Recent Advances in Ultraprecision Machining for Freeform Optics

Xiaoqin Zhou, Ph.D.
Prof. in Mechanical Engineering
School of Mechanical Science and Engineering
Jilin University, Changchun, China
xqzhou@jlu.edu.cn

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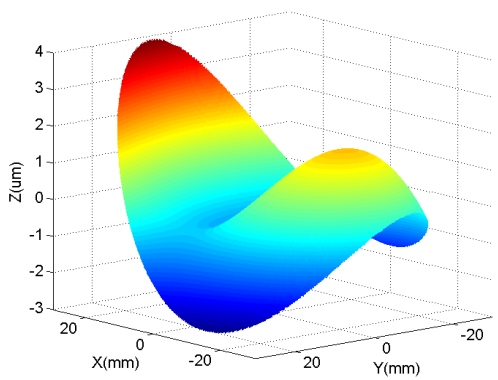
- **Freeform optical surfaces**
  - Definitions, Advantages, Mathematical Description, and Engineering Applications;
- **Diamond turning for freeform surfaces**
  - Fast tool servo, Principle for generating freeform surface, Modeling freeform workpiece, Toolpath generation, topography of machined surface;
- **Polishing for freeform surfaces**
  - Bonnet polishing (Zeeko), Magneto-rheological finishing (QED), Belt polishing (Optipro), etc.

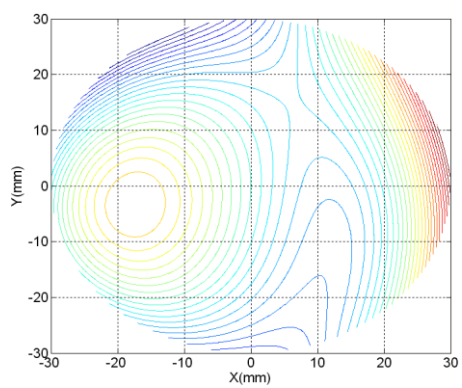
How to define freeform optical surface?

- Any non-rotationally symmetric (NRS) or non-axisymmetric optical surfaces (North Carolina State University, Prof. T. Dow, et al, 2005);
- Optical surfaces without rotational symmetry, or that depart or deviate from rotational symmetry (Univ. of Rochester, Prof. J. Rolland, et al, 2012);
- For the freeform surfaces described in S: $z=f(\rho, \theta)$, the shape of S not only depends on the radial variable ρ, but also the azimuthal variable θ.

Geometrical features

- Let $S(\rho, \theta, z)$ or $S(x, y, z)$ be a freeform surface, then
  - for the plane with $z=z_0$, the generated contour is always a noncircular curve;
  - for the cylindrical surface S_2 ($x=\rho\cos\theta, y=\rho\sin\theta, z$), the space curve C can be formed by the intersection between the S_2 and S, which could not be degenerated into a circle.



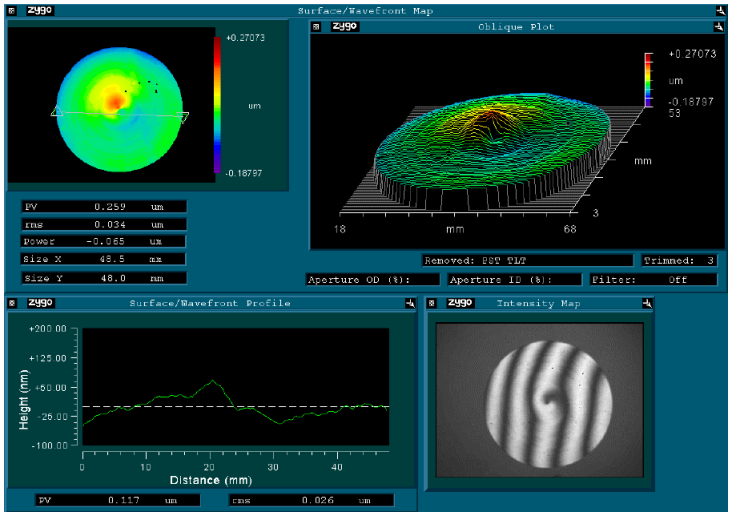


$$z = 1.73\rho^2\cos 2\theta + \rho^2\sin 2\theta + 2(3\rho^2 - 2)\rho\cos\theta$$

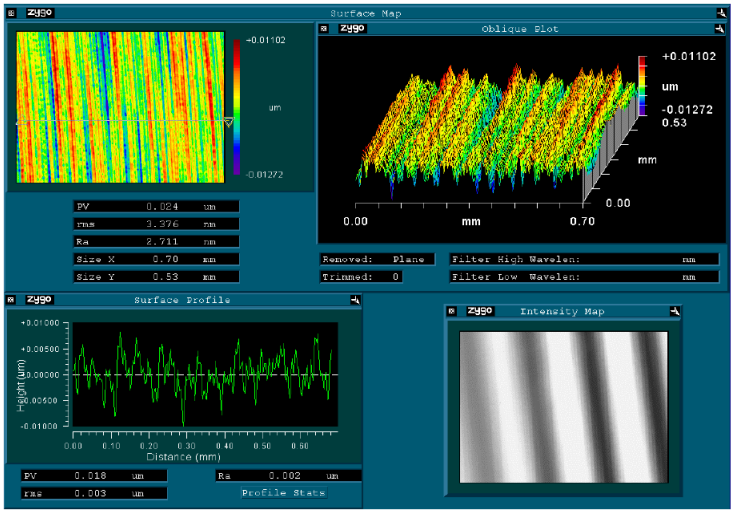
An example of freeform optical surface, which is represented by Zernike Polynomial and originally used to design a wavefront corrector by Meinel et al, 1986, in LLNL.

Machining requirements for freeform optical surface?

- Form errors: from submicrons to nanometers;
- Surface roughness: from nanometers to angstroms;
- Surface waviness: nanometers;
- And position errors (linear and angular position).



Titled flat-form results, P-V error: 0.259 µm.



