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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 shear 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

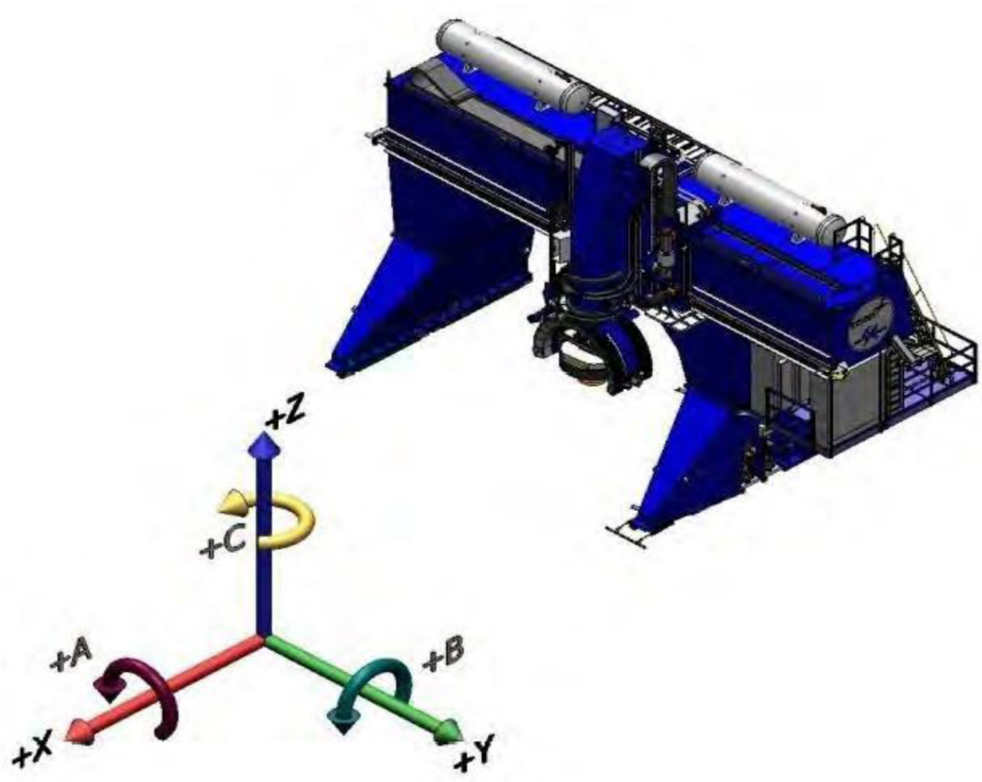


Figure 1. Axis naming convention.

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.

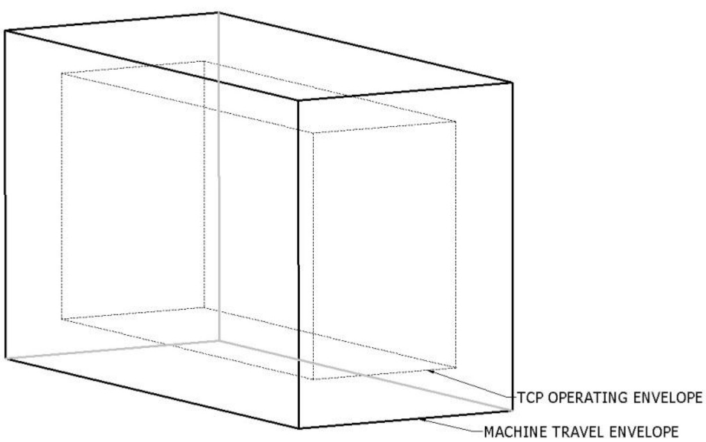


Figure 2. Machine envelope vs. Working envelope.

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.

