Live Axis Turning

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INTRODUCTION

The objective of the development of the Live Axis Turning (LAT) process is to apply recent advances in air-bearing slide design and linear motors to increase the velocity and range of tool motion and demonstrate a commercially viable device that will extend the fabrication capability of non-rotationally symmetric (NRS) surfaces. This technology, aided by high-resolution feedback devices and advanced control algorithms, will allow NRS surfaces to be machined efficiently and accurately on currently available diamond turning lathes. The goal is to create a tool axis capable of 4 mm displacement at 20 Hz.

Diamond turning has revolutionized optical fabrication because of its ability to accurately and rapidly create optical surfaces as well as opto-mechanical features used in optical alignment. An emerging trend in optical design is the use of optical surfaces that are not rotationally symmetric (NRS). When such surfaces are included in an optical system, the complexity, bulk and weight of the system can be reduced[1]. The shape of these surfaces can typically be divided into a best-fit sphere or asphere and a non-symmetric component as illustrated in Figure 1. It is this non-symmetric component of a surface that required the use of a fast axis.

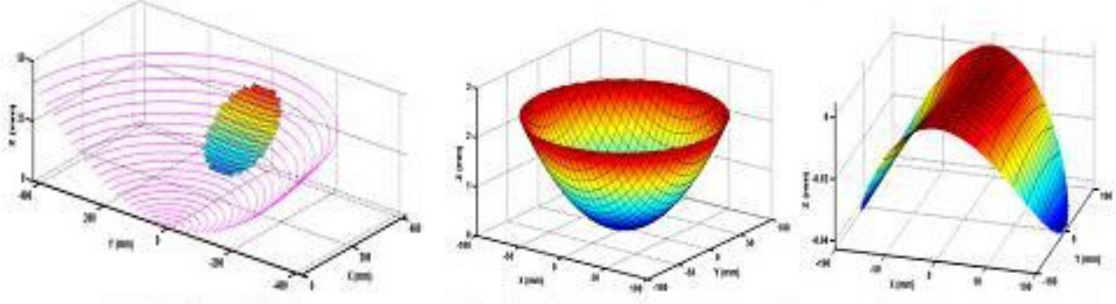

Figure 1: Decomposition of off-axis toroidal mirror surface (left) into symmetric (center) and non-symmetric (right) components for on-axis fabrication.

Presently, NRS surfaces can be created on a diamond turning machine (DTM) by using two slow-speed axes (slow) to generate the entire surface or three slow-speed axes with a fly cutter to raster scan the surface. Problems arise with these two methods: in the first method the spindle speed must be less than 50 rpm because of the low bandwidth of the slow-speed axes and thus the time for one pass of the tool for a 25 mm part will be over one hour. The second method requires exceedingly slow scans to produce an optical surface finish with a flycutter. Thus, long machining times and the associated thermal drift hamper both methods. Another technique is to add a Fast Tool Servo that is synchronized to the rotary position of the spindle on a 2D lathe. This arrangement will make a diamond turning machine more versatile and can efficiently produce an NRS optical surface. The main axes of the DTM create the symmetric component, the FTS adds the non-symmetric component and together they create the desired optical shape. The range of this auxiliary FTS axis dictates the maximum feature size possible while the feed rate and spindle speed have a direct bearing on the time to fabricate the surface and the cost. The new LAT Axis exceeds the range of the commercial FTS by a factor of 10 while the operating frequency is more than 25 times greater than when using the machine slides.

ACTUATOR DESIGN

The goal is to develop a light-weight, high-speed, air bearing, linear motor driven slide that can operate with a stroke of 4 mm at 20 Hz. The LAT design consists of a lightweight aluminum-honeycomb slide driven by a linear motor and guided by stiff air bearings. A holder for a diamond tool is attached to the front of the slide. A drawing of the proposed LAT system is shown in Figure 2.

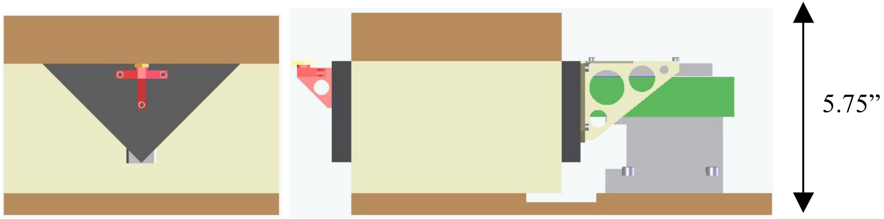

Figure 2. Front view (left) and side view of the LAT Axis

Slide Material The first step in the axis design was to select a material for the slide and develop the shape of the cross-section. The slide require a small moving mass, high stiffness to produce a high natural frequency for the system and sufficient surface area to produce a stiff air bearing. For these reasons, aluminum honeycomb was selected as the working material. Aluminum honeycomb consists of a honeycomb core of thin aluminum sandwiched between two thicker aluminum faces. The core cell structure holds the face sheets apart to generate the high bending stiffness but its low shear strength tends to decrease the theoretical stiffness by about 80%. The properties of flat honeycomb samples were calculated and measured, and a model for the actual material properties (modulus, density) was constructed. This model was used in the analysis discussed next.

FEM ANALYSIS

To help select an optimum cross-section shape, finite element models were created for different candidate shapes. Three basic shapes were analyzed: a box, a V-shape, and a triangle as illustrated in Figure 3. The properties of interest are the bending stiffness, mass, first natural frequency, center of gravity, location of the linear motor and location of the position sensing encoder.

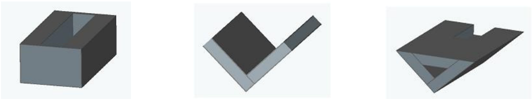

Figure 3: From left to right, the box, V-shape, and triangular slide designs

After simulating bending and frequency analysis tests for each slide shape, the box design was eliminated because removal of material to embed the motor caused a large drop in natural frequency. The remaining designs were compared using data obtained from simulations and shown in Table 1.

