2007-01-3913

One Piece Barrel Fastening

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ABSTRACT

Kawasaki Heavy Industries (Nagoya, Japan) designs and builds the fuselage barrel section #43 of Boeing's 787 Dreamliner. The one-piece-barrel (OPB) fuselage design offered a new challenge to fastening equipment assembly cells. Using conventional methods, a fastening machine built around the roughly 6 meter diameter barrel would be very large, heavy, slow and inaccurate. The solution was to use Electroimpact's EMR technology on two smaller independent post machines with a reduced working envelope offering better speed, reliability and still maintaining the high accuracies required.

Optimizing the working envelope and using EMR technology were pivotal factors in achieving the positioning accuracies required for a reliable fastening process that is maintainable in a production environment and increased access to fastener locations.

Figure 1: KHI Post Machines In Production

INTRODUCTION

Barrel Section #43 of the Boeing 787 fuselage is designed and built by Kawasaki Heavy Industries (KHI) in Nagoya, Japan. KHI needed an automated assembly cell for fastening the major structural parts inside the barrel using two piece fasteners. Since the fasteners require actions on either side of the work piece, Boeing's move to the One-Piece-Barrel (OPB) design has created several new challenges for the fastening equipment manufacturers.

Figure 2: Boeing 787 One-Piece-Barrel (OPB)

There are a number of technologies available today that were considered for this cell. The most applicable to the task were large custom machine tools, smaller more standard post machines, and robot cells. In order to determine which of these technologies to use, the engineers at Electroimpact identified six major issues. The solution would be the one that best addressed all of these issues:

FASTENING PROCESS FORCES

Force needs to be applied during the fastening process between the two sides or between the two "process heads". The forces required are up to 3000kgs for 5/16 diameter fasteners. The type of fastening process used dictates the required amount of reaction forces between the two heads. The resulting cell would have to efficiently react the process forces and still maintain alignment between the heads.

Fasteners are positioned in areas with limited access for automated equipment because access is complicated by tall obstructions or even the geometry of the barrel. Certain process types might limit access so a focus was placed on a fastening process that offers more variations of tooling for better access to each fastener location.

FASTENER TYPE

There are several types of fasteners that may be used for fuselage fastening including bolt/collar combinations, bolt/nut combinations, or single sided fasteners. The fastener required also dictates the fastening process to be used and conversely, the fastening process can limit the options of which fastener can be installed. Cost, weight and ease of installation are the main concerns for Boeing fastener selection, but ease of installation is usually the main focus of the equipment manufacturer. For this cell, the focus would be on the lightest and least expensive fastener option regardless of the ease of installation.

WORKING ENVELOPE

The One-Piece-Barrel (OPB) fuselage for Boeing's 787 Dreamliner requires that the process heads are positioned over a large working envelope. Together, the barrel, support tooling and automated guided vehicle (AGV) are roughly 6 meters in diameter and 16 meters in length. Reducing the working envelope of the positioners while still accessing the entire barrel was a prime goal.

Also, the closed cross-section OPB eliminates a stable base for the inner positioner since the positioner cannot be supported by a foundation along the entire travel. This further complicates error compensation schemes between the two positioners since the foundation under each side of the process is vastly different. The lighter the positioners could be, the better the performance and ability to maintain alignment between the two sides.

ACCURACY

Accuracy of the fastener positions on the barrel is of concern for both strength of the joint and clearance reasons. Fasteners must be positioned within tight tolerances over the working envelope and in all varying conditions (i.e. temperature, foundation settlement, etc.).

Accuracy of the alignment between the two heads is required to reliably place collars on to the tail of the bolts. Installing two piece fasteners on an OPB decouples the positioners for inner and outer process heads requiring an independent positioner for each side. Alignment must be maintained between independent guide systems and independent error compensation schemes must be used to correct errors due to alignment of bearing guides, servo positioning, backlash, etc. Global and relative compensation schemes are considered.

