

Unique Non-Orthogonal TCP Intersecting AFP Axes Design

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ABSTRACT

Automated Fiber Placement (AFP) machines typically consist of 3 linear and 3 rotary axes of motion in order to manufacture complex shapes. These axes are generally orthogonal and semi-coupled. In these designs, a linear axis move will not affect the rotary axes orientation whereas a rotary axis move will affect the Tool Center Point (TCP) location with respect to the linear axes position. The wide range of motion required to maintain the compaction-axis normality needed for carbon fiber layup tends to prevent all of the rotational axes from passing through the TCP. The location and arrangement of these rotational axes has a great effect on the AFP machine performance and controllability during high speed layup. This paper presents a unique kinematic AFP axes design consisting of replacing the 3 orthogonal rotary axes with 3 tool-center-point-intersecting coupled-axes which decouple the linear axes from the rotary axes.

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INTRODUCTION

Automated Fiber Placement (AFP) machines accurately place composite fiber where structural designers need it and in the orientation required. They produce high quality tow consolidation while achieving high lay-down rates. Therefore, aerospace manufacturers have increasingly used AFP machines to produce larger and more complex structures. However, these large structures require large machine working envelopes with wide ranges of angular motion. This pushes the AFP machines to be larger, more complex and consequently more costly. Furthermore, larger machines become more difficult to control during high-speed complex motion. Their sheer mass limits the available accelerations needed to change axis positions in the time required to stay on path. In order to produce high quality parts AFP machines must maintain strict adherence to the programmed path of the Tool Center Point (TCP) as well as keeping the compaction axis orientation normal to the part surface. Machine stiffness and natural frequency along with mechanical backlash in drive systems and mechanical error during manufacture all contribute to the final machine accuracy. Controlling the effects of these parameters during high-speed layup is not difficult on flat or low contour parts. However, it can be quite challenging on high-contour parts. The kinematic design of these machines also has a significant effect on their controllability at high speeds. A good kinematic design makes smooth high-speed on-part motion

possible and, to some degree, reduces the size and cost of the AFP machine for a given angular range.

TRADITIONAL AFP KINEMATICS

Traditional AFP kinematic arrangements have the compaction roller attached to 3 rotary axes (ABC) allowing for any angle to be achieved within the required range of motion. The C-axis provides tow steering while A and B account for compaction axis orientation. These rotary axes are then attached to 3 linear axes, which translate the compaction roller throughout the working envelope. The standard naming convention is to have the ABC axes rotate about XYZ respectively. See [figure 1](#).

The compaction roller is where the carbon fiber is applied to the part surface and is considered the TCP. As the compaction axis orientation-angle range is increased it becomes more and more difficult to pass the rotary axes through the TCP. When the rotary axes do not pass through the TCP they cause a translation of the TCP when they are rotated. This translation occurs regardless of whether the axis of rotation is ahead of or behind the TCP and must be compensated for by moving one or more of the linear axes. This requires the machine to sweep out a larger envelope than the specified working envelope of the TCP. See [figure 2](#). The additional travel increases the machine cost and mass. When maximizing machine stiffness, speed and acceleration, the worst possible place to add mass is out near the tool point. Each axis in the kinematic chain must support all the subsequent axes and corresponding masses between it and the

