the operators stand on a moving platform 250 mm below factory floor and 500 mm above the machine beds. From the platform, operators can reach the wing surface, operator controls and quill box for changing tools. The platform has handrails and a gate on two sides, to protect the operator from falling and to protect from shear points between the GRAWDE and assembly jig components. Manual access can also gained by driving the GRAWDE away from the immediate area and standing directly on the machine bed. A drawing of the machine and operator platform is shown below in Figure 3.

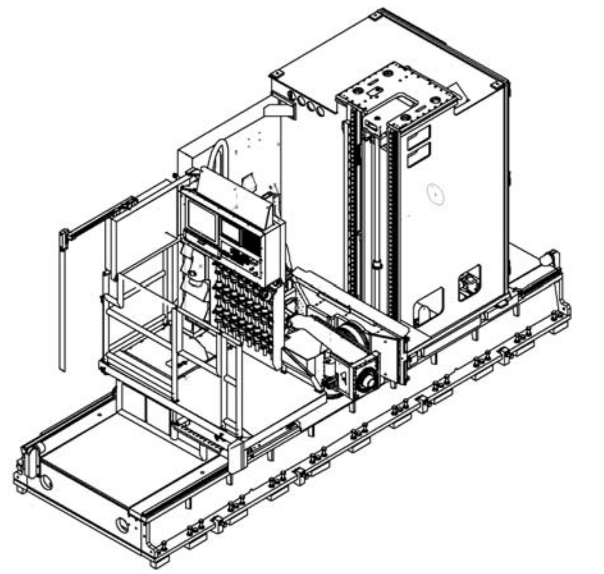

Figure 3 - Isometric view of GRAWDE and operator platform

Integrated into the jig on the ground level are hydraulically actuated bi-fold floors. When in the open position, the floors allow access for the GRAWDE. Because visual access is quite limited in the jig when the floors are open, the doors are of a bi-fold design, which provides a line of sight from the GRAWDE to the rest of the ground floor stage 1 jig. When closed the floors provide a working surface at factory floor height, which provides optimal worker access to the rear spar area. A pre-production image of the GRAWDE in the transfer area with the bi-fold floors open is shown in Figure 4.

Figure 4 - GRAWDE bed and bi-fold floors

POSITIONING

Drilling, while a major portion of the assembly process, is only part of building a wing. There is a significant amount of part loading, fitting and fastening, which must also take place. To maximize the usage of this asset, the machine had to be able to be transferred between jigs and work surfaces. One of the major challenges presented was the requirement to work on multiple independent machine bed systems. The GRAWDE beds are each fitted with linear incremental position encoders. The encoders are distance coded so that the machine can be homed without driving to a home switch somewhere at the end of the bed. To establish an origin, the GRAWDE is driven to the re-synch target and centered. An offset value is then entered into the CNC. The CNC contains a data table of offsets for each bed. Each X-sled has a bed number coded into the wiring to so that the CNC knows which offset table to use.

The re-synch target is used to establish datums for both X and Y-axes. It is also used to compensate the normality sensors in the nosepiece, for pitch and yaw rotations.

SOFTWARE COMPENSATION

Measurable deviations exist in the rails, bearings and in the linear encoder scales. To account for these deviations, each axis on the GRAWDE is electronically compensated improve position accuracy. Data tables for each of the beds are stored in a PC on the GRAWDE. Compensation data is automatically transferred to the Faunc 15i CNC via serial link for the appropriate workzone at startup.

Compensation involves establishing a table of offset values for an axis as function of the position of the same or another axis. For example, there is a table of values for compensating the Y-axis positions at various X-axis positions. Presumably Y-axis compensation with respect to the X-axis would be to compensate for deviations in the X-axis rails or beds. Non-linearity of the encoder scales is also compensated for in the same way.

A laser tracker or laser interferometer is used to measure the deviations and establish the offset values. Since the data is measured at discrete positions, the Fanuc CNC interpolates between values establish a smooth compensation curve.