Special consideration must also be given to control the thermal effects in order to maintain alignment due to the differing conditions on the inner and outer side of the process. Thermal effects become more pronounced considering the supporting structure for the inner head and positioner. The Nagoya Factory maintains temperatures in a relatively large range of 0 to 40 degrees Celsius, which exacerbates the issue.

CONTROLS

Control architecture has a major impact on the maintainability and performance of the fastening cell. A single CNC control handles positioning and cycle operations of both the inner and outer process heads. Maintenance personnel can access complete information from one simple interface since the integrated logic control handles I/O for both heads and all the process tools. High performance CNC servo functions greatly enhance the accuracy of the system.

RELIABLE COLLAR FEED TOOLING

A significant portion of downtime associated with automated fastening equipment can be attributed to collar feeding issues. Although a large portion of miss-feeds are due to positioner misalignment issues, collar feed tooling reliability accounts for a significant portion of the downtime as well. The collar feed system includes feeding the collar from the bulk stage to the process head, loading the collar to the tooling on the process head and finally transferring the collar with the tooling to the tail of the bolt. Each stage of the collar feed system offers an opportunity for collar miss-feed as they must function thousands of times per barrel. Achieving the expected reliability (1 miss-feed in 1000) with the added challenge of aligning independent positioners had yet to be implemented in a production environment to the level of reliability expected. This issue would need to be not only attacked on the accuracy front, but in the collar feed tooling itself.

MAIN SECTION

For each issue identified, the different technologies available were considered. Fastener type and accuracy were heavily weighted. The expectation of reliability of the feed system and machine uptime were based on experience with existing cells.

EMR: ENABLING TECHNOLOGY

The type of fastening process used dictates the required amount of reaction forces between the two heads. The reaction forces seen by the positioners greatly affect the size and type of machinery. Of the three leading, production hardy fastening process, Electromagnetic Riveting (EMR) fastening offers the lowest reaction forces as compared to hydraulic and ballscrew processes. The EMR reaction forces are limited to 100-150 kilograms as compared to up to 3000 kilograms for the other two processes.

Because the reaction forces using the EMR are so low, lighter and smaller positioning platforms can be used. The final weight of the inner and outer machines was 10,000 kilograms and 20,000 kilograms respectively. The bearings and support members only need to accommodate clamping loads required during the drilling process. This has the largest impact on the structure that supports the inner machine part of the process.

EMR technology also allows for the use of true offset fastening where the center of the fastener can be offset from the center of the end-effector, or even outside of the inner head profile. This increases access to fasteners that would otherwise be inaccessible to cells that use other fastening processes.

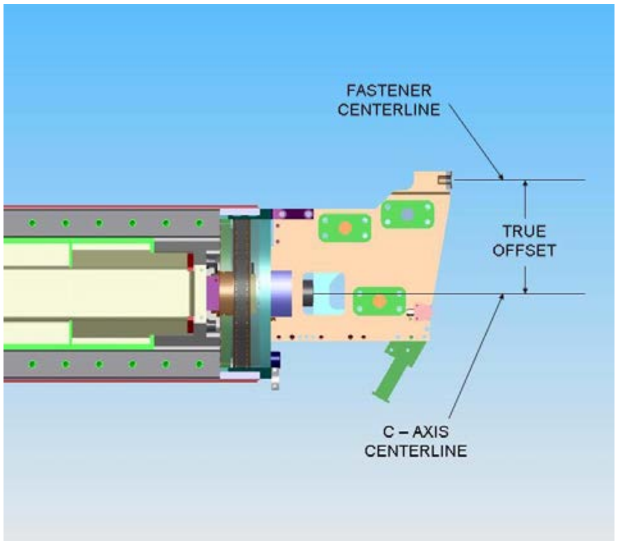

Figure 3: True Offset Fastening

Lastly, the EMR end-effectors themselves are small and lightweight, removing much of the inertia of the system parts. These small components are used to measure the position of both collars and bolts. The position of the fasteners can be measured quickly and precisely to detect if each side is properly seated before firing. This greatly increases the reliability and quality of the fastening process. The dry-fire protection (preventing forming of an incorrectly seated or missing fastening) has proven itself on EMR systems throughout the world.

