Considerations for Design of a Micropositioner for Cryogenic Accelerators

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ABSTRACT

This paper describes design considerations for load-bearing, low-thermal-conductance micropositioners used with cryogenic particle-accelerating components. This paper also includes a description of initial prototypes, detail of their expected and actual performance, and a discussion of the possible sources of observed inaccuracies. The complete redesign of these positioners improved their thermal and positioning performance and reduced fabrication cost while maintaining their high load-carrying capacity, precise positioning capability, and minimal hysteresis. The paper discusses the performance of the redesigned positioners and presents a discussion of potential additional improvements.

I. INTRODUCTION

Alignment of the ground test accelerator (GTA) is greatly simplified by the use of remotely actuated positioners. Assymmetrical shrinkage of the RF structures, loading of components that penetrate the vacuum vessel, and thermal expansion of supporting structures can be compensated for by moving the structures back into place with the positioners.

The operational environment for GTA components is very demanding. The RF structures operate at cryogenic temperatures, the supporting structures closer to room temperature. Feed lines for the RF and cryogenic cooling penetrate the surrounding vacuum vessel, causing pressure-induced loads. A temperature gradient along the accelerator causes the supporting legs to contract by differing amounts. All of these factors require that final alignment be done by the positioners.

This paper discusses the initial design of the positioning system for the accelerator, problems that occurred during testing of the positioners, the solution developed for problems, and a newly designed positioner that we plan to use for the rest of the accelerator.

II. MOTION REQUIREMENTS

Motion of the GTA RF structures is referenced to a right-handed, rectangular coordinate system. The Z axis is parallel to and in the direction of the beam. The positive Y axis is up. The origin of this system is generally taken to be inside the injector, but it is usually translated along the beam line to more conveniently describe the motion of any particular structure. The radio-frequency quadrupole (RFQ) is required to move ± 0.040 in. in the X and Y directions with a positioning accuracy of 0.001 in.. The drift-tube linac (DTL) modules are required to move ± 0.400 in. in the X and Y directions with a positioning accuracy of 0.001 in.

Motion of these modules is complicated by the fact that the positioners do not act along the X and Y axes. Figure 1 illustrates the arrangement of the positioners for the RFQ. All of the positioners are allowed to rotate freely about a line parallel to the Z axis. Positioners 1 and 3 apply forces mostly in the X direction, while positioners 2, 4, and 5 apply forces mostly in the Y direction.

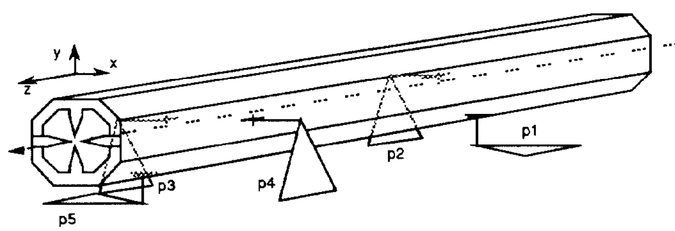

Figure 1. RFQ Motion Model

In operation, each RF structure is treated as an independent rigid body. The Z position of each is physically constrained to one location along the beam line, which allows the position of a structure to be completely described by specifying X-Y displacement vectors for the ends of the structure. Analysis of the geometry produced a single 4x5 matrix that directly translates these displacements into changes in the positioner height. The control system software has been designed to change the length of the positioners with reference to a "zero" position. This makes calculations for the transfer matrix more straightforward than if all the various lengths had to be taken into account.

III. INITIAL POSITIONER DESIGN

A more detailed drawing of an individual positioner is shown in Figure 2. It consists of a triangular "wishbone" whose height is controlled by varying the length of its base. The legs of the wishbone are connected to linear bearings whose separation is controlled by a ball screw driven by a stepper motor. The separation of the bearings is measured by an LVDT (linear voltage differential transformer).

According to the positioner design, simple geometry defines the relationship between the separation of the bearings and the height of the positioner. Since the LVDT measures the separation, the height can be calculated. Using a computer to control the motor and read the LVDT, the operator can set the positioner to any height.

A. Testing

The height of the positioner should be directly related to the readback from the LVDT. But when tests were performed to

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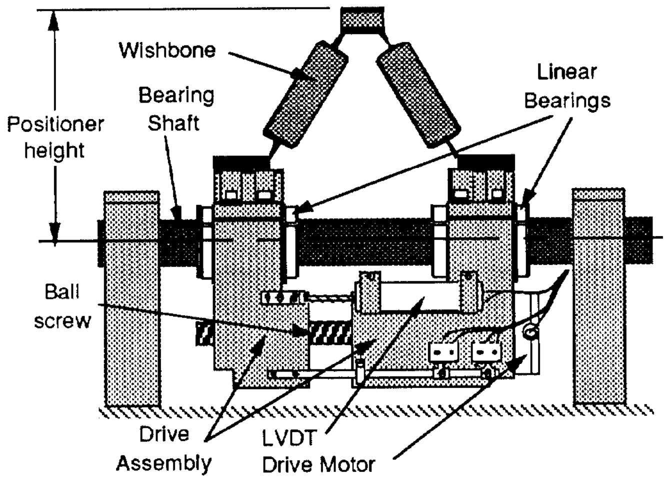


Figure 2. Wishbone Based Positioner

verify the assumption, the results were less than encouraging.

