

2011-01-2592

One Piece AFP Spar Manufacture

Author: Todd Rudberg

Co-authors: Guy Faubion, John Nancarrow, Andrew Purvis

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ABSTRACT

Manufacturing C cross-sectional components with high aspect ratios out of carbon fiber reinforced composites is desirable by the aircraft industry. Modular AFP heads with short, fixed tow path have the fundamental performance characteristics required to successfully and productively automate the production of these part families. Aircraft parts in this family include wing spars, stringers, and fuselage frames .

INTRODUCTION

Most large composite wing spars are currently manufactured using a hot drape forming process. Maintaining consistency in drape forming can be hard, and spar designs must be simple enough to allow for use of that process. Because the material must be formed after the flat charge is made, the initial charge must be done with less heat and pressure when compared to layups of final shapes resulting in poor consolidation. This lack of initial consolidation allows the various layers of the charge to slip by each other as it is formed into the final C shape of the spar. This can also cause issues in the final layup quality in terms of charge placement, material consolidation and wrinkles.

Some newer designs of wing spars are manufactured by AFP process but use equipment of non-ideal configuration. Most existing AFP equipment is configured as post mills or lathe type machines that can only access one side of a fixed part. This type of equipment requires that rotating tooling be used in order to reach all 3 sides of a spar. Because spar tools must be rotated the designers are limited by the max allowable length (or really aspect ratio) of a rotating spar tool.

Ideally a spar or frame production machine would have the following characteristics:

1. The part should be made as complete as possible. In the case of a spar, this eliminates joints which add weight, complexity and cost.
2. The part designer should be able to refine the design to optimize for weight and other performance considerations. This means the process must be able to reliably and repeatedly generate complex path geometry, ply boundaries and path orientation.
3. Composite layups must have good consolidation over the entirety of the part.
4. The part has to be produced in a reasonable amount of time.

Hot drape forming can satisfy characteristic #1 and is currently the best candidate for #4. Traditional AFP machines can generally achieve #2 and #3.

All of these ideal characteristics can be achieved by holding the tooling stationary so that it can be supported along its entire length while a multi-lane AFP machine maneuvers around the three primary sides of the part (flange-web-flange) and moves along the part's length. In the case of a frame (looks like a curved spar) it is impossible to rotate the tool and a stationary tool is mandatory.

Due to Electroimpact's unique head geometry, the above configuration is possible. Spar parts are efficiently manufactured with a static tool, full-length, and in-form, without using the unstable drape forming process or rotating the part. There are several key

features to Electroimpact's equipment that make this build process possible and economical. We will cover three: a compact-fixed AFP process that isn't affected by toolpoint orientation, high-performance six axis path control, and placing rotary axis pivots close to the toolpoint.

BODY

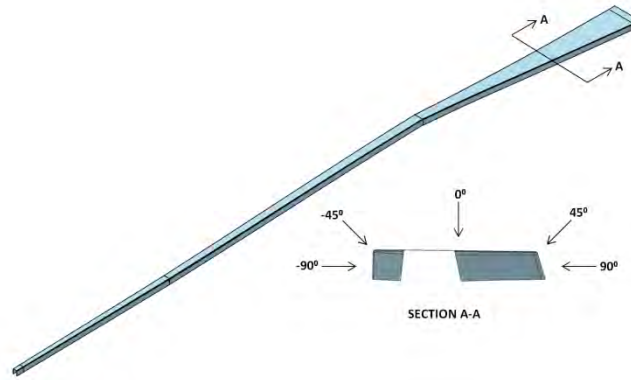


Figure 1 – representative wide body wing spar (90' long)

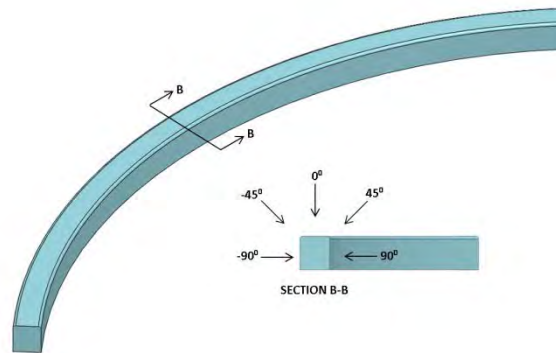


Figure 2 - representative wide body fuselage frame (chord approx. 12' long)

