Investigation of machining dynamics in ultraprecision machining of freeform surfaces using the slow tool servo (STS)

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Abstract

Over the last decade or so, ultraprecision machining has become a key enabling technology for machining complex freeform surfaced products on an industrial scale. The research presented is aimed at providing an integrated approach to and scientific understanding of the precision design, manufacturing and metrology of freeform surfaces using the slow tool servo (STS) technique.

To fulfil the highest resolution and enhancement for a freeform surface, the factors of the dynamics, material and mechanical stiffness, friction, tooling and accuracy of the servo component should be considered in the ultraprecision machining system. In this research and development, several types of freeform surfaces with various sag have been machined using a diamond turning machine (DTM) further supported by the STS technique, whilst the effects of the cutting tool geometry and configuration on the surface resolution have also investigated. The design of a novel STS technique and novel tool paths generation using the ADAMS/solver are discussed. Moreover, a comparative investigation of the multibody dynamics based approach to the Ultraprecision Machining of Free-form Surfaces is explored. The generated trace points were post-processed, and the experimental process was compared with a toolpath generated by the traditional ultraprecision machining method.

1 Introduction

Ultraprecision machining of freeform optics through diamond turning is becoming the most reliable enabling process, as it can deliver high accuracy and efficiency by integrating distinctive techniques known as fast tool servo (FTS) and slow tool servo (STS). Freeform optics are increasingly being employed in precision engineering industries, including the automotive, defence, aerospace and medical industries [1, 2]. According to the process chain, this initially involves employing computer-aided design/manufacturing, two common steps required using 3D CAD/CAM software, to generate the toolpath trajectory, a); toolpath generation based on the real form of the freeform surface and b); tool compensation trajectory to deal with surface form error and correction modification of the final toolpath [3, 4]. In the Machining components with NRS surfaces, the diamond tool has to move as a function of the spindle rotation and translation of the machine slide. The methodology above is different from using tool servos separately to generate the tool motion [5, 6]. Moreover, the mechanism of material removal is different for the FTS and STS configurations. In addition, achievement of good surface finishing is still challenging in ultraprecision machining [7, 8]. To fulfil the highest resolution and enhancement for the freeform surface, the factors of the dynamics, material and mechanical stiffness, friction, tooling and accuracy of the servo component need to be considered in the ultraprecision machining system. The research presented in this paper involves investigating an innovative integrated approach to precision engineering design, ultraprecision machining, metrology measurement of freeform surfaces and the scientific understanding of the underlying integration protocol and algorithms. In sum, ultraprecision machining of components with freeform surfaces is carried out through the integration of direct 3D modelling and a CAD/CAM system in an exact precision engineering context.

2 Slow Tool Servo and Dynamic Effects

STS can be applied directly to a standard precision turning machine in ultraprecision machining. It can also achieve much higher displacements in non-rotational symmetric applications in millimetre units [9]. Unlike the FTS technique, STS does not require any additional axes for tool motions, as the tool sits directly on the Z-axis and slides to produce a synchronised displacement [10].

2.1 Dynamic Specification

Several key characteristic featuresneed to be valid for achieving a successful STS method implementation in the diamond turning machine. Most of these are applied to friction-free linear and rotary axes. The control system with high-speed data processing plays a key role in running the motors and all the direct drive axes very accurately. The parameters that influence the precise positioning in the system that should be considered, include the encoder resolution, thermal expansion, high-order trajectory generation, precise data acquisition method and structural stiffness in the control loop.

The analysing of the positioning loop is critical in ultraprecision machining when using the STS technique. Also, the freeform surface topology has a direct effect on the cutting tool velocity and acceleration. Regarding which, the implementation of high close position loop bandwidth becomes an essential requirement in STS. The evaluation of the acceleration and velocity of the system is dependent on the freeform surface curvatures and sagittal features so as to maintain adequate bandwidth. Thus, analysing the freeform surface geometry on both the tools and workpiece is required to specify the electrical and all the associated structural dynamics on the system. The tool trajectory in the conventional ultraprecision toolpath generation methodology is not capable of calculating the structural dynamics affected by the freeform surface in the system, such as tool velocity and acceleration, tool friction and surface contact force. In the next section, a multibody dynamic methodology is employed to investigate the dynamic effects in the freeform surface tool trajectory for STS in ultraprecision machining. A new methodology for toolpath generation using multibody dynamics is also presented.