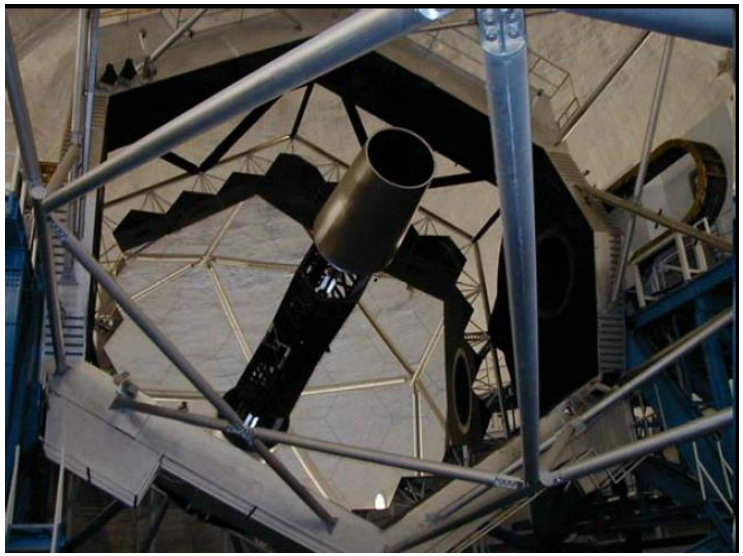
Titled flat-finish results, Ra: 2.711 nm

Benefits of freeform optical surfaces?

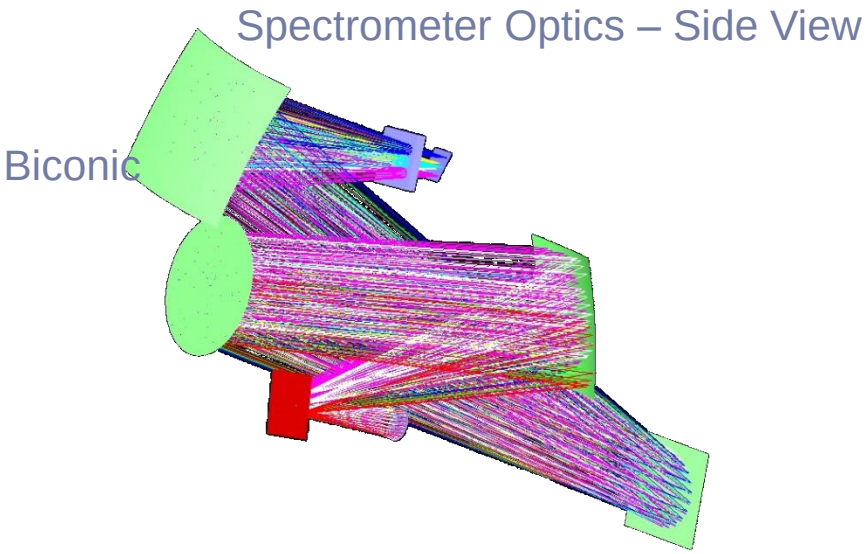
- Significantly improve the performance of an optical system, compared with spherical and rotationally symmetric aspheric optical surfaces;
- Dramatically reduce the number of optical elements used in an optical system;
- Enable the optical system to be much more lightweight, and reduce the calibration complexities of optical elements;
- Increase the optician’s design degrees of freedom, and facilitate the performance target driven design of optical system.

Simple examples of freeform optical surfaces

- Off-axis conic surfaces;
- Toroidal surfaces;
- Biconic surfaces;
- x-y polynomial surfaces.



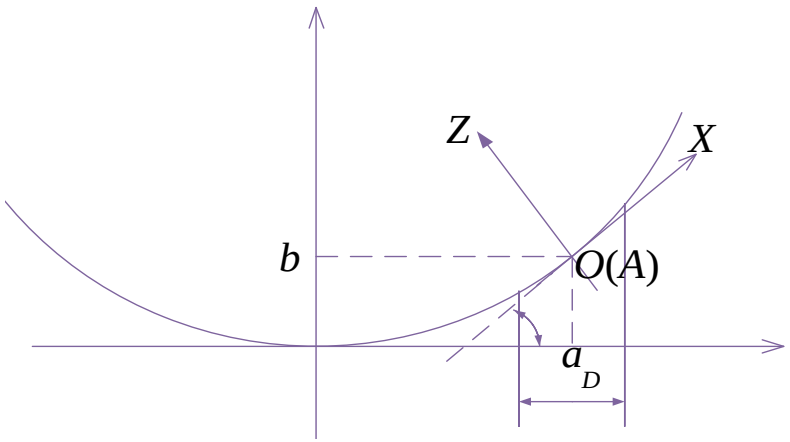
Off-axis conic used in Keck Telescope primary mirror

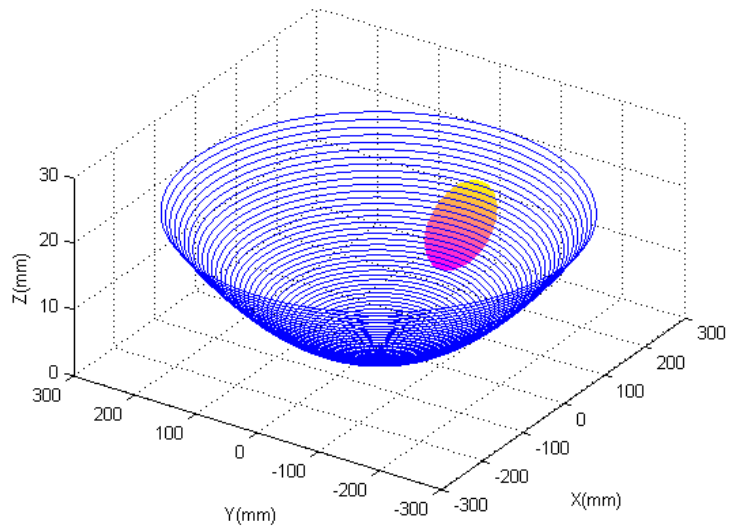


Biconic used in Infrared Multi-Object Spectrometer (IRMOS)