Consider in more detail the layup of a fixed spar (Figure 1). Via the use of computer simulations, it is possible to measure the maximum angular toolpoint excursions needed to layup existing production parts that are currently manufactured using drape forming or traditional AFP processes with rotating tools. Looking at a generally representative large spar part, from a major aircraft manufacturer, verifies the intuition that +/-90 degree range of motion is needed about the part axis (relatively little motion perpendicular to the part axis is needed, +/-10 degrees in this case, and 360 degrees continues motion around the normal axis is needed for full bidirectional layup).

Looking at (Figure 2), it is fairly clear that rotating this tool is a difficult prospect at best. A new way of manufacturing C-channel parts is required. Spirit Aerosystems in Wichita, KS, has successfully built just such a part using Electroimpact equipment.

COMPACT, FIXED AFP PROCESS THAT ISN'T AFFECTED BY TOOLPOINT ORIENTATION

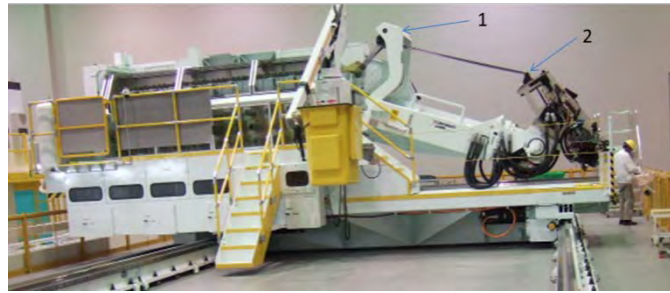


Figure 3 – Example of traditional AFP equipment

Traditional AFP equipment has some key kinematic limitations due to their long tow path.

In traditional AFP machines, angular excursions of the toolpoint change the tow path from the creel to the head. As you can see in Figure 2, at points 1 and 2, the tow path passes over redirects. Although how machine tool builders handle this varies, it is typical in the majority of AFP equipment that exists today. Therefore, any roll, pitch or yaw required to stay normal to the part must be reconciled by these redirects between the creel house and the AFP equipment's toolpoint. This greatly limits the angular excursions possible for the process; the equipment pictured above has a maximum angular excursion of ± 45 degrees about the part axis and ± 45 about the vertical axis. Due to the limitations of motion of the toolpoint, in order to reach three sides of a part (as in a u cross section) the part must be rotated in front of the process head. Even when operated within a ± 45 degree angular range, the control of the tow path becomes difficult, unwieldy and unreliable. Common problems are tows jumping the redirects, tow twists and splice failures. The splice failures occur because the cold brittle tow must pass over extra re-redirects. The tow jumping is due to slack in tow tension. The tow twists are due to the angular change in tow path. Further, because the tow is passed over a large number of redirects the tow tension control is necessarily low performance due to the mass and length of the system involved.

Electroimpact's modular AFP head (Figure 3) has a number of advantages over traditional AFP equipment. The heads are capable of dispensing 16 tows in 1/2", 1/4" or 1/8" tow width configurations (with changing tow size only needing a 2 minute change of heads). With the modular concept other special use heads are possible; currently a probe head is used for locating the layup tool and for machine compensation purposes. Other options are an NDI head or an ultrasonic cutter head, both of which would have the same part access as the AFP head. The current 16-tow design can also be used with reduced tow count for better compaction as required by complex geometry. The modular concept used allows periodic maintenance and material loading to be done offline without tying up valuable capital equipment. Design details like quick release clamps, which hold the process modules in place during production, allow for equipment to be easily cleaned without tools. For the purposes of this paper, we will focus on the tow path and tow tensioning system. The main enabling concept for being able to use modular AFP heads over the wide range of angles needed for fixed spar layup is the idea of a machine independent minimal, fixed tow path.

