RFQ POLE-TIP CONSTRUCTION*

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Summary

The success of the radio-frequency quadrupole (RFQ) proof-of-principle (POP) tests[1] conducted in 1980 at Los Alamos have essentially guaranteed that the RFQ linac will be used in many accelerator projects soon. Several RFQs are already under construction at Los Alamos, and we expect to be designing and machining the vanes for several RFQs to be built at other installations.

The technique for machining the vanes for the POP RFQ was developed by Williams and Potter.[2] While retaining their basic approach, we have modified their technique for generating the data required by the milling machine from the parameters defining the vane shapes. The objective of this exercise has been to develop a generalized fabrication procedure that could be used in commercial machine shops.

Computer Numerically Controlled (CNC) Machine

The ideal cross section for RFQ vane tips is pseudohyberbolic, a shape that is difficult, even for the most advanced milling machines, to reproduce. Typical CNC mills do, however, have linear and circular interpolation capabilities. For this reason, the ideal cross sections are approximated by straight and circular milling cuts.

For machining RFQ vanes, AT Division has leased a MAZAK V-10 three-axis vertical mill equipped with temperature control and a FANUC 7-M controller. The controller memory contains the generalized software for machining vane tips, and specific vane-tip data are read from punched paper tape. By taking advantage of certain advanced features of the controller (cutter size compensation, stored subroutine capability, internal arithmetic operations, etc.), the required data set has been reduced to a minimum.

Cutting-Tool Path

To describe the vane-tip geometry in the milling machine reference frame, we use a left-handed cartesian coordinate system; the x-axis being in the longitudinal direction, increasing with particle velocity, y positive to the right and z positive upwards. The origin is defined to be in the center of the vane-tip's base at its upstream end. In some cases, the vertical origin is taken to be a horizontal reference surface, machined into the vane blank, to be used for inspection and alignment measurements. The finished vane tip has left-right symmetry about the y=0 plane.

At discrete longitudinal positions spaced Δx_c apart, the tool makes one transverse path as shown in Fig. 1. The mill is programmed to cut a straight-line segment up one side, cut a circular

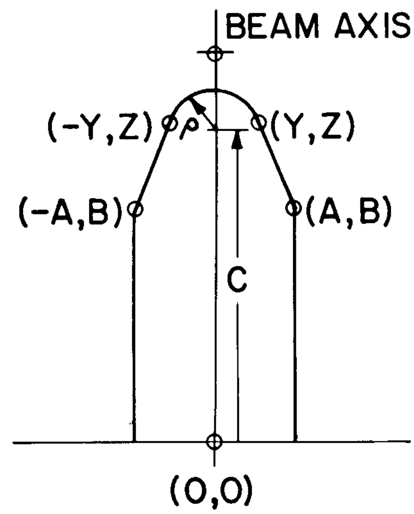

Fig. 1. Vane cross section showing cutting-tool path.

arc across the top, and cut a straight-line segment down the other side.

Except in the radial matching section, the vertical height, B, remains fixed throughout the length of the vane. At points (Y,Z) and (-Y,Z) in Fig. 1, the straight-line segments are tangent to the circular tip. The radius, ρ, and the location of the center of the circle, C, vary continuously along the length of the vane. In the radial matching section, ρ may be larger than the half-width, A, of the part, in which case the tool path is a single circular arc.

Machining Procedure

A vane is usually machined in two passes. The first pass is a rough cut that removes most of the metal. The second pass is the finishing cut. When the rough cut is made, the machinist can set a switch on the control panel that causes only one out of three transverse cuts to be made. If the same-diameter tool is used for both the rough and finish cuts, then the same paper tape can be used for both operations. It is desirable in some cases to use a larger tool for the rough cut, in which case a special tape generated for that tool size is required.

In the rough-cut mode, the mill cuts metal on both the clockwise and counterclockwise pass to shorten the machining time. For the finish cut however, where surface finish is an important consideration, this technique causes an irregular surface because of the backlash inherent in the milling machine. This effect can be tuned out numerically for individual parts and is a standard

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feature of the controller. We find it more satisfactory in general to cut metal only in the clockwise direction. This eliminates transverse backlash and requires compensation in only the vertical direction. At the completion of one cutting pass the tool moves away from the part and returns rapidly to the other side of the vane for another clockwise cut.

Because the machining procedure is so repetitive, the instructions governing the motion of the mill are programmed into subroutines that are loaded into the memory of the controller. There are subroutines for clockwise and counterclockwise passes for both the radial matching section and the general case. Some additional coding is used to determine whether a rough or final cut is desired. The paper tape itself is considered to be the main program but contains only work-surface coordinates and subroutine calls, plus an occasional longitudinal coordinate to allow the machinist to restart in the middle of a vane if necessary.