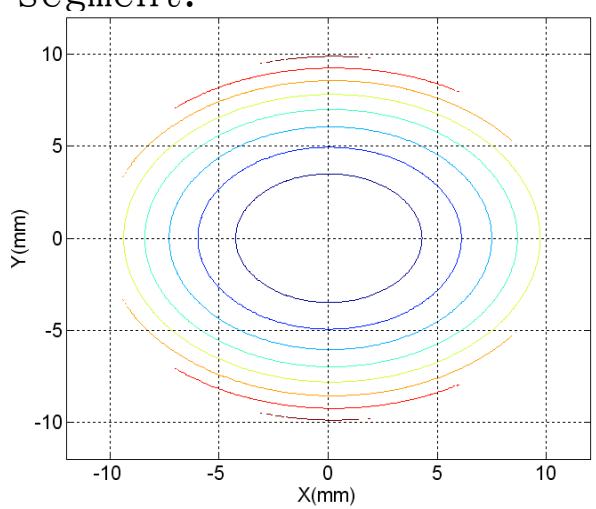
	Typical applications	Refs
Off-axis conic surfaces	Keck telescope	Lawrence Berkeley Laboratory, TMT Report No. 91, 1982
	Three-mirror-anastigmatic (TMA) telescopes	NCSU, Thomas A. Dow, 2005
Toroidal surfaces	Ophthalmic optics	Institute of Applied Optics (Poland), J. Bartkowska, 1998
Biconic surfaces	Infrared Multi-Object Spectrometer (IRMOS)	Space Telescope Science Institute, R. Winsor, 2000
x-y polynomial surfaces	Cubic Phase Plate	U.S. Army Night Vision Lab., K. Bryant, 2004
	Head-mounted display (HMD)	Zhejiang Univ. (China), Z. Zheng, 2010

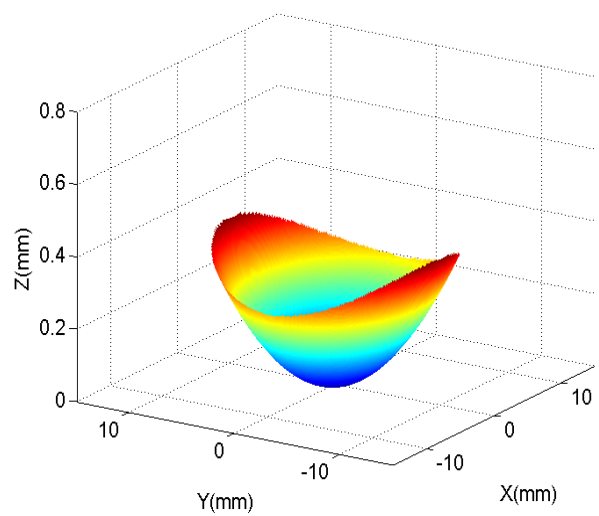
- Mark C. Gerchman. "Description of off-axis conic surfaces for nonaxizymmetric surface generation", Proc. SPIE 1266, In-Process Optical Measurements and Industrial Methods, 262 (August 1, 1990);
- R. Winsor, J. W. MacKenty, M. Stiavelli. Optical Design for an Infrared Multi-Object Spectrometer (IRMOS), Proc. SPIE 4092, Novel Optical Systems Design and Optimization III, (October 2000);
- Z. Zheng, X. Liu, H. Li, and L. Xu. Design and fabrication of an off-axis see-through head-mounted display with an x–y polynomial surface. Applied Optics, Vol. 49, Issue 19, pp. 3661-3668 (2010)





Off-axis conic geometry.
(a, b): the center of off-axis segment.





The contours of an off-axis conic surface

$$z = R_b - \sqrt{(R_b - R_c + \sqrt{R_c^2 - r^2 \sin^2\theta})^2 - r^2 \cos^2\theta}$$

Toroidal surface, S. Ludwick, 1999

***R_b* and *R_c* are the radii of the toric lens along each of the two major axes.**

$$z = \frac{x^2/R_x + y^2/R_y}{1 + \sqrt{1 - (1+k_x)x^2/R_x^2 - (1+k_y)y^2/R_y^2}}$$

Biconic surface, R. Winsor, 2000

$$z_3 = d_1 + d_2\rho\cos\varphi \pm \sqrt{d_3 + d_4\rho\cos\varphi + d_5\rho^2 + d_6\rho^2\cos^2\varphi}$$

Off-axis conic surface, M. Gerchman, 1990

$$z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + A_1x^1y^0 + A_2x^0y^1 + A_3x^2y^0 + A_4x^1y^1$$

$$+ A_5x^0y^2 + \cdots + A_Nx^{i-j}y^j$$

x-y polynomial surface, Z. Zheng, 2010

Freeform optical surface representations

- Orthogonal basis functions
  - Zernike polynomials, wavelet basis functions, Forbes functions, etc;
- Radial basis functions (RBF)
  - Gaussian basis function;
- Spline basis functions
  - B-spline surface, NURBS.

Hybrid freeform optical surfaces

- Any freeform surfaces constructed by incorporating a non-rotationally symmetric (NRS) surface into a rotationally symmetric aspheric surface (substrate)
  - e.g., hybrid conic and Zernike or x-y polynomial;
- Any freeform surfaces constructed by incorporating a series of aspheric surfaces into a plane, spherical, or aspheric substrate
  - e.g., lens array, mirror array;
- Any freeform surfaces represented by two NRS surface equations
  - e.g., hybrid RBF and local ϕ-polynomial surfaces proposed by Univ. of Rochester, 2013.

$$z=\frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}+\sum_{m,n}\left[a_{m,n}Z_n^m(\rho,\varphi)+b_{m,n}Z_n^{-m}(\rho,\varphi)\right]$$

$$Z_n^m(\rho,\varphi)=R_{m,n}(\rho)\cos(m\varphi),Z_n^{-m}(\rho,\varphi)=R_{m,n}(\rho)\sin(m\varphi),\rho=r/r_{\max}$$

Hybrid conic and Zernike polynomial surface

$R_{m,n}$: radial polynomials;

ρ: normalized radial coordinate, $0\leq\rho\leq1$;

c: vertex curvature;

k: conic constant.

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{m,n} w_{m,n}\phi_{m,n}(x,y)$$

$$\Phi(\tilde{x},\tilde{\mu},\Sigma) = e^{-\frac{1}{2}(\tilde{x}-\tilde{\mu})^T \Sigma^{-1}(\tilde{x}-\tilde{\mu})}$$

Hybrid conic and RBF surface

$\Phi_{m,n}$: radial basis functions;

$w_{m,n}$: coefficients;

c: the vertex curvature;

k: the conic constant.