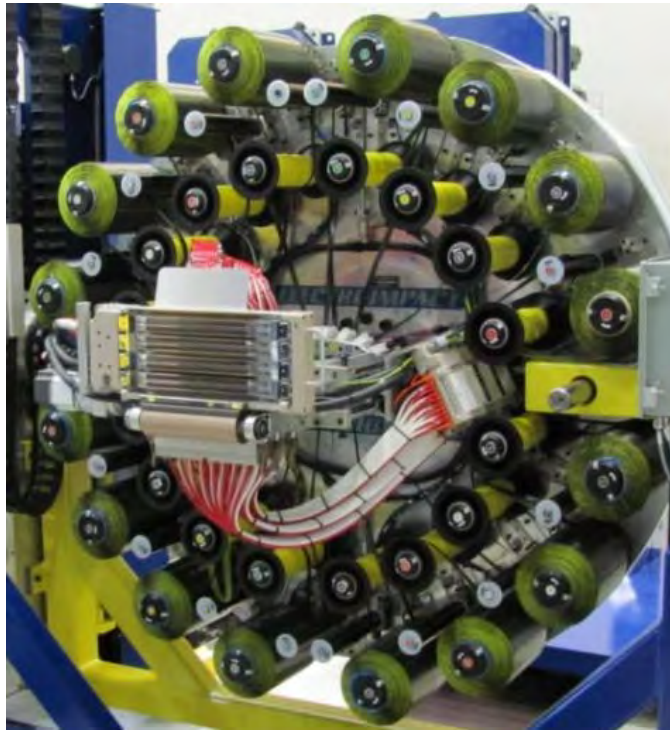


Figure 4 – Electroimpact Modular AFP Head in Tool changing stand

In Figure 3 the reader can see that from the payout bobbin to the application point is essentially a rigid body. This means that the relationship from the payout bobbins (or creel house) is fixed relative to the application point and not affected by the position and orientation of the toolpoint. Figure 4 shows the constant length tow path. The result is that the tow path and performance of the AFP head is completely unaffected by the position of the machine axes and equally unaffected by the position and orientation of the part. Figure 7 shows modular AFP heads in both the vertical and the horizontal position.

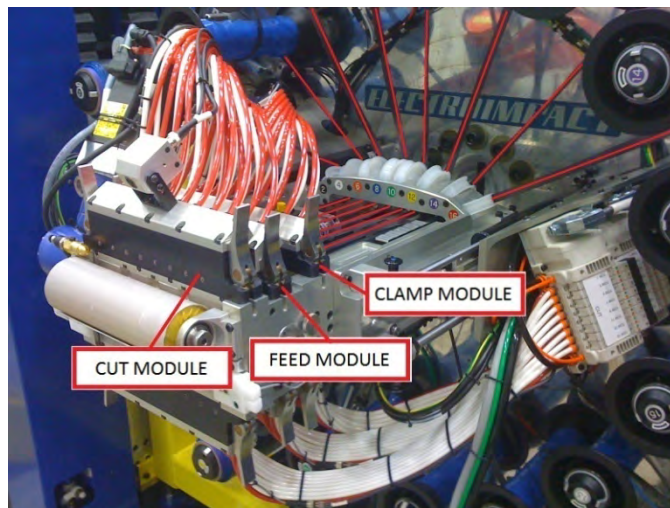


Figure 5– AFP Head Simplified tool path

Active Tow Tensioning System

By eliminating tow path variations, Electroimpact engineers must only solve one tow path problem. The result is a low mass, high performance closed loop PID tension control system (Figure 5). This simplified tow path eliminates issues with redirect jumping and

splice failures. This high performance tension system is critical to the high accelerations and consistent short course performance required to efficiently manufacture U channel cross-sectional parts.



