

Automated layup of high-angle-range carbon composite parts with static tools.

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Abstract

Composite aircraft spars are currently manufactured by hand layup, or on large rotating tools of limited lengths. Computer simulation of layups of actual production parts shows that making these parts on fixed tooling requires a much larger angle range of the tow placement process on such parts when compared to layup on a rotating tool. Fixed tooling eliminates the length limitation of layup on rotating tools, permitting parts as long as the travel path of the Automatic Fiber Placement (AFP) machine. Testing with a high-angle-range fiber placement machine verifies the results of the simulation. Simulation shows a wider range of parts, such as stringers, fuselage frames, and winglets can also be produced with high-angle-range AFP machines.

Introduction

As the use of composite materials in aircrafts matures, design tools have become more sophisticated. Aircraft designers are now optimizing their geometry and layups, resulting in more complex parts. A decade ago, fairly straight simple C channel spars were the status quo. Now designers are starting to want composite spars having joggles, pads ups, and even some with curves and twists.

Automated Fiber Placement (AFP) machines, which lay bands of narrow carbon fiber tape or tow, (typically in the 1/2" to 1/8" range) have proven to be better suited for complex parts when compared to machines that lay wider tape, or to hand layup of carbon fiber sheets. However, many current AFP machines are still unable to manufacture some of these parts in their desired final state. This inability is due to the design of AFP machines, where the carbon fiber tow is stored on a series of spools and threaded through the machine to a tow laying head. The geometry of this threading limits the range of motion of the machine head.

Historically, these issues have resulted in two methods of addressing this inability. The first is manufacturing flat carbon fiber layups that require a secondary shaping operation. The second is redesigning parts to be manufactured within the limitations of the fiber placement machines. These methods often result in the reduction of the consistency of tow layup or needing more massive final parts.

In this paper we discuss some current methods of producing carbon fiber composite parts and their limitations and drawbacks for producing these complex parts. We will then analyze some actual high complexity parts via validated computer simulation. This will demonstrate that the angle-range that the tow layup head is capable of determines the range of parts it can fabricate in final form and that high ranges are necessary for many parts. Finally we will discuss how modular head AFP machines are well suited to

manufacture high angle range parts, and that they work well with a wide range of machine geometries specialized for a given part.

Body

Carbon Fiber Layup and Angle Range

Testing and production of carbon fiber panels and parts has demonstrated that the normality of an AFP head is critical to ensure high quality layup. Being normal to a surface enables adequate compaction, no wrinkles, and accurate placement of carbon fiber tows with controlled spacing. This means that the possible layup geometry of carbon fiber parts is strictly limited by the geometry of the AFP machine.

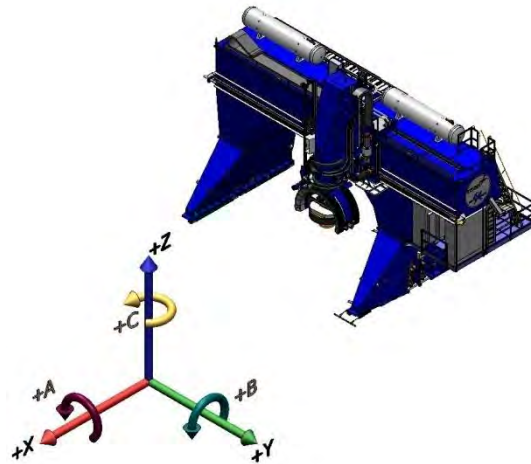


FIGURE 1 - AXIS DEFINITION

In general, an AFP machine's layup range will be defined by the travel range of its head in 3 linear axis (X, Y, and Z), 3 rotary axis (A, B, and C, around X, Y, and Z respectively) as depicted in Figure 1, and optionally, a tool rotary axis U (typically also around X). X, Y, and Z determine location, A and B determine normality, and C determines the direction of the tow being laid.



