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A High-Performance Milling Machine for Aerospace Applications

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Abstract

As the aerospace industry moves toward determinate assembly and ever-tighter manufacturing tolerances, there is a need for automated, high-precision milling, trimming and drilling equipment that is specialized for aerospace applications. Precision countersinking is a common requirement for aircraft parts, but this is not a process that typical general-purpose milling machines are able to accommodate without the use of specialty tools such as depth-stop tool holders. To meet this need, Electroimpact has designed a 5-axis milling machine with high-speed clamping capability for countersink depth control. A custom trunnion and head with a quill and an additional clamp axis provide clamping functionality similar in speed and precision to a riveting machine, while maintaining the accuracy and features of a conventional machining center. An additional focus on design for pre-compensation accuracy has allowed the system to achieve post-compensation path and positioning tolerances that are competitive with premium milling machines. This combination of capabilities makes the system well suited for a variety of cutting and drilling processes for aircraft manufacture. This paper will describe the background and design process that led to the development of this system, and will provide details on its capabilities, specifications, and possible applications.

Introduction

Electroimpact was approached by a customer with a requirement for a large, highly accurate 5-axis CNC milling machine that would also be capable of fast precision countersinking and of locating datum features with a machine vision system. The resulting machine satisfied all of those needs and represents the first time that a high-speed BUCA pressure foot has been integrated with a full-function milling machine.

Figure 1. Electroimpact's 5-axis milling machine optimized for aerospace applications.

The subject of accuracy will be addressed first, as it was the most fundamental requirement to the design of the system. Accuracy requirements drove many aspects of the machine design and were stringent enough that they also imposed unusually challenging requirements on the design of the foundation. An innovative method for achieving the required foundation performance was developed and will also be discussed.

A discussion of the method for maintaining countersink depth and the resulting machine head design follows.

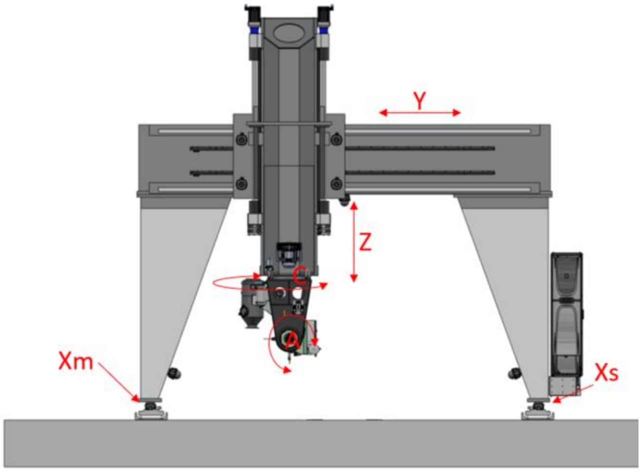

Figure 2. Machine axis layout and designations.

Accuracy

A high degree of accuracy is generally necessary for machining centers to meet their requirements. For certain specialty and aerospace-specific purposes such as the drilling of holes for use in determinate assembly, the requirement for accuracy is even more demanding. While highly accurate milling machines are not new, we can say from our knowledge of and experience with similar systems that the levels of accuracy that have been achieved here are noteworthy, as are the methods that were used to achieve them.

Design for Pre-Compensation Accuracy

Methods for electronic compensation of CNC machinery are mature and effective, and Electroimpact has extensive experience with large machine compensation to achieve high accuracy for many machine configurations, and using many methods, including our own proprietary kinematics solvers [1,2,3]. That experience is put to use on this system, but even the best compensation methods are no substitute for mechanical accuracy, and with a highly mechanically accurate machine as a starting point greater post-compensation accuracy is achievable. Mechanical accuracy was thus an overriding priority in the design. Pre-compensation axis flatness and squareness were emphasized, and effective methods were developed to achieve those goals.

For each step of the machine build, from bed-setting through alignment of the major assembly, an accuracy "budget" was established that would allow the entire system to meet specified tolerances in a worst-case tolerance stack-up scenario (Figure 3). Each engineer engaged in the build had a clear understanding of the alignment accuracy that needed to be achieved during each step of the process before it could be called complete. This process is especially important because of the fact that a particular error somewhere in the tolerance stack-up will not necessarily lead to a one-to-one effect at the tool center point. For example, for a gantry-type machine such as this one, a flatness deviation for the Z-rails in the YZ plane will lead to a deviation at the tool center point in the X-direction that is much greater than flatness error itself (Figure 4).

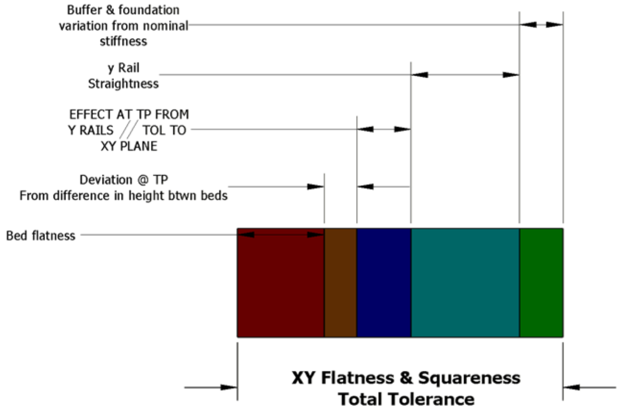

Figure 3. Example of pre-compensation mechanical "accuracy budget" for flatness and squareness of a particular plane.