Figure 6 – AFP Head Spool, Backing Film Take-up & Dancer Configuration

As shown in Figure 5 the tow is unwound from the spool and the backing film is removed on a take up spool that redirects the fiber towards the dancer. The dancer axis of travel is in-line with the tow re-direct that align the tow into the process equipment on the compaction sled as shown in Figure 4. Even with movement on the compaction sled the length of tow between the process equipment and spool is constant eliminating the need for any type of re-spooling.

When a tow is activated the feed module forces the tow onto a drive roller that matches the surface speed of the machine on the tool. The drive roller feeds the fiber from the point it was cut to the "nip point" where the fiber is captured between the compaction roller and the substrate. Since the drive roller can be required to feed from 1 to 16 tows at a time the dancer was introduced between the spool of material and the process equipment to reduce the inertial shock on the motor due to the acceleration of the spool. In order to prevent over-tensioning during feed or under-tensioning during the dancer rebound we actively regulate the pressure applied to the tensioning brake on the spool using electronic pneumatic regulators, commonly called ITVs. We calculate the drag required using a tuned PID controller with a position input. The position input samples at 400 Hz (.0025s) with an accuracy of .004" (.1mm). The ITV inputs are updated at a rate of 125Hz (.008s).

Figure 6 shows the measured dancer position and the commanded drag force on the spool. The figure clearly shows a large amount of dancer compression as the tow is fed towards the nip point and the spool of material begins rotating from rest. As the dancer is compressed the drag is reduced to zero to allow the spool to accelerate to an angular velocity which matches the rate at which tow is being pulled out of the head. Once the spool is rotating fast enough to allow the dancer to begin to retract, the drag on the spool spikes to prevent the dancer from bottoming out on retract.

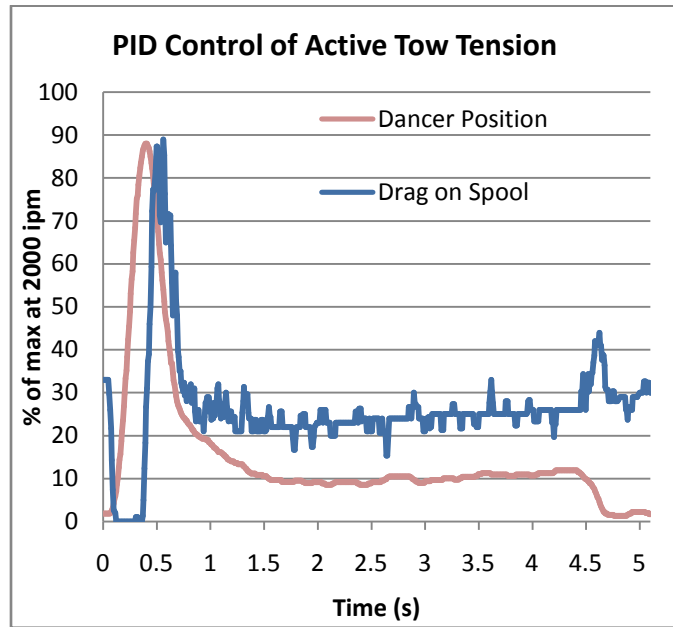


Figure 7 - PID Control of Active Tow Tension

Because the AFP head is modular and can operate equally well in any orientation, EI mechanical engineers have the freedom to design many different machine configurations to support the needs of various parts (see Appendix: Example modular head machine configurations). In the case of Electroimpact AFP, equipment part geometry drives machine design. This approach bypasses the limitations of the traditional AFP process which fixes machine design and drives part configuration causing manufacturers to limit the length of a spar section so that it can be rotated in front of their AFP process or requiring utilization of a drape forming process. Neither of these two compromises is necessary with a short-fixed tow path and an appropriate machine design. Note that this layup ability also enables layup of other similar complex shapes without the need for rotating the part or drape forming, such as the winglets depicted in Figure 10.