FIGURE 2 – EXAMPLE OF TYPICAL AFP MACHINE WITH MULTIPLE REDIRECTS SHOWN AT POINTS 1 AND 2 LIMITING ANGULAR MOTION

In a common large creel-house AFP machine, changes in the angle of the head cause changes in the path of the tow from the creel to the head. As illustrated in Figure 2, the tow passes over multiple redirects as it is routed through the machine (see point #1 and #2 in figure). This results in machines designed for maximum angle ranges of +/- 45

degrees in A and +/- 45 degrees in B. In addition, many of these machines are best operated in even smaller angle ranges as the change in angle, and the resulting changes in the tow paths result in tow jumping off redirects, tow twists, and splice failures.

Current Carbon Fiber Production Methods

In light of the limitations of the typical AFP machine, manufacturing methods must be based on operating within a limited angle range.

Airplane wing spars, long C shaped channels, are a common example of large and complex carbon fiber parts. One of the main manufacturing methods used to produce them is the hot drape forming process. In this process, a flat charge of tow, tape, or cloth is laid up, and then formed into its final shape. To enable this forming, less heat and pressure can be applied to the charge than to a final shape layup, permitting the layers to shift and slip against each other during the forming process. This may result in problems with material consolidation, wrinkles, and voids. Additionally, draping only works for spar designs which can be flattened by bending.

Some wing spars are manufactured in their final shape via the AFP process, but due to the limited angle range of their tow laying heads, they must utilize rotating tooling. Mounting the tooling on a rotator permits a lower angle range head to access all three sides of a C shaped spar. This, however, is limited to only the range of parts where the tooling is suitable to mount on a rotator. Thus the part must be substantially straight and the part is limited in length to the length of tooling that can be suspended between a pair of rotators. To make these parts practical, they must be divided into smaller parts, and joined post-layup, requiring extra mass for attachment points, and extra time and materials to assemble the joints.

Angle Range Requirements of Sample High Complexity Parts

AFP simulation software permits engineers to generate tow paths to form desired parts, and to verify all machine motion during the layup process. Internal Electroimpact testing has validated that the simulation software used, Vericut by CGTech, to be an accurate model of machine motion and layup through comparing simulation results to actual part builds. Using the Vericut software, various machine configurations can be quickly constructed and iterated to simulate AFP layup on highly contoured parts such as spars and frames (A 3 sided part with bends along the length, shown in Figure 3).

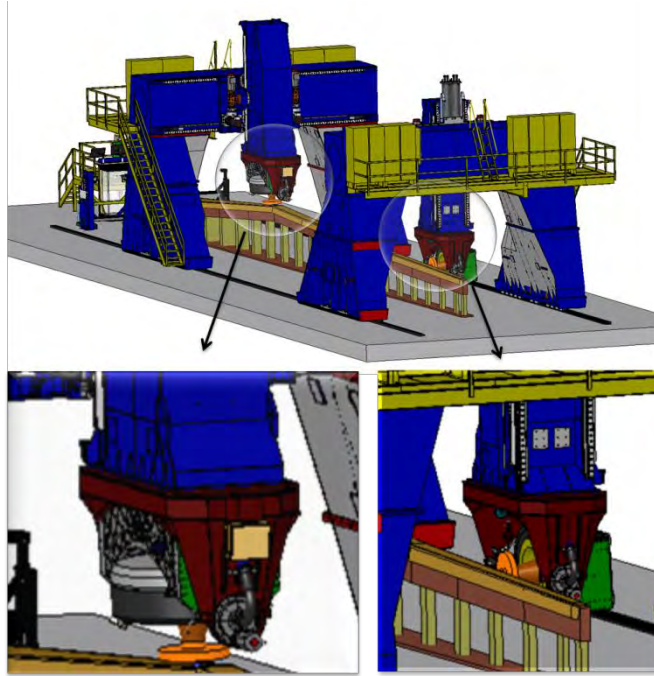


FIGURE 3 - TWO ELECTROIMPACT AFP MACHINES ON A 90' ONE PIECE SPAR. NOTE THAT ONE AFP HEAD IS POINTED HORIZONTAL (WORKING ON THE FAR FLANGE) WHILE THE OTHER IS POINTED VERTICAL (WORKING ON THE WEB). BOTH OPERATE IDENTICALLY SINCE THEIR TOW PATH AND PROCESS OVERALL IS COMPLETELY UNAFFECTED BY THE VARIATION IN ORIENTATION.

