2005 WJTA American Waterjet Conference
August 21-23, 2005 • Houston, Texas

Paper 7A-2

TAPER-FREE ABRASIVE WATERJET CUTTING WITH A TILTING HEAD

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ABSTRACT

A tilting head angles an abrasive waterjet's nozzle as it moves along the cutting path, resulting in a taper-free cut. This paper offers insight into the product development process of this innovative concept — a mechanism that allows the nozzle to tilt about the jet entry point with minimal compensation motions in the X, Y and Z direction. Tilting and compensation motions are computed with a mathematical model of the 5-axis motion system and interpolated into motor steps along the cutting path. Use of servomotors and harmonic drives, as well as other precision components, ensure high motion accuracy. Error mapping on each individual tilting-head assembly further enhances precision. In each cutting application, a built-in taper model considers material type and thickness, radius of curve and other process parameters to accurately predict the corresponding taper angle, which is then removed by the tilting head. A taper offset feature is also available to offset any remaining taper. Cutting tests prove that tilting head produces virtually taper-free parts.

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1. INTRODUCTION

The waterjet industry has experienced rapid growth in recent years, which is partially attributable to improvements in the machines, allowing them to cut much more precise parts. Machine manufacturers are more experienced in building precision X-Y tables and have a better understanding of sources of errors. Servomotors (rather than stepper motors) are used, which reduce positioning errors. Precision ball screws (rather than lead screws) are used, which reduce pitch errors. Precision bearings reduce backlash and improve repeatability. More attention is paid to straightness, squareness, and rigidity of the machine structure. Ballbar and laser interferometer are often used for geometric error measurement, and error mapping is sometimes used for error compensation. Cutting models are used to predict and compensate for various jet behaviors, such as jet lag, kick-back and so forth.

A typical part cut with a waterjet has a certain amount of taper, especially when cutting sheet metals. Existence of taper is one of the drawbacks of abrasive waterjet cutting, compared to traditional milling and EDM machining. If taper can be eliminated, many more applications for this technology will be created. Parts that are currently cut with wire EDM could be cut with an abrasive waterjet, at much faster cutting speeds.

Figure 1. The tilting head of this paper

Taper-free abrasive waterjet cutting presents a major challenge to the equipment manufacturing community, however. Theoretically, taper can be eliminated by proper adjustment of the cutting speed, but this may result in a slow and inefficient job, because only a small portion of the jet is involved in taper removal, with a majority of the jet being pushed away by the walls on the two sides of a kerf.

Manipulating the jet to achieve desired geometry was first proposed by Henning. His paper in 1997, and a later paper with Anders in 1998 described automated taper correction in abrasive waterjet cutting. Based on this idea, tilting head products have been developed. Figure 1 shows a currently marketed tilting head that has proved to be an effective technology for taper-free abrasive waterjet cutting. This paper will provide some insight into the development of this product.

2. INNOVATIVE CONCEPT OF A TILTING HEAD

One of the chief requirements for the tilting head mechanism is that it must allow quick tilting motion along the cutting path, so that tilting and cutting are synchronized. Quick motions of the tilt head imply high accelerations of the X-Y mechanism, unless the tilting mechanism pivots about the tool tip. A previous paper by the authors (2003) described a patent pending mechanism that closely approximates a tool tip pivot. For an easier understanding of this mechanism, a two-dimensional, simplified version was described. A schematic of this 2D version (Figure 2) shows that the tool tip has only a small displacement even with a large tilting angle.

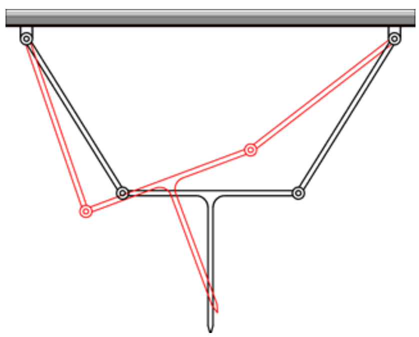


Figure 2. Two-dimensional simplified version of tool tip pivot, showing two positions

When this idea was extended to three-dimensions, a third link was added. The three-link mechanism had two more degrees of freedom than the 2D version. Adding a third link also meant the tilting plate could twist about a vertical axis. This twist motion was restrained by using universal joints at one of the three links. It is easiest to understand this 3D mechanism with an earlier prototype, as shown in Figure 3.

Figure 3. Early prototype of a tilting head (Note that nozzle has been replaced by a rod that has a sphere at its end, representing tool tip)

3. MECHANICAL DESIGN

Implementing the innovative concept for the tilting head required creative mechanical design. Because no part of the nozzle or tilting plate was fixed in three-dimensional space, and the tilting plate has two degrees of freedom, determining how to drive the tilting plate became a great challenge.

In the initial prototype design, the tilting plate was driven by two linear actuators (Figure 4). These two actuators connected the tilting plate to a fixed plate with ball joints at their ends. This design was not ideal in terms of rigidity and accuracy. A bold idea was proposed — replace the two perpendicular yokes of the top universal joint with two independently powered rotary drive shafts (Figure 5). This idea proved to be a key to the success of the device.