FASTENER TYPE

Ideally, the lightest and least expensive fastener would be the fastener of choice for KHI and Boeing. EMR technology is capable of swaging collars onto Hi-lok bolts. Compared to other fasteners types detailed below, this combination offers the best clearance, weight, cost and availability advantages.

<u>Pin tail lockbolts with Titanium Collars</u>

Pin-tail lockbolt might prove the easiest for collar feeding considering the extra length of the bolt tail could help reduce the effects of alignment errors on collar placement, they are also the lightest of the fastener combinations, once installed. However, these bolts are costly and they create waste. The waste must also be handled automatically creating reliability and maintenance issues throughout the life of the cell.

Another detriment is that they cannot fit in some areas of the fuselage due to the extra pin length. The pintail lockbolts require more clearance behind the fastener for the extra long tail that is broken off during the fastening process. The tail prevents this particular bolt from being used in some areas such as the door surround that are under flanges or other structural components.

<u>Single sided fasteners</u>

The advantage with these fasteners is the elimination of the inner side of the fastening process. Many of the reliability, maintenance and cost issues associated with a two sided process would be diminished, however these fasteners are not certified for many areas on the fuselage and they cost more than other fastener types.

<u>Threaded Hi-lok bolts with titanium nuts</u>

Hi-lok threaded bolts are the least expensive of the bolts types and are available from various sources. The nut portion costs more than collars, and weighs more after installation. Automating the nut installation is also difficult and the nut requires re-torquing when installed over areas with face sealant. The nuts are however, easer to place on the pins and are not as sensitive to inner to outer machine alignment when compared to placing collars.

<u>Threaded Hi-lok bolts with titanium collars</u>

As mentioned above, Hi-lok threaded bolts are the least expensive of the bolts types and are the available from several sources (as compared to the proprietary pin-tail lockbolts). The collars are lighter and less expensive when compared to the titanium nuts and they do not need to be re-torqued. Combined with the titanium collars, they offer the best price and weight combination for the customer.

However, the Hi-lok/collar combination requires the tightest positioning accuracies to reliably place collars onto the tails. The challenge with feeding these fasteners is detailed in the “Collar Feed Accuracy” portion of this paper below.

REDUCED MACHINE TRAVEL

The One-Piece-Barrel (OPB) design of Boeing’s 787 fuselage requires a working envelope of 16 meters long, and 360 degrees access to a roughly 6 meter diameter. Trying to access 360 or even 180 degrees of travel would have required very large and heavy machines. Machine alignment would be difficult to maintain throughout the entire working envelope, throughout a varying work environment and over a period of normal wear over time. However, it was determined that the best way to accurately locate fasteners relative to the frames was to base fastener positions relative to tack fastener positions for automatic fastening. It was also determined that the tooling that supports the barrel would rotate the barrel through 360 degrees of rotation. Therefore, by limiting the positioner travel to access only a few degrees of rotation between tack fasteners, and by using the barrel rotation axis to access each “segment” of the barrel, the positioner working envelope was greatly reduced.

When part programming was considered along with tack fastener locations, the working envelope was reduced to 19 meter long with only 30 degrees of rotation at a 3 meter radius.

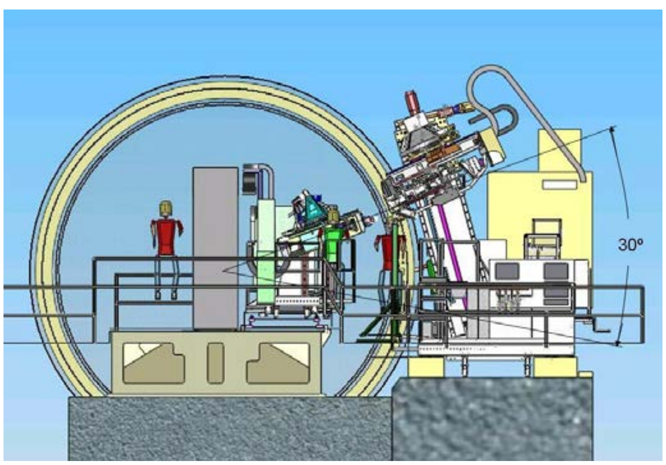

Figure 4: Reduced Machine Travel

The reduced envelope also reduces the size and/or length of the support bearings which makes them easier to maintain and align. The final weight of the inner and outer machines was 10,000 kilograms and 20,000 kilograms respectively. The smaller positioners can be accelerated faster resulting in increased speeds. Working in segments yields minimal reduction in cycle times or rate since the machine speed is increased due to the smaller size of the positioners.

