AUTOMATED FIBRE PLACEMENT EDGE OF PLY ACCURACY WITH RESPECT TO MACHINE PERFORMANCE AND DESIGN

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Keywords: Automated Fibre Placement, Edge of Ply, Process Variables, Automation, Prepreg

Abstract

The positional accuracy of ply placement is critical to the dimensional conformance of carbon composite components manufactured by an Automated Fibre Placement (AFP) machine. Appropriate process tolerances and expectations of an AFP machine must be understood for any high value production solution, and if required, ways to improve the process must be developed.

Positional accuracy is strongly impacted by AFP machine performance, and, the influence of laminate curvature and programming methodology. This work develops an understanding of these contributions and utilises an experimental approach to measure ply position compared to the nominal design intent.

The AFP deposition process capability to maintain a Edge of Ply (EoP) tolerance was determined. The main contributor to the error was found to be material feed variability and the influence of laminate geometry. Both of which have some potential to be compensated for.

1. Introduction

This paper is an investigation into the principal contributing factors to tow placement accuracy in an Automated Fibre Placement (AFP) manufacturing process.

AFP is an additive manufacturing process which deposits composite tows in an automated manner onto a tool, placed by a pre-determined, programmed, path. A number of tows are laid together within the same machine path to make up a course of material. A number of offset courses are laid in succession to construct a ply of material which has a thickness equivalent to one. Plies are laid on top of one another, shaped to build locally changing thickness gradients, and orientated to achieve the required anisotropic properties. A plybook is a laminate design of ply shapes which together fill a nominal part volume.

It is important that tow placement accuracy is held within a positional tolerance. If material is positioned in the wrong place to design intent, then the dimensional profile will also be different to design intent. Tow placement is a function of relative positioning to deposition tool datum features, but also, it is dependent on the accuracy of design representation. Other contributing factors such as material tack are not discussed in this paper.

Excerpt from ISBN 978-3-00-053387-7

There is little independent literature on the tolerance stack-up resulting from the ability of an AFP machine to deposit material accurately, neglecting its possible importance. Studies [1] [2] are focused on the programming task of an AFP process, and propose machine control improvements to existing machine path generation techniques, reducing deposition time and tow to tow gaps. There is also a field of study for live monitoring and correction of machine movement by using independent optic measuring systems to improve accuracy. [3] Investigates this in an AFP context, however, without characterising deposition.

Electroimpact Inc. promote their robotic motion control machine equipped with secondary optical encoders. This additional positional input is used in a high-order kinematic model to compensate the tool centre point machine parameter. The compensations are executed within a Siemens 840d control system, increasing tool point accuracy from +/-0.45mm to +/-0.08mm [4]. A secondary advantage is the compensation of deflections in the robotic arm, which serves to replicate the behaviour of a *stiffer* system. While this improvement was demonstrated for a drilling process, with non-contact edge of ply measuring systems available (Laser Projection Technologies, or, Assembly Guidance Systems), a more applicable study in this context would be to utilise the approach with AFP metrics.

The aims of the study are: to quantify process capability, to ask whether additional deposition roller motion will improve tow placement accuracy, and, to characterise the sensitivity of principal contributing factors of ply placement accuracy. This was achieved by empirical data collection of machine accuracy and design representation inputs that were investigated against one outcome metric – edge of ply accuracy to nominal design curve intent.

2. Methodology of Experimentation

Industrial standard equipment and tooling was used throughout all experimentation work. The AFP machine utilised was an industrial 6-axis gantry type, first commissioned in 2013, loaded with a composite deposition tool. All sample laminate geometry is component specific, which is complex in shape, i.e. a double curvature component with the likelihood of a significant number of ply drops in high curvature regions. The material used was a unidirectional pre-impregnated carbon/epoxy tape, with typical aerospace standard characteristics.

The contributing factors to Edge of Ply (EoP) accuracy are numerous, (Fig. 1) summarises some of the principal inputs that were selected for experiment.