Figure 4. Initial design of tilting head with two linear actuators

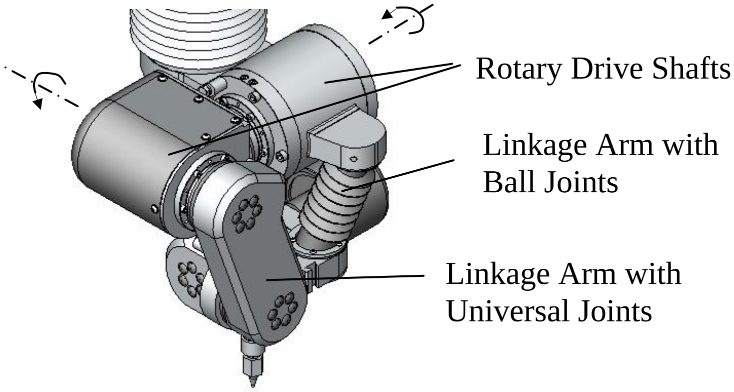


Figure 5. Current design with two rotary drive shafts

3.1 Precision Components

Each of the two rotary drive shafts consists of a servomotor and a harmonic drive. Servomotors offer smoother motion and higher torque than stepper motors of similar size, as well as more consistent performance, especially at low speed. The dynamic performance of a particular servomotor is also a factor. Dynamic stiffness, settling time, and tracking accuracy are all important considerations for consistent performance.

General information about harmonic drives is covered on the Harmonic Drive Systems, Inc. website (2005). A harmonic drive (Figure 6) consists of a wave generator, a flexspline, and a circular spline. The wave generator deflects the flexspline into an elliptical shape so that its teeth engage with those of the circular spline. When the wave generator rotates one revolution, the flexspline will rotate to the opposite direction by two teeth relative to the circular spline.

Using a harmonic drive for speed reduction has many benefits. A harmonic drive has a high-speed reduction ratio (1/30 to 1/320) and no backlash. Because about 30% of the total number of teeth are engaged simultaneously, it offers high precision, high torque, and quiet and vibration-free operation. The teeth mate with each other in two symmetrical positions 180 degrees apart, which reduces the impact of tooth pitch errors and accumulated pitch errors. Compared with other drive components of equal torque and speed reduction ratio, its size is smaller. Because minimal sliding motion occurs in the driving force transmission, it is also more efficient.

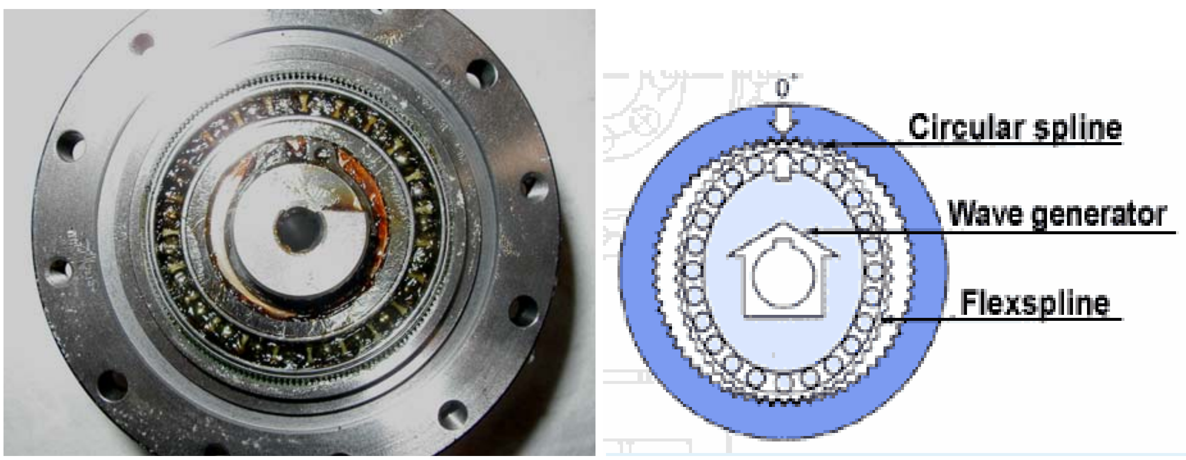


Figure 6. Harmonic drive and its illustration (from reference website)

The housing unit of the harmonic drive incorporates a high-stiffness crossroller bearing to support output loads. This type of bearing can withstand high axial and radial forces, as well as high tilting moments. The reduction gear is thus protected from external loads, guaranteeing a long life and consistent performance. The integration of an output bearing also reduces subsequent design and production costs by removing the need for additional output bearings.

The linkage arm with the universal joints is subjected to an axial load and a twist moment. A unique design was employed to provide sufficient strength. The other two linkage arms are subjected to axial loading only. The focus of their design was that they were made to equal length.