Univ. of Rochester

Optics Express, Vol. 16, Issue 3, pp. 1583-1589 (2008)

Comparison for freeform surface description

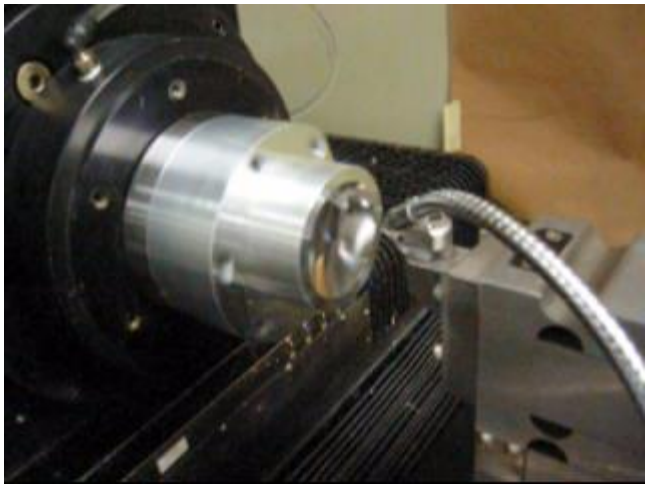
	Examples	Features
Orthogonal basis function	Zernike polynomials; Forbes polynomials;	• Global approximation; • Thousands of terms are required to approximate the local asymmetric features.
Radial basis function (RBF)	Gaussian function;	• Local approximation; • Only tens of terms are required to achieve an acceptable accuracy (nanometers).

Univ. of Central Florida, Univ. of Rochester

Kaya I, Thompson KP, Rolland JP. Comparative assessment of freeform polynomials as optical surface descriptions. Optics Express. 2012 Sep 24; 20(20): 22683-91.

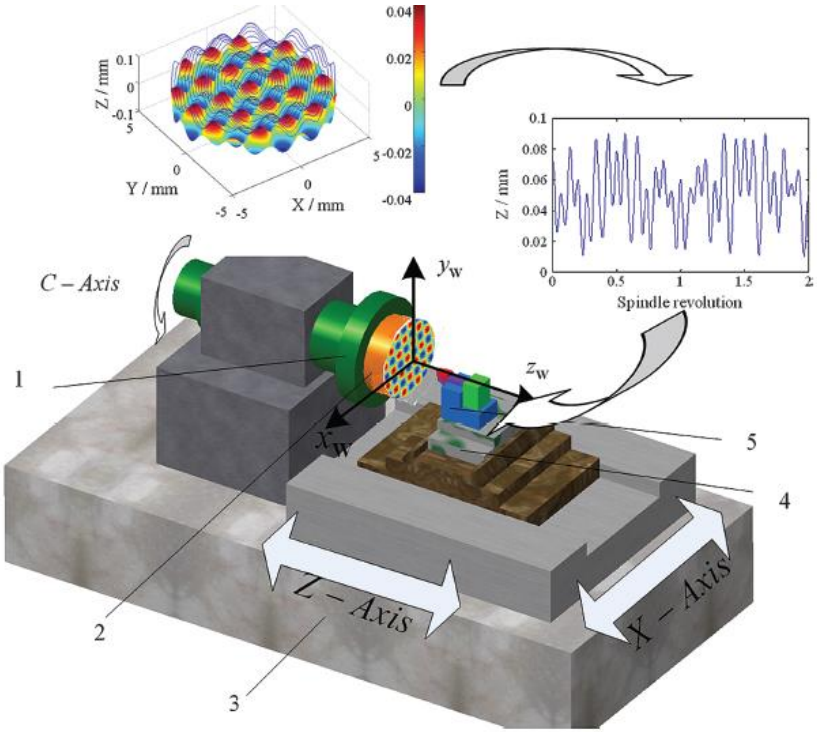
Fast tool servo (FTS)

- To generate a NRS surface in diamond turning, an oscillatory motion Δx or/and Δz of diamond tool relative to the machined surface along x or/and z directions is required;
- FTS is an apparatus to enable the diamond tool to oscillate precisely relative to machined surface along x or/and z directions;
- The motion trajectory tracking of a FTS apparatus can be implemented by the closed loop control or the inverse dynamics based open-loop control.



Principle of freeform diamond turning

- A workpiece is clamped on the spindle, rotating by the angle θ around the axis z;
- The x-slide translates x forwards along the x-direction;
- A FTS apparatus is mounted on the z-slide of a turning lathe, and the diamond tool held on the FTS apparatus oscillates Δz relative to machined surface;
- The z-slide translates z forwards along the z-direction, thus the motion of diamond tool is (z+Δz);
- With the motion (x, z+Δz, θ) of the diamond tool relative to the machined work, a NRS surface can be created.