From Desired Vane Shape to Cutter Path

The equation defining the circular portion of the vane surface is

$$f_S(x, y, z,) = (z - z_0)^2 + y^2 - R^2 = 0 \quad ,$$

where z_0 is the center of the circular tip and R is its radius; both z_0 and R are known functions of longitudinal position, x. The radius vector $\vec{r}_c$, specifying the center of a spherical cutter of radius R_c, when the cutter is in contact with the vane surface at $\vec{r}_S$, is

$$\vec{r}_C = \vec{r}_S + R_C\vec{n}_S \quad ,$$

where $\vec{n}_s$ is the unit vector normal to the vane surface at $\vec{r}_s$, and is obtained by taking the gradient of $f_s(x, y, z)$.

For each longitudinal position along the vane surface at the midplane, $(x_s, 0, z_s)$, one can calculate the corresponding location of the center of the cutter $(x_c, 0, z_c)$. Because we wish to make the cuts at discrete longitudinal intervals, separated by a constant value of Δx_c, we must use an iterative procedure to determine the x_s corresponding to each x_c. Having found x_s, then the radius of curvature R at the tip is known, and one can calculate the quantities ρ and C (refer to Fig. 1) required by the milling machine.

Milling-Machine Data

By taking advantage of its symmetry, the vane-tip shape can be uniquely described for any value of x by only four parameters, two of which (A and B) are constants. If the program capability of the milling-machine controller were powerful enough to calculate the tangency points, then two parameters, ρ and C, would be sufficient to describe each longitudinal cross section. The 7-M controller does not have this capability; however, it is sufficient to specify C and the point of tangency (Y,Z). Only three parameters are required, therefore, to describe each unique cross section to the controller: Y, Z, and C. The data for a single step requires only 3.7 in. of paper tape.

The data punched on tape are for the finished surface. When the part is actually cut, the tool path is calculated by the controller based on the surface coordinates and on the radius of the cutter. During the rough cut, typically 10 mils of excess material is left uniformly on the surface by entering into the tool compensation register a tool radius 10 mils larger than the actual radius. This excess material is removed during the finish cut. If the surface is given a 2 mil copper plating, then an additional 2 mils is removed by entering into the register a tool size 2 mils smaller than the actual radius.

From the Cutter Path to the Actual Vane Shape

The above procedure ensures the finished vane's having the correct z_s and R at all points along the midplane. But, because of the finite cutter size, the actual cross sections of the vane tip will deviate slightly from the desired circles. However, knowing the complete cutting-tool path, it is possible to calculate the resultant vane shape.

The coordinates of the tool's center are known for the entire vane. The locus of points swept out by the center of the cutting tool can be thought of as defining a surface, which we will call the cutter surface. Unless the cutter tool is too large, there is a one-to-one correspondence between points on the cutter surface and points on the resultant vane surface

$$\vec{r}_S = \vec{r}_C - R_C\vec{n}_C \quad ,$$

where $\vec{n}_c$ is the unit vector normal to the cutter surface.

Choosing Size of Tool and Longitudinal Step

Some compromises are necessary in choosing the cutter size and the step size. The cutter should be as large as possible so that a good surface finish can be achieved with a large step size. This means reduced time and cost for machining a vane. On the other hand, a cutter that is too large will distort the surface or gouge out material. The radius of the cutter must be less than the minimum radius of curvature of the "valleys" along the vane tip. However, the vanes usually have more curvature at the side, and it is not clear where one should set the limit.

Cutting Tool

Using the generalized software written for the milling machine, RFQ vanes could be machined with either a ball end mill or a circular cutter having radiused teeth and mounted on a right-angle tool holder. Experience has shown that end mills in this application have some limitations. Even carbide tools tend to wear out during the finish cut, leaving at least an esthetically unpleasing surface. This effect is different on either side of the part because in one case the tool is climb cutting, whereas on the other it is cutting conventionally. In addition, cutting speed is slow because of the limited ability of the tool to cut well near its tip. A circular cutter would have substantially longer life, higher cutting speed, and should produce a better surface finish. This technique has not been tested to date, because most of our development has been aimed at 440-MHz structures where the vanes are small, relative to a right-angle tool holder, and interference with holding fixtures has been a problem.

Practical Experience

To date, vane tips have been machined for four different projects at three different frequencies: 80, 200, and 440 MHz. Each vane tip has been machined using ball end mills in copper, steel, or aluminum. The paper-tape capacity of the machine is only about 800 ft, or the equivalent of 1.3 m worth of vane assuming a cut were made every 0.5 mm. In some cases, multiple tapes were required. Machining tolerances have been held within ±0.0015 in. over a length of 1.3 m. Primarily, errors have been caused by tool wear and misjudgments in repositioning the part when its length exceeded the stroke of the bed. The surface finish is determined by tool size and step size. On vanes that are to be electroplated, the surface finish has been totally satisfactory. We have experienced no catastrophic errors from tape errors, programming, or procedural errors. We feel that vane tips could be produced in industrial shops equipped with this type of milling machine.

References

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2. S. W. Williams, J. M. Potter, "Vane Fabrication for the Proof-of-Principle Radio-Frequency Quadrupole Accelerator," IEEE Trans. Nucl. Sci. 28, No. 3., p. 2976-2978 (June 1981).