Also, the inner positioner is supported on a structure, called the inner floor, that must span the entire length of the part. The fuselage barrel section length combined with clearance for tooling that supports the barrel and additional travel for maintenance activities totals over 16 meters long. Therefore, the inner floor must span the part, tooling and reach out to supports on each end to total just over 22 meters long.

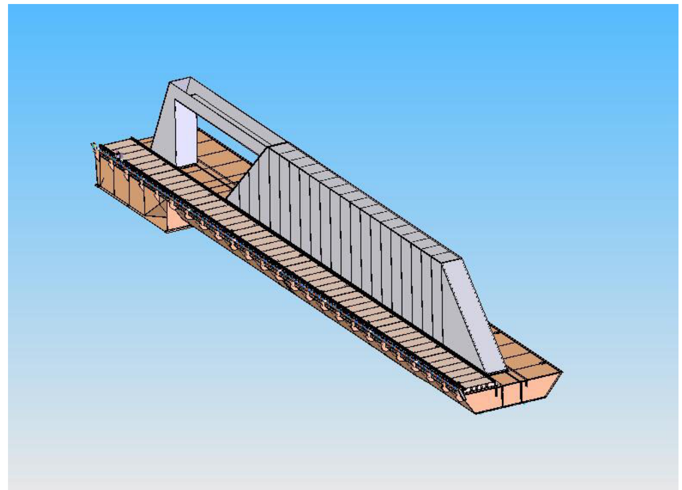

Figure 5: Inner Floor Structure

This structure not only supports the weight of the inner positioner and head, but must react the clamp load and fastening forces as well. Keeping the floor fixed was important to compensating errors due to deflection. The structure is fixed and the maximum design deflection with the inner machine roughly in the center of the span, was 0.338mm (0.0133”) and in practice, was measured at 0.330mm (0.0130”) max. By using smaller positioners and the EMR process, the size and weight of the inner floor structure was reduced as well. These reductions also trickle down to the foundation and possibly the required floor space depending on the actual cell requirements.

ACCURACY

Accuracy requirements can be divided into two main components, the need to drill and install the fastener in the correct position on the fuselage, and the need to install and swage the collar onto the tail of the bolt to complete the fastening process.

Fastener Positioning Accuracy

The first component of accuracy, fastener positioning, is influenced by both fuselage variation and outer positioner accuracy. Since the holes are drilled and the fastener is installed from the outer side, the inner positioner accuracy does not influence the fastener positioning accuracy. Four normality sensors on the outer positioner determine relative angle and distance between the fuselage skin and the machine. The resulting overall accuracy of the outer machine is 0.200mm (0.008”) at all conditions. Final acceptance testing results showed the machine accuracy was 0.150mm (0.006”) over the entire travel.

A vision system is used to automatically measure the location of tack fasteners. By subtracting the known nominal position of this tack fastener from the measured location, the position and offset is calculated. With this offset, the positioner will accurately place fasteners relative to the tack fastener. To further increase the accuracy two tack fasteners are measured to add a scale factor to the compensation.

Regardless of global positioner accuracy, tack fasteners must be measured at intervals to compensate for the tolerance of the installed frames. So, the method of resynching on tack fasteners eliminates many errors that effect global positioning accuracy, such as thermal growth, straightness of guides, orthogonality of axes, etc. However, compensation schemes were implemented to protect accuracies between the two machines detailed below.