$$39.4*\sin 6° = 4.1”$$

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

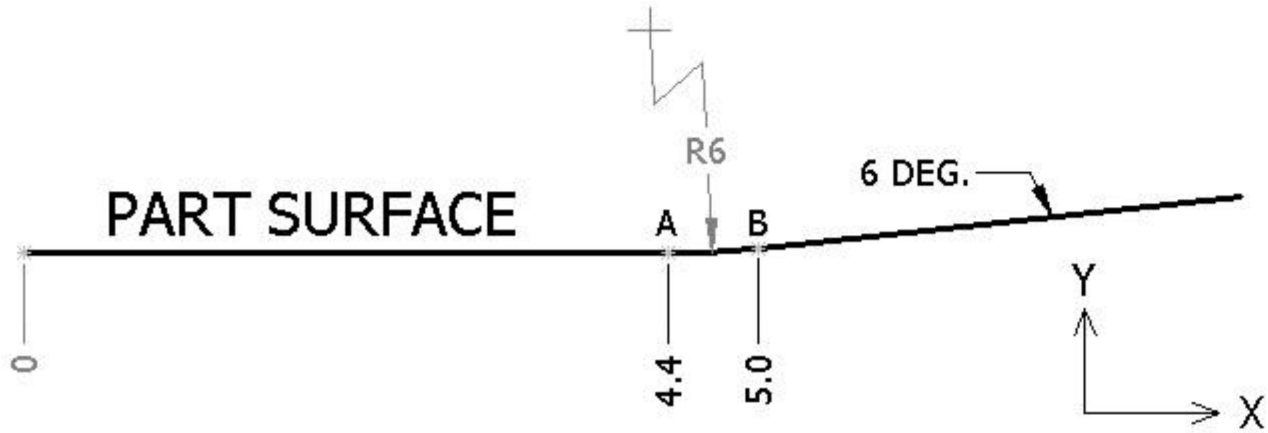


Figure 3. Small 6-degree ramp on part surface.

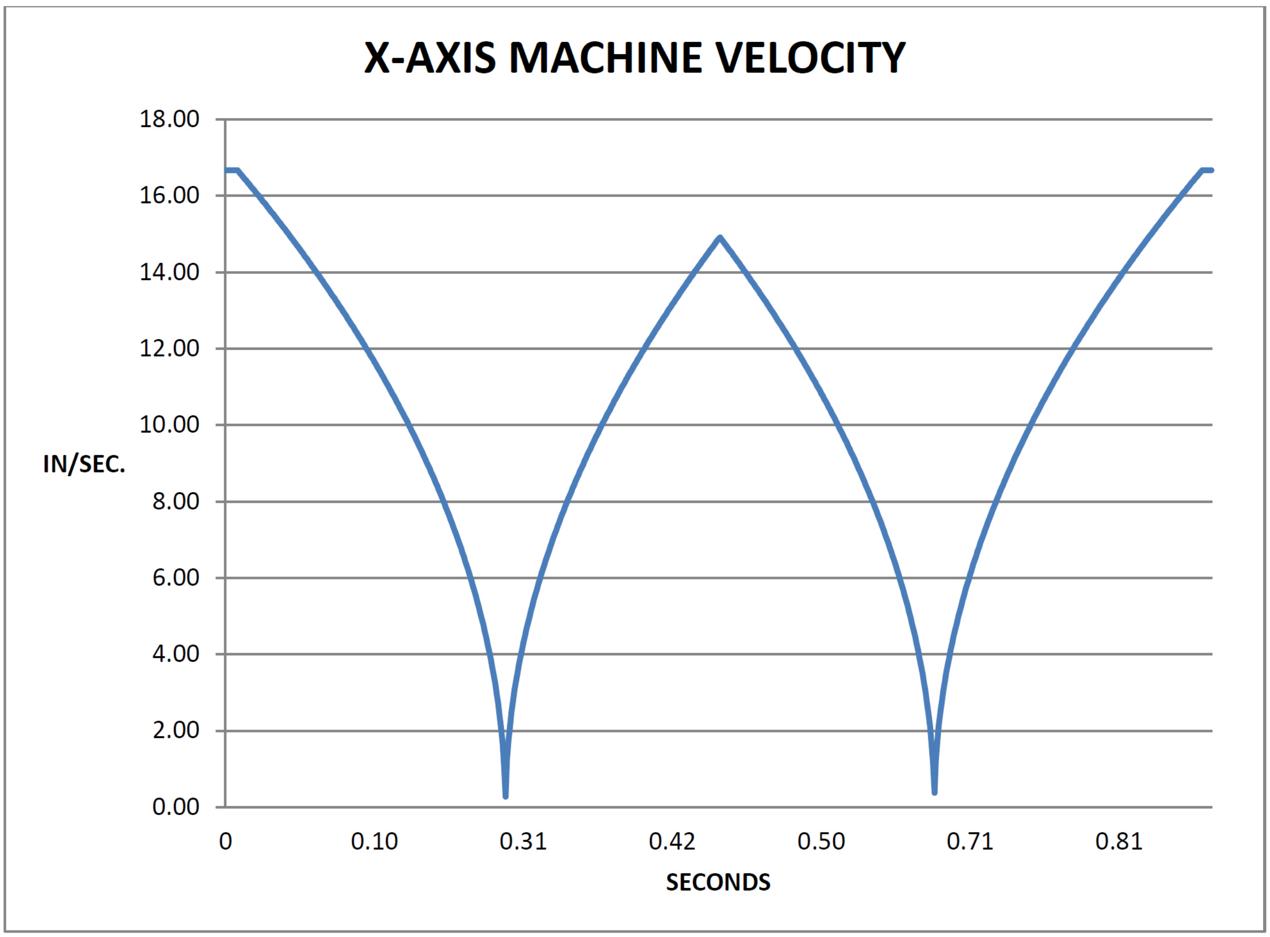


Figure 4. Machine velocity along the X-axis.