C-shaped spar parts require layup on three sides, the flange, web, and flange. As expected, simulation and trial layup verify that a machine needs to achieve at least +/- 90 degrees of A-Axis travel around the simplest spars while the tool is fixed. The spar length no longer needs to be a design limitation as the tool is supported as needed along the length. Electroimpact built AFP machines have successfully manufactured similar fixed spar layups. As bends or changing cross sections are introduced along the length, as with frame manufacturing, greater machine travel is necessary.

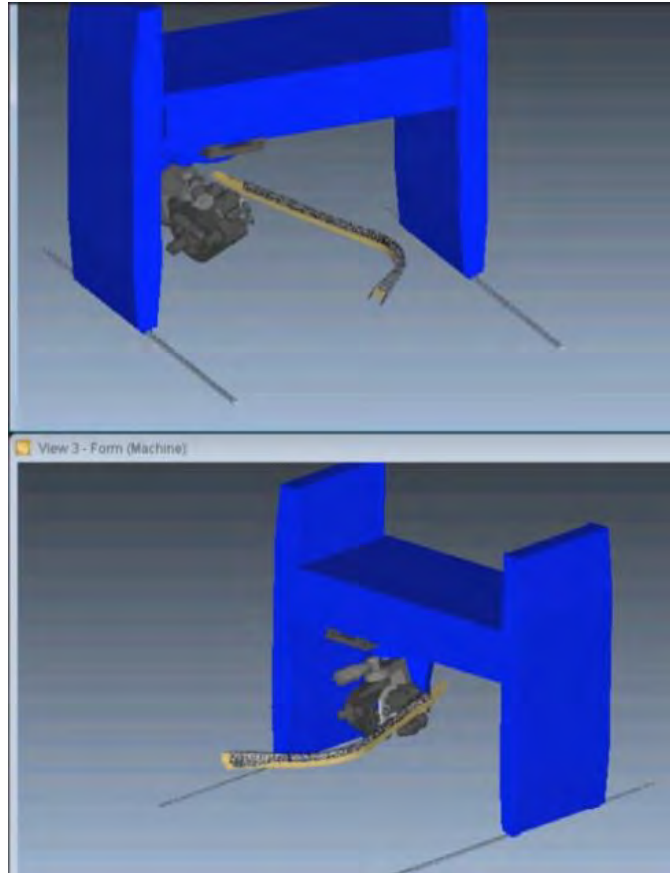


FIGURE 4 – 7 AXIS SIMULTANEOUS GANTRY STYLE MACHINE ON CURVED-TWISTED SPAR.

Figure 4 shows a layup of a complex spar part under a suitable Electroimpact AFP machine. This part requires ± 110 degrees of motion about the axis of the part (A-Axis) and ± 45 degrees of motion about the vertical axis (B-Axis). The complex geometry makes this spar incredibly difficult to manufacture by spinning the tool. With a fixed tool, an over part gantry style machine is preferred for layup as long as the AFP head and creel are sufficiently small enough. This enables machine clearance on all sides of the spar without becoming excessively wide and consequently massive. The rotating mass of the machine becomes increasingly critical on higher contoured parts where more rotational motion is necessary per course. A lighter, faster machine is necessary to place carbon fiber around spars and spars at a higher rate than their traditional manufacturing methods. A simpler aircraft component family not shown is door frames. This family of parts requires similar axis ranges as the curved-twisted spar shown above.