3.2 Hard Plumbing

Earlier 5-axis waterjet machines were not designed for taper removal and they were typically used in applications that required large tilting angles. In those machines, hard plumbing included high-pressure swivels for each axis. These swivels are expensive and difficult to maintain, and they are large, taking up more space. Rather than incur the trouble and expense of these swivels, a flexible coil design of hard plumbing was used to accommodate the 5-axis motion requirements (Figure 7).

Figure 7. Coil of high pressure tubing for tilting head

3.3 Hard Stop

Using a hard stop gives the tilting head a repeatable and known home position. If the tilting head loses its position because of power outage, interruption of program or any other reason, control software can drive it back to home, and then reestablish the vertical position that is perpendicular to the X-Y plane.

3.4 Protection Against Harsh Environment

Abrasive waterjet cutting presents a harsh environment for precision mechanical devices that may be close to the nozzle. Abrasive grit and water can affect precision components in the tilting head, so the drive shafts are protected with aluminum housings with hard anodize on the outside; the Z-axis and linkage arms are covered with bellows; and “V” ring seals are used at the bearings, making the tilting head virtually maintenance-free.

3.5 Solid Modeling

The entire tilting head assembly was designed with SolidWorks® 3D CAD software (Figure 8). Using the latest solid modeling technology allows design optimization, error checking, and motion simulation. It also provides a highly visible, step-by-step assembling procedure. This project won an award in the 2003 SolidWorks® Worldwide Mechanical Design Contest (3rd place out of 150 contestants).

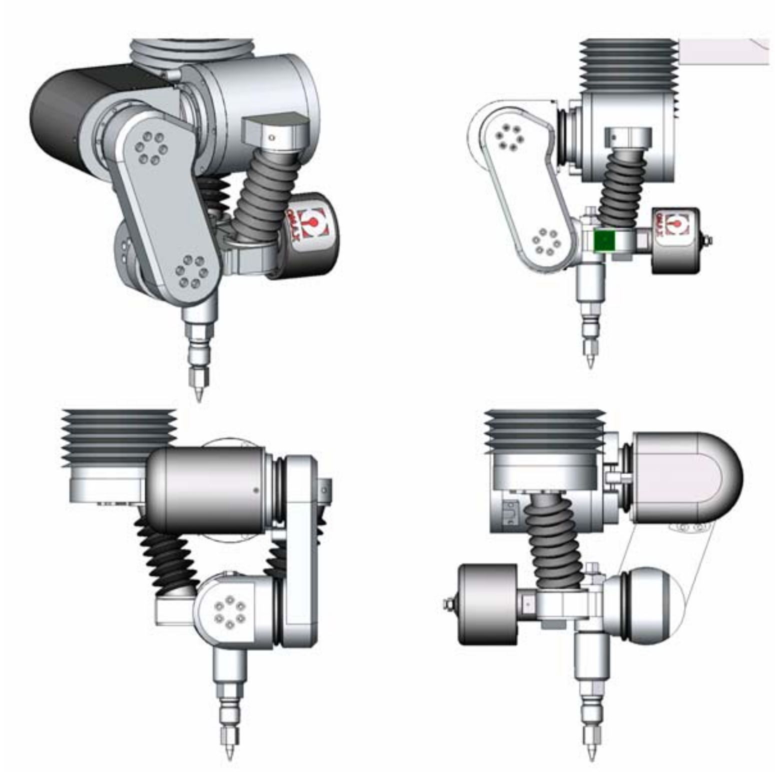


Figure 8. Solid model of the tilting head

4. SOFTWARE DEVELOPMENT

Software is a vital part of this product. The basic requirements for the software were: to predict the amount of taper that would occur for a given scenario, and thus the tilting angle; compute the required motions of the five-axes to accomplish the tilting; compensate for any known errors; interpolate the tool path into motor commands and then feed the motors with the step and direction commands when they are needed. The software also gives the tilting head the capability of squaring itself and allows the removal of any remaining taper that is not predicted by the model.

4.1 Five-Axis Motion Computation

Figure 9 is a schematic of the tilting mechanism for computation purpose. The plane defined by P5-P6-P7 is considered a “fixed” plane, which means no tilting motion occurs. The plane defined by P2-P3-P4 is the “tilting” plane. The “tilting” and the “fixed” planes are connected with three linkage bars (P2-P5, P3-P6 and P4-P7) of equal length. One of them (P2-P5) has universal joints at its ends and the other two have ball joints.

The universal joints provide a constraint for the twisting motion of the “tilting” plane. In the two perpendicular yokes of the top universal joint are the two drive shaft assemblies. The nozzle (P1-P0) is mounted on the “tilting” plane. The point P0 represents the jet entry point, at the joint of the extension lines of the three linkage bars when no tilting occurs, and P0n the new position of P0 at tilting. Points P2-P3-P4 and P5-P6-P7 form two equilateral triangles.