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.

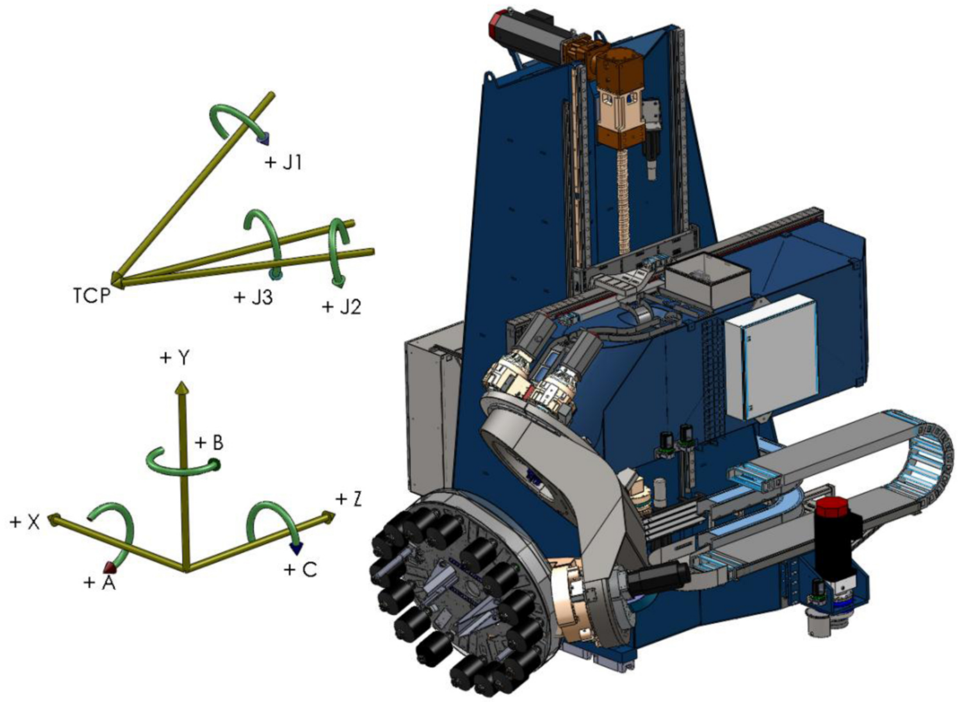


Figure 5. Naming convention for non-orthogonal axes.

NEW MACHINE AXIS ARRANGEMENT

The new design consists of 3 coupled non-orthogonal rotary axes which all pass through the TPC. See figure 5. In order to differentiate these axes from the standard orthogonal axes we named them J1 J2 and J3. Manipulating any or all of these rotary axes will only change the steering direction and/or compaction axis angle while having zero effect on the TPC location. Therefore, the linear XYZ axes do not have to move during a rotational axis change. As was mentioned earlier, it is very desirable for the linear axes to be decoupled from the rotary axes for smooth machine kinematics. With this arrangement, the lay down rate can remain high over high-contour surfaces because the linear axes never reverse direction during a change in compaction axis normality.