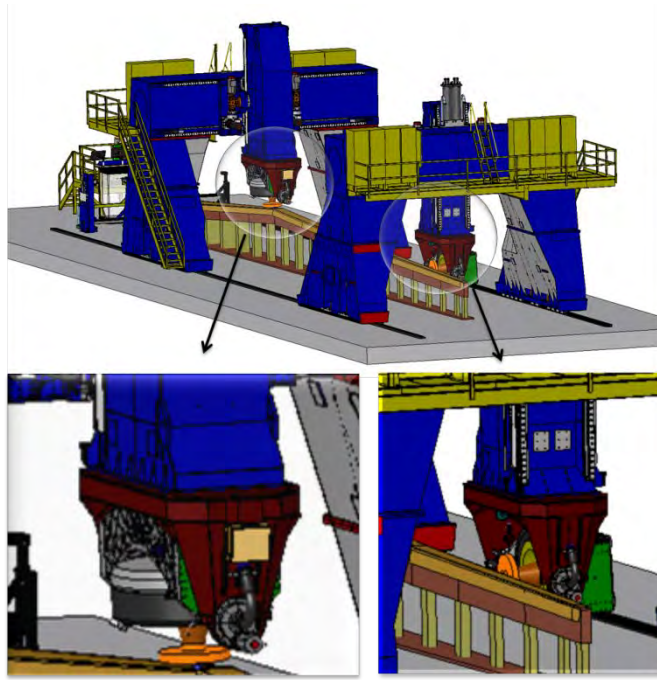


Figure 8 - Two Electroimpact AFP machines on a 90' one piece spar. Note that one AFP head is pointed horizontal (working on the far flange) while the other is pointed vertical (working on the web). Both operate identically since their tow path and process overall is completely unaffected by the variation in orientation.

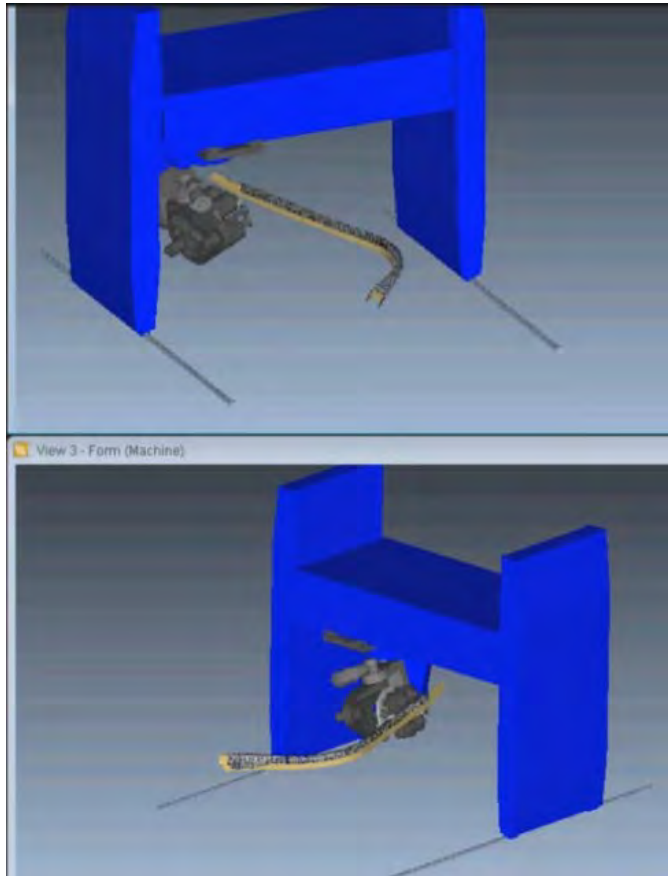


Figure 9 – 7 axis simultaneous gantry style machine on twisted spar on the far flange. +/-110 degrees about the part axis is required and possible with this machine configuration. It would be very difficult to manufacture this part by spinning it.