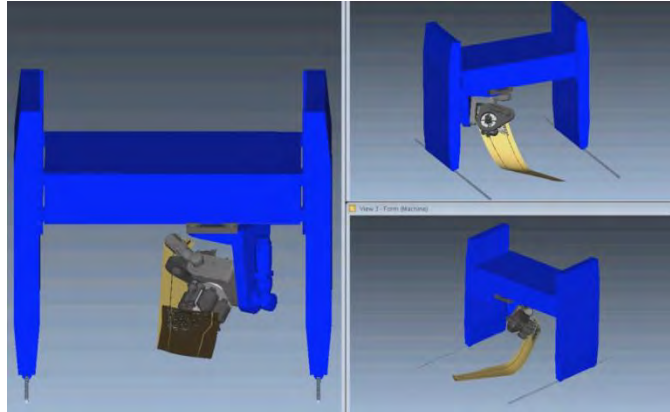


FIGURE 5 - 7 AXIS SIMULTANEOUS GANTRY STYLE MACHINE DEMONSTRATING CAPABILITY ON A WIDE RANGE OF COMPLEX GEOMETRY

A SIMILAR STYLE OF MACHINE WITH LARGE ANGULAR CAPABILITY IS ALSO NEEDED FOR CONCAVE PARTS AS SHOWN IN - 7 AXIS SIMULTANEOUS GANTRY STYLE MACHINE DEMONSTRATING CAPABILITY ON A WIDE RANGE OF COMPLEX GEOMETRY

The winglet shown requires nearly +/-45 degrees of motion perpendicular to the length (A-Axis). It also involves significant motion to maintain normality through any steps along the length of the part. Concave parts can require a high angular range while still maintaining part clearance between the machine and tool. Simulation of the winglet part build shows the Electroimpact machine is configuration capable of building such a contoured part. A benefit having a higher angle range in a machine than the part requires is that it reduces the need to optimize the tooling for the part position while doing layup. The extra angle range permits rotationally offsetting the tooling position, which may simplify handling, inspection, or other production steps.

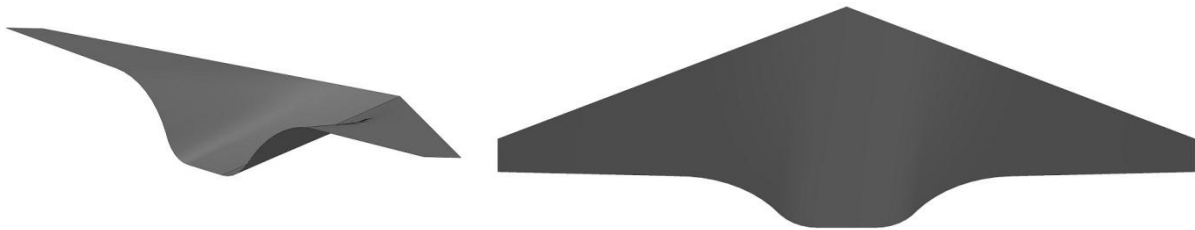


FIGURE 6 - HYPOTHETICAL MONO-BODY FLYING VEHICLE

Other complex parts also benefit from wide angle range capability. Examining a proposed mono-body for a smaller flying vehicle(Figure 6) shows a requirement for slightly over +/- 50 degrees of B. While it may be possible to redesign the part due to the limits of some AFP machines, having the option to not do so lets the designers of this part focus on its performance requirements.

To summarize the per-axis angle range requirements (all axis ranges in degrees):

Part	A-Axis	B-Axis	C-Axis
Straight Spar	+90/-90	+0/0	+180/-180
Bent Spar	+105/-122	+45/-40	+180/-180
Winglet/Sharklet	+62/-22	+8/-22	+180/-180
Mono-wing	0/-35	+50/-52	+180/-180

Note that the +180/-180 degree angle range requirement is for instantaneous tool position. It does not ensure continuous layup or full bi-directional layup of any tow can be done within that angle range. That level of performance may require a wider angle range, which would still be a subset of the 360 degree continuous angle range that modular head AFP technology provides.