Two dial gauges were attached to a positioner; one measured the distance from the top to the base of the wishbone and the other measured the length of the LVDT coupling shaft. After being set to a center zero, the positioner height was changed by the control computer while recording dial indicator readings. The positioner was moved from zero to its positive limit, back through zero to its negative limit, and back to zero again. Figure 3 shows results typical of three of the positioners. The other two positioners produced results that were much closer to predictions.

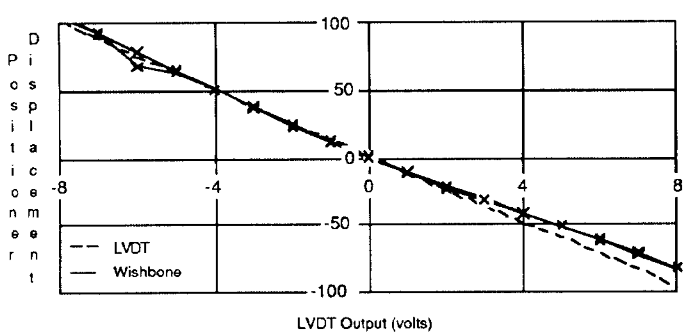


Figure 3. Wishbone Positioner Performance

We expected both the LVDT and the wishbone measurements to correspond fairly well to the LVDT readback. In other words, both lines on the graph should be straight and pass through zero. Hysteresis, produced by the positioner's moving in both the positive and negative directions, should have been undetectable.

As can be seen in the graph, the LVDT produced a fairly reliable measurement of the portion of the drive assembly to which it was connected. However, the measurement of the wishbone height shows an unacceptable degree of nonlinearity as well as significant hysteresis.

Although testing was not exhaustive , a considerable effort was put into identifying the causes of these problems. The load carried by the positioner was varied; the orientation of the positioner was changed from vertical to horizontal; and various components were adjusted. None of these tests identified a primary source of the problems. However, they did prove that the performance of the positioners was repeatable allowing software to be developed which compensates for the nonlinearities.

B. A Simple Fix

The nonlinearity and hysteresis problems are probably due to manufacturing tolerances in the bearing housings and, possibly, other mechanical adjustments. Any pitching or yawing of the drive assembly about the bearing shaft axis will show up as a change in the base of the wishbone, but the LVDT will indicate that the change was in the opposite direction. This could account for the change in slope as the positioner height passes through zero.

The problems with this positioner could have been eliminated by moving the LVDT to a location from which it measures the height directly. Computer control could then be used to adjust the height directly,eliminating the need to characterize each positioner. Instead, however, we decided to abandon the design in favor of a simpler and more cost effective one. In particular, cost projections for implementing the positioner on the remainder of the accelerator revealed the need for an entirely new design. The new positioner would have constraints placed upon it in five areas: strength, stiffness, thermal properties, resolution, and cost would all have to be considered.

IV. NEW DESIGN REQUIREMENTS

A. Strength

Although Figure 1 depicts the schematic of the RFQ, it could just as easily represent any accelerator structure and its positioning system. The structural strength problem can be reduced to a single analysis with varying rigid body weights. The largest load that would experienced by any positioner was projected to be 500 pounds. To ensure adequate structural strength, the new positioner was designed to withstand 2000 pounds.

B. Stiffness

The maximum allowable displacement of any drift tube within a DTL module determines the required stiffness of the positioner. Using finite element models along with the measured floor-power spectral density, we calculated the minimum allowable stiffness for the DTL positioner to be 40,000 lbs/in.

C. Thermal Properties

Because this is a cryogenic accelerator, the thermal properties of the positioners had to be considered. The positioner must provide a thermal break between the cryogenic module and the room-temperature support stand. In addition, thermal contraction must not cause significant uncertainty in positioner operation.

D. Resolution

According to beam dynamics studies, the relative position of any DTL module must be known within 0.001 inches. To reliably move the module with the required precision, the positioner should be able to provide ten times that resolution.

E. Cost

Each of the ten DTL modules requires five positioners (three vertical and two horizontal), or fifty in all. The original positioner cost approximately $20,000 per copy, making the total for the accelerator $1,000,000. The new design would have to keep the total cost under $230,000.

V. DTL Positioner Redesign

The DTL positioner shown in Figure 4 was developed to satisfy to the above requirements. It uses a uniaxial load-carrying strut to provide the required stiffness. Rod ends are used on either end of the strut to transfer the load between the positioner mechanism and the strut. The rod ends will not allow moments to be transmitted through the strut.

The rod ends are threaded to the strut with a right-handed thread on one end and a left-handed one on the other. This allows coarse adjustments to be made on the DTL. Locking nuts are used to prevent the struts from unwinding after adjustment.