GRAWDE SPECIFICS

The GRAWDE's working envelope covers the entire A380 inner rear spar workzone for both upper and lower surfaces. Presently, the GRAWDE can be situated on any one of twelve (with unlimited expansion possibilities) monolithic machine bed systems. These beds are located in a trench such that the top of the beds is below factory floor. This allows the beds to be covered for manual operation when the GRAWDE is not in use.

The beds extend from about the first third of the wing on the inboard end to the transfer area outside of the jigs. This transfer area is effectively the working envelope of a modified stacking crane, which can transport the GRAWDE between any of the twelve beds.

CLAMP NOSE AND NORMALITY

One of the key features of the GRAWDE is the rotating clamp nose and integrated normality sensors. When clamped, the nosepiece must be parallel to the outside skin surface in order to prevent marking the wing skin, as well as to measure the distance to the panel for determining counter sink depth. The gear rib reinforcing plate represents a challenge because the holes are drilled normal to the wing surface below, but can be off parallel from the outside surface of the reinforcing plate by more than two degrees.

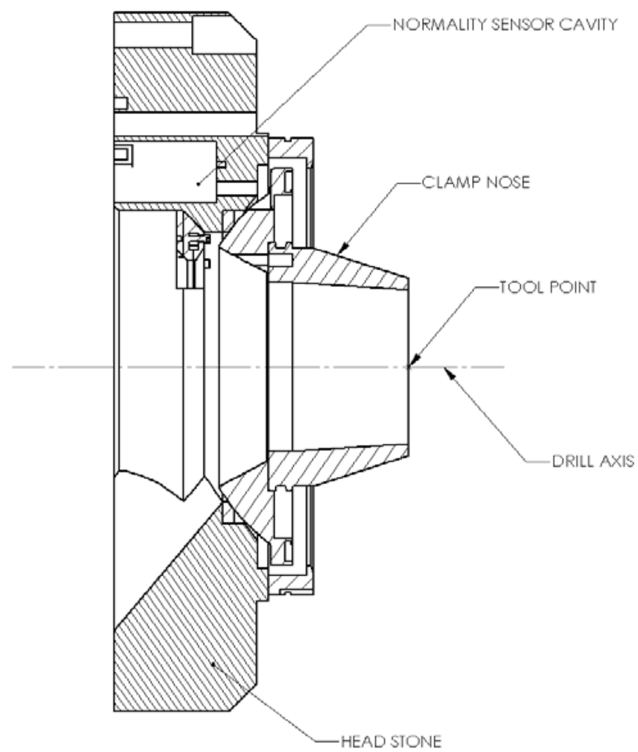

Figure 5 - Cross section of head stone and clamp nose

The clamp nose on the GRAWDE is mounted on a spherical bearing to allow off-angle drilling while maintaining tool point distance and clamping ability. There are linear pots built into the head stone, which effectively measure the orientation of the nosepiece. This design is also a more robust normality system as the delicate components are buried behind the clamp nose. Figure 5 shows a drawing of a sample headstone and clamp nose.

The GRAWDE controls have were designed to take advantage of the spherical motion of the nosepiece by making coordinated axis moves. It can rotate the axis of the drill around the tool point or any point along the drill axis while maintaining the position of the point in space within .025 mm.

GRAWDE-TRANSPORTER INTERFACE

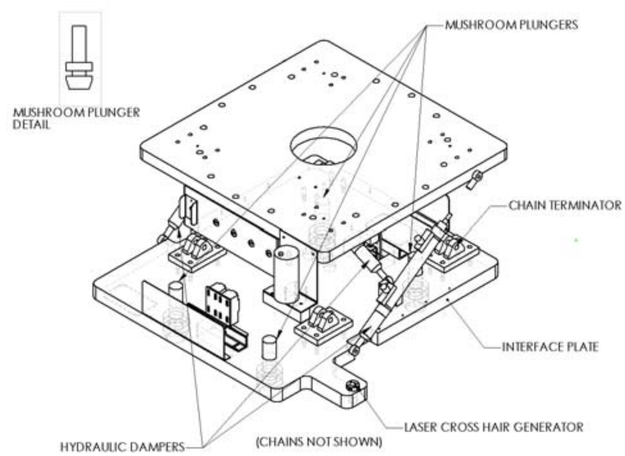

Figure 6 - Interface assembly

One of most enabling features of the GRAWDE is relative ease with which this precision machine can be moved between parallel workzones. This is accomplished by the use of a modified version of a standard stacking crane. To facilitate ease of use, the stacking crane interface was designed with the following criteria in mind.