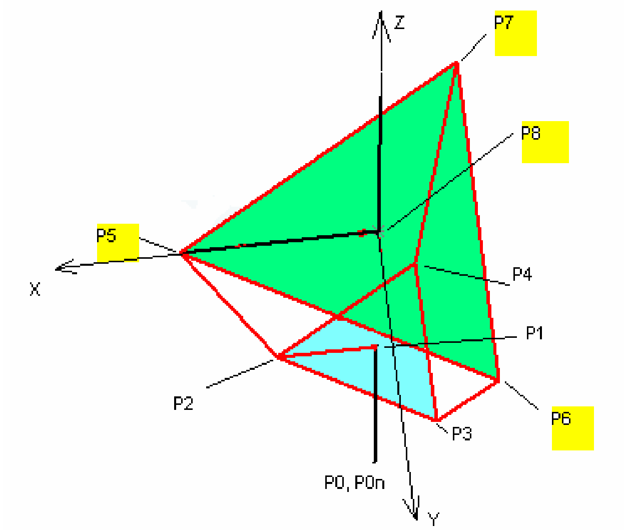


Figure 9. Schematic of the tilting mechanism

With known positions of P0, P5, P6, and P7 and for given tilting angles (Ax for angle in the Y-Z plane and Ay for the X-Z plane), the goal is to determine the new positions P0n and the angular motion of the two drive shafts. However, these unknowns cannot be determined directly without knowing the positions of intermediate points P1, P2, P3, and P4. Therefore, we need to establish and solve 15 nonlinear equations for the 15 unknowns (X, Y, Z positions of P0n, P1, P2, P3, and P4). Among the 15 equations, 12 of them come from the distance formula. The other three equations are:

$$\frac{Y1 - Y0n}{Z1 - Z0n} = \tan(Ax) \tag{1}$$

$$\frac{X1 - X0n}{Z1 - Z0n} = \tan(Ay) \tag{2}$$

$$\frac{Y1}{Z1} = \frac{Y2}{Z2} \tag{3}$$

The first two equations can be easily derived from the schematic. The third equation is the universal joint constraint. The U-joint at P5 has a rotary axis along the X-axis and the U-joint at P2 has one along P1-P2. These two rotary axes always share the same plane, which is perpendicular to the Y-Z plane and passes the origin (P8). When this plane is projected onto the Y-Z plane, the third equation can be easily derived. The angular motion of the two drive shafts can be calculated using these two formulas (Tx is for rotation about X axis and Ty about Y axis):

$$Tx = -\arctan\left(\frac{Y2 - Y5}{Z2 - Z5}\right) \tag{4}$$

$$Ty = \arctan[\frac{X2 - X5}{Z2 - Z5} \cdot \cos(Tx)] \qquad (5)$$

4.2 Tilting Motion and Error Compensation

A true tilting mechanism has no motion in X, Y, or Z direction when it tilts. Our tilting mechanism is an approximation of such a mechanism, and it does introduce a small amount of displacement in the X, Y, and Z directions.

When it tilts, the tool tip will move about the true pivot point in the pattern shown in Figure 10. This plot shows positions of the tool tip when the tilting head is tilted 9° off the Z-axis and swings around to 16 equally spaced positions (note that (0, 0) is the true pivot point).

The amount of displacement depends on the tilting angle. The larger the tilting angle, the larger the displacement is. With the algorithms described earlier in this paper, the amount of displacement is computed for a given tilting angle and is then compensated for on every motor step when the cutting tool path program is compiled.

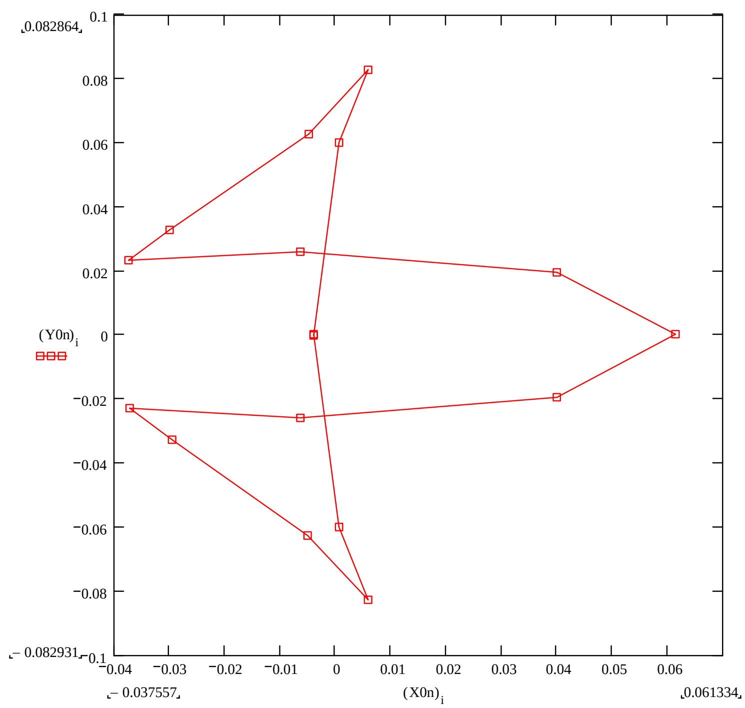


Figure 10. Displacements of nozzle tip for 9° tilt ((0, 0) is true pivot point)

Even though high-precision components are used for constructing the tilting head, a small amount of error for each component can accumulate to a significant amount for the assembly. Figure 11 shows the accumulated errors for one of the tilting head assemblies at 9° tilt and 16 equally spaced positions around the Z-axis. To achieve the desired precision level, these accumulated errors are measured for each individual tilting head assembly and are then compensated for on every motor step when the cutting tool path program is compiled.