Collar Feed Accuracy

For the second component of accuracy, needed for collar feeding and swaging, the inner positioner must be aligned to the outer positioner throughout the working envelope. This is because the inside diameter of the collar closely matches the outside diameter of the fastener tail. If the collar is not aligned to the fastener tail prior to feeding, the collar will not feed, or will go on crooked to cause a miss-feed. Downtime and fastener installation quality have a large impact on the productivity of the cell and predictability of these factors often determines the value of having the cell. Inner to outer positioning accuracy has been found to be the greatest contributors to collar feeding reliability.

The OPB is a closed cross-section geometry that results in a decoupling of the inner and outer fastening process. Maintaining alignment between independent positioners is complicated by the fuselage skin blocking direct measurement between them at most locations. Since it was not practical, in this particular application, to add a resynching function on the inner positioner (due to dimensional constraints at the tack fastener locations), the two positioners must then stay located within tolerance of each other over the entire working envelope.

The primary alignment of the machines is done independently to a global reference measured by a laser tracker. This allows each machine to be updated and corrected with no affect on the other. Once both machines have been measured and compensated, the vision system and distance sensors can be used to provide an independent check that both machines are tracking together. This check can be performed by a machine operator without the need for any additional equipment or training. The takes less then 5 minutes to complete. The check can vary from a single measurement to comprehensive grid covering the entire work envelope between the two machines. A check procedure is required by Boeing's "D6" document that controls maintenance checks for the fastening process.

The errors between the machine were maintained below 0.200mm from November 2006 through to the writing of this paper (June 2007). All values are recorded in a data collection system (DCS). The data from this check can also be used to correct either machine in the event that one of the machines has a likely error due to a collision, measured settling or other cause.

The quick machine to machine alignment check has the added benefit of quick recovery immediately after minor seismic events, which is important in the Nagoya installation.

Post Machine platform vs. Robot Platform

A robot positioner was considered for this cell due to its commodity pricing. It is known that the robots have a "sweet spot" in their working envelopes where the positioning accuracy is more accurate. The overall working envelope could be limited to the "sweet spot" zone, but, the lack of repeatability and stiffness of the robots still held the positioning tolerances of the robots to 0.015" even after compensations were made. Commercially available robotic positioners are improving, and can now meet the accuracy necessary for successful fastening in some cases. However, when using two robots together, these errors are additive. It became evident that the inner to outer robot positioning error were higher than could be tolerated to achieve robust collar feed in a production environment. These large positioning errors left no margin to deal with thermal, settling and wear issues that arise in a production environment. Therefore, a decision was made to use a purpose built post machine positioning platform that currently meets the accuracy needs of the fuselage bolting process.

Role of temperature compensation

Temperature compensation is used to correct any linear changes that take place since the last vision system measurement. This is necessary because the factory temperature varies due to intermittent use of heaters during the winter and follows the outside temperature in the summer. Actual temperatures have been recorded between 5 and 33 degrees Celsius (the specification calls for 0 to 40 degrees Celsius) in the Nagoya factory from October 2006 through June 2007).

Different areas of the machine have varying thermal characteristics with more massive parts and those connected to the foundation changing at a slower rate. Also, the inner machine is supported by a free standing structure as opposed to the outer machine foundation supported along its entire length.

To compensate for thermal growth of the inner machine floor, the vision system is used to measure the position of the inner machine relative to the outer machine at two locations just past each end of the barrel. These measured values are then used to scale and offset the position of the inner machine relative to the outer machine. Note that this compensation is in addition to any resulting from measuring the location of tack fasteners.

With the use of temperature sensors at multiple locations on the machine and foundation the machine position can theoretically by compensated to maintain accuracy over a wide temperature range. In practice this is complicated by the time component of the temperature growth, for instance a machine element may be a different length at a given measured temperature depending on whether the previous temperature was warmer or cooler. An additional difficulty is that the factory temperature varies seasonally with the weather. Compensation and verification of compensation would need to be done over several seasons. For these reasons we periodically correct for any error that has built up in the temperature compensation by checking the machines relative to each other with the vision system. This is typically done at the beginning of each part program.