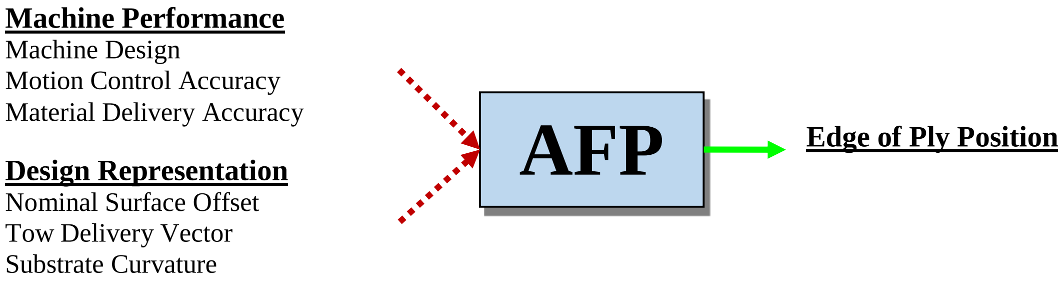

Figure 1. A Simplified Representation of Process Inputs Contributing to an AFP Output

The experimental study deposited a 12 ply laminate on a tool surface of challenging curvature. Each ply was deposited in-board of the last to represent different deposition roller to surface interactions (Fig. 2). The deposited plies were then measured using non-contact laser triangulation, and assessed within CAD packages and statistical software for the edge of ply accuracy to nominal definition (Fig. 3). This process was repeated with two manufacturing settings (Table 1): Setting 1 used a deposition roller modification

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to assist delivery of the tow to the laminate over complex laminate features, and, Setting 2 did not. The modification to the deposition roller facilitates increased *roll* motion. This was then repeated for different ply angles; 0° and +45° orientations.

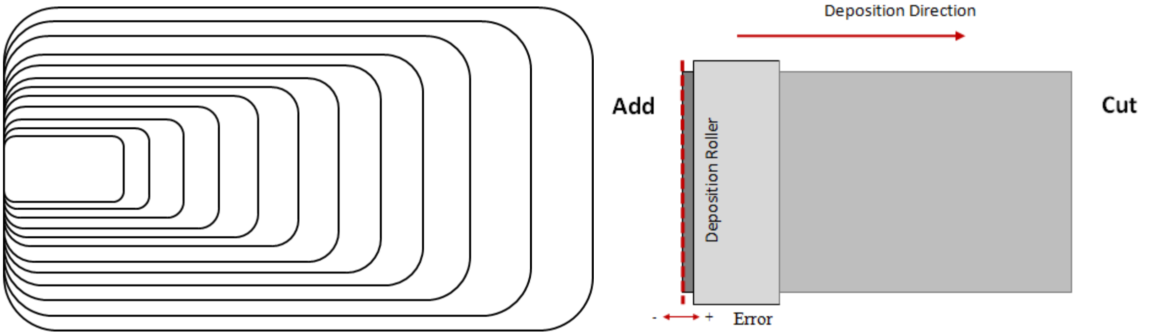

Figure 2. Left; Plybook Edge of Ply Depiction, Dropping from the Part Boundary, Right; Add and Cut

Table 1. A Table of Test Cases to Evaluate Tow Placement Accuracy

Test Case	Ply Orientation	Deposition Roller Setting
1	0°	1
2	0°	2
3	+45°	1
4	+45°	2