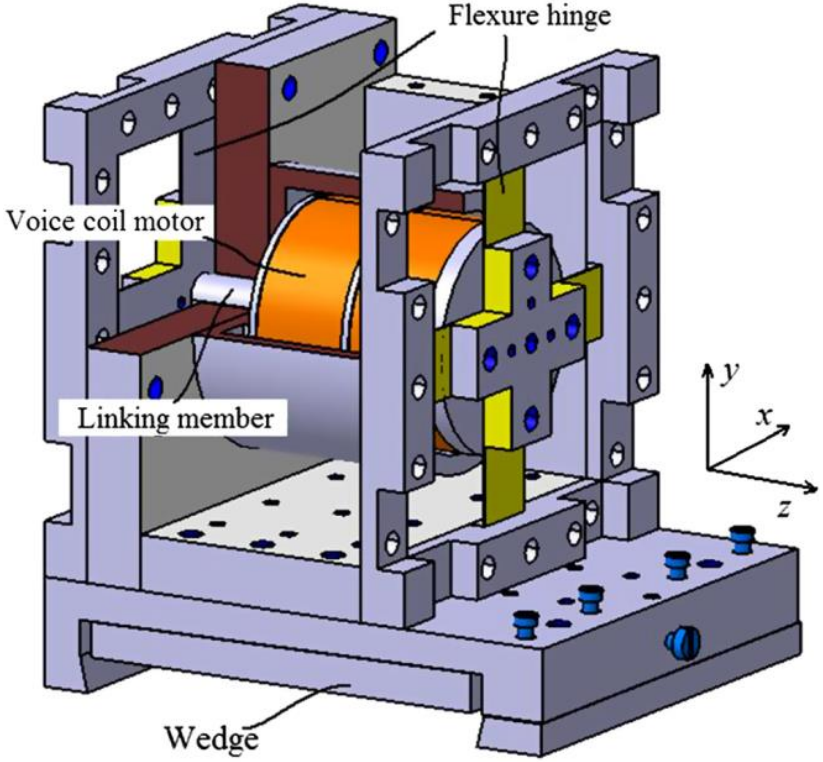


1-spindle; 2-machined workpiece; 3-lathe base; 4-tool height adjustment; 5-FTS

Supporting/guiding fast tool servo

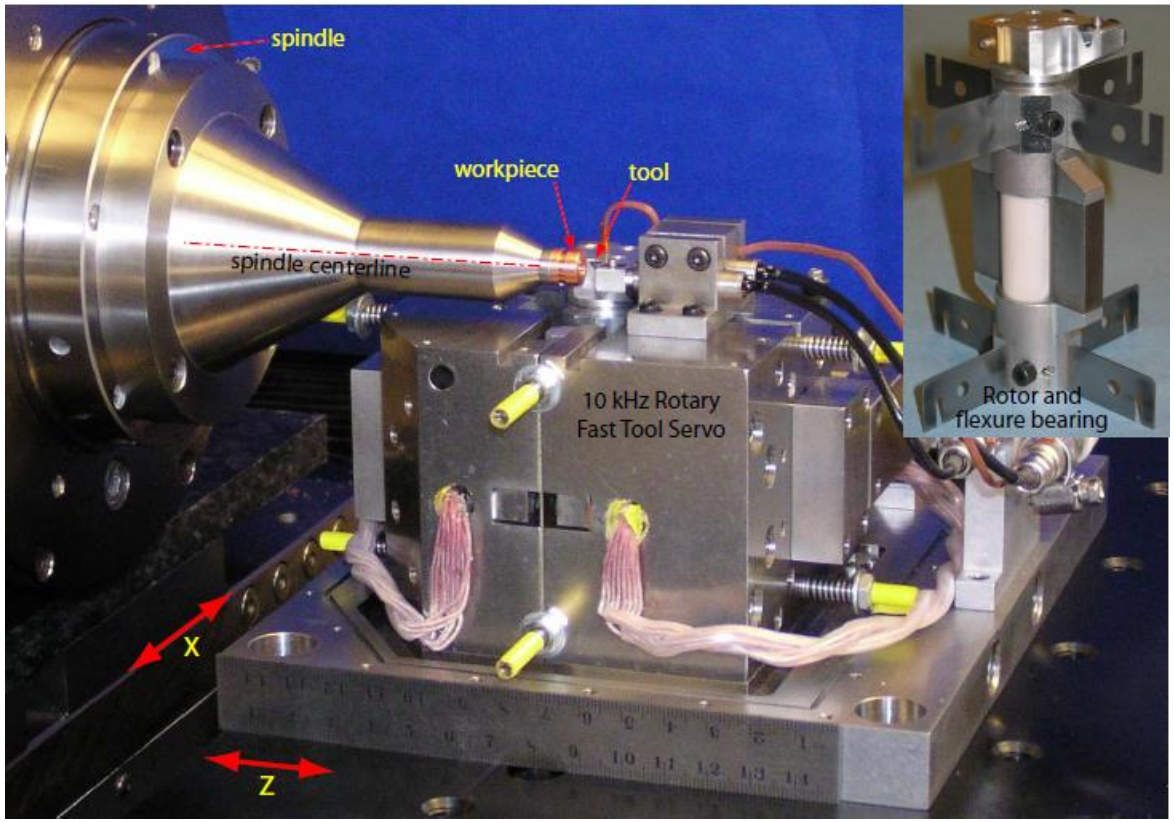
- Linear fast tool servo
  - Flexure hinges, air bearing;
- Rotary fast tool servo
  - Blade flexure, magnetic levitation.

Flexure hinges



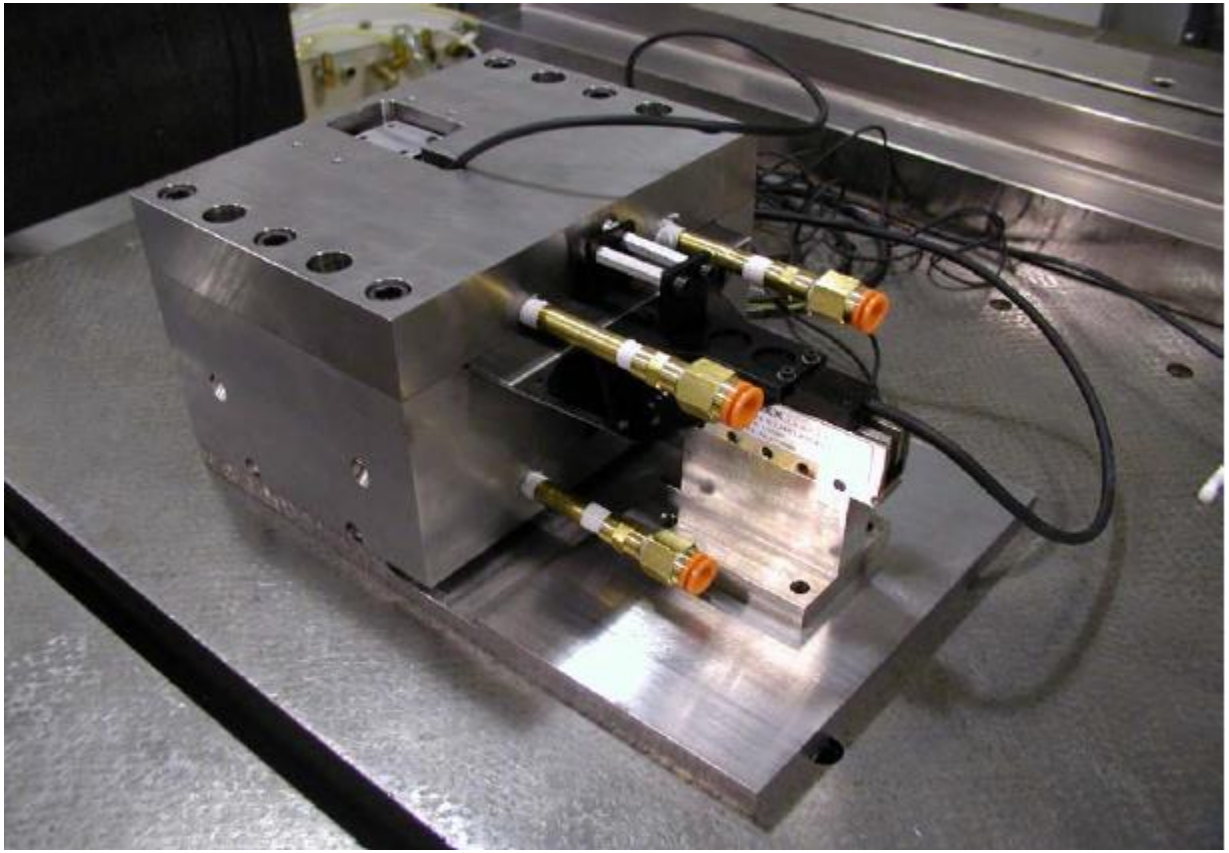
Flexure hinges used in a linear FTS actuated by VCM, JLU (China), 2013