1. Maintain the GRAWDE in vertical attitude despite a poorly centered load

2. Do not allow the GRAWDE to swing when transported.

3. Connection must be simple and eliminate rigging such as straps and hooks

To accomplish this, while minimizing the stresses imposed by a rigid connection, an interface plate was suspended by four chains approximately 300mm long. As long as the CG of the load is between the chains it will maintain a vertical attitude. In addition, as long as lateral accelerations are limited the load will maintain its attitude. A drawing of the transporter side interface plate is shown in Figure 6. An isometric drawing of the GRAWDE and transporter is shown below in Figure 7.

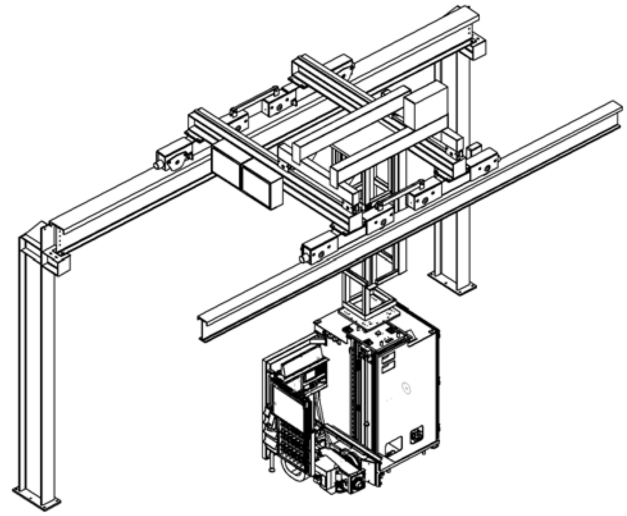

Figure 7 - GRAWDE and transporter

The effect of the chains while safely maintaining a vertical attitude is to effectively change the load from a long pendulum, to a 300mm pendulum with the same mass, thereby raising the natural frequency. This configuration however also creates a torsional pendulum. This can result in rotational oscillations if excited by sudden the slewing of the mast. To eliminate these oscillations, three hydraulic dampers were added between the chains.

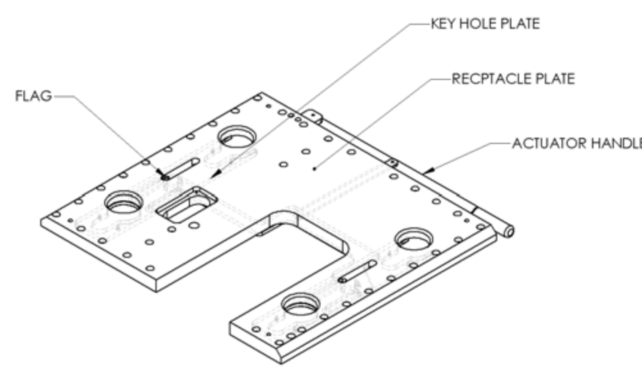

Figure 8 - Transporter receptacle plate on GRAWDE

The interface itself consists of four 80 mm mushroom shaped plungers attached to the interface plate. The receptacle on the GRAWDE consists of a plate with four holes to accept the plungers. On the bottom side of the receptacle plate, there are two keyhole plates. Each of these has two keyhole shaped cutouts with a lever mechanism to move them. The mechanism is actuated manually from a handle on the outside of the GRAWDE. Detents on the keyhole plates eliminate any possibility of the plates sliding while under load.