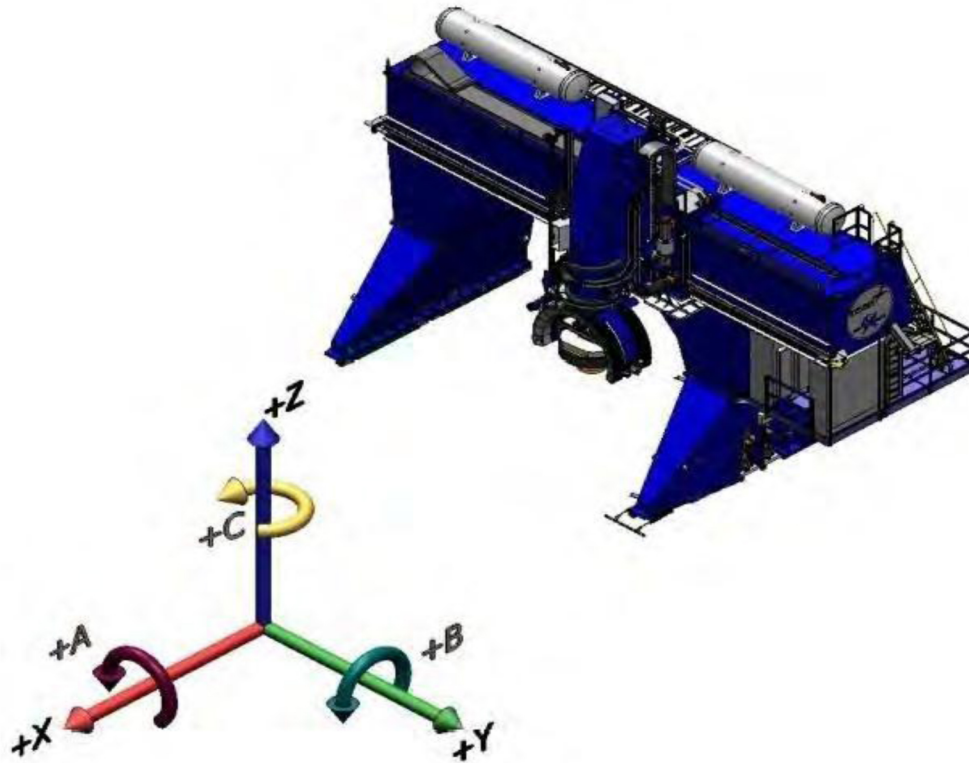


Figure 1. Axis naming convention.

tool point. Therefore, any increase in travel of an axis adds mass, increases cantilevers, increases moment loads and requires all supporting structures and axis drive systems between that axis and the foundation to increase accordingly. Hence, the cost of the machine increases while the overall machine controllability decreases.

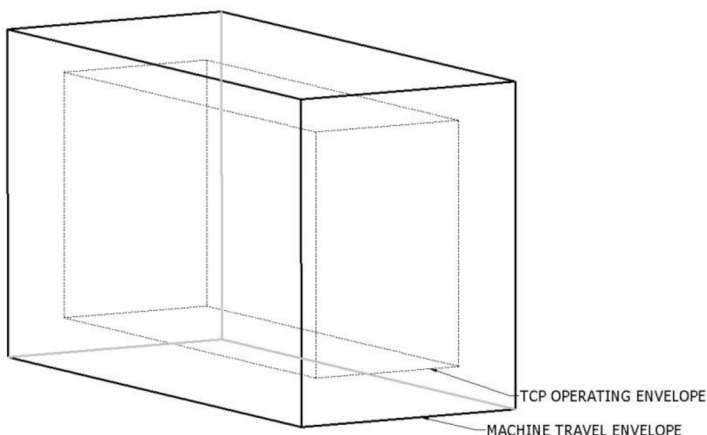


Figure 2. Machine envelope vs. Working envelope.

An even more critical component of machine controllability is the kinematics required to keep the compaction roller on path and normal to the part surface. When the rotary axes do not coincide with the TCP the machine will be required to reverse directions as it traverses

various part contours. For example: Let's look at a typical part surface ramp with a single rotary axis necessary for normality. See [Figure 3](#)

In this example the rotary axis center of rotation is 39.4" (1m) behind the TCP. (A reasonable distance for traditional AFP machines.) The part surface has a 6° ramp with an approximate 6-inch lead-in radius. The machine is traveling in the positive X-direction and as you can see from [Fig. 3](#) there is 0.6" of X-travel from point A to point B for the compaction axis to adjust from vertical to 6° degrees. However, a 6° counterclockwise rotation of the rotary axis will push the compaction axis 4.1" in the positive X-direction.

$$39.4 \cdot \sin 6^\circ = 4.1''$$

Therefore, the machine must travel in the negative X-direction in order to keep the compaction roller on the part path from A to B. At some point during this reversal in travel direction the machine velocity obviously falls to zero. [Figure 4](#) shows the velocity curve of the machine using the previous example traveling at 1000"/min. with 0.2g available acceleration. The first part of the graph shows the machine decelerating to a stop as the compaction roller reaches point A. Then it accelerates in the opposite direction (negative X) until it must decelerate to another stop once the compaction roller has reached point B. Finally it accelerates in the positive X-direction up the ramp. AFP machines can lay down tow at upwards of 2000"/min, which would make this graph even more pronounced. This unsmooth machine

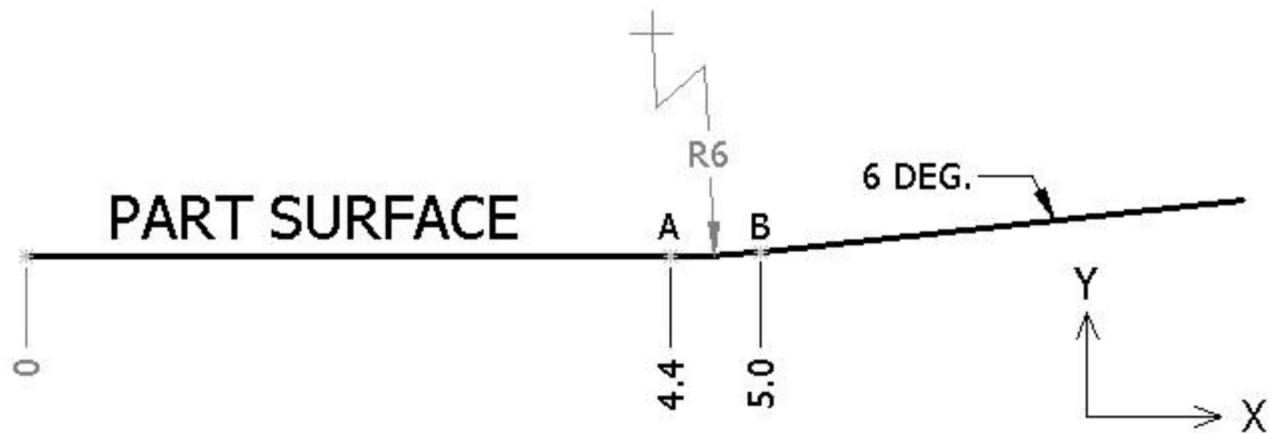


Figure 3. Small 6-degree ramp on part surface.