Modular head AFP

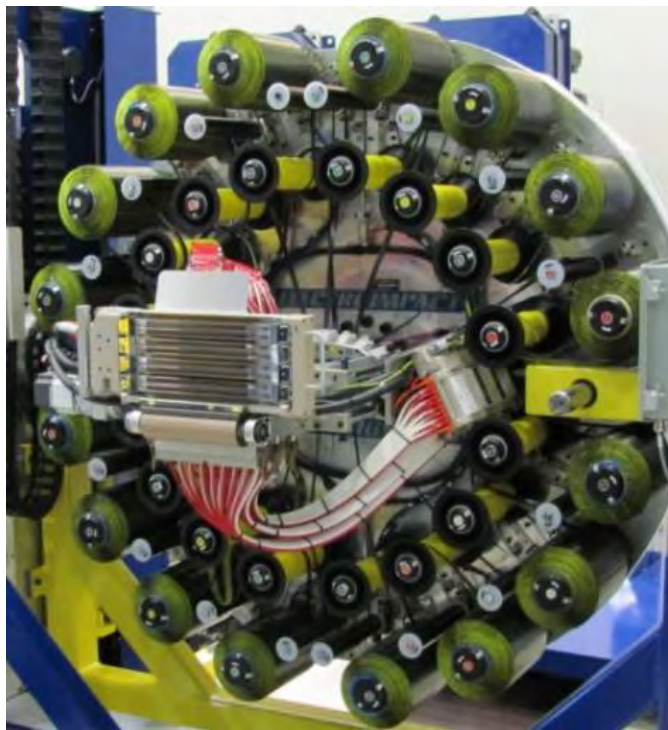


FIGURE 7 - ELECTROIMPACT MODULAR AFP HEAD IN TOOL CHANGING STAND

In a modular head (Figure 7 & Figure 8) AFP machine [1] the creel unit is integrated with the layup head. This means the tow path does not need to adjust itself to the X, Y, Z, A, B, & C axis motions of the machine. Additionally, and equally important, the axes are not limited a need to accommodate the tow paths. This means that, given an orientation independent head design [2], only the machine actuation and performance issues act as limits to the motion of the head.

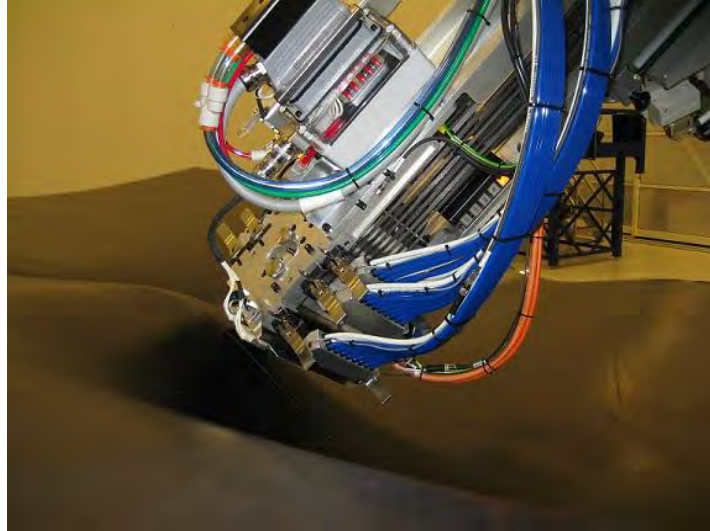


FIGURE 8 - ELECTROIMPACT MODULAR AFP HEAD BUILDING A HIGHLY CONTOURED PART

This also decouples the design of the head from the design of the machine, making possible a wide range of machine designs possible while retaining tested and refined head design.