2.2 Tool and Surface Geometry

2.2.1 Diamond Cutting Tool Geometry

Tool geometries play a significant role in successful machining using STS methodology. The tool feature selection relates directly to the freeform surfaces topology, such as curvature and sagittal elements. As shown in Figure 1, typical diamond cutting tool geometrical parameters include the rake angle, diamond height, tool nose radius, included angle and clearance angle.

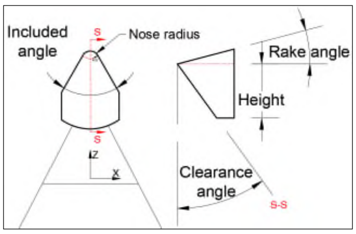

Figure 1: Typical diamond cutting tool geometry

2.2.2 Freeform Surface Geometry

A freeform surface consists of various curvature features that need to be considered very carefully in STS machining. Compatibility between the cutting tool nose radius and surfaces maximum and the minimum curavature is a key requirement to avoid any interference during the machining process. As illustrated in Figure 2(a), a form error can occur when the minimum surface curvature is less than that of the tool nose. The curvature can be defined as 1/R for both the tool nose and the freeform surface. Tool included angle and front clearance angle are dependent and should be less than the maximum surface curvature angle at the tangent point. Figure 2(b) shows the relation between the tool clearance angle and the maximum surface curvature angle in the Z-Y plane. Dynamically, in the larger sagittal curvature of the surface, the tool acceleration and velocity are higher for the STS machining technique. Thus, the dynamic and kinematic effects of the tool on the surface geometry should be considered.

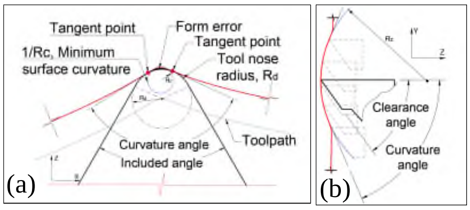

Figure 2: Surface geometry: (a) Included angle and curvature angle effect and form error; (b) Clearance angle and curvature effect

2.2.3 Typical Toolpath Generation and Characteristics

Based on the freeform surfaces specification and design, at the initial stage of the cutting process, the toolpath should be generated. Machining parameters based on both tool and surface geometry should be selected to fulfil the targeted requirement. Tool interference analysis needs to be carried out to check for and where identified, eliminate overcutting between the tool and surface. The toolpath generation process is also required for tool axes motion analysis, for which numerical modelling will be employed to predict the theoretical surface generation and its reliant features. Tool compensation analysis is a key activity to make sure that the real surface profile topology will be achieved after machining. Whilst the current toolpath generation methodology can provide a cutting tool path for freeform surfaces in ultraprecision machining, the dynamic and kinematic effects of the tool and surface features are not included and further research is required to investigate the relationship between those dynamic effects, surface finish and accuracy.

2.2.4 Tool Compensation

The geometry feature of the diamond cutting tool nose is circular, with a tilted clearance and can be defined as a cylindrical or conical. Employing the suitable type for STS machining depends on the surface topology, as abovementioned. However, due to the circularity of the tooltip, the cutting edge can occur overcut on the finished surface at the higher sagittal feature. These overcuts can disintegrate the surface accuracy and final geometry shape after the machining, hence not meeting the requirement of the exact proposed surface. Figure 3 illustrates the effect of the overcutting phenomenon on the toolpath. The current methodology to overcome these issues in ultraprecision machining is using a mathematical shifting algorithm to reposition the compensated points to the tangent point between the tooltip and the surface. However, there are such issues that the mathematical modelling can not ideally compensate for the overcut in very complex freeform surfaces and machining process can fail due to the lack of sufficient data generated points on the surface. Dynamically, the stiffness and cutting force is higher in the overcutting position, and this can lead to a significant mismatch between the ideal and finished surface geometry.

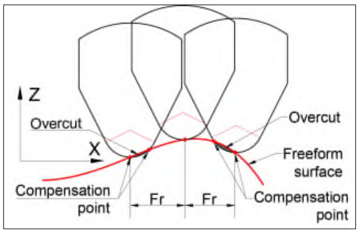

Figure 3: Tool compensation phenomenon

3 The Principle of Multibody Dynamics

3.1 Precision Toolpath Generation

In this subsection, the dynamic effect on the freeform surfaces using the STS technique is investigated. To overcome all challenges mentioned above multibody dynamic analysis has been employed. The interfacial dynamics between the diamond tool and workpiece surface in ultraprecision machining can be considered as a mass-spring-damping system [1]. The system can be considered as being a simple single degree of freedom mass-spring system, where the mass (m) is affected by the applied force (F) in the direction of (u). As illustrated in Figure 4, the workpiece mass (m) is affected by the cutting force (F) and damper (c) in the direction (u).