	Mass (g)	Nat. Freq. (Hz)	Lateral stiffness (N/µm)	Vertical stiffness (N/mm)	# Parts
V Shape	400	3450	8.145	8.17	4
Triangle	445	3950	25	10.5	2

Table 1: Comparison of V Shape and Triangle slide designs

Although slightly heavier, the triangle cross-section slide was selected because it proved more resistant to static forces resembling tool-tip loads and displayed a higher natural frequency than the V shape. Additionally, the air bearing structure supporting the slike consists of fewer parts, simplifying the assembly process.

Slide Length Another important design issue is the length of the moving slide. As the slide length increases, the bearing stiffness and natural frequency increase due to the larger surface area. However, the structural natural frequency of the moving slide decreases as the length increases. After analyzing the changes in natural frequency and the rate of change of stiffness with bearing length, a 7" slide in a 6" bearings was selected as the optimum length. This allows for 1" total stroke at lower frequencies. Also, the rear faceplate of the slide has a relieved area to accommodate the magnet track of the motor used to drive the system.

Motor Selection A brushless linear motor was chosen for its smooth motion characteristics, high accuracy, repeatability, high acceleration capabilities and stiffness. To reduce the moving mass of the system, the smallest/lightest motor capable of producing enough continuous force to drive the system was desired. Equation (1) was used to determine the force needed to drive the system:

$$F = mA\omega^2 \tag{1}$$

where m is the mass in Kg, A is the amplitude in m and ω is the frequency in Hz. For an assumed moving mass of 500 g, an operating frequency of 20 Hz , and amplitude of 2 mm (for a total stroke of 4 mm), 15.8 N are needed to drive the system. From the Airex Linear Motor P12 Series, the P12-1 is chosen (continuous force 27 N [2]. This motor weighs 100 g.

Mount Bracket The motor mount bracket connects the motor to the slide. The bracket must support the full weight of the motor coil, provide a rigid coupling to the slide and have minimum weight. The first bracket tested had a square faceplate to be bolted to the rear of the slide and a channel with 1/16" thick walls and vertical gussets to contain the motor as illustrated in Figure 4. However, this bracket was disappointingly flexible, allowing the motor and slide too much deflection. As a result of modeling, the faceplate was made taller to provide more resistance against vertical bending and horizontal gussets were added. Lightweighting holes were also added to the bracket in non-critical locations to reduce the mass.

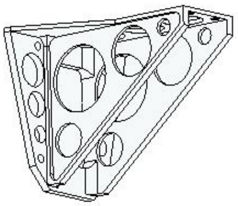

Figure 4: Improved final bracket

The new bracket performed well in dynamic simulations. The natural frequency of the slide-bracket-motor system was increased by nearly 50% and deformation was reduced to magnitudes seen in the slide and motor, indicating sufficient stiffness.

Experimental Verification When the moving slide was fabricated, accelerometers were used to observe its dynamic characteristics and compare those results to the predicted behavior. A free-free natural frequency test was used both with and without the motor and bracket. The setup for the experiment is shown in Figure 5.

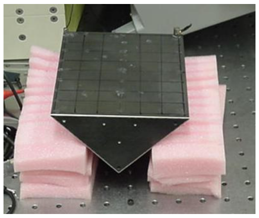

Figure 5: Setup for frequency analysis

A hammer was used to strike the slide resting on soft foam. The attached accelerometer then reported the vibration. The results are given below in Table 2.

	1st Natural Frequency (Hz)	2nd Natural Frequency (Hz)	Ratio of First/Second
Predicted Results	3950	5110	0.77
Actual Results	3540	4660	0.76

Table 2: Experimental results for natural frequency test (moving slide only)

With the values for the first and second natural frequencies showing a near match, two accelerometers were used to observe the vibration at different spots simultaneously on the slide. The relative magnitude and phase data of the two positions confirmed the predicted mode shapes – a twisting motion at the first frequency and a bending mode at the second.

CONTROL SYSTEM DEVELOPMENT

A linear motor depends on the control system to provide both static and dynamic stability. The following error, stiffness, disturbance rejection and stability depend on the drive system, the moving mass, the feedback sensor, the controller algorithm and update time. The control system must have fast loop update time, be flexible enough to support different control strategies and have the appropriate input/output configuration to support the required hardware. In this application, a straightforward proportional, integral, derivative (PID) control scheme may not be sufficient [3]. Feedforward gains will be investigated to eliminate following error. The UMAC controller from Delta Tau Systems is used to implement axis control.

MACHINING EXPERIMENTS

The goal will be to create optical surfaces that can be measured to evaluate the quality of the machining process. Two types of surfaces will be created. The first will be a tilted flat. For this type of surface, the LAT axis moves one cycle per revolution in a sine wave motion that linearly increases with radius. Because the resulting surface is flat, it can be easily measured using interferometers and profilometers to quantify the figure error and the surface finish. The second surface to be created will be a more complex NRS surface. Each of these surfaces will be used to test the capability of the LAT process to generate complex surfaces.

CONCLUSIONS

The 7” long slide for the Live-Axis turning system is made of aluminum honeycomb and has a triangular cross-section with faceplates at the front and back. In preliminary testing, the slide exhibits predicted behavior in dynamic applications. A linear scale encoder will be mounted on the flat top of the slide to provide position feedback to the controller.

1. K. Garrard, A. Sohn, R. G. Ohl, R. Mink, V. J. Chambers. “Off-Axis Biconic Mirror Fabrication.” *Proceedings from the EUSPEN 2002 Annual Meeting* (2002).