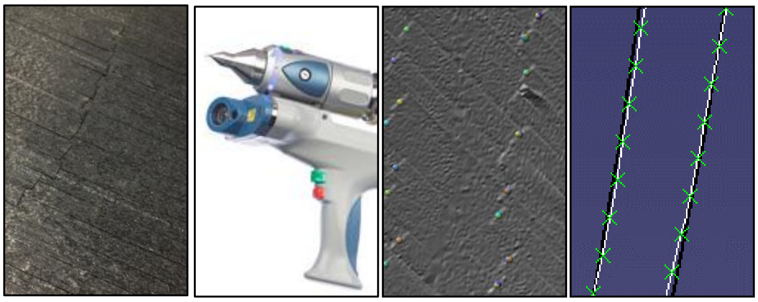

Figure 3. From Left to Right; Deposited Plies, Faro Edge Scan Arm [5]. Raw Data Mesh and Picked Points at Tow Centre. Constructed EoP Spline and Assessed Data Point (Green = within tolerance)

For error trending analysis, separate inspections and design extractions were made:

- The motion control system, which moves the deposition head, was independently measured with contact and laser based approaches to characterise its accuracy. The equipment used was a Renishaw Ballbar, IBS Trinity Probe, and, a Lieca Laser tracker (Fig. 4). The measurement processes used are industry standard as recommended by the manufacturer, as such information can be sourced online.
- The material feed system was assessed by measuring tow nip position error.
- The laminate design was characterised as the following geometric functions measured in a CAD package:
  - The pitch of the deposition head relative to the substrate normal at the first Tool Centre Position (TCP) of a course path.
  - The surface curvature at the start and end of a course.

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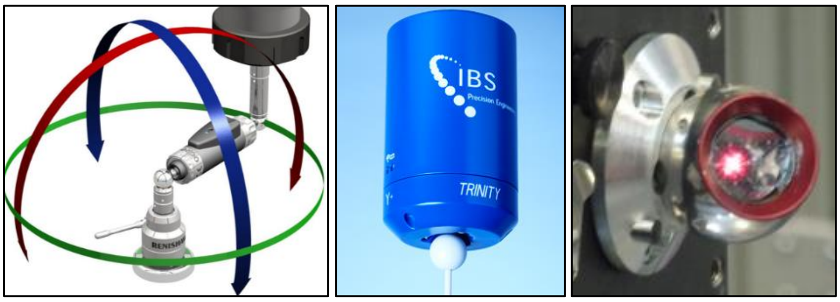

Figure 4. Left to Right; Renishaw Ballbar [6]. IBS Trinity Probe [7]. Lieca Laser Tracker SMR

3. Results

The first observation in the results was that Test Case 4 failed to deposit the full 12 plies. The test was stopped as the level of deformation of the deposition roller could have become damaging. This was attributed to unacceptable deposition roller performance for the test application, thus, increasing the possibility of over compaction due to CNC error and non-flat substrate features. The data set for Test Case 4 therefore has diminished as a result (3 of 12 plies were deposited).

A Process Capability Index (Cpk) is used as a measure of process capability in normal distribution data sets. The metric is an indicator that measures how close a process is to tolerance limits and is defined by the following equation (Eq. 1), where, LSL = Lower Specification Limit, USL = Upper Specification Limit, σ = Standard Deviation.

$$Cpk = Min\left(\frac{Mean - LSL}{3\sigma}\right)\left(\frac{USL - Mean}{3\sigma}\right) \tag{1}$$

The Cpk for EoP accuracy was calculated for all test cases, however, just Test Cases 1 and 3 are considered to be of a standard production configuration at Rolls-Royce. The calculation is based on a statistically robust sample size of over 3000 points per test case (inclusive of both tow Add and Cut data points). A result of 1.00 would be equivalent of +/-3 sigma. This means that the distribution of data lies at the specification limits. This would not necessarily be ideal in a production environment. A more realistic aim often used is 1.33 which is a spread of 8 sigma around the mean, this gives an allowance for the mean to drift. Table 2 presents the process capability results for all test cases.

The capability of the process to conform to specification is then the average of Test Cases 1 and 3, which is equal to 0.32. This is an indication that the process is incapable of conforming to the specification. For a process to achieve a benchmark of a Cpk equal to 1.33, the calculated tolerance would have to be higher than typical Aerospace EoP tolerances. This tolerance band is unlikely to be acceptable in a design, as it could result in ply drops being coincident in adjacent plies when a laminate has a taper rate of less than or equal to 1:25.