To aid in aligning the transporter to the GRAWDE a laser crosshair generator is affixed to the interface plate on the transporter and a cross hair target on the GRAWDE. The target is fixed to the GRAWDE at about eye level and rotated about 40 degrees with respect to the floor to aid in visibility. This allows both rotational and translational alignment.

There is minimal communication between the GRAWDE and the transporter. The interface plate on the transporter has three proximity and four mechanical switches. The mechanical switches determine whether the keyhole plates are in the locked, indeterminant or unlocked position. The proximity switches on the crane determine that the GRAWDE is present. This is important as the transporter is also designed to move the other equipment.

Because the GRAWDE always faces the wing surface that it's drilling, it needs to be rotated approximately 180 degrees between beds. To accomplish this, the stacking transporter is fitted with slewing capabilities.

THE GRAWDE-BED INTERFACE

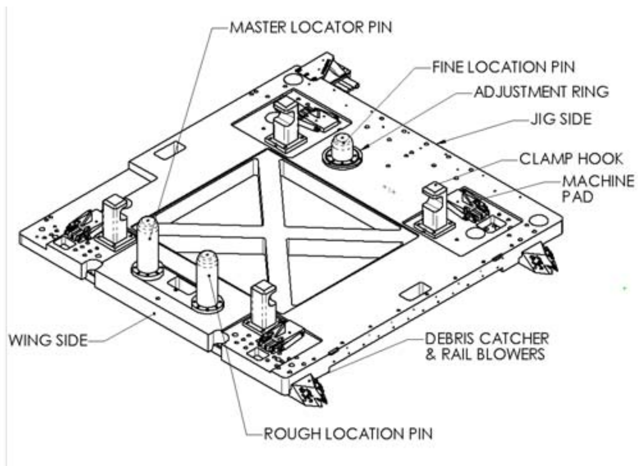

Figure 9 - The X-Sled

As previously mentioned, the GRAWDE resembles a five-axis post mill. To make it portable, a means of separating it from the precision X-axis bearing rails was necessary. To accomplish this, each bed is fitted with a 100 mm thick base plate permanently fixed to the bed via bearing cars – also referred to as the X-sled. The X-sled is shown in Figure 9. The X-sled is fitted with various features to precisely locate the GRAWDE as well as clamp it to the X-sled. The X-axis drive motors and scale are attached to the X-sled.

Machine Pads

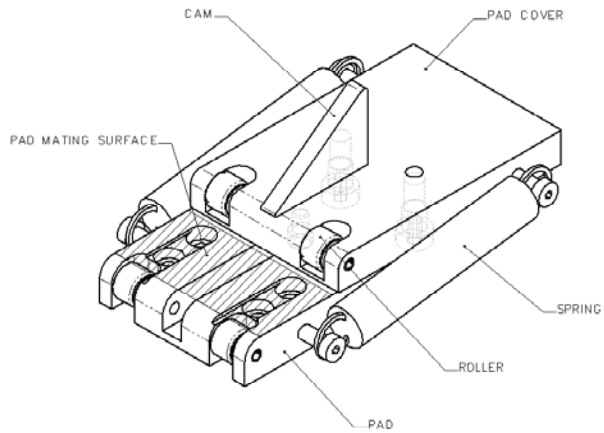

Figure 10 - Machine Pad

There are four pads to locate the GRAWDE in the vertical direction. See Figure 10. Though three pads would prevent an over constrained condition, four pads lend stiffness. The X-sled is fitted with 8 bearing cars, two at each corner of the sled. The machine pads are located above each pair of bearing cars on the X-sled. There is a mating set of pads fixed to the GRAWDE. Each of these is also hardened and precision ground to create a mating plane perpendicular to the Y-axis rails. Perpendicularity is measured with a laser tracker.

In order to prevent swarf and dust from contaminating the mating surface and effecting alignment, the pads are fitted with automatic covers. Both the GRAWDE and the sled have covers, and each has a cam and roller to push the other open as the interfaces approach. Each cover is spring-loaded in the closed position.