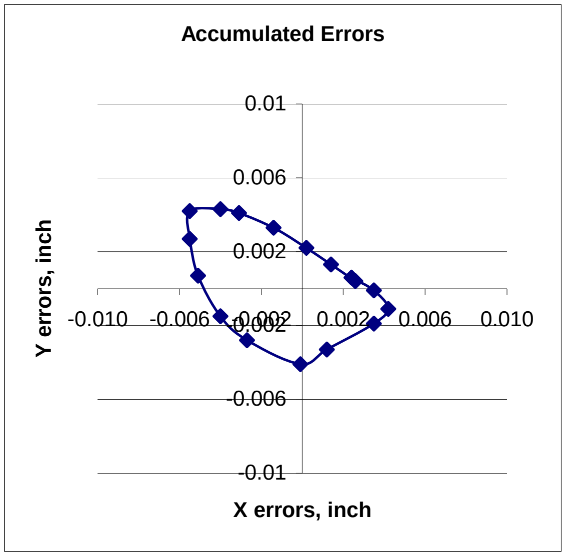


Figure 11. Accumulated errors at 9° tilt and 16 equally spaced positions around the Z-axis

4.3 Taper Model

The previous paper by the authors (2003) has discussed the impact of process variables on the amount of taper in a cut. Among the 11 variables investigated, seven of them are the most important. The seven variables are abrasive size, orifice diameter, water pressure, quality index (an indication of cutting speed), abrasive flow rate, workpiece thickness, and machinability. A taper model was developed to predict the impact of these seven variables on taper.

Taper on an arc, however, is more complex, because of extra taper caused by the jetlag, as shown in Figure 12 (JL stands for jetlag, TE for taper error as if it were a straight line, R for arc radius at top, and BR for radius at bottom of part).

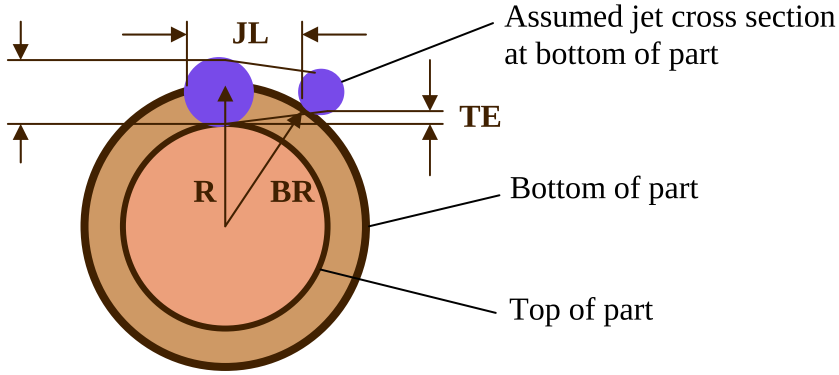


Figure 12. Extra taper on arc caused by jetlag

Theoretically, taper on an external arc (such as in a disk) and on an internal arc (such as in a hole) can be calculated with the following two equations.

For an external arc:

$$TaperExt = TE + \sqrt{R^2 + (JL - TE)^2} - R \qquad (6)$$

For an internal arc:

$$TaperInt = TE - \sqrt{R^2 + (JL - TE)^2} + R \qquad (7)$$

During the compiling of a tool path program, the built-in taper model receives input about the path geometry (straight line or arc, internal or external, and radius) and the cutting speed of each motor step, and then predicts the appropriate tilting angles at each motor step along the path.

4.4 Motion Interpolation

Motion interpolation follows the concept described by Olsen in US patent No.5,508,596 (1996). When the software compiles a tool path with tilting motion, it first calculates the appropriate speed for each entity in the path, based on the type of entity (line or arc), radius, quality selection, workpiece thickness, corner sharpness, and machinability, as well as other jet parameters (water pressure, orifice diameter, mixing tube diameter, abrasive type, mesh size, and flow rate). At this point, the path is described like a typical G & M code program — the speed has jumps between entities.

The software then interpolates each entity into the command resolution of the motors. Next the entire path is reviewed, making speed adjustments at the motor command level to set accelerations that do not exceed either machine limits or limits imposed by jet behavior affecting accuracy.

After the speed of each point is determined, the taper model predicts the appropriate tilting angle for each individual step. In this manner, the tilting not only corrects for the taper error of each entity, but also corrects for the taper change caused by speed variation within an entity.

For example, when cutting a 90° corner from aluminum that is 51 mm (two inches) thick, without a tilting head the corner will have a “wash-out” effect caused by the slowdown towards the corner. However, a tilting head gradually changes the tilting angle as it slows down on its approach to the corner. As a result, the part has a squared corner while all the “wash-out” effect is left on the scrap (see Figure 13).