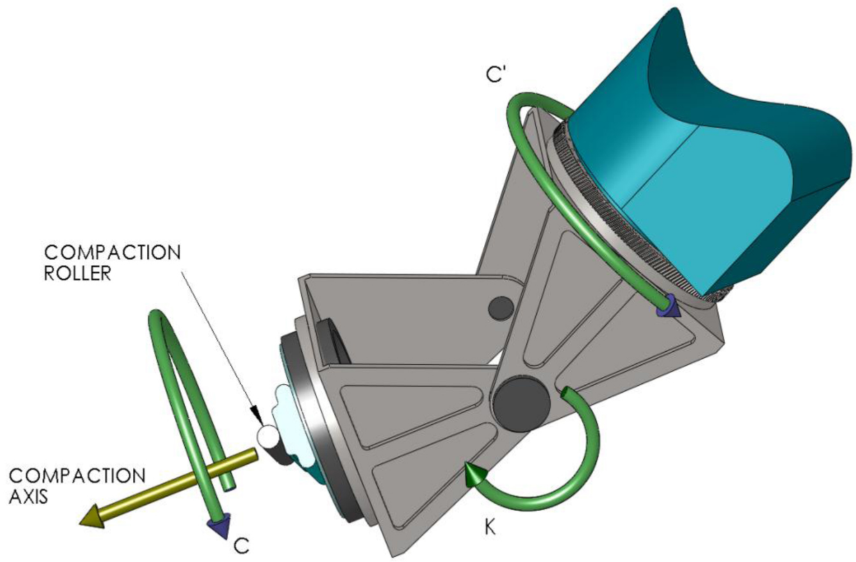
The rotary axes linkage of this machine was designed to attain any angle between +/−20° of true "A" rotation and +/−45° of true "B" rotation per our customer's requirements. The individual angles of this linkage were also designed to minimize the speed-up effect caused by non-orthogonal axes. In a traditional orthogonal configuration there is a one-to-one relationship between an axis rotation and the corresponding change in the compaction axis angle. However, with this arrangement a one degree rotation in the compaction axis angle requires each of the J1, J2, J3 axes to rotate more than one degree. Hence, their rotational angles are changing faster than the compaction axis angle is changing. This speed ratio varies throughout the angular range of motion as well as changing with different individual fixed linkage angles.

Another consideration in the design of this linkage was the mass and stiffness of each member. Electroimpact uses a compact fully contained process head on their AFP machines. Its physical size, mass and tool point distance are known. The individual linkage angles were designed around this process head in order to maintain part clearance while minimizing the size of each member. By minimizing their size, their mass was reduced while still achieving the necessary stiffness. In fact, each and every component (brackets, wire-ways, housings, etc.) was analyzed and designed to reduce the moving mass. For example, the manufacturer's stock gearbox housing for the J2 joint would have been a significant percentage of the linkage's rotational mass. Therefore, the housing was redesigned and 70% of its mass was removed. Furthermore, the angles of this linkage design shifted the combined moving-mass as far back as possible toward the machine foundation for reasons stated earlier.

Kinematic Singularity

The designed linkage angles were chosen so as to remove the J1-J3-axes singularity from the working range of motion. A singularity prevents stable machine motion at high speeds and occurs when the axes align and become identical. To explore this further we look at a kinematic arrangement being used on some current AFP machines. See figure 6. For this discussion the axes are named C'KC with the K-axis perpendicular to both C and C' and acting similar to a knee joint.

First we define C'=0° when the K-axis is parallel to the X-axis so that a rotation of the K-axis will change the A-angle



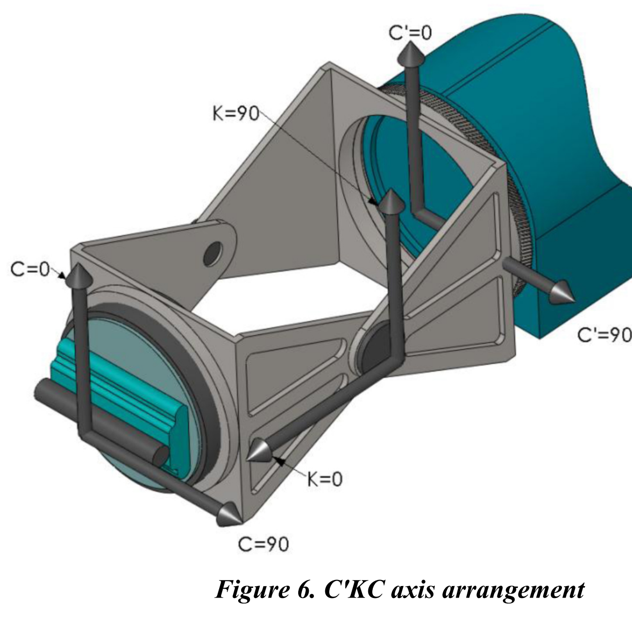


Figure 6. C'KC axis arrangement

of the compaction-axis. When C'=90° the K-axis is parallel to the Y-axis so that a rotation of the K-axis will change the B angle of the compaction-axis. Now we start with C'=0°, K=0° and C=0°. At this point the K axis is parallel with the X-axis and any angle of A can be achieved simply by rotating K. It is important to notice that the compaction axis can never have