The result was a positioning accuracy between the inner and outer machine of 0.200mm throughout a working envelope of 19m x 30 degrees at a 3m radius, even between inner to outer machine check. This will be monitored for the first year of production in order to reduce the checking requirement to a 6 month check.

CNC CONTROL

The inner and outer fastening heads are mechanically independent and can be viewed as separate machines. Individual CNC's or PC's could be used to control each head and coordinated through a cell-level controller. However, in recent years, improvements in high-speed, highly noise-immune bus communications have allowed machine tool builders the flexibility of placing motor drives a long distance from the control. In this application, it's possible to have the CNC control on one fastening head and to run a fiber optic cable 90 meters through the X axis cable tracks to the other head.

There are clear advantages in coordination and maintainability with a single control. This arrangement effectively gives coordinated motion of the two machines 'for free', since all axes run through a single set of kinematics. Interpolated moves of the inner and outer heads, including all axis compensations, are coordinated on the update rate of the CNC position loop. This means that the heads stay aligned and accurately follow the programmed path.

The control system consists of a single Fanuc 30i CNC controlling 18 servo motors, 10 on the outer head and 8 on the inner head. The CNC is physically mounted to the outer system. There is a fiber optic cable for servo communication, and a fiber optic cable for I/O. Both fiber systems are configured in a daisy-chain arrangement with each servo drive or each I/O rack being a node in the chain.

Since the inner and outer heads interact extensively to clamp the panel and install two-piece fasteners, having a single controller facilitates a high level of integration. For maintenance, it is extremely helpful that the fastening cycle is programmed in one location, without the need for cycle-level hand shaking between separate systems. Error checking or alarm sharing are handled by low-level system functions which are well-developed and well-documented. Complete, up-to-date information is available for the entire cell from one point, rather than only a small 'window' of data communicated between systems.

In addition to the coordination and maintainability benefits, a CNC also has the advantage of servo control functions which are unavailable of robot controls. 'Torque Tandem' for example, is an extremely effective anti-backlash function used on the inner and outer systems' rack-and-pinion X axes. Each X axis is driven by two motors, each with its own gearbox and pinion, electronically preloaded against each other. This simple feature completely eliminates backlash error, but it is not available on any robot commercially available today. Similarly, secondary position feedback such as linear scales is commonplace on machine tools, but not found on robots. In some cases this feedback is vital to maintain accuracy when high loads cause drive system deflection.

RELIABLE COLLAR FEED TOOLING

Reducing the downtime associated with collar installation requires tooling that could reliably reduce sensitivity to misalignment, reliably feed collars from bulk to the head, reliably load collars to the tool point, and finally transfer the collar onto the tail of the bolt.

Reducing the sensitivity to misalignment of independent fastening heads would increase reliability of collar feed. To achieve a reduced sensitivity to alignment, a unique mechanical compensation system is employed that allows the backside collar swage die to move +/-0.75 mm radially as the bolt engages the collar. Since the collar and die must 'comply' to the position determined by the bolt tail we call this method the 'compliant die' collar feed system. The compliant die has proven itself on production machines including the cell at KHI. Of the thousands of fasteners installed on barrel #3, there were only two miss-feed of the collar feed system. This compliance also eliminates the potential for damage to the bolt, collar or to the drilled hole.

The collar feed cycle begins when the two machine heads clamp up on the work piece and a hole is drilled through the material stack. The step are visually depicted in figures 6 through 13. During the clamp and drill steps of the fastening cycle the, inner machine swaging die is retracted away from the work and a portion of the collar feed path is actuated into position so that a collar can be presented to the center axis of the swaging die. A single collar is escaped from a vibratory bowl and is pneumatically conveyed to a pair of fingers that stop the collars motion on the tool centerline. An inductive proximity sensor detects the flanged end of the collar when it arrives at the fingers. The collar is restrained in all degrees of freedom except for the direction of the feed path. This was critical in preventing collar tumbling which was the major cause of collar miss-feed in this portion of the system.