Table 2. A Table of Process Capability Indexes for all Test Cases

	Test Case 1	Test Case 2	Test Case 3	Test Case 4
Cpk	0.36	0.28	0.27	0.14
R^2 from Per Ply Average	0.78	0.96	0.53	n/a

Displaying the error data by test case as a function of ply (Fig. 5), starts to reveal some further design considerations which could be a source of process variance. The nominal EoP for all plies is designed

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on the tool surface, so there could be an offset error that explains some of the increase in error with ply height. It could also be that the latter plies possess a greater majority of data points that are in difficult regions of geometry. This trend is strong for the 0° plies, however, breaks down for the +45° plies, where the standard deviation is also higher. The high deformation in the deposition roller seen in Test Case 4 and not in Test Case 2 suggests that there is less control of +45° plies. The reduction in control could be because at this ply orientation, the process is less capable to meet the optimum tow delivery attitude relative to the substrate.

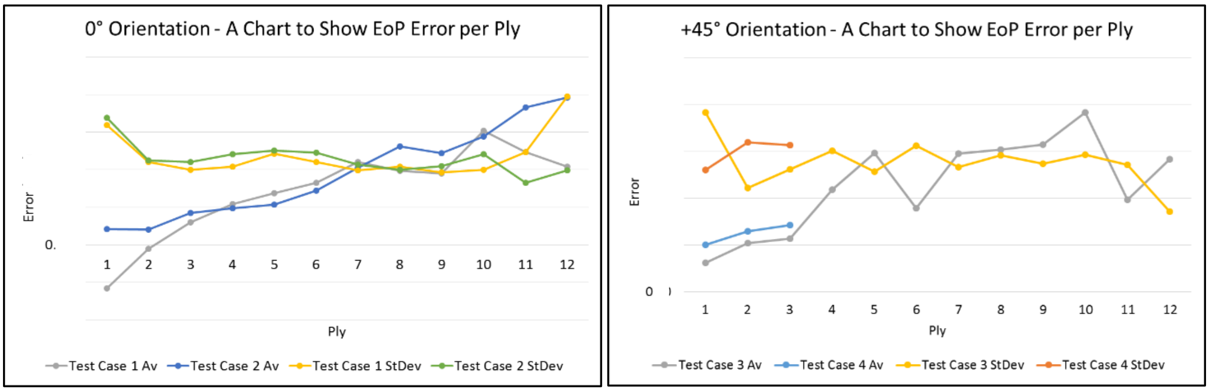

Figure 5. Top; EoP Error for 0° Plies. Right; EoP Error for +45° Plies

The dependency of the deposition roller setting on tow placement accuracy was determined by performing a paired t-test between Test Case 1 and 2. This test determines whether there is a statistical difference between two population means, it asks whether the difference in data set averages is representative of a real difference or a statistical miss-direction. The test cases have a sufficiently large data set (>3000 points per average), there is a necessary difference (Test 1-2 = 25%), and there is a wide spread in the data, as such, the data sets meet the requirements for a robust t-test.

The hypothesis to test is whether lower *roll* motion of the deposition roller will improve tow placement accuracy. The concluded result is that, tow placement accuracy during the Add of tows is significantly worsened by the lower *roll* setting, and there is potentially a weak suggestion that the tow placement accuracy at the Cut is improved. The emerging disparity in Add and Cut accuracy is also observed in the +45° orientation plies (Fig. 6). The conclusion is, the average Cut end of the tow conforms marginally better on average than the Add end of the tow, however, with a larger spread in results.