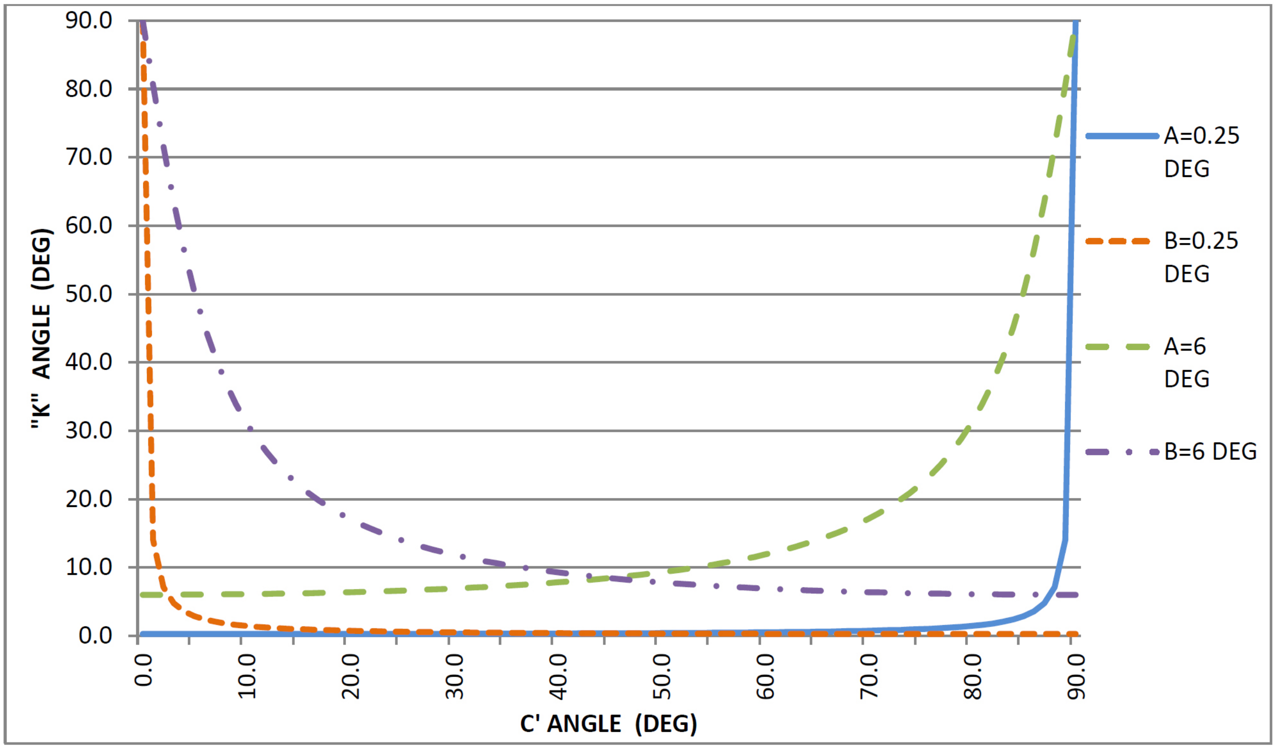


Figure 7. K and C' angles for constant A and B axis angles.

any "B" angle besides zero while C'=0°. Of course, with C' rotated 90° "A" will equal zero throughout the full range of "B" angles. However, when the knee axis is not parallel to either the X or Y axes then both the "A" and "B" angles will change as the K-axis rotates. Coordinating the C' and K axes will allow for any combination of A and B angles necessary for compaction axis normality which makes this arrangement seem attractive.

The problem with this kinematic arrangement arises when the CNC tries to keep the compaction axis normal to the changing contours of the part surface while laying down tow. Here, we examine the angles of each of the C' and K axes as the part surface requires the compaction axis to change from an angular orientation of (A=0.25°, B=0°) to (A=0°, B=0.25°) while maintaining the steering axis "C" at C=0°. This would be, for instance, like a very small bump on the part surface. In order to have compaction axis angles of A=0.25° and B=0° the machine must have C'=0°, K=0.25° and C=0°. In order to then change the compaction axis orientation to A=0°, B=0.25° requires C' to rotate until it reaches 90° and "C" to counter-rotate 90° to maintain the same steering direction. The CNC will command this move, but the machine has no possible chance of manipulating the axes in the time required. Figure 7 shows the K and C' angles for constant A and B compaction axis angles of 0.25° and 6°. From this graph it can be seen how decreasing angles of A and B increase the rotational travel of C' in order to achieve compaction axis normality. Keep in mind, the steering axis C must always counter-rotate equal to C' so as to prevent a change in tow path direction. This is why a singularity prevents smooth high speed machine kinematics.