While the pneumatic air blast holds the collar in position against the fingers the swaging die is then moved toward the feed tube and a centering pin in the middle of the die enters the hole in the middle of the collar. With the collar successfully loaded onto the die pin the feed tube can then be retracted and the fingers, which are held closed with a stiff spring, are stripped off of the collar. This ensures that the collar is restrained during the entire loading of the collar onto the die pin, preventing collar miss-feeds.

Typically, the process of loading the collar onto the die pin is much faster than the clamp and drilling process. This part of the sequence does not add any time to the overall fastening time. Once the hole is drilled, the collar is ready for placement against the work piece, where the servo EMR system can measure and verify that the collar has been correctly placed and oriented. The low inertia of the EMR system allows for precise measurements and quick detection of the collar because of the smaller components. At this time the bolt is inserted from the outside of the barrel through both the hole and collar simultaneously.

Radial misalignment between the hole and collar inside diameter is corrected via the compliant die process described in the paragraph above. When the bolt is installed in the work and collar the EMR swaging process is initiated and the die is stripped off the formed collar. The machines then unclamp, move to the next fastener position, and the fastener cycle repeats.

The collar feed system was certified last year (testing completed in early November and letter of certification was dated December 11, 2006) and the system has installed over 7000 fasteners in production barrels.

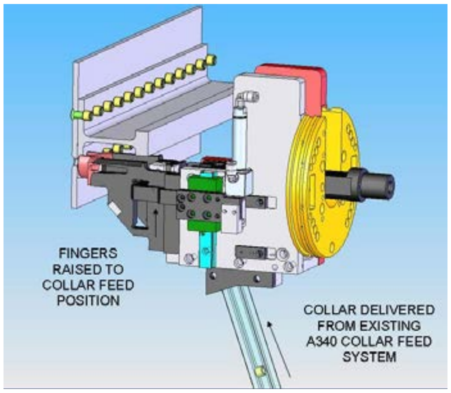

Figure 6: Feed collar from bowl to head

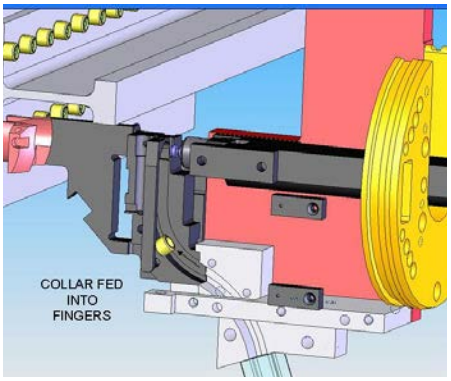

Figure 7: Collar continues to fingers

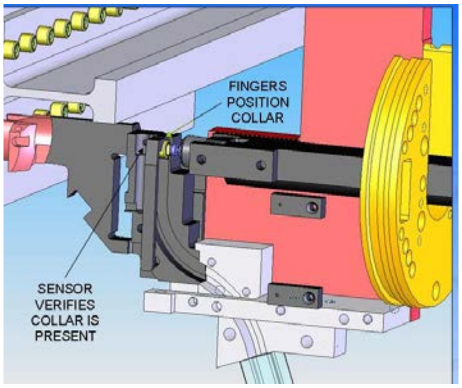

Figure 8: Collar stops in fingers

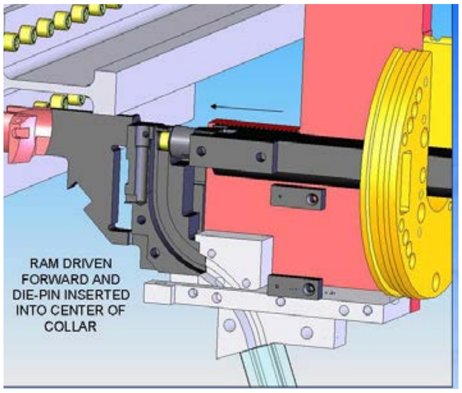

Figure 9: Die pin picks up collar

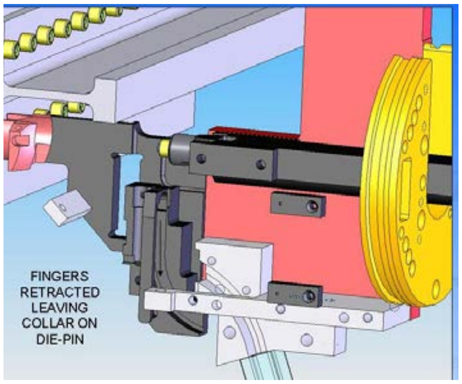

Figure 10: Fingers retract

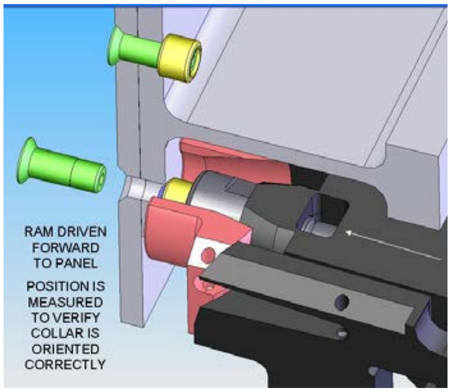

Figure 11: Collar moved to part

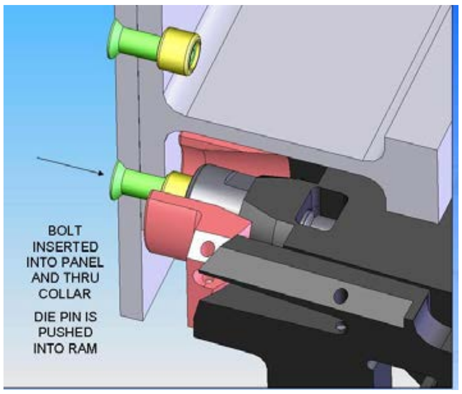