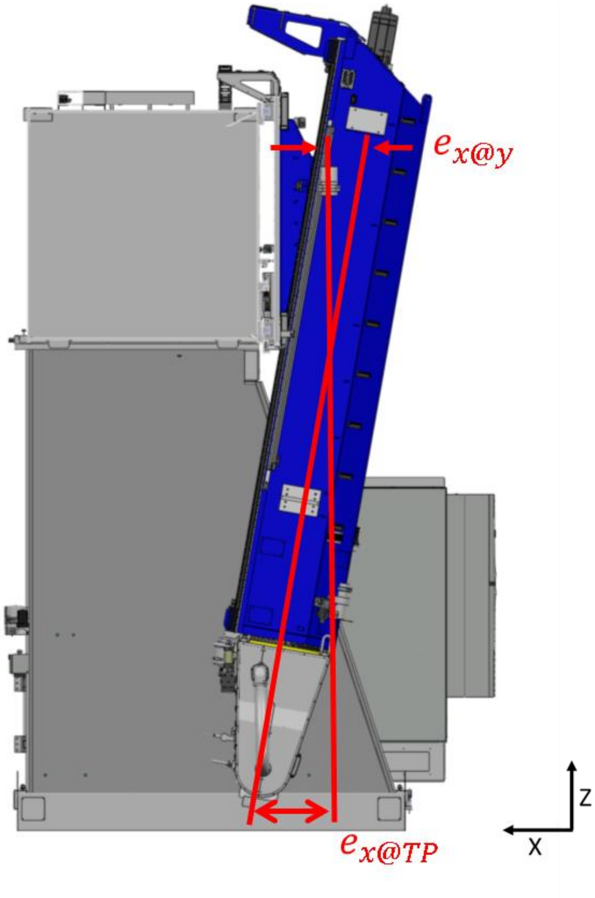

Figure 4. Exaggerated view illustrating that for a gantry machine, a flatness error in the X-direction at the upper Y-rail, $e_{x@y}$, leads to a magnified error at the tool point, $e_{x@TP}$, such that $e_{x@TP} >> e_{x@y}$.

The design of each machine axis for pre-compensation accuracy was then a matter of meeting two criteria:

1. Design for the rigidity required for deflections to fall within the allotted budget for that axis or system.
2. Incorporate methods in the design for easily making mechanical adjustments after complete assembly and

power-up of the machine, so that if the overall tolerance had been exceeded, corrections could be made.

Design for rigidity was primarily accomplished through utilization of finite element methods to optimize the geometry of structural components. In some cases, results of finite element analysis were used to predict grind spacer thicknesses, reducing the likelihood that adjustments would be needed after final assembly.

Several methods were employed for enabling post-power-up adjustments. One such method was a redesign of our typical linear bearing-grind spacer arrangement, so that any individual spacer could be removed for adjustment without the need for major disassembly (Figure 5).

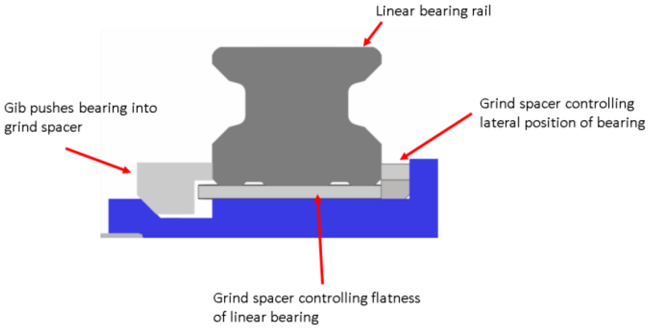

Figure 5. Example of a linear bearing-grind spacer arrangement designed with post-build adjustments in mind. By removing the gib, and potentially a single bolt in the linear bearing, an individual grind spacer controlling flatness may be removed without removal of the entire linear bearing..

Foundation

Pre-compensation accuracy requires a foundation that deflects uniformly as the machine moves across it. Machining centers commonly require custom foundations that are designed to meet specific deflection requirements, but there are reasons that the foundation requirements are especially demanding for this system:

- The emphasis on pre-compensation accuracy means that less variation in foundation stiffness is allowed than would otherwise be the case. A portion of the accuracy budget is dedicated to foundation deflection, and the actual deflection at any location must not exceed that amount.
- A flood coolant system is integrated with the machine, necessitating that gutters and sumps be included in the foundation. These features lead to a variable cross section in the foundation slab, making uniform deflection difficult to achieve.

Solution: Finite element design using micro-piles with variable spacing

An initial soil exploration was performed including two soil borings located in the vicinity of the machine’s eventual location within the facility. The exploration revealed that the site’s soil was typically a clay stratum over weathered limestone rock layer. The soils were determined to be capable of supporting the machine as a shallow mat foundation system. An alternate deep foundation consisting of piles embedded into the rock layer was also deemed an acceptable alternate foundation system.

Due to the stringent displacement requirements, a traditional grade-supported shallow mat foundation would require use of an improved soil zone. The improved soil zone would be located directly under the foundation block, would be a minimum 36” deep and would extend a minimum of 36” outward beyond the footprint of the foundation in all directions. The zone would be established by excavating the in-situ soils followed by installation of alternating layers of Tensar TX160 geogrid and 1” maximum sized crushed limestone. One layer of the geogrid would be placed against the native soils at the bottom of the excavation, followed by a 12” thick layer of properly placed and compacted crushed limestone. The installation of an additional layer of geogrid followed by an additional 12” thick limestone layer would then be repeated until the bearing elevation is reached. The improved soil zone would effectively double the expected stiffness of the soil when compared to the stiffness of the native soils. Even with the improved soil zone, the displacement requirements mandated use of a foundation block that was longer, wider, and thicker than preliminarily estimated. Rectangular and trapezoidal shaped foundation blocks of various thicknesses were considered in an attempt to create a relatively uniform stiffness profile throughout the length of the travel of the gantry.

The use of a shallow foundation system was rejected due to issues related to constructability of the improved soil zone within the confines of an operating facility and uncertainty as to the accuracy and precision of the soil stiffness parameters beyond the depth of the improved soil zone.

Once the election to use a deep foundation system was made, five additional soil borings were completed so that an approximate map of the elevation of the top of the rock layer could be created (the two initial borings implied a steeply sloping rock surface). Concrete micro-piles were chosen due to constructability issues including access of drilling machinery to the location within the facility, headroom limitations with the existing roof framing, and reduced airborne contaminants within the facility when compared to the installation of other pile types.

A three-dimensional finite element analysis was performed modeling both the foundation block and the piles. An iterative process was used. The stiffness of the foundation block was varied primarily through changes to its overall thickness. The stiffness of each of the piles varied based on its length to the sloping rock surface, so location and spacing of the piles was varied in an attempt to maintain a relatively uniform stiffness profile. As the location of the piles were revised, their length was also adjusted based on the rock surface map. Ultimately, seventy-one piles were used to support a 4’-6” thick foundation block. Isometric views of the model are shown in Figures 6 and 7.