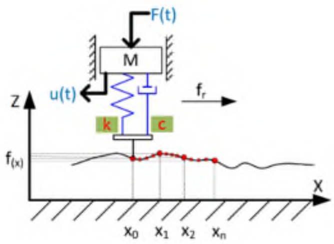

Figure 4: Multibody principle for freeform surface toolpath generation

The mass is permitted to have a displacement only in the (u) direction. Newton's second law applies for this system, whereby force is equal to the mass times the acceleration at step time (t):

$$m\ddot{u}(t) + c\_u(t) + ku(t) = F(t) \quad (1)$$

where, $m\ddot{u}$ is the mass acceleration at the time (t), which is the second derivative of (u), with a specific step time, k is the stiffness constant and c is the constant for damping induced by the loss of energy due to friction between the contacts.

The ADAMS/ Solver is a method that has a robust algorithm to solve the problem for multibody systems numerically. This methodology has been employed in this project to generate the toolpath for a freeform surface directly from a CAD model. It precisely generates the position output coordination at each time step of the tool motion, while being in 3D contact with the surface of the workpiece. The ADAMS solver using Newton's method is commonly used to solve the non-linear equation. Nevertheless, the freeform surfaces can be recognised as a non-linear system[11, 12]. An additional equation for a constrained multibody is required to impose the condition of motion for the system. Reagrding which, the Jacobian matrix can be written for deducing and representing the acceleration, forces, reaction forces, and the positions. For the toolpath generation, the unknown position points are re-evaluated for the Jacobian forces concerning the time and initial condition, which will define the curve by integrating these points at each iteration. The assumption can be made that the tool can be recognised as an indicator of that which can be moved very smoothly across the freeform surface with intense and high resolution properties.

3.2 Numerical Analysis

Numerical analysis has been carried out to investigate the dynamic effects of the STS machining process.

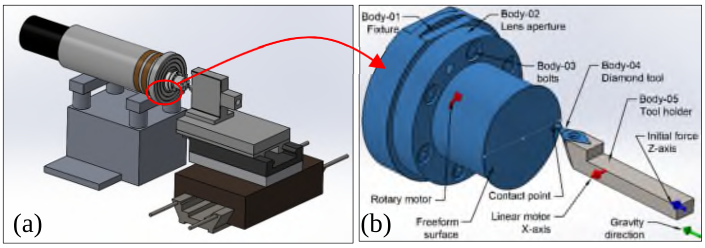

Figure 5: Dynamic principle of STS Machining: (a) multibody STS diagram; (b) multibody of the freeform surface schematic diagram

Two different freeform surface models have been designed in CAD Solidworks version 2016 and a dynamic motion study analysis employed for the proposed approach. Figure 5(a) and (b) shows STS machining in terms of its schematic bodies, constraints and features for generating the toolpath only in the workpiece. Rotary motor present the C-axis and linear motor are in steady X-axis position. The tangential point between the tool position and the freeform surface in the Z-axis is one of the unknown factors that will be calculated by the ADAMS/solver based on the initial force applied to the tool, contact point elastic stiffness, static and dynamic friction coefficient and the maximum damping between the diamond and freeform surface. Table 1 shows the ADAMS/solver parameters data for the numerical setup. Figure 6(a) and (b) illustrate the final 3D toolpath curve, which has been generated in a vector form of X, Y and Z direction in the Cartesian plane.

Table1: Numerical motion study analysis data

Analysis data	**Value [unit]**		**Integrator**	**Value**
Rotary motor speed	30 [rpm]		Frame (time step)	360/s
Feedrate(linear motor)	0.01 [mm/s]		Contact resolution	High
Initial force	1 [N]		Accuracy	0.0000001
Dynamic friction contact	0.25		Integrator type	WSTIFF
Static friction	0.3		Initial step size	0.00001
Elastic impact Stiffness	1,000,000 [N/mm]		Min step size	0.0000001
Max damping	2,000 [N/mm/s]		Max step size	0.01

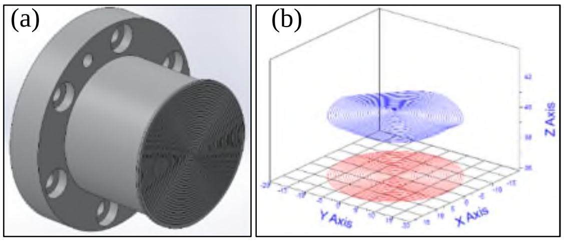

Figure 6: Toolpath generated by the ADAMS/solver

A different approach has been created to investigate the dynamic impact in a freeform surface with more considerable sag. Figure 7(a) shows a freeform surface that includes several different groves with higher curvature value. As can be seen in Figure 7(b), the curvature analysis shows the maximum curvature value in the groves. After running the algorithm, a precise toolpath was generated based on the tool and surface geometry, as illustrated in Figure 7(c).