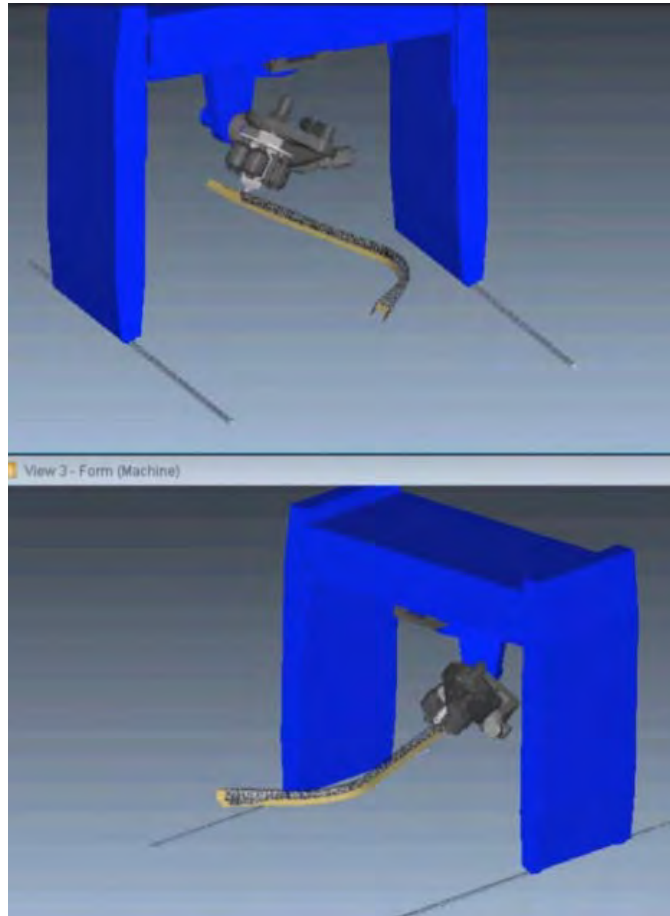


Figure 10 – 7 axis simultaneous gantry style machine on the twisted spar approaching the near flange.

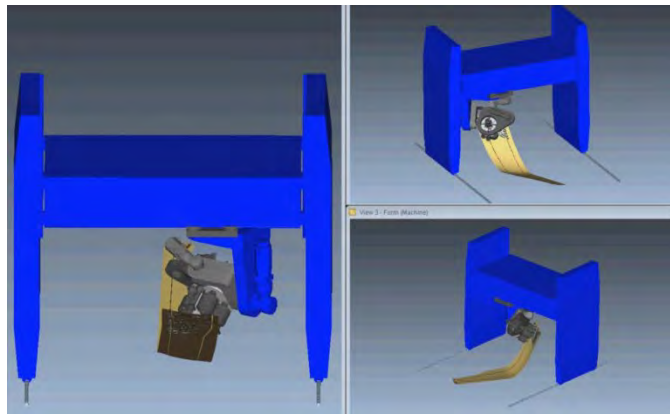


Figure 11 – 7 axis simultaneous gantry style machine demonstrating capability on a wide range of complex geometry.

MACHINE PERFORMANCE AND PATH CONTROL

When manufacturing these c-channel part families the machine performance becomes a critical factor in the producibility of the parts. An AFP machine can drive very fast on a straight and flat course. However, when the machine must articulate around corners, machine efficiencies require a reduction in toolpoint speed in order to maintain an accurate tool path. When a machine moves from the flange to web or from the web to flange on a 45 degree course, the position of the toolpoint must remain coordinated with the

orientation of the tool point. This is actually quite difficult to do when the desired traverse rate is high (>1000"/minute). A large, high performance gantry machine may have .2G available on its linear axes. The machine control must obey the following rule:

$$\text{DecelDist} = \frac{\text{FeedRate}^2}{2 * .2G}$$

Eq (1)

The following table illustrates this effect:

Table 1

Acceleration = .2G	
Linear Feedrate (inches/minute)	Decel Distance (inches)
100	0.02
500	0.45
1000	1.80
2000	7.20

For rotary axes:

Table 2

Acceleration = 300 deg/s	
Rotary Feedrate (degrees/sec)	Decel Distance (Degrees)
20	0.67
40	2.67
60	6.00
80	10.67