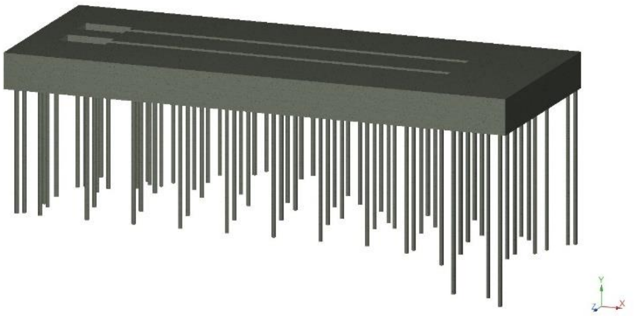

Figure 6. Isometric view of the foundation model. The sump and gutter system affecting the cross section is visible. The variation in micro-pile lengths is due to the inconsistent bedrock depth and led to differences in pile stiffnesses that had to be accounted for.

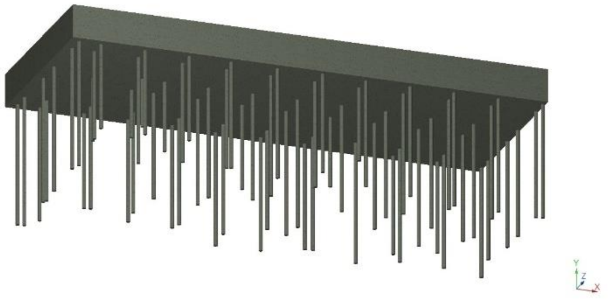

Figure 7. Bottom view of the foundation model, with the variable micro-pile spacing apparent. By adjusting the spacing of the micro-piles, relatively uniform stiffness was maintained.

Design for Pre-Compensation Accuracy - Results

All pre-compensation accuracy targets were achieved. Final axis-by-axis squareness data, before electronic compensation was applied, is given in the appendix. It can be seen that over the entire working envelope of the system, tool point errors are smaller than is often achievable even after compensation for typical milling machines [4,5]. Milling tests confirmed that these accuracies were predictive of actual machining tolerances.

Deflection of the vertical (Z) axis as the machine travels along its longest axis (X) is of particular interest, as this is largely dependent on the performance of the foundation. Any difference in foundation deflection under machine loading at different locations will be additive to the Z error from other causes.

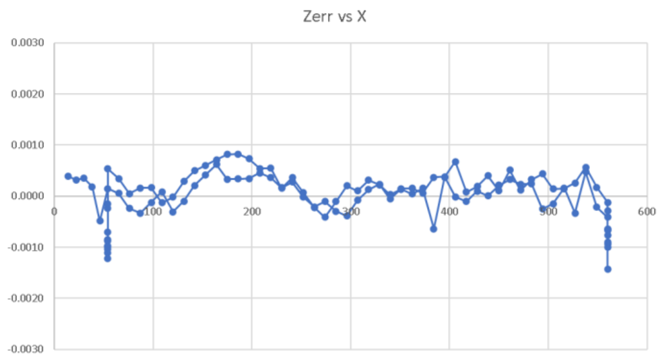

Figure 8. Pre-compensation error in tool point position in vertical axis (Z) versus X-axis position, for entire 48' length of travel (values in inches).

The Z-axis measurements show that the deflection is remarkably consistent along the entire length of travel (Figure 8). These results validate the foundation design methodology.

Compensation

In certain applications, customer quality requirements mandate frequent verification of machine accuracy, with the application of new compensation as appropriate. Many methods for machine compensation have been developed and are in use, but most require some level of technical expertise, either with the metrology equipment, with the mathematics of machine kinematics and statistical analysis, with the machine controller, or all three. We set out to create an easy-to-use compensation system that could be run by a machine operator or maintenance personnel, without the need for technical experts, and without sacrificing accuracy.

Compensation consists of three main parts:

1. Measurement of actual machine positions (both for initial evaluation and for verification of compensation after it is applied)
2. Analysis of the measured values to determine whether the system is within specifications, and if not, to calculate the required updates to the compensation.
3. Application of compensation to the machine controller.

Measurement of Machine Positions

To reliably measure the accuracy of a machine ANSI B5.54 recommends the measuring instrument have an accuracy at least four times better than the desired machine accuracy. ISO 230-9 has similar requirements for including measurement uncertainty. These requirements preclude the use of a laser tracker because they do not have sufficient accuracy over the large envelope of the machine.

Linear positioning accuracy can be measured and compensated using a laser interferometer. This is the method used on this machine for compensating linear positions and as this method is routine in industry will not be further explained.

Straightness and squareness of large axes are more difficult to measure accurately due to refraction of the laser beam in air and, in the case of laser trackers, angular encoder error. To reduce these errors, we used a precision spinning laser with detectors to measure the beam position. Data was collected by moving the machine through a series of positions in three orthogonal planes over the machine volume.

Calculation of Compensation

The measured values are inserted into a spreadsheet and the error is calculated as the difference between the nominal commanded machine position and the measured value. A custom program is then run on the measured values to do a six degree of freedom transform to minimize the error. This eliminates setup errors resulting from the position of the measuring device, greatly reducing the precision necessary for the measurement device setup. The transform can be to a measured known coordinate system or a least squares fit to the data. The error can then be compared to the required tolerance to determine if additional compensation is required.

If compensation is required, another program is run to least squares-fit the measured values to three nominally orthogonal cubic spline surfaces. A cubic spline was chosen as it is a good model for the physical straightness errors of the linear rail sets on the machine. Figure 9 shows an example of the calculated spline surfaces. The program allows the figure to be rotated and zoomed to check for problem areas such as missing measurements or erroneous values.

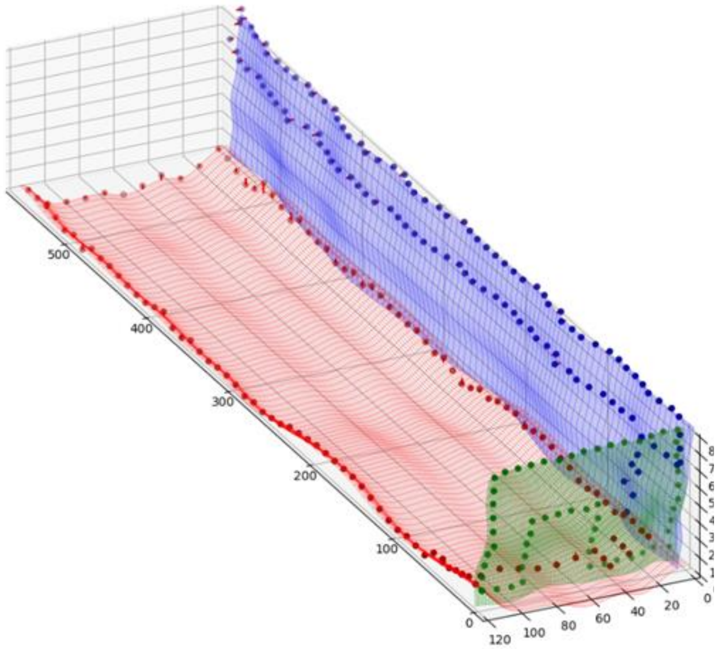

Figure 9. Example of calculated spline surfaces. Errors are scaled 10,000x.