Blade flexures



Blade flexures used in a rotary FTS actuated by Maxwell force, MIT, 2005

Air bearing



Air bearing used in a linear large stroke FTS actuated by linear motor, NCSU, 2005

Actuating fast tool servo

Principles	Actuating elements	Refs	Strokes	Freq.
Piezoelectric effect	Piezoelectric actuators		~100 µm	~1 kHz
Lorentz force	Linear motor	Fraunhofer IPT, Weck, et al, 1995	12 mm	40 Hz
	Voice coil motor	UNCC, Rakuff, et al, 2009	2 mm	140 Hz
	Brushless rotary motor	MIT, Ludwick et al, 1999		0.5 kHz
Maxwell force	Normal-Stress Variable Reluctance Actuator	MIT, Montesanti et al, 2004	5 µm	10 kHz
		Tianjin Univ., Nie et al, 2014	11.3 µm	3 kHz

Basic specifications for fast tool servo

- Maximum stroke
  - Linear FTS (nano, short, medium, and long stroke);
  - Rotary FTS
- Frequency (open-, and closed-loop)
- Frequency bandwidth
- Tracking accuracy

Performance tests for FTS

- Static stiffness
  - along the x-, y- and/or z-directions, static loads are respectively exerted on diamond tool tip, and the displacements are measured;
- Dynamic behaviors (e.g., frequency response)
  - along the x-, y- and/or, z-directions, dynamic loads (e.g., impulse, sinusoidal, or stochastic excitations) are respectively exerted on diamond tool tip, and the vibration responses of the diamond tool tip are respectively measured;
- Actuating behaviors (e.g., resolution, frequency response)
  - Driving electric voltages (e.g., impulse, sinusoidal, swept sine, stochastic excitations) are exerted, the displacements and/or accelerations are measured along the x-, y- and z-directions of the diamond tool.

Configuring fast tool servo

- Motion configuration
  - linear, or rotary
- Degree of freedom (DoF)
  - Single DoF: a translation, or a rotation;
  - Two DoF: two translation (x- and z-axis), or a translation (z-axis) plus a rotation (B-axis)
- Questions
  - Why is a two DoF FTS desired for freeform diamond turning?
  - How to reduce the cross-talk or coupling between the x- and z-directions in a two DoF FTS?

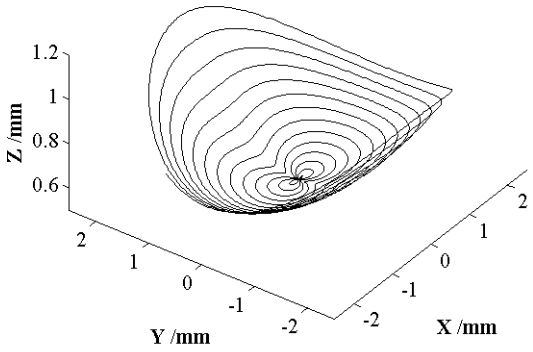
Representing freeform workpiece

- Cylindrical coordinates are generally used to represent the machined workpiece;
- The datum references of workpiece in x-, y- and z-directions should be set as the origin of the workpiece coordinates;
- Desired machined freeform surface should be mathematically represented on the cylindrical coordinate system of workpiece.

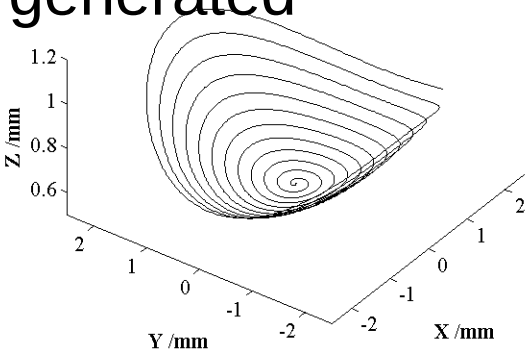
Toolpath for FTS based diamond turning

- Establish the mapping between tool location points and tool contact points
  - Reduce to the tangential contact between the tool tip profile and the desired machined surface.
- Determine the toolpath of tool contact points on the desired machined freeform surface
  - **Criterions**: maximum scallop height constrained, constant scallop height, chip load constrained, minimum thickness of cut constrained, optical performance driven, and so on.
- Decompose the obtained toolpath of tool location points;
  - Monotonic tool trajectories (ρ, θ, z), and oscillatory tool trajectories (ρ, θ, Δz).