Backlash

The new kinematic J1-J2-J3 axes arrangement presented here has another benefit in that it essentially removes any errors caused by backlash. All gearboxes have backlash as well as torsional windup which combine to produce machine error. 1arc-min (.017°) is a fairly standard amount of backlash for gearboxes used on AFP machines. Therefore, the backlash of a gearbox-driven axis located 1m (39.4″) behind the TPC will contribute .3mm (.012″) of error in the location of the TCP of the machine.

$$1000mm * \sin(.017) = .3mm$$

Since all the rotary axes of this linkage pass through the TCP there is no TCP positional error caused by backlash in the joints. There is, however, a compaction axis orientation error as well as a steering axis error. Earlier we described the speed-up effect of this axis arrangement. This speed-up effect now works in our favor to reduce compaction-axis orientation errors due to backlash. If a particular axis is in a position where the ratio of axis-rotation to compaction-axis orientation is e.g. 2:1, then for that same manipulation the backlash effect on the compaction-axis is reduced by 1/2.

Now let's look at the backlash error on the steering axis. In terms of angular tow path direction the 1arc-min of error is more than an order of magnitude smaller than even the strictest aerospace manufacturer's AFP specification. Next, we look at the tow-placement error caused by backlash. The

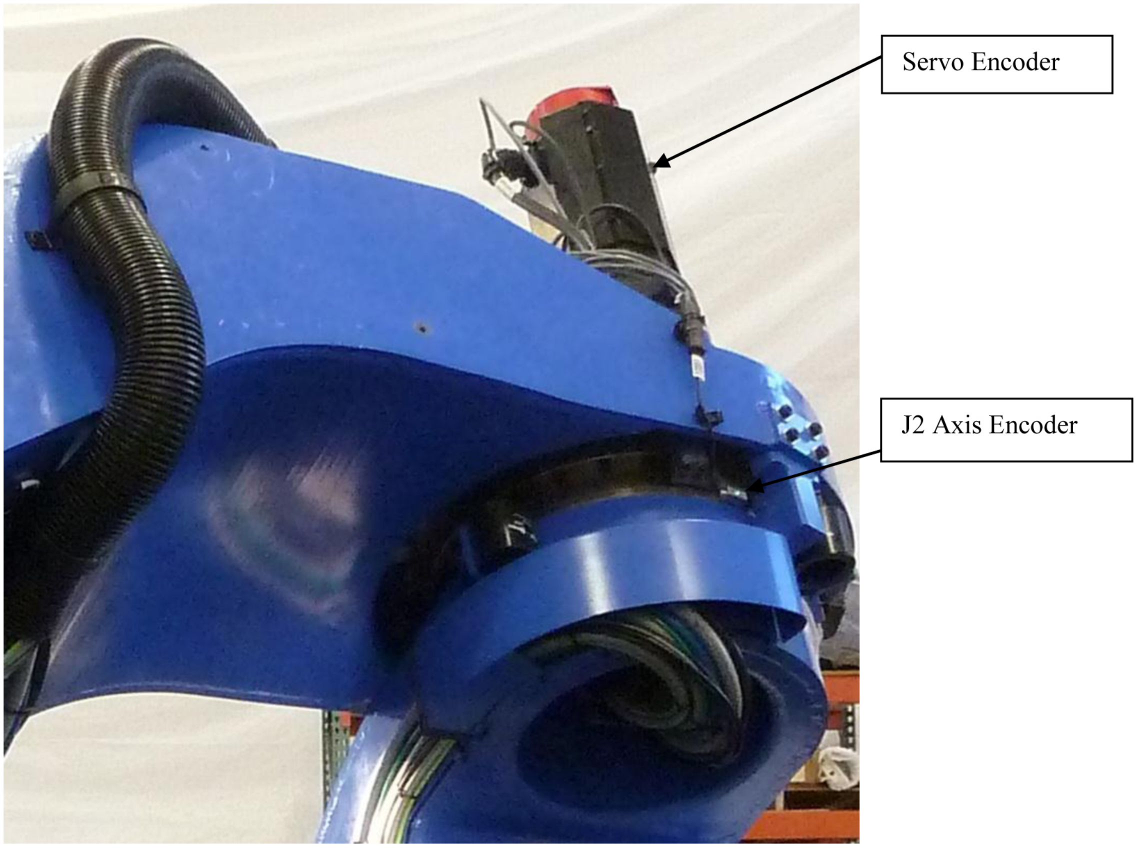


Figure 8. Servo encoder and axis encoder locations.

modular AFP heads Electroimpact manufactures can lay down 16 strips of ⅛, ¼ or ½ inch tow. The rotational backlash will have the greatest effect on the widest band; 16 half-inch tows for a width of 8″. Since the steering axis coincides with the center of the band of tow, the furthest edge of tow is 4″ from the axis. The positional error of the fiber placement is then:

$$4'' * \sin(.017) = .001''$$

This error is also more than an order of magnitude less than any AFP specification for fiber placement.