Figure 12: Bolt and collar position check

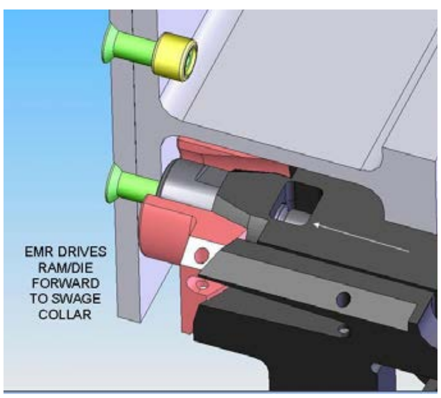

Figure 13: Collar Swage

CONCLUSION

EMR technology was chosen for it's ability to reduce (almost eliminate) the forces produced during the fastening process. This, in turn resulted in a reduction of the weight of the positioners and the deflections due to those forces. Also, the smaller components of the EMR system are more sensitive to measuring the fastener positions just prior to swaging. This sensitivity eliminates the potential for a 'dry-fire' on a miss-fed fastener.

Also, EMR true offset tooling increased access to fasteners in difficult to reach locations. KHI decided to leave the cargo floor beams in the cell, requiring the machine to reach around the parts using the true offset tooling.

The EMR cell installs Hi-lok threaded bolts with titanium collars, which are the most cost effective and lowest weight for the aircraft.

The positioner travels were reduced to 30 degree segments, relying on the barrel rotation axis for segment to segment access. This reduced the deflections due to weight and increased speeds because the machines are lighter and easier to set-up, compensate and maintain.

Accuracies less then the specified tolerances were maintained in production for fastener placement. The tack fastener resynch process reduced positioning errors further, which vary depending on the part. Accuracy of 0.200mm was maintained between the inner and outer machines throughout the entire working envelopes and under all conditions in production.

The cell was qualified for production December 2007 and has been used on every production barrel to date. Over 7000 fasteners have been installed in production barrels as of June 2007. Cycle times were recorded in production as being 11.25-11.5 seconds per cycle of typical and spacing. Floor to floor rates expected around 3 fasteners per minute. The floor to floor rate includes barrel loading, rotations and resynching. An ATC allows for offline setting of the drill countersink since drill wear on CFRP can be so high.

Collar feed reliability has been maintained at the specified levels since production started in December 2006.

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