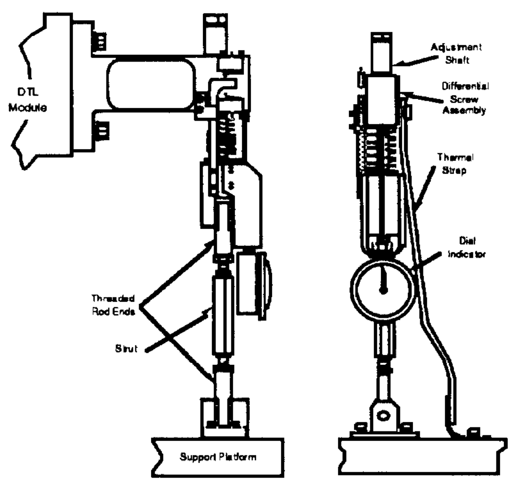


Figure 4. Redesigned Positioner—Front and Side Views

The positioning mechanism is in series with the strut and uses a differential thread. The outer thread is a .75-20 UNEF while the inner thread is a .50-13 UNC. Since the threads are used in series, the outer thread moves in the direction opposite that of the inner thread. The combined thread is:

$$\Delta = 1/13 \text{ inches/revolution} - 1/20 \text{ inches/revolution} = 0.02692 \text{ in.} \quad (1)$$

For one mil of linear motion, the required angular motion is

$$\Delta\emptyset = .001'' \times (360°/.02692'') = 13.4° \quad (2)$$

To obtain the required linear resolution of 0.0001 in., the angular resolution must be 1.34°. This defines the upper limit on tolerance buildup in the positioner. To minimize these buildups, preloading components were added wherever possible. First, locking nuts were used against the rod ends to ensure that the threads were well seated against each other. Second, a large spring was placed around the positioning mechanism to keep the differential threads loaded in their operational range. Third, spring pins were used in both the upper and lower joints.

Several tests were done with and without the preloads. Figure 5 shows a plot of the load deflection curve for the positioner. At a load of -185 lbs, a large nonlinear response occurs (the compression load of the spring). The location of the nonlinearity can be moved by changing the spring constant. The original design used shoulder bolts to attach the rod ends to the DTL module and its support. Figure 6A shows

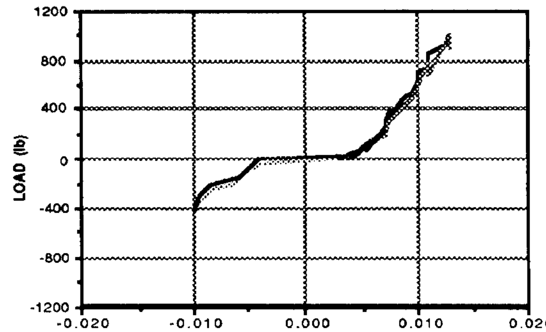
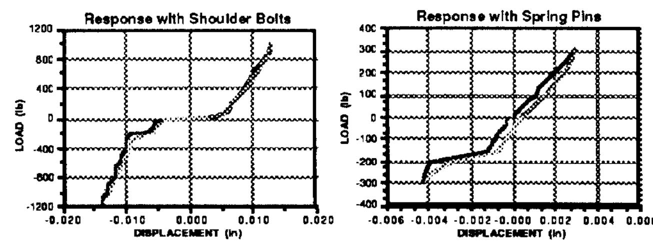


Figure 5—Positioner Stress

the load deflection curve with shoulder bolts, and Figure 6B is the same plot after the shoulder bolts had been replaced with spring pins.



Figures 6A and 6B—Preloading Comparison

To meet the required thermal characteristics, a copper strap is used to minimize the thermal gradient across the positioner strut and to keep the mechanism close to room temperature. The support arm is machined from stainless steel, which has very low thermal conductivity, in the form of a boxed-end I beam. The shape minimizes the cross sectional area of the support, reducing the conductance even further.

The positioner mechanism can be remotely adjusted from outside the vacuum vessel using either a gear motor drive or a box wrench. The mechanism requires only torque to make adjustments; therefore, a rotary feedthrough can be used to transmit the torque. The feedthrough turns a linkage system that comprises two universal joints: a spline and a drive shaft.

An Empire Magnetics GMA23 gear motor with a 10-to-1 gear reduction is used to drive the mechanism. The motor itself has 200 steps per revolution. The 10-to-1 gear reduction will increase this to 2000 steps per revolution of the drive shaft. The displacement resolution of the positioner is 1.34×10^{-5} in./step.

The positioner's relative displacement is measured directly from its length, eliminating errors due to bending moments or mechanical uncertainties in the positioner.

Fabrication cost for a set of five RFQ positioners was $82K. The projected cost for five DTL module positioners using the new design is estimated to be $23K. This is a 72 percent reduction in cost.

Conclusion

The GTA can be aligned to the required resolution using a fairly simple positioning system. The system can be sufficiently accurate to support the needs of the commissioning team as well as cost-effective enough to support the needs of the program.