Similar to backlash is gearbox windup. The gearbox windup or torsional-rigidity is a measure of how far the gearbox output will rotate per unit of applied torque while the input is held fixed. It has the same effect on the axis error as backlash. The difference is the amount of error from the torsional stiffness changes as the applied torque changes. Applied torque to the axis comes from a variety of sources. Compaction axis forces, which are necessary to bond the composite fibers to the mold, commanded axis accelerations, position of the linkage center of gravity relative to the joint-axis and accelerations of other axes all vary during laydown and combine to make up the total torque on the axis joint. It is not uncommon to keep track of the joint-axis position with an encoder attached to the servo motor. Unfortunately the encoder at this location in the drive system does not accurately reflect the true axis position because it does not account for backlash or windup errors. Therefore, this new arrangement borrows from Electroimpact's accurate robot program and attaches an absolute encoder directly to each link at the point where the link connects to the gearbox output. This technology greatly improves machine accuracy because the actual joint positions are known thus removing backlash and windup errors from the system. See figure 8.

OVERALL MACHINE ACCURACY

The kinematic compensation results for the above Electroimpact Automated Fiber Placement machine (Figure 9) were typical of our other AFP equipment and only at the extremes of the rotatory axis envelope did a slight increase in orientation deviation occur. This error is still very small and an order of magnitude better than what is required by Boeing specifications for AFP application. The machine's working envelope is 20m × 2m × 1.7m. (65.6ft. × 6.6ft. × 5.6ft.)

It is important to note the following when viewing these results:

1. Compensation data was taken in a non-cleanroom environment (note that actual part production typically takes place in a temperature and humidity controlled clean room which results in more consistent machine performance).

2. Verification data was also taken in a non-cleanroom environment.

Figure 9. Electroimpact AFP machine with new rotary kinematics.

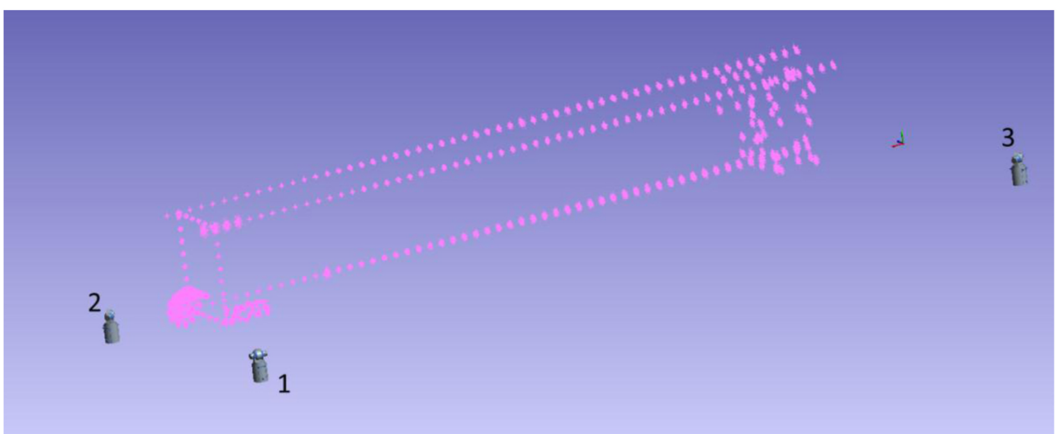


Figure 10. Volumetric measurement point cloud

3. Verification data was taken 48 hours after the compensation data was taken.

4. Due to factors 1 - 3, the results below should be considered very conservative.

5. Finally, the accuracy values claimed are generated from measurements taken at the tool center point. Therefore they are direct valuations of the machine's positioning capability. There is no need for further extrapolation due to any factors such as rotary axis deviations, arm length, temperature compensation, or machine member deflections as the measurements are taken at a point which will be affected by all of the potential error sources listed.

Electroimpact's volumetric compensation system measures machine position as it methodically moves each individual axis through its envelope. Additionally, a Y-Z rectangle is tracked. The corners of this Y-Z rectangle are then tracked at intervals along the X axis. The 6 degrees of freedom possible for each axis are evaluated and manipulated using a multivariable iterative solver that minimizes the difference between forward kinematics prediction of the