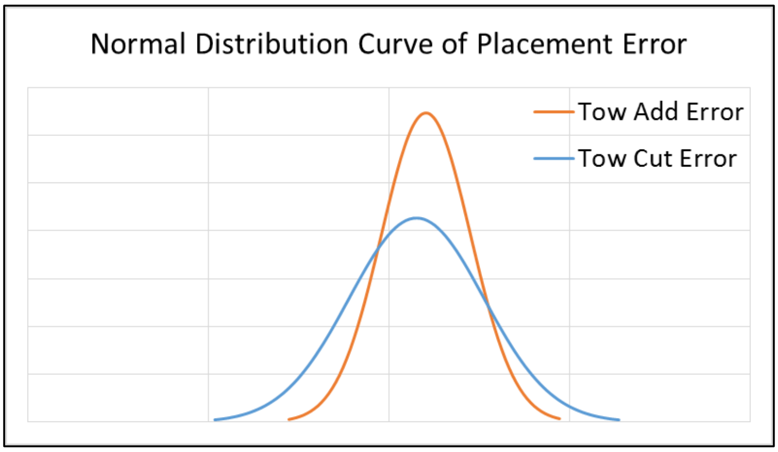

Figure 6. Non-Centred Normal Distribution, of Tow Placement Accuracy

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4. Machine Performance Analysis

A separate fundamental study of the effect of motion control accuracy and precision on the accuracy of tow placement was performed in isolation using verification equipment to plot key metrics of machine performance over a 9 month time period. A change in performance was induced to expose any causal effect, however, no such effect was observed (Fig. 7). Tow placement error actually increased as motion accuracy improved, which suggests a randomness, or, that there is another parameter of higher influence. In this instance, this is due to material feed system synchronisation error (i.e. tow feed timings). The metrics of the chart in Fig. 7 were measured by the following tests:

- XY Positional Tolerance, and, XY Squareness – Renishaw Ballbar Test
- Volumetric Error, and, 6-Axis Error in X – IBS Trinity Probe 6-axis R-Test
- Tow Add, and, Tow Cut Error in X – Flat Ply Deposition Test
    - Measured against machined scribe lines on a tool

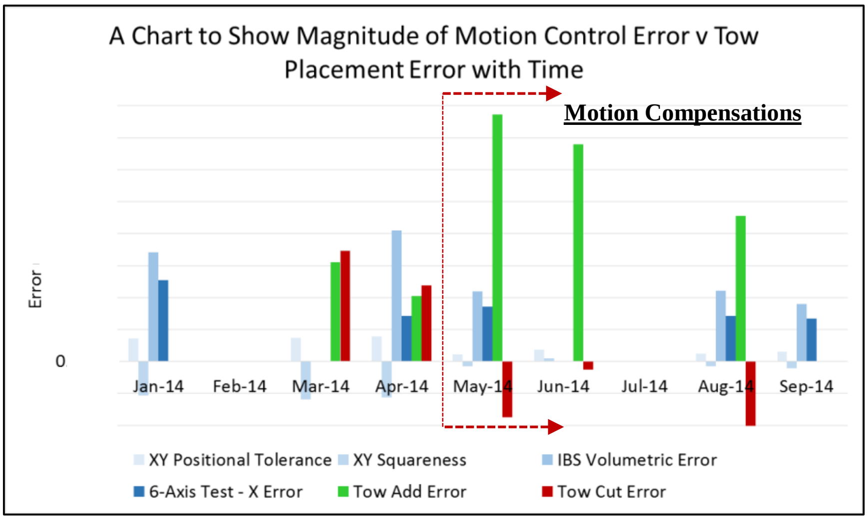
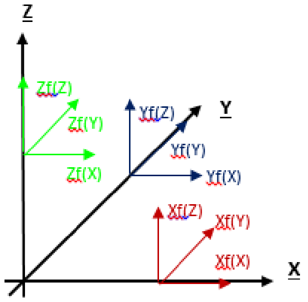


Figure 7. Motion Control Machine Error v Tow Placement Error with Time. Tow Placement Error Data Points are Averages for that Month

Laser tracker measurements of fundamental motion errors (i.e. un-compounded) at the time of test case deposition demonstrated linear axis errors in the sub-mm range across the part, Table 3, yet the EoP data suggests a mm-scale variation that is local to certain geometrical regions of the laminate. This equally suggests that the scale of motion control error is not currently a key parameter relating to the magnitude of the tow placement error results.