Graphs in the Excel spreadsheet are also updated to show the error before compenstion, the calculated spline, and the expected residual error after compensation (Figure 10).

Figure 10. Example of error vs axis position.

Application of Compensation

After verifying that the compensation values are reasonable a program is run which converts the surface spline values into a piecewise linear approximation and generates a program file using standard Siemens cross axis compensation. This file is then loaded onto the control and run to update the compensation.

Thus the three major steps involved in compensation have been simplified. Some skill and knowledge is required to set up the measuring devices, but this can be obtained with a minimal amount of training. Set-up time is reduced because the transform performed in the calculation step eliminates any error from imperfect alignment of the device with the machine. After measurement, the mechanic or operator performing the compensation needs only to run the supplied program to analyze the data, and if it is determined to be out of tolerance, to then run an automatically-generated part program on the machine controller to load the new compensation values. These can then be verified in the same way that the original data was collected.

Countersink Depth Control

When precision control of countersink depth is necessary on general-purpose milling machines the usual solution is to use a compliant depth stop tool in the spindle. Such tools contact the surface of the part during drilling, and will not allow the drill to advance beyond a pre-set amount, thus limiting the depth of the countersink. Some of the drawbacks of these tools are:

1. Setting accuracy and countersink repeatability are limited.
2. Tools are typically limited to low spindle speeds, limiting machine hole-to-hole rates.
3. There is no feedback to the machine controller when the tool contacts the part. Therefore it is vital that the surface of the part is located accurately relative to the NC programming model.
4. Setup is manual and time-consuming.

Borrowing from the Fastening World

Riveting machines used for the manufacture of aircraft parts, on the other hand, are most often designed to have native countersinking capability. The typical system uses a pressure foot that is integrated with the machine and is completely independent of the drill. Contacting the panel with the pressure foot and applying some preload ensures that the panel is a known distance from the drill spindle, allowing the machine to drill to a precise depth relative to the panel. Modern CNC machines with servo-controlled spindle feed can electronically control the final position of the spindle relative to the pressure foot, making mechanical depth stops obsolete.

Two Clamping Methods

Traditional riveting machines use a pneumatically extended pressure foot to contact the panel. The pressure foot extends to a fixed position, where it is held with significant force, and the panel is pushed into the then-fixed pressure foot by an anvil on the opposite side. This “fixed work line” process relies on there being some compliance in the panel, either due to its flexibility or to compliance in the part-holding tooling.

On the other hand, on Electroimpact’s single-sided fastening machines – robots are one example – or in cases where the work piece is held very rigidly and is not compliant, such as for wing panels held in tack fixtures, the machine must move to the panel under servo control [6]. The position of the pressure foot is therefore not always the same relative to the universe, so these machines are referred to as having a “moving work line”. In moving work line machines, a load cell in the fastening head provides feedback to the controller to indicate that the part has been contacted, and then to allow the application of the appropriate clamping force. This is sometimes referred to as “rigid clamp-up”, since the clamping force is applied through a rigid drive train by a servo, and there is no compliance in the system.

Because of both the lack of compliance and the extra time it takes to include load cell feedback in the CNC control loop, rigid clamping is an inherently slow process. The machine must drive slowly toward the part starting at some distance away. After contact is made it must again go slowly until the desired force is reached, to avoid overshoot and potential damage to the part.

High Speed Rigid Clamp-Up

A great improvement to the time required for the rigid clamp-up process was realized through the use of the BUCA system. In its relevant implantation, the BUCA clamping methodology incorporates a pressure foot that is pneumatically extended, as with fixed work line machines. Unlike those machines, though, it is extended with minimal pressure – enough to create on the order of twenty-five to fifty pounds of force. A sensor monitors the extension of the BUCA and alerts the controller if it is back-driven. Typically there may be one-half to one inch of travel in the pneumatic extension of the BUCA.

Because of the compliance added to the system by the BUCA, clamping can be done much more quickly. This is best illustrated by a step-by-step description of the clamp process.

1. The BUCA pressure foot is pressurized and is therefore fully extended. This is its normal state as the machine moves around the panel.
2. The clamping routine is initiated. Because there is some uncertainty regarding the exact position of the panel, the machine head is some distance away from the panel when the command to begin clamping is given. As the clamping cycle initiates, the machine head is driven toward the panel at a high feed rate.
3. At some point while moving toward the panel the clamping surface of the pressure foot contacts it. As the head continues to move forward, the force exerted on the panel overcomes the pneumatic force extending the pressure foot, and the pneumatic cylinders pushing it forward are back-driven.
4. Once the pressure foot is back driven slightly, the sensor that was monitoring its position turns off, alerting the controller that the panel has been contacted.
5. The distance between the sensor “off” position and the complete bottoming out of the pressure foot is a calibrated, known quantity. Therefore the head is commanded to move at high speed to a position just shy of that which would fully collapse the pressure foot.
6. The head continues to move forward, but now under force control and at a much slower rate, until the pressure foot is fully collapsed and the desired clamp force is read by the load cell.

Thus it can be seen that all of the machine moves in the clamping process except for the very small move in step 6 are able to proceed at high speed, and under position control. Because of its speed advantages this system was chosen to be adapted to and integrated with the milling machine head.

A Machine Head for High-Speed Countersinking

Utilizing a pressure foot for countersink depth control necessitates a separate spindle feed, or quill, axis on the machine, since the spindle must be able to move independently from the pressure foot. Clamping motion in the same direction but independent of the spindle is also necessary. This could be provided by through 5-axis interpolated motion utilizing the rest of the machine axes, but for the sake of process speed it was decided to include an additional servo-controlled clamp axis.