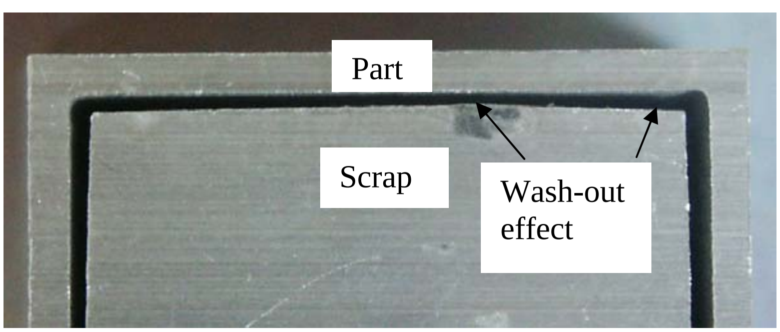


Figure 13. Wash-out effect is put on the scrap with tilting angle varying towards the corner

The 5-axis motion computation module computes the appropriate tilting motions for the two rotary axes and the error compensation motions for the three linear axes. The appropriate motor steps are then inserted into the program, and the complete preplanned path is stored in digital form as an array of position vs. time data for motion axes.

When cutting begins, the array is simply fed to multiple servomotor drivers as step and direction commands. Such an extremely computation-intensive interpolation is almost impossible for a traditional CNC motion control, because it is capable of interpolating only one or a few lines of G & M codes at a time as the machine is moving.

4.5 Squareness Calibration

The cutting head must be exactly perpendicular to the work surface prior to machining parts. This is accomplished via a one-time setup that tells the computer where the nozzle must be to be considered “square.” Before machining each part, the nozzle is returned to this known square position. The squaring calibration process involves placing a flat surface over the slats on the cutting table, and replacing the nozzle with a shaft, on which a dial indicator is attached (Figure 14).

Figure 14. Squareness calibration tool in action

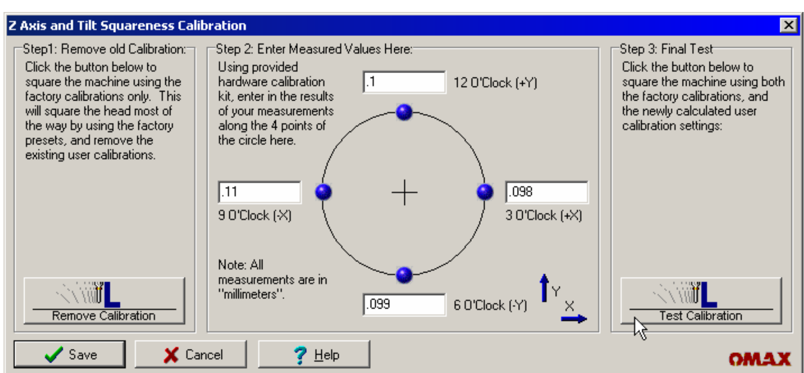


Figure 15. Software dialog for one-time calibration to insure nozzle is square to work surface

The dial indicator is then swung around to four different positions, and the measurements are entered into the computer (Figure 15). It only takes three points to determine a plane—the fourth point is used to check the accuracy of the measurements, preventing potential measurement mistakes.

Once the calibration has been performed, and the nozzle position at square to the work surface has been determined, it is possible to quickly square the tilting head. This is done without user intervention. The computer moves the tilting head all the way to a hard stop to establish its home position and then moves it back a specific angle, as determined by the squaring calibration. The procedure is automatically done for both rotary axes in sequence. The squaring process is typically run when the machine is first turned on. From then on, the computer tracks the position of all axes, so further squaring is not necessary, unless something abnormal, such as a power outage, necessitates re-squaring.

4.6 Taper Offset

Taper is accurately predicted using the taper model. However, even the best model cannot always predict the exact amount of taper. For example, there may be additional taper as the result of a worn nozzle, or other conditions beyond the visibility of the model. Therefore, a setting in the software for “taper offset” is used for fine-tuning by the operator of the machine.

For example, if a part is cut, and found to have 0.025 mm (0.001 inch) of taper, a taper offset of -0.025 mm could be entered into the software to reduce the taper to almost nothing. For most applications that require only a medium amount of precision, the taper offset would simply be left at zero.

Taper offset can either be entered in degrees, or in a unit of measurement such as inches or millimeters for taper error at bottom of part.

The “taper offset” is analogous to the “tool offset” — for high precision applications, it is adjusted based on tool wear and measurements from previously machined parts. Advanced users can also use “taper offset” for deliberately adding taper to parts.

5. MANUFACTURING AND TESTS

Manufacturing and testing are the last steps in transforming this idea into a product. Done properly, the design goal can be achieved — making precise, taper-free parts. This process involves machining parts to the specifications, assembling using proper procedures, and finally testing the assembled products.