Toolpath generated

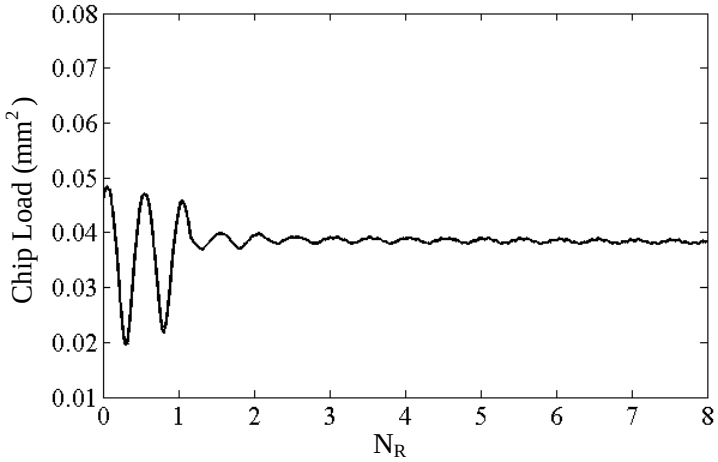


constant chip load approach

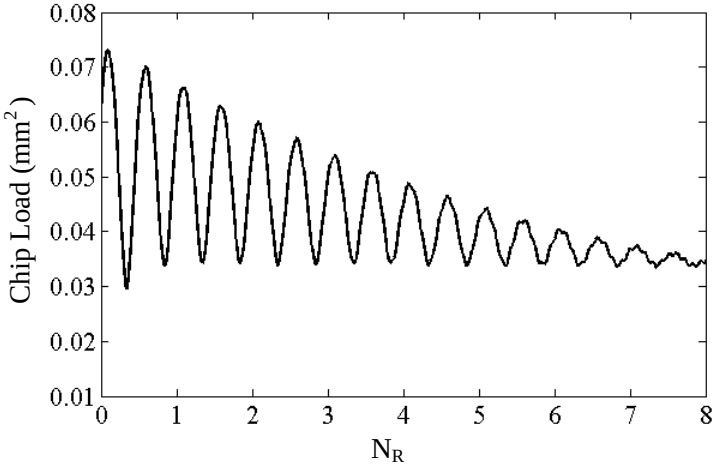


constant radial feed approach

Chip load comparison



constant chip load approach



constant radial feed approach

Machined surface topography for FTS based diamond turning

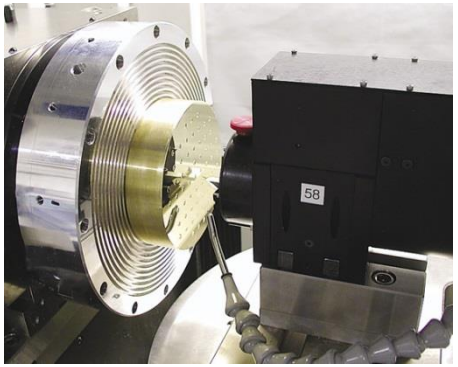
- Establish the workpiece and diamond tool coordinate system;
- Represent the desired machined surface and the workpiece surface to be cut on the workpiece coordinates;
- Establish the equations describing the diamond tool tip on the workpiece coordinates;
- Determine the coordinates of tool location points on the workpiece coordinates, according to the predetermined toolpath, and measured the errors of motion axes;
- Generate the machined surface according to the intersection, tangential contact, or separation between the diamond tool and machined workpiece.

Machines for FTS based diamond turning

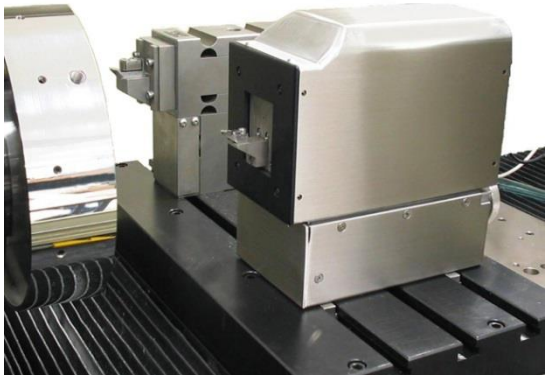
- Moore nanotechnology system, LLC
  - www.nanotechsys.com
- AMETEK Precitech Inc.
  - www.precitech.com
- Cranfields Precision, A Division of Cinetic Landis Ltd.
  - www.cranfieldprecision.com

Commercial single DoF fast tool servo

Co.	FTS	Specifications	Actuation
Precitech	Fast tool servo	1000µm@119Hz 500µm@168Hz	Piezoelectric actuator
	Slow tool servo	10mm@2Hz	Linear motor
Moore nanotech.	Fast tool servo	6mm	Voice coil motor
	Slow slide servo	≤25mm, 60Hz	Linear motor



Precitech FTS



Nanotech FTS

Challenges for freeform diamond turning

- Ultraprecise mathematical description for freeform surfaces, generated toolpath, and decomposed tool trajectories;
- Innovative processing approaches for brittle and ferrous materials to be diamond turned;
- Backlash effects of high frequency fast tool servo against diamond turning machine;
- Static/dynamic coupling between the x- and z-directions in a two DoF fast tool servo;
- Size effect resulted from the variation of chip load during freeform diamond turning;
- Ultraprecise in-process measurement of cutting force components during FTS based diamond turning.

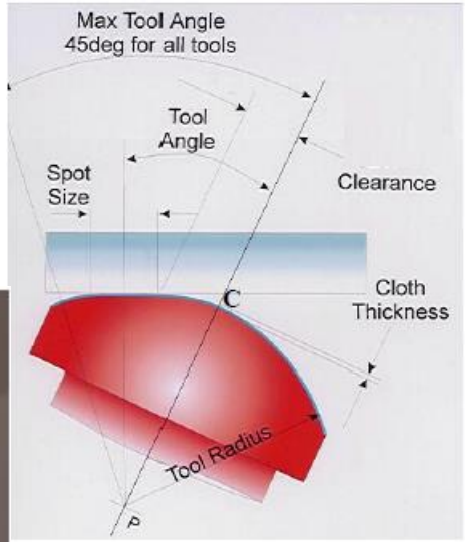
Conformal polishing for freeform surfaces

Institutes	Polishing processes	Refs
University of California	Stressed mirror polishing	Applied Optics, Lubliner and Nelson, 1980
Zeeko Ltd University college London	Bonnet (inflated membrane) polishing	Proc. SPIE 5180, Walker, 2004
	Grolishing	Proc. SPIE 6671, Walker, et al, 2007
University of Arizona	Stressed lap polishing	Applied Optics, 33(34), West, et al, 1994
	Non-linear visco-elastic effect based polishing	Optics Express, 18(3), Kim and Burge, 2010
University of Rochester QED technologies, Inc.	Magneto-rheological finishing (MRF)	OSA OF&T Workshop, Prokhorov, et al, 1992
Optipro systems, Inc	Ultraform finishing (UFF, a belt polishing with a compressive wheel)	Proc. SPIE 8016, Bambrick, et al, 2011

Bonnet Polishing

- Two principal functions – to remove surface and sub-surface damage from a ground part, and then to correct the form.
- A sub-aperture flexible polishing tool is used– an inflated, bulged, rubber membrane of spherical form (‘bonnet’), its rotation axis H inclined to the local normal of the polished surface.
- The polishing pressure and the contact area can be modulated independently.