To accommodate the BUCA clamping system a head with two rotary axes (A and C), in addition to a linear clamping axis and a parallel linear spindle feed axis is used (Figure 11). The result is a machine with five kinematic axes, as well as a spindle feed and an independent clamp axis that can be used for countersinking operations.

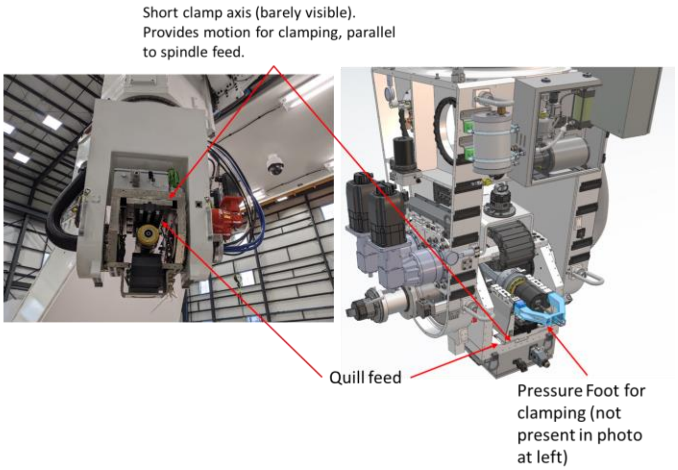

Figure 11. Two-rotary-axis machine head with additional linear axes for clamping and spindle feed.

The machine head with pressure foot installed is shown in Figure 12. Importantly, the pressure foot is designed to be removed or reinstalled quickly and repeatably. With the pressure foot in place the machine is capable of high-speed, high-precision countersinking operations that are equivalent in speed and accuracy to a dedicated fastening machine. With the pressure foot removed, the system becomes equivalent to a premium milling machine, capable of high material removal rates with great accuracy.

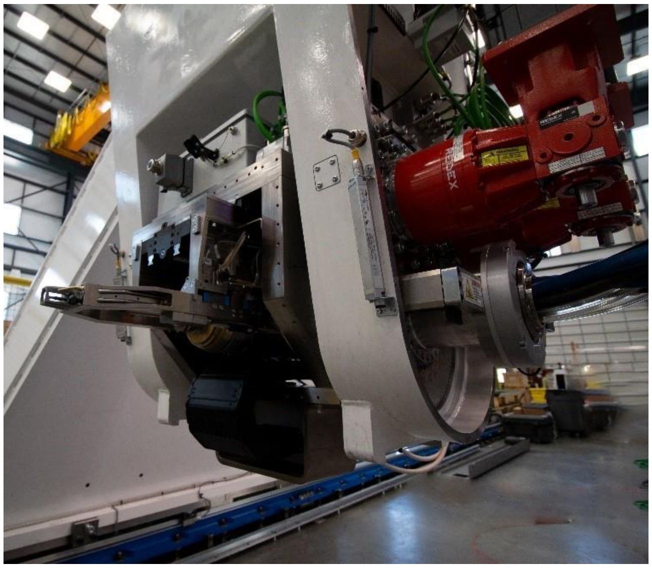

Figure 12. Machine head with removeable pressure foot installed for countersinking operations.

Summary/Conclusions

While our accuracy targets were surpassed, accuracy data for other comparable machines is not readily available, making comprehensive comparisons difficult. Our first-hand experience with similar machines and our knowledge of the market lead us to believe that the accuracy of this system, as reflected by data given in the appendix, and the methods used to achieve it are novel and unique in the industry.

A limitation of the compensation method described is that we are compensating for the rigid body motion of the tool point along each axis, but not the change in shape of those paths as other axes are moved, as these errors were not large enough to be measured repeatably. This could be a significant limitation for machines that are less rigid or are on a less consistent foundation. Investigating and quantifying the significance of those interactions is a potential area for further study.

Through several innovations a highly accurate 5-axis CNC milling machine with the countersinking capabilities of a dedicated aircraft drilling system has been developed. A thoughtful foundation design and a machine design with a focus on pre-compensation mechanical accuracy reduces the reliance on complex compensation methods. A simple and easy-to-use compensation process ensures that accuracy can be verified and maintained by the customer for many years after the system is commissioned.