5.1 Assembling with Special Tools and Care

To achieve design precision, several special assembling tools are used. One of them, a tool used to calibrate the length of the two linkage arms, is as shown in Figure 16. The picture on the left shows the tool itself being calibrated with a special pin. The picture on the right shows two linkage arms being set to the exactly same, calibrated length.

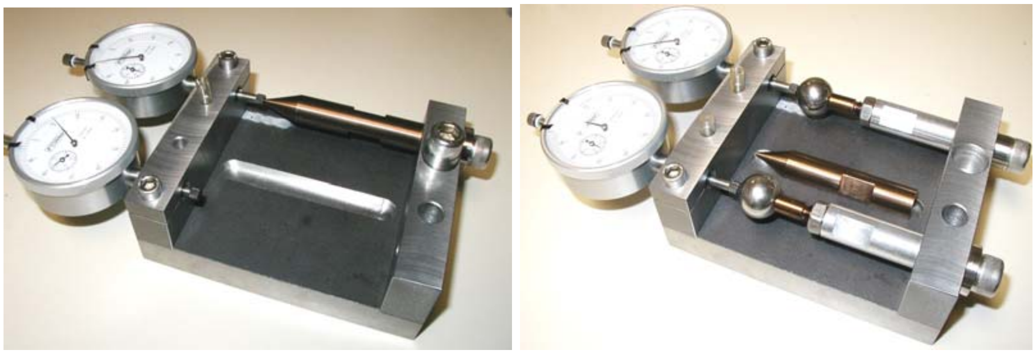


Figure 16. Linkage arm calibration tool

Human factors are also important in building quality products. It is important that all people involved pay close attention to detail. Failure to follow correct procedures can end up resulting in costly rework.

5.2 Error Map Creation and Quality Control Tests

To eliminate errors resulting from accumulation of part tolerance, each tilting head assembly goes through a process of error map creation and quality control tests. Figure 17 shows the test stand for these tests.

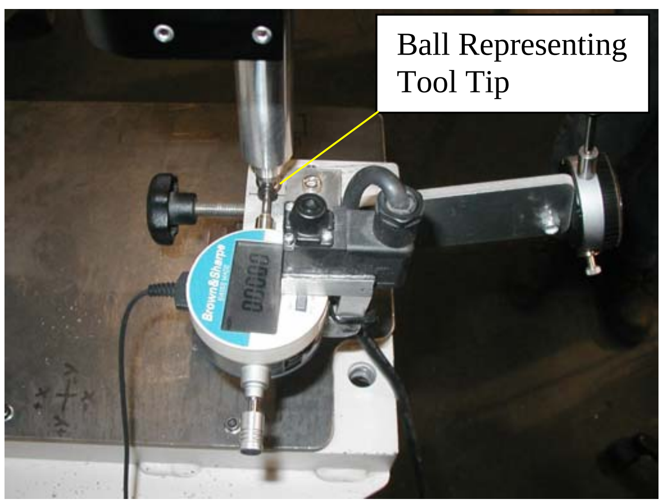
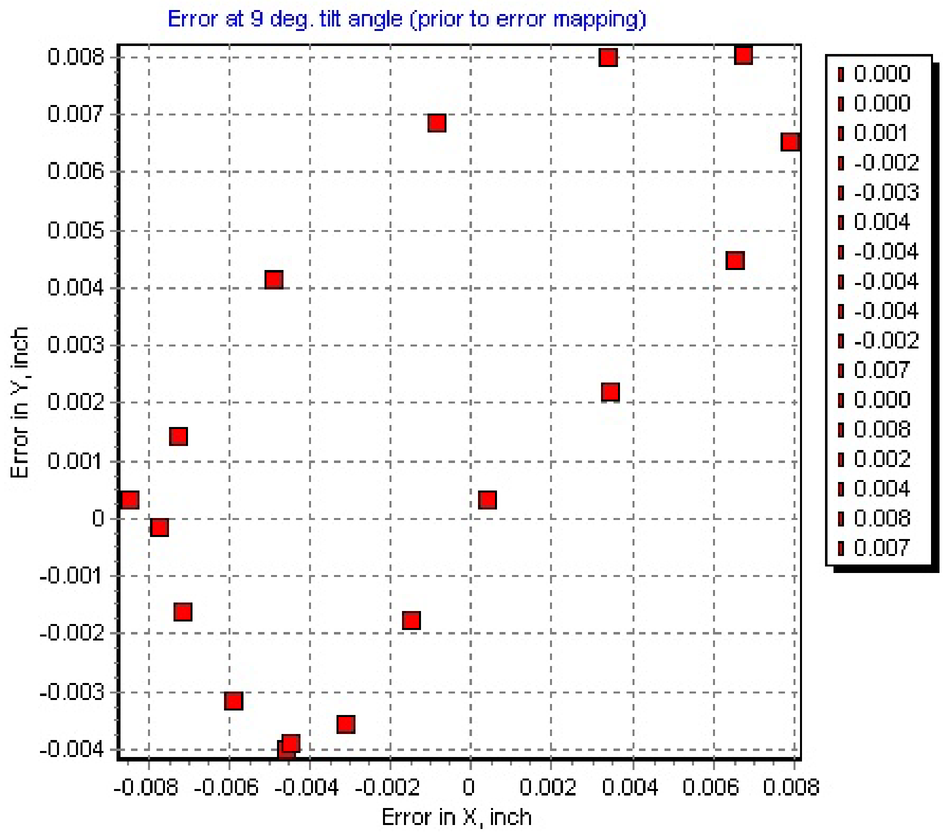