Additional benefits of modular heads and high angle range machines

The primary additional benefit to modular heads is, by attaching a tool-change interface to the back of the tape head module, that module can be replaced by a different head. This means that, with two identical heads, spools can be replaced offline without interrupting production. Also, this design enables easy variation on the head tool. This permits different heads with different sized tows laying up on the same part without additional setups, as well as other specialized heads. Moreover, the same heads can be used by and moved between different machines.

From a machine design perspective, the modular nature of the head also enables more options for machine kinematics for the A, B, and C axis. In particular, this enables a design that moves the center of rotation of the A and B axis to near the tool point of the head. The center of rotation being near the tool point results in reductions of required X, Y, and Z motion as the head moves around the angle of a part, and may result in higher accelerations and speeds when laying up over these angles. Note that C shaped spars are extended sections with angles, and as such, rotating around angles will be a frequent occurrence in the layup of such parts.

By combining modular heads with tool point based programming [3], part production can be easily moved between machines, even machines with different geometries. If all machines have the volume and the angle range for a required part, then any machine can produce said part.

Conclusions

Modular AFP heads enable and simplify the design of tow laying machines with high angular ranges in their rotary axis. AFP machines with high angular range rotary axis enable or simplify the manufacturing of large and complex aviation parts such as spars and winglets.

By using computer simulation, machine design can be optimized to ensure that a given AFP machine can handle or exceed the angle requirements of a given part.

By maximizing the angle range of a machine, an option is kept open for the widest possible range of parts to be made in the future.

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2. *One Piece AFP Spar Manufacture*. Todd Rudberg, Guy Faubion, John Nancarrow, Andrew Purvis, 2011 SAE International, Paper No. 2011-01-2592
3. *Automated Fiber Placement Machine Developments: Modular Heads, Tool Point Programming and Volumetric Compensation Bring New Flexibility in a Scalable AFP Cell*. Rob Flynn, Todd Rudberg, Justin Stamen, SME, 2011 Composites Manufacturing Conference

Commercial References:

VERICUT Composite Programming and Simulation Suite is a product of CGTech

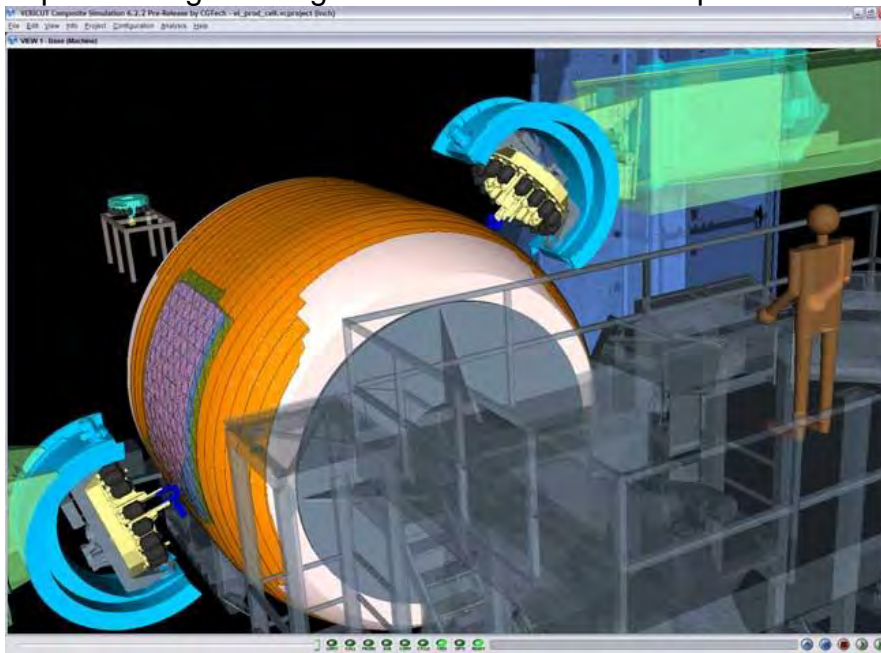


FIGURE 9 - CG TECH SIMULATION OF 2 MACHINE AFP CELL WITH ROTATOR