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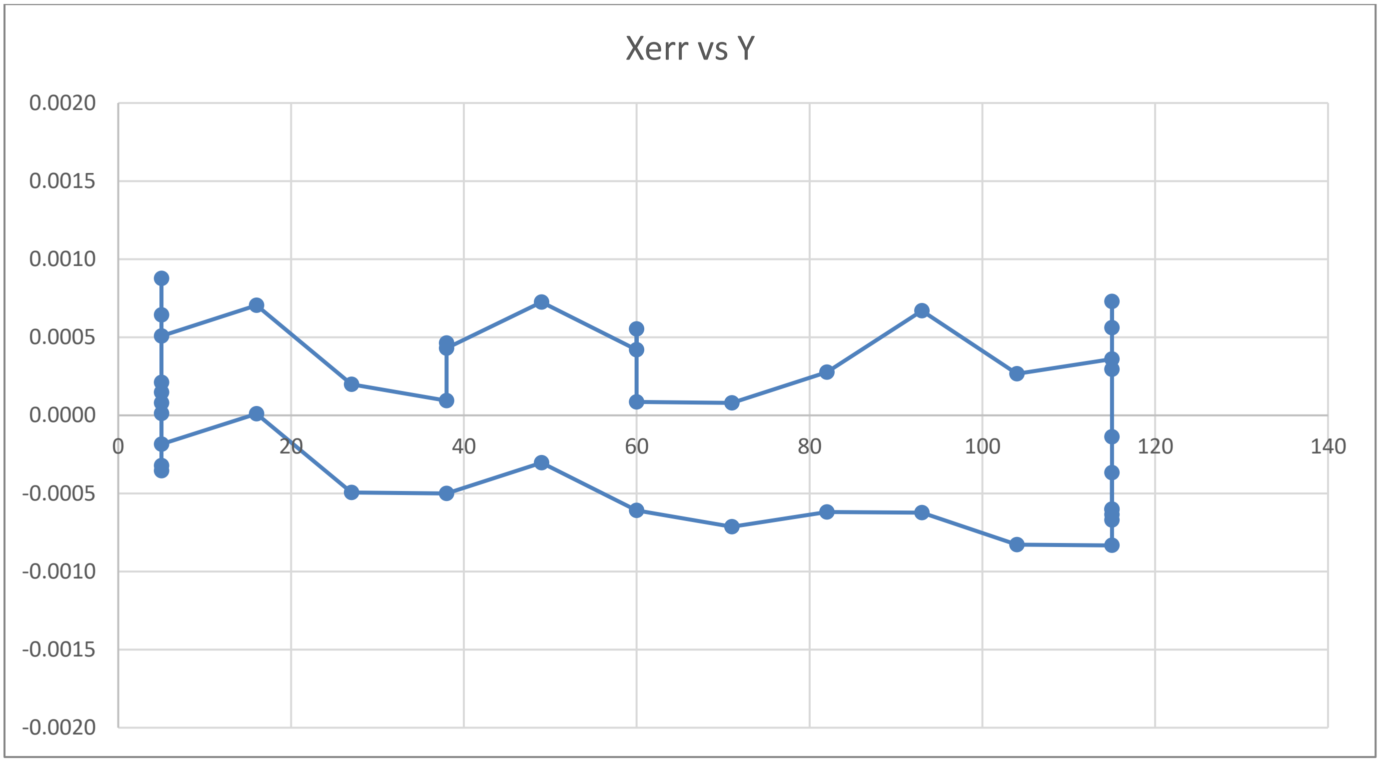
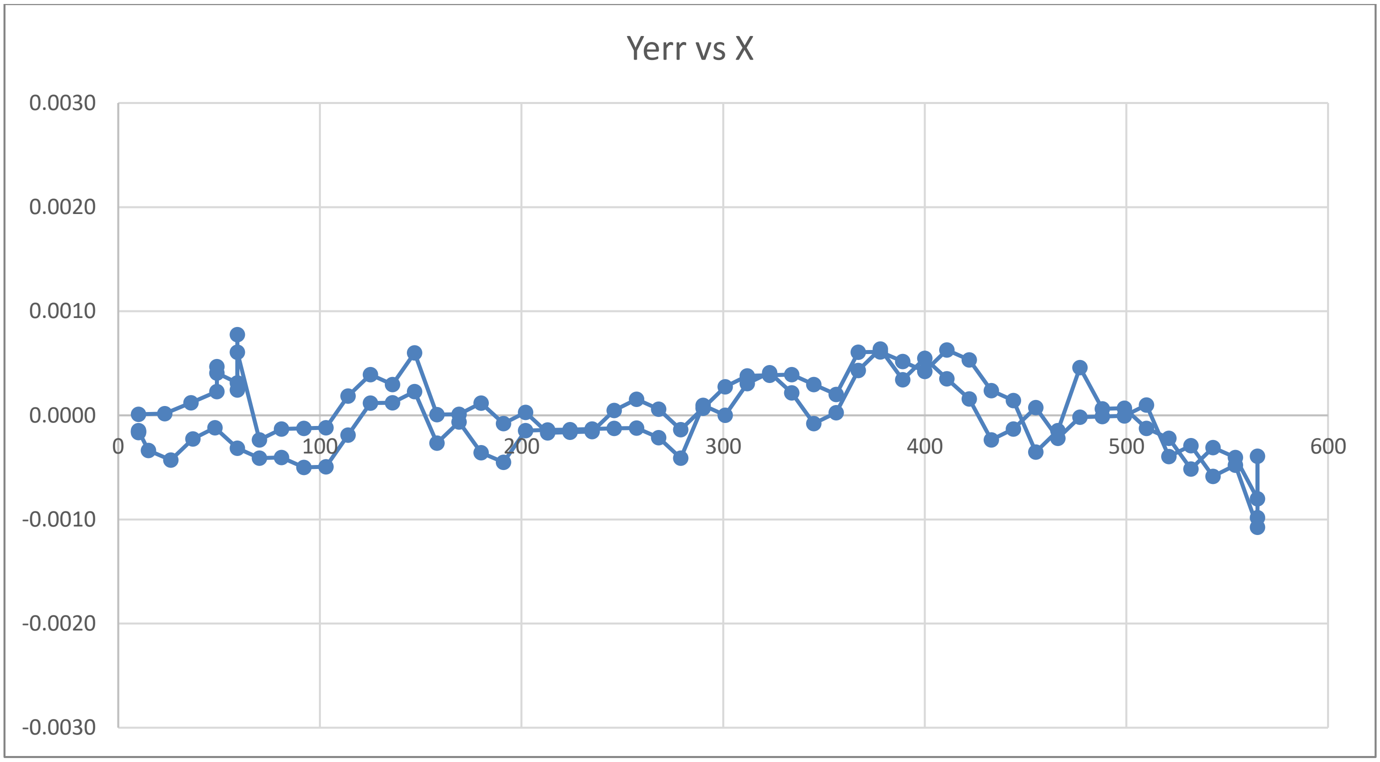
Definitions/Abbreviations