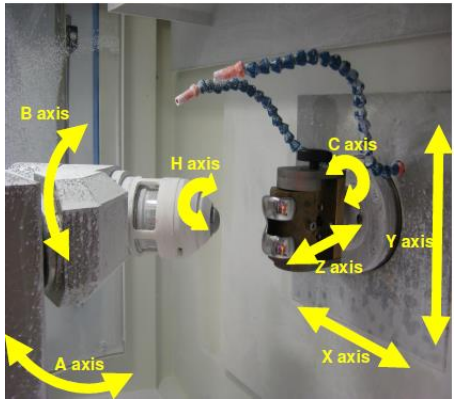
Zeeko, Standard 80mm radius polishing bonnet

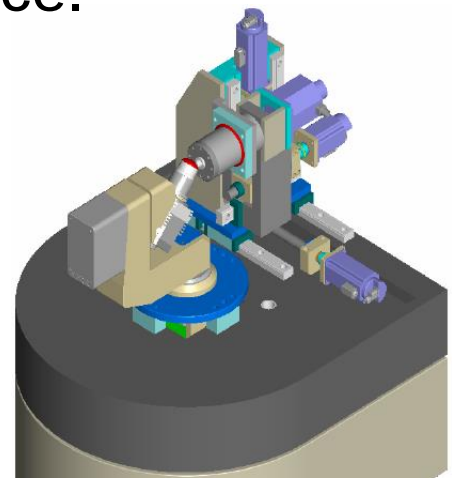


Precessing bonnet

Bonnet polishing machine

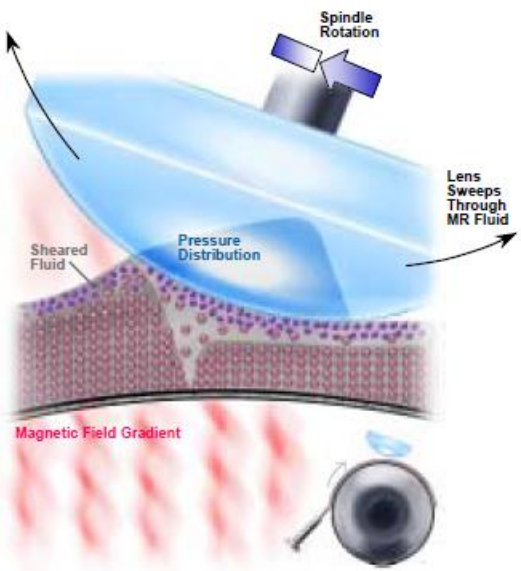
- A seven-axis CNC polishing machine providing the following the DoFs.
  - H axis: rotation of the bonnet about its axis of symmetry;
  - X,Y, Z axes: positioning of the bonnet with respect to the workpiece;
  - A, B axes: orientation of the bonnet's axis in the coordinate frame of the machine;
  - C axis: rotation of the workpiece.

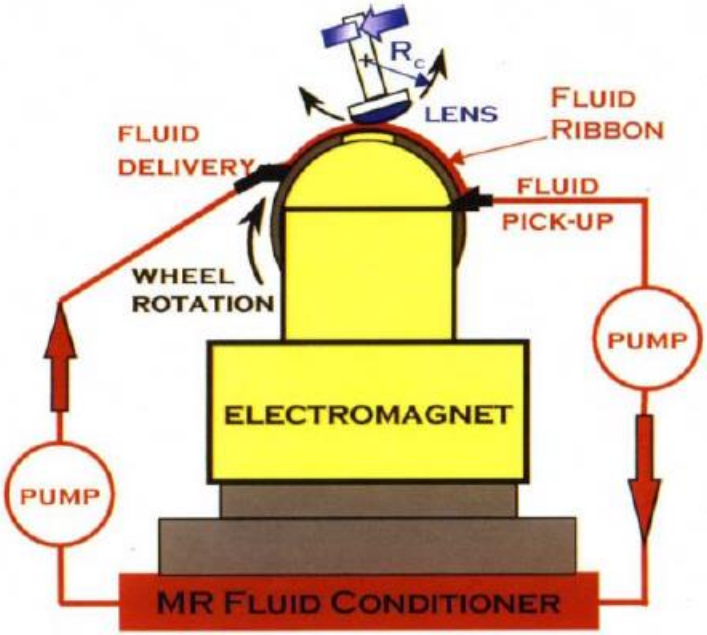




Magneto-rheological fini

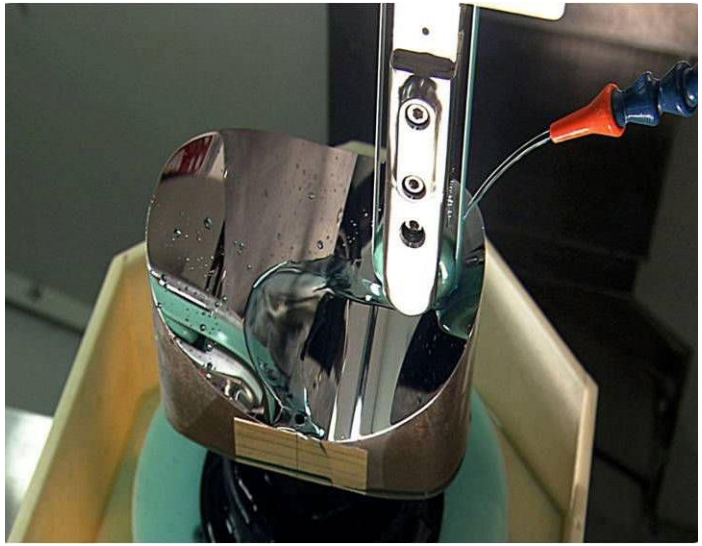
- A magnetorheological (MR) fluid inside a magnetic field creates a sub-aperture "polishing lap", the shape and stiffness of which can be magnetically controlled.
- This sub-aperture "polishing lap" conforms to the local surface curvature in such a way that it does not have the problems with tool/part shape mismatch.
- Figure errors: better than λ/50 (P-V); Roughness: less than 1nm.





Ultraform finishing (UFF)

- UFF utilizes a belt of polishing material wrapped around by a compliant wheel that rotate and contact the part to remove material.
- This belt polishing system provides a tuned stiffness that is capable of conforming to the polishing surface.



Notes on freeform polishing

- Have a stable and deterministic tool influence function (TIF) or material removal function;
- Demand highly precise full-aperture metrology for freeform surfaces;
- Avoid zones resulted from the curvature mismatch between the tool and the surface;
- Have a polishing tool that conforms to freeform shapes, and maintains a intrinsic smoothing.

Summary

- Fast tool servo (FTS) based diamond turning is recognized as a promising approach to creating freeform surfaces, it is of the advantages of high efficiency, high precision, and cost-effective, but there exist some issues to be solved, such as generating the freeform shapes of brittle and ferrous materials, developing two degrees of freedom or more than FTS, and so on;
- The existing conformal polishing for freeform surfaces, e.g., bonnet polishing, magneto-rheological finishing, and ultraform finishing is of excellent capability of shape adaptation, but how to balance the compliance and smoothing effect of polishing tool should be further investigated.

Thank you for your attention.