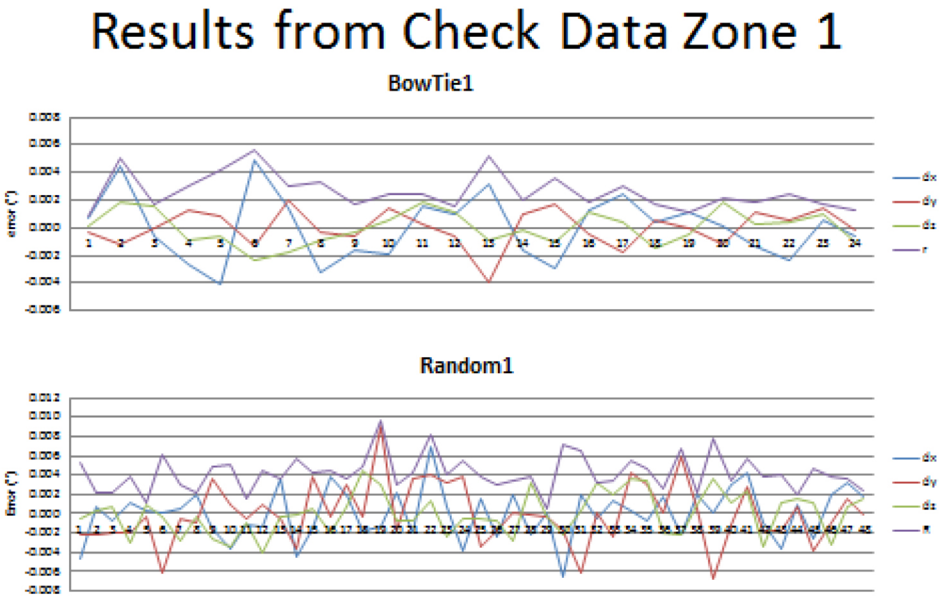


Figure 11. Machine volumetric test data

toolpoint and the laser tracker's measured values. This results in a volumetric compensation model for the specific machine. See figure 10.

The check data taken, labeled BowTie1, (Figure 11) is from a motion test pattern that is a representation of the linear capability of the machine. Toolpoint motion in the three primary linear axes is performed, but this motion is not the same pattern as the compensation motion. Some motion is along only one axis and some is a combination of all three. As you can see the machine easily holds .005″ radial in the machining envelope.

The check data taken labeled Random1 (Figure 11) is the result of moving the machine randomly throughout the machining envelope and comparing the tool center point tracker measured value to that of the compensated commanded position. Aside from one point indicating .009″ error all data fits easily inside of .008″ radial.

Finally, toolpoint orientation check data is taken. In addition to capturing tracker measured data at the tool center point (as done to validate the XYZ positions), at least two additional points of the tool head are also measured. From them, we can calculate the orientation of the machine's toolpoint. For any orientation changes about the X axis or Y axis, all three axes must move. So in the chart provided below, all three axes move for every pose. The results follow in Table 1:

Table 1. Commanded angle vs. error in deg.

commanded			error		
rX	rY	rZ	err_rX	err_rY	err_rZ
0.000	0.000	0.000	0.000	0.000	0.000
-15.000	-40.000	0.000	-0.029	0.014	-0.004
-15.000	-30.000	0.000	-0.025	0.008	-0.003
-15.000	-20.000	0.000	-0.020	0.001	0.001
-5.000	-10.000	0.000	-0.008	0.001	-0.001
-5.000	0.000	0.000	0.002	0.001	-0.006
5.000	5.000	0.000	0.004	0.001	0.000
5.000	10.000	0.000	0.007	0.004	-0.010
15.000	20.000	0.000	0.012	0.002	-0.007
15.000	30.000	0.000	0.024	0.001	-0.025
15.000	40.000	0.000	0.034	-0.001	-0.036

As stated earlier, it is important to remember that the orientation error shown above is measured at the tool center point (which is the ultimate application point) and not back at the joint as many old-school mechanics do. For reference, the quarter inch AFP head has a 4″ wide roller. The worst error depicted above is .034 degrees. This means that the farthest corner of the application roller will have a deviation of about .0012″ from expected.

SUMMARY/CONCLUSIONS

This unique kinematic design of Electroimpact's latest AFP machine allows for high-speed composite fiber laydown rates over highly contoured complex part molds. All of the rotary axes pass through the TCP using carefully chosen non-orthogonal axis angles. These angles push the linkage axes singularity outside the working envelope as well as eliminating major machine reversals, both of which cause unsmooth machine kinematics. The new AFP machine is highly accurate throughout the entire working envelope.

Furthermore, the compact linkage, designed around Electroimpact's modular AFP process head, reduces the mass carried by the major machine and therefore reduces the overall size and cost of the AFP machine.

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DEFINITIONS/ABBREVIATIONS

AFP - Automated Fiber Placement

Tow - Resin impregnated carbon fiber slit to widths of 1/8″, ¼″, & ½″

TCP - Tool Center Point