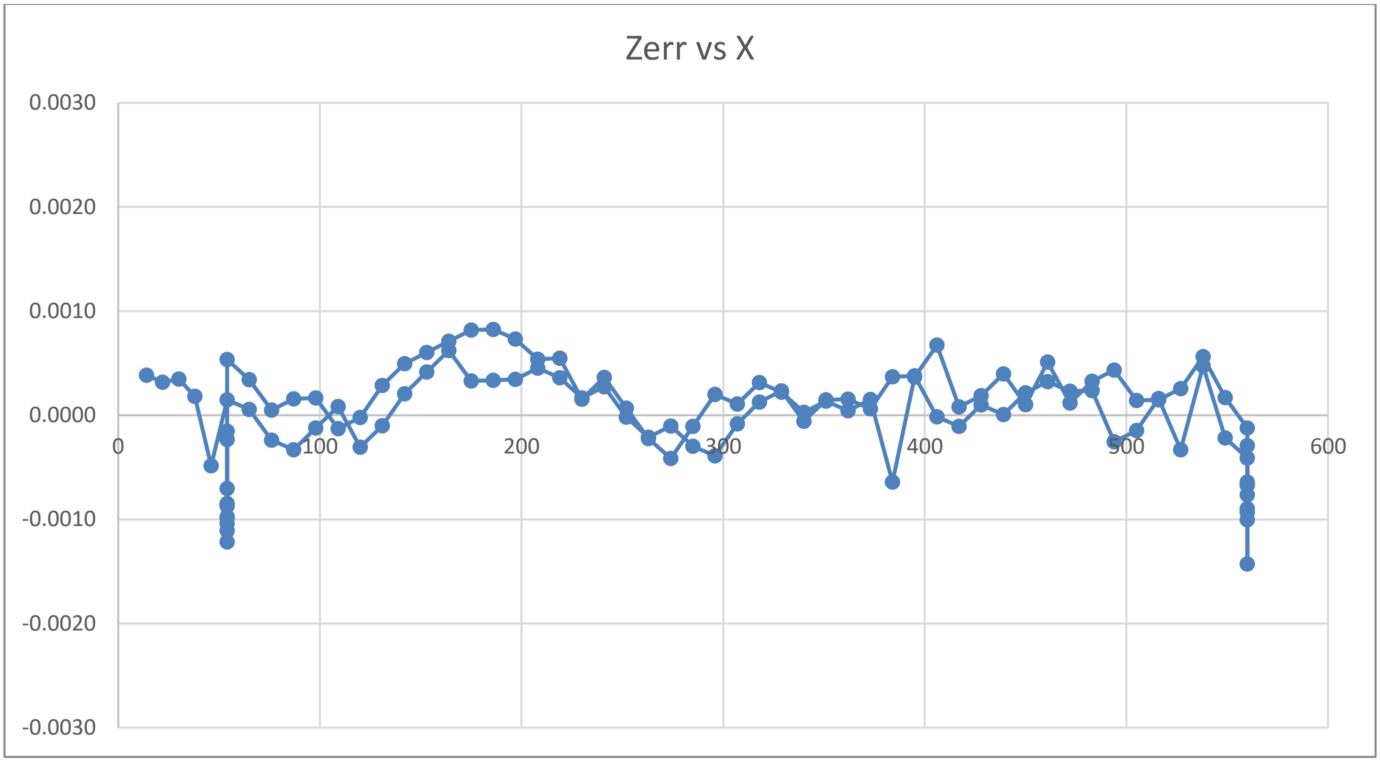
BUCA	Back-Up Carriage Advance. This is an industry term for the described clamping method. The name originated with the first historical use of the system on a machine with a “Back-Up Carriage”, circa 1986.

Appendix – Pre-Compensation Axis Squareness, As Measured at the Tool Point

The plots below show tool point axis squareness errors over the entire approximately 58’ x 10’ x 7’ working envelope of the system. All dimensions are in inches.