For a .2G machine, you can see in order to accurately follow a curved path, we will have to operate the machine at relatively low feedrates. The transition from a flange to web is a not only a curved path, but also a 90 degree change in orientation. However the flange and the web features are essentially flat, so it is desirable to operate at high feedrates during these phases of motion. It is important that the control can recognize transitions from straight motion to curved motion and then back to straight motion. A 6 degree of freedom look ahead control is necessary to ensure that the machine can accurately traverse the part geometry allowing the NC programmer to program high feedrates without worrying about the ability of the machine to follow path. The Electroimpact AFP machines have a custom CNC executive that is especially tailored to the challenges of the c-channel geometry. The NC programmer can program feedrates in the 1000"/min to 2000"/min feedrate without any quality issues related to machine path error. The control queries the part program by looking ahead and analyzes the part geometry. When a curve is detected, the machine automatically reduces speed to ensure that good path compliance will be achieved. Imagine a race car driver transitioning from a straight section through a 90 degree curve and then back onto a straight. To keep the car coordinated the driver must slow down to remain in tolerance (on the track is the tolerance). As soon as the car exits the curved region, he should accelerate to his top speed for the straight sections. This analogy is not exactly what the control does, but it is close enough to transmit the main idea of the look ahead control. The control scheme ensures that the velocity vector and path remain within constraints dictated by parameters. The control drives the machine at maximum performance to remain within tolerances specified. Even though deceleration distances are matters of inches and degrees for linear and rotary axes respectively, we actually are able to achieve feedrates and rotary axis rates of over 1000"/min and 60 degrees/sec while maintaining acceptable path geometry. Utilizing maximum machine performance is a key factor in achieving reasonable laydown rates.

ROTARY AXES CONFIGURATION

Finally we must consider the inter axis relationships that exist when a machine's toolpoint orientation is changed.

The geometric configuration of the rotary axes has a tremendous effect on the entire machine kinematics, overall machine performance and AFP lay-down rates. Electroimpact's modular head allows the rotary axes to be optimized to match the rest of the machine axes for smooth high speed operation. While the linear axes translate the tool point along the part surface, it is the rotary axes which combine to provide tool point orientation. The highest quality tow consolidation is achieved by maintaining the tow-compaction axis normal to the part surface. Ideally the axis of rotation for any given rotary axis will go through the tool point and therefore, only affect tool point orientation when moved. However, if the axis of rotation does not coincide with the tool point then a rotary axis move will also produce a tool point translation which must be compensated for by moving multiple linear axes.

The tool point translations, caused by a rotary axis not coinciding with the tool point, cause the linear axes to accelerate/decelerate in order to maintain tool point position on the part surface, and often times, reverse direction altogether. This is extremely difficult to do during high speed laydown rates as the linear axes are the largest axes, moving the most mass. Making these quick reversals requires larger drive components and adds extra wear and tear on the machine components such as bearing cars, rails, ball screws, rack and pinions and gearboxes.

Part geometry drives the machine envelope and the range of motion of the rotary axes. So it is rare for all the rotary axes to rotate about the tool point. When it is not possible for a rotary axis to pass through the tool point, every effort should be made to reduce the distance to the tool point and thus minimize the linear translations of the major machine. Furthermore, it is advantageous to choose the rotary axis which moves the least amount of machine mass to be the one not passing through the tool point. Electroimpact's modular head allows for this flexibility in rotary axis design.

SUMMARY/CONCLUSIONS

Machine geometry and modular head design combines to make the in-form, full length, scalable AFP production of composite spars a reality. This automation process is economical, reliable and repeatable and meets the criteria laid out earlier and displayed again below:

1. The part should be made as complete as possible. In the case of a spar, this eliminates joints which add weight.
2. The part designer should be able to refine the design to optimize for weight and other performance considerations. This means the process must be able to reliably and repeatedly generate complex path geometry, ply boundaries and path orientation.
3. Composite layups must have good consolidation over the entirety of the part..
4. The part has to be produced in a reasonable amount of time.

At the time of this writing, Electroimpact has been involved in prototyping several representative spar parts. The process is brought to bear on the part by manipulating the modular AFP head about the fixed, fully supported spar tool. In every case, this process proves to produce extremely high quality parts with high laydown rates, satisfying all of the listed desirable criteria.