Table 3. A Table of Error Variation Across the Experimental Test Case Volume

	Error Variation (mm)	Representation of Linear Axis Errors
Xf(X)	0.3	
Xf(Y)	0.06	
Xf(Z)	0.2	
Yf(X)	0.2	
Yf(Y)	0.04	
Yf(Z)	0.05	
Zf(X)	0.05	
Zf(Y)	0.3	
Zf(Z)	0.08	

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4.2 Design Representation Analysis

Fig. 8 shows the same increase in error with ply as Fig. 5, and additionally, suggests local regions of error magnitude. Two positive trends are observed; an increase in Add error toward the right side of the laminate, and, an increase in Cut error toward the left side of the laminate. Laminate curvature and deposition head approach angle will be tested for any causal effect in tow placement error.

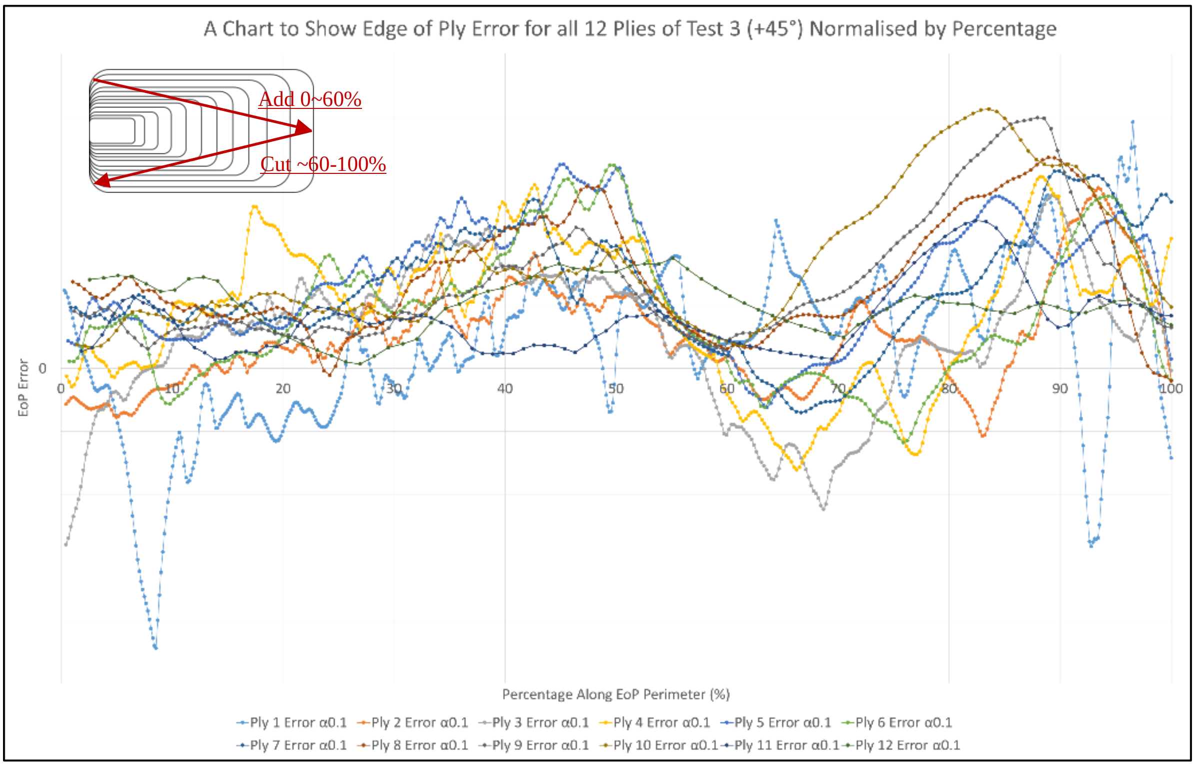

Figure 8. Exponentially Smoothed Edge of Ply Error for Test Case 3 v Percentage Normalised Data Point Location. (Inset) Direction of Data Point Relative to Plies