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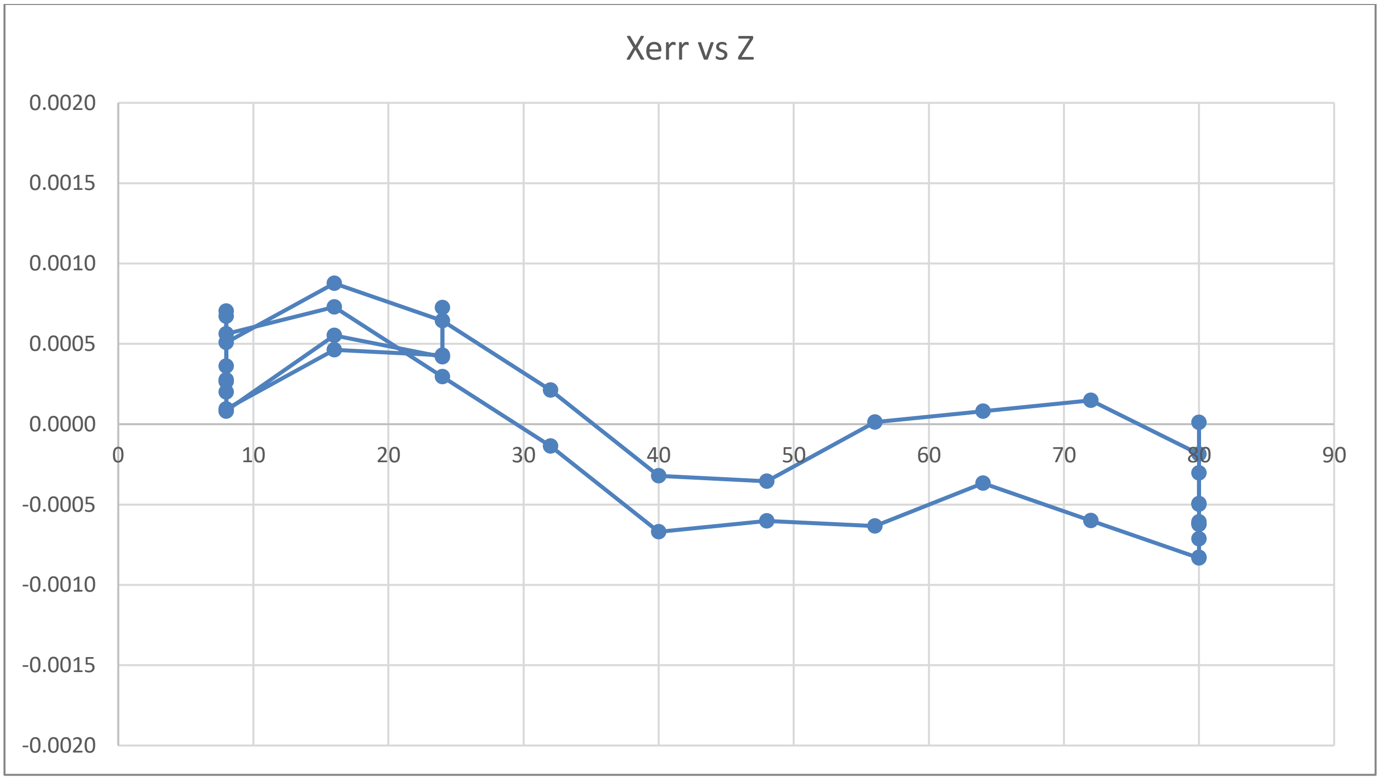
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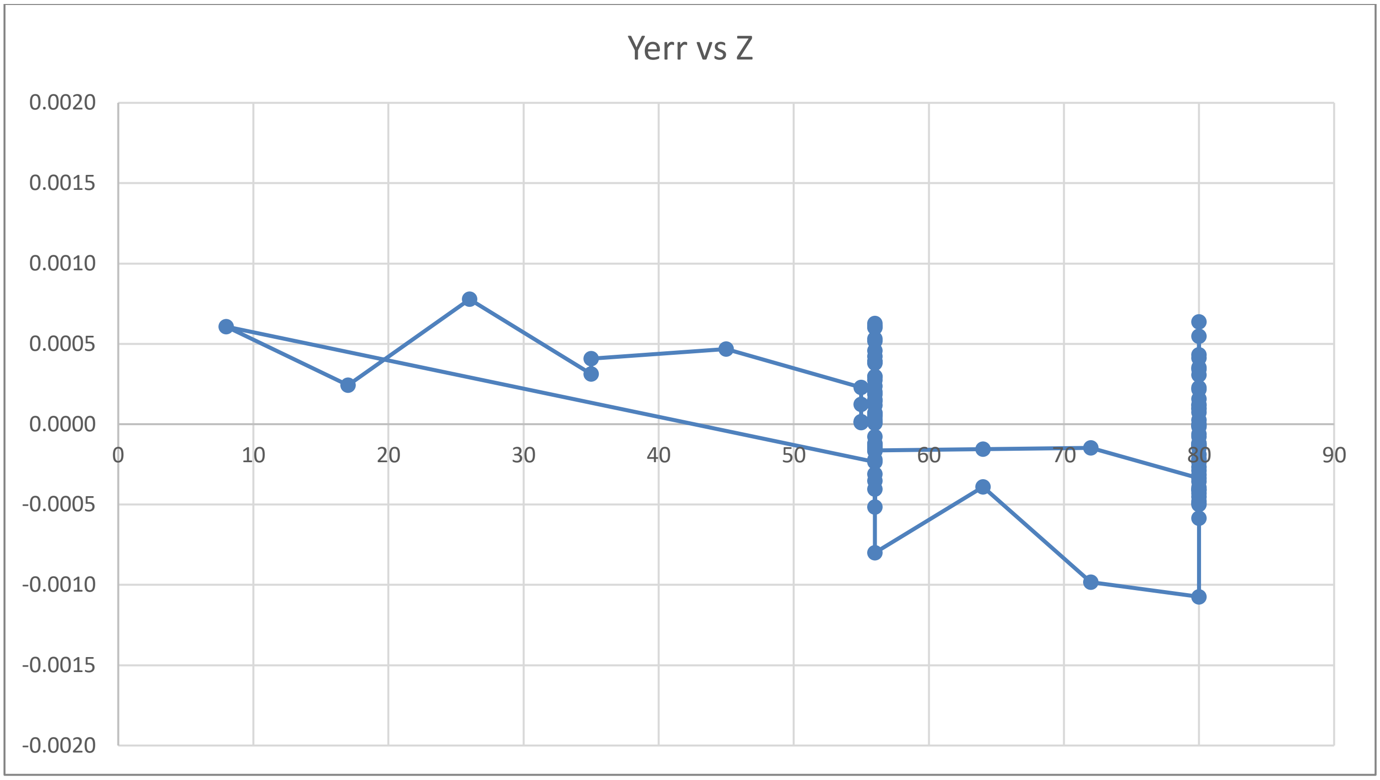
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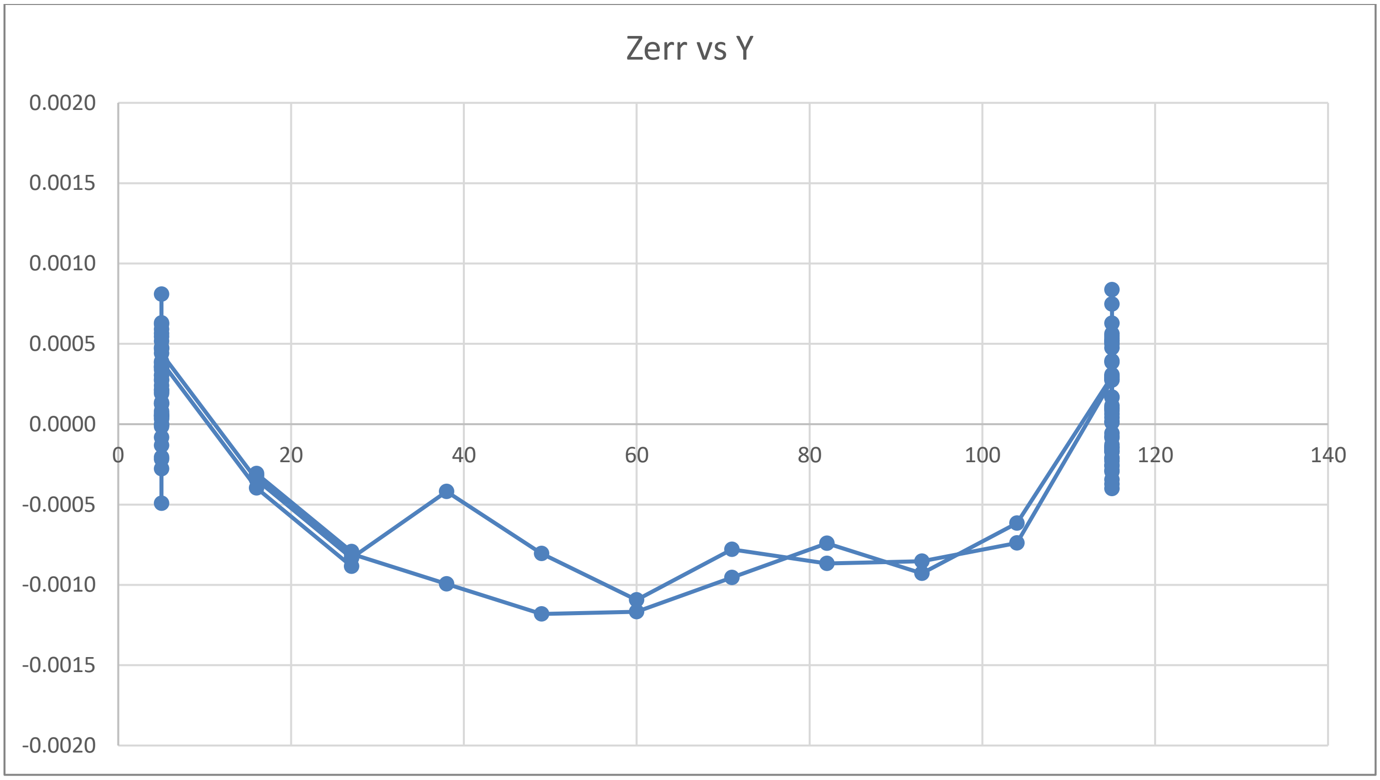
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