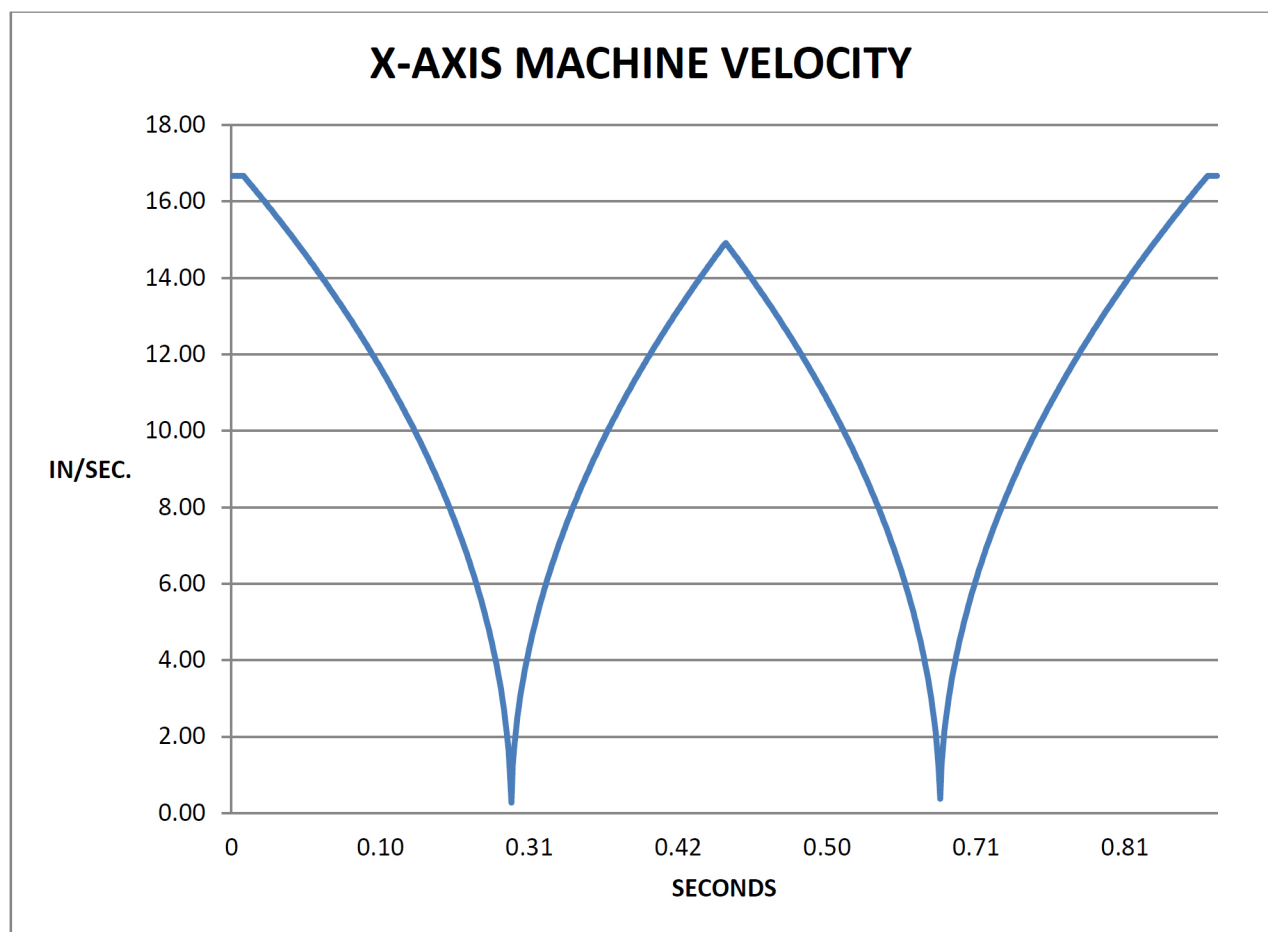


Figure 4. Machine velocity along the X-axis.

motion slows down the entire process in order for the individual machine axes to have enough time to complete their moves without inducing excessive machine vibrations while doing so. Excessive vibrations and unsmooth machine motion leads to inaccurate tow placement, puckers and in extreme cases, broken tows. More often than not the part

contours require a full 6-axis machine move in order to maintain compaction axis normality. This demonstrates how the linear axes are coupled to the rotary axes whenever their rotational centers do not coincide with the TCP.