Some of the key features of Electroimpact equipment that make this possible are 1) a compact-fixed AFP process that isn't affected by toolpoint orientation, 2) high-performance six axis path control, and 3) placing rotary axis pivots close to the toolpoint.

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CONTACT INFORMATION

Todd W. Rudberg
425-876-2583
toddr@electroimpact.com

Andrew Purvis
425-348-8090
andrewp@electroimpact.com

John Nancarrow
425-348-8090
john@electroimpact.com

Guy Faubion
425-348-8090
guyf@electroimpact.com

ACKNOWLEDGMENTS

Nearly every person in the Electroimpact AFP group has contributed in some way to the ideas and concepts presented in this paper. The AFP development was championed by a few, but the hard work of many have made it possible. Most importantly though, are the visionary first customers at Spirit Aerospace and Boeing who saw the benefits of the EI modular head and machine designs. Without these customers we would have never needed even think about these topics.

DEFINITIONS/ABBREVIATIONS

AFP	Automated Fiber Placement
ITV	Electronic Pneumatic Regulator
PID	Proportional-Integral-Derivative Controller
Tow	Resin impregnated carbon fiber slit to widths of 1/8", 1/4" & 1/2"

APPENDIX – EXAMPLE MODULAR HEAD MACHINE CONFIGURATIONS

Figure 11 through Figure 14 show different configurations of machines using the same type of modular AFP head.



Figure 12 - AFP Large Envelope Post Mill With Rotator (In Production - Wichita KS)

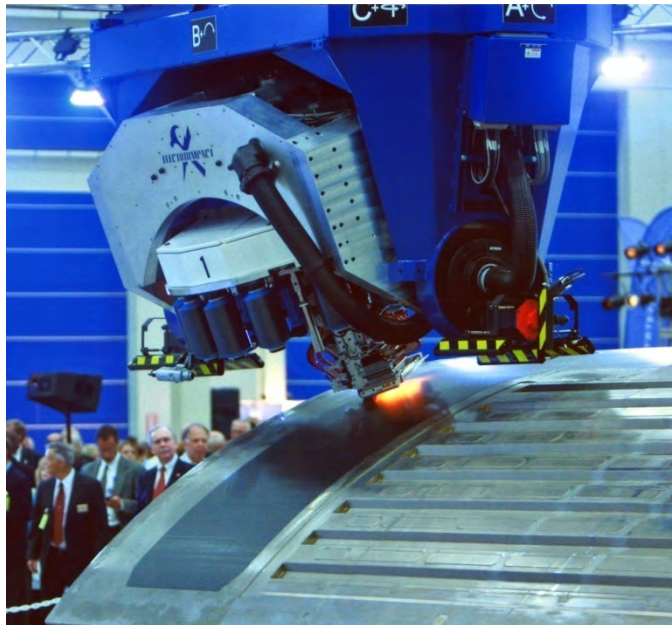


Figure 13 – AFP Gantry System (In Production - Kinston NC)



Figure 14 – AFP 7-axis Gantry System (In Production - Wichita KS)

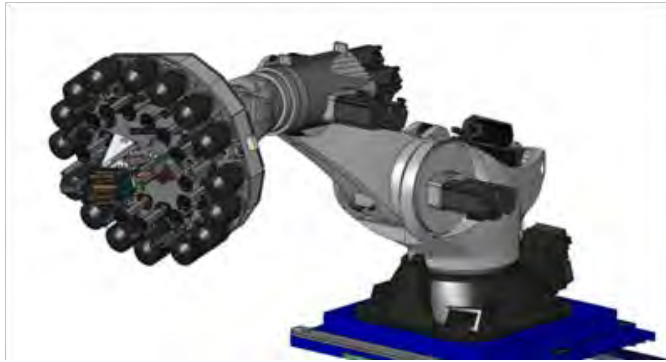


Figure 15 – Robotic AFP Cell (In Development - Mukilteo WA, Delivery Fall 2011)