Deposition head pitch is defined as the angle between the deposition head normal vector and the surface normal, and alters due to clash avoidance. Taking a sample data set and analysing the error results against the deposition head pitch and laminate curvature, tow by tow for the start and end TCP, a weak causal effect was ascertained. A regression analysis showed no correlation of results between the independent variables of: head pitch, maximum substrate curvature under the deposition roller axis at the start and finish TCP, and, maximum substrate curvature in the first/last section of a tow path. The R-Squared values were, 0.3 and 0.1 for tow Add and Cut results, respectfully, although the charts visually show some correlation in trends (Fig. 9).

The possible explanation for the poor statistical robustness of the link between placement error and pitch is the absence of other factors that affect tow trajectory, such as error as a result of lower deposition roller *roll* motion, and the variance in material delivery of this particular machine. It is this higher-order noise that makes it harder to model and embed all behaviours into a conclusive compensation algorithm. Changing geometric functions in course path definition and laminate design are still the foreseen source of the subtle error trend, and experiments such as this provide sufficient empirical data to refine any compensations. In addition, optimisation of deposition head design could alleviate this variability issue.

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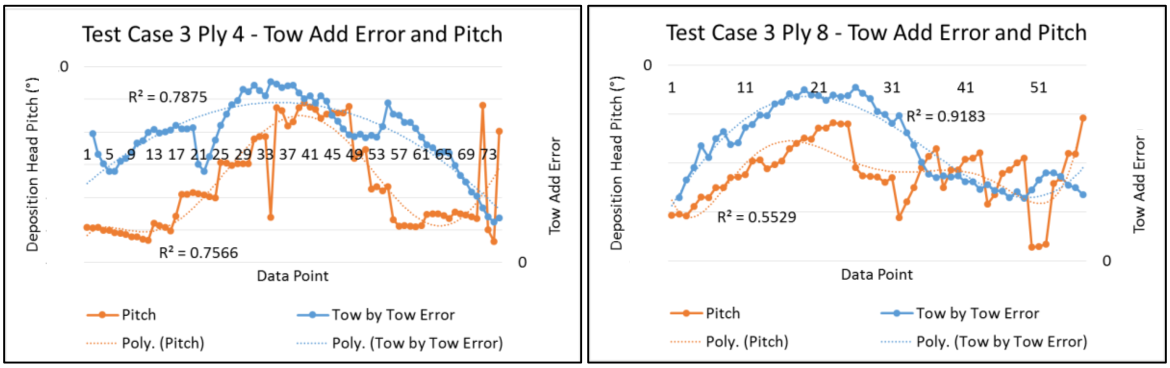

Figure 9. Exponentially Smoothed Tow Add Error and Deposition Head Pitch.

5. Conclusion

In this study, the measurement of actual versus nominal ply curves allowed process control limits of EoP precision to be established. The results highlighted the criticality of improved deposition roller motion to deposition quality, and that the higher *roll* movement did not negatively impact EoP accuracy. Additionally, the EoP error contribution from machine capability, the laminate and machine path design was investigated. The analysis concluded that the recorded motion control error is not currently at a scale to effect tow placement. The key parameters which determine the magnitude of tow placement error are those that effect the variability of tow delivery to the laminate surface, appearing to change with laminate geometry and the relative trajectory of a delivered tow.

6. Acknowledgements

This work was supported by the EPSRC through the Industrial Doctorate Centre in Composites Manufacture [EP/K50323X/1]. The Author would also like to acknowledge the endless support of colleagues in Rolls-Royce and at the National Composite Centre.

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