Figure 17. Tilting head test stand

As the tilting head moves to a certain angle off the vertical Z-axis, the error movement on the horizontal plane of the ball, representing tool tip, is picked up by a precision digital dial-indicator and recorded into a data file. An error model is then built based on these data and is used to construct an error map. With the error map activated, measurements are done again at 1, 3, 6, and 9 degrees off the vertical axis, and at 16 equally spaced positions around to verify that residual errors are within ±0.025 mm (0.001 inch). The errors before and after error mapping of a sample unit is displayed in Figure 18 (the angle, Phi, is the angle between the X axis and the nozzle axis projected onto X-Y plane).



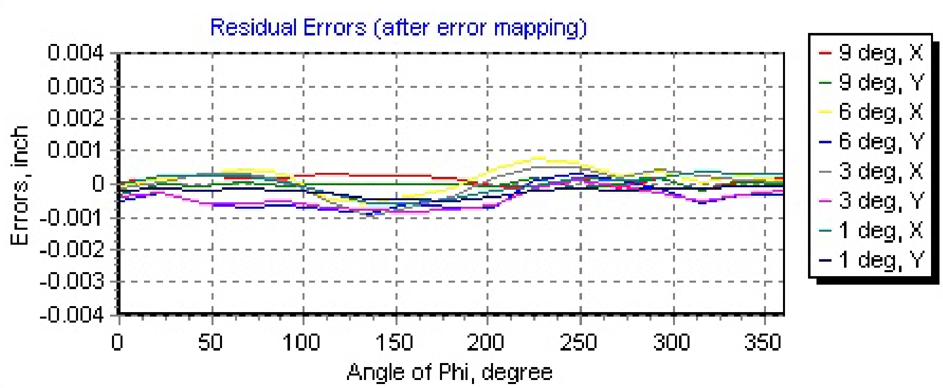


Figure 18. Errors before and after error mapping

5.3 Cutting Tests

Cutting tests were conducted to validate the performance of the tilting head. In one test, an "all-feature" part was cut, as shown in Figure 19. This part allows measurement of remaining taper for all cutting qualities and examination of quality of all different features. The measured remaining tapers for this particular sample part are listed in Table 1. The data for this particular part may give an impression that a higher quality index produces a smaller taper. This is usually true without the tilting head. With a tilting head, this may not be true. A tendency, however, is that the model provides more accurate predictions at higher quality indexes.

Figure 19. An "all-feature" part cut with a tilting head

Table 1. Taper errors measured from the part shown in Figure 19 (top section)

Quality Index	Q1	Q2	Q3	Q4	Q5
Taper/Side, mm (inch)	0.030 (0.0012)	0.025 (0.0010)	0.015 (0.0006)	0.015 (0.0006)	0.015 (0.0002)

This part also shows the fine features cut with the tilting head. Sharp corners are the most revealing fine features, because they can magnify any existing taper angle, making the taper easily visible. In order to showcase this technology, a pair of tweezers was selected as a sample part. Figure 20 shows the tilting head completely removes taper at sharp corners.

Figure 20. A pair of tweezers cut with a tilting head showing taper-free tips

6. SUMMARY

Taper-free cutting opens up many opportunities for the abrasive waterjet industry, while at the same time presenting a great challenge. Taper is eliminated by use of an innovative tilting head that approximates a tool tip pivot, allowing easy synchronization of cutting and tilting, while use of precision machine components ensures product reliability and minimizes part tolerance errors. Unwanted motions from tool tip pivot approximation are calculated and compensation is made. Errors due to part tolerance accumulation are also compensated for. A taper model predicts taper angle by considering path geometry, speed variation, and jet parameters. The five-axis motion program is generated by interpolating the tool path into motor step commands for all five axes based on path geometry, speed variation, the cutting model, and the taper model. Hardware and software methods are used to make sure the tilting head begins at a repeatable vertical position, exactly perpendicular to the material to be cut. A taper offset method is used to remove any taper that may remain. To ensure accuracy and reliability of the tilting head, the manufacturing process must employ special tools and care. Errors due to accumulated part tolerance or assembling mistakes are detected in the quality control procedure. Assembling mistakes, if any, are corrected and remaining errors due to part tolerance are mapped and compensated for during tool path interpolation. Cutting tests are done to verify the accuracy of the taper model, motion interpolation, and the overall performance of the tilting head as a product. The results indicate that the tilting head achieves the goal of taper-free cutting.

7. AKNOWLEDGMENTS

The authors are thankful to OMAX Corporation management for permission of publishing this paper and to Robert Gidley for the editing work.

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