Lateral and Rotational Alignment

To accomplish constraint in the remaining degrees of freedom, the X-sled is fitted with three pins and the GRAWDE with three receptacles. The pins are precision ground 100 mm case hardened steel. Only two pins are required to constrain the remaining degrees of freedom, but geometry and visibility prevent ideal positioning of the pins. One pin is the master, the other a rough locator, the third is a precision locator. The precision locator is shorter than the other two and out of sight from the operator. The master locator and the rough locator pins can be seen by the operator through holes in the tower and, serve as visual alignment guides, but are too close together to provide a good moment arm for precise yaw alignment.

The master receptacle on the GRAWDE is designed to constrain in two directions and fixes the GRAWDE'S position. The rough locator receptacle constrains in only one direction to prevent rotation about the master pin without over-constraining. The fine locator, serves the same purpose, only with preload.

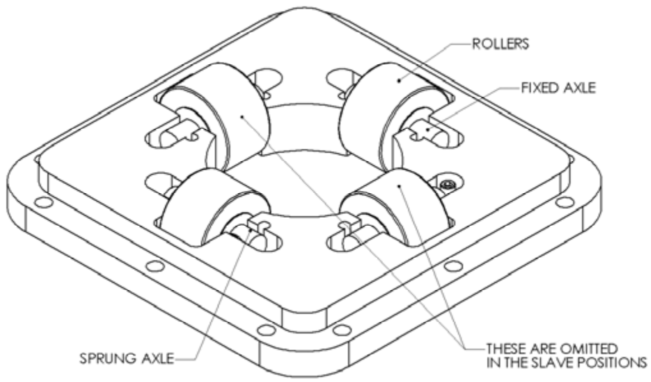

Figure 11 - Location pin receptacle

The receptacles consist of a 38mm thick plate with either two or four 2-1/2 inch diameter rollers. On the master, two of the rollers are on floating axels that are sprung to the center of the receptacle via belleville washers. The other two are fixed. On the rough locator, both axels are fixed. On the fine locator, one axel is fixed while the other is sprung. When in position, the rollers are loaded with about 4400 newtons force.

Hooks

The flying portion of the GRAWDE weighs about 7000 kg. While this is theoretically enough to prevent skidding on the pads, a greater margin was desired. To this end, the base was fitted with hooks and the GRAWDE with a mechanism to grab and load the hooks, each with about 26600 N for a total of 10600 N. The hooks consist of 100mm square bar with notches machined into them. The mechanism consists of rollers situated on a ramp, driven by an air cylinder.

CONCLUSION

The GRAWDE presents the start of a paradigm change in wingbox assembly. The mobile machine is fully integrated into the A380 assembly jig to provide both automation drilling and unrestricted manual access. The concurrent design of the wing drilling machines and the assembly jig enabled the design of a system, which provides superior quality holes in less time, with less rework in an area which is typically rate-limiting to the wing build process.

The GRAWDE can precisely position countersunk fastener holes up to 1.25 inches in diameter through a 4-inch stack. It has the ability to re-synch to a feature on the wing or in the jig, drive to a precise location, adjust for normality and drill a hole in a single shot. It eliminates the use of pneumatic drill motors and templates. It reduces drilling time to less than one minute per hole, while producing superior quality holes. The mobility of this machine provides maximizing of a valuable capital asset over multiple parallel workzones.

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DEFINITIONS

Laser Tracker: A very accurate 3 dimensional laser interferometer.

Stack: Term used to describe the total thickness of various layers of wing skin, internal flanges and reinforcing plates sandwiched together

Swarf: Coolant, chips and residue resulting from cutting operations

Tapes: Fanuc controllers refer to CNC programs as tapes. It is carried over from previous technology where programs were stored on punch tapes.

ACRONYMS

CNC: Computer Numeric Control – also known as a programmable motion controller

GRAWDE: Gear Rib Automated Wing Drilling Equipment

HAWDE: Horizontal Automated Wing Drilling Equipment