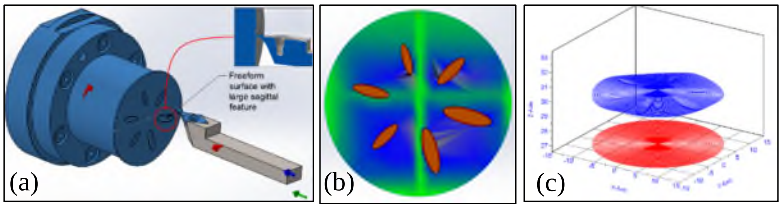

Figure 7: Freeform surface with large curvature: (a) freeform workpiece with groves; (b) surface curvature analysis; (c) toolpath generated by the ADAMS/solver

From an advantage perspective, the dynamical effects within the toolpath generation, such as contact force, velocity, acceleration, moment force and displacements can be calculated with the multibody-dynamic method. Accordingly, Figure 8 illustrates the graph of the calculated contact force between the tool and the freeform surface, acceleration and velocity. As can be seen, the maximum value of the contact force, acceleration and velocity have been calculated in the freeform surface, where the curvature of the surface geometry was rapidly increased during the toolpath generation process.

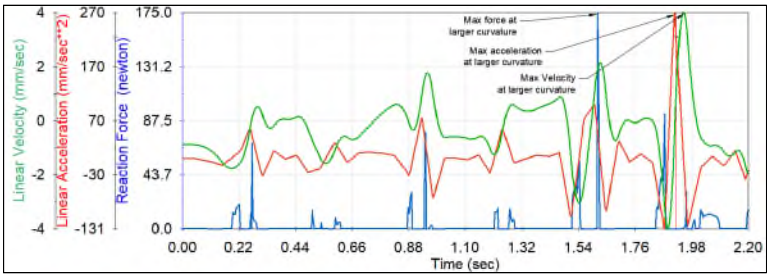

Figure 8: Calculated contact force, acceleration and velocity during the toolpath generation process using the multibody dynamic methodology

4 Experimental Results and Discussion

The experiments were carried out for final validation of STS machining based on multibody-dynamic toolpath generation. Also, a comparative process was carried out between traditional ultraprecision machining toolpath generation and ADAMS, with NanoCAM software being employed for validation. The experiments were operated using Moor Nanotech 250UPL. The extracted points for displacement in the X, Z and C axes from ADAMS were post-processed, and an NC file with G-code was created for the diamond turning machine.

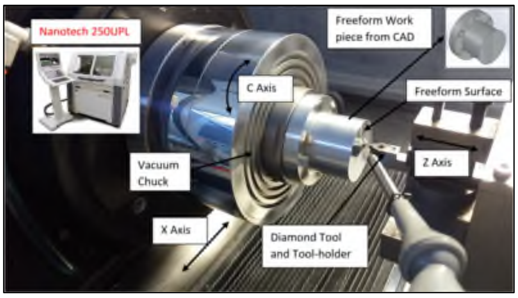

Figure 9: The experimental process with a Nanotech 250UPL diamond turning machine

Figure 9 illustrates the machining process for the experiments, with the STS machining technology being used. Two different workpieces with the same geometry shape have been used: one to test the effect of the surface resolution with the NanoCAM methodology and the second, to test the novel multi-dynamic toolpath generation, which in this paper is ADAMS. An alloy aluminium material was selected for machining and he same diamond tool geometry with a 0.6mm tool nose radius was used for both experiments. The machining parameters for the NanoCAM NC code were set as 30rpm of spindle speed, 0.01 mm/s feed in the X direction, a point distance of 0.01 mm and a spiral pitch of 0.01 mm for the cutting path.

4.1 Surface Resolution and Metrology

A Zygo 3D surface profiler was employed for final validation. The experimented upon machined components of ADAMS and NanoCAM have provided the measured roughness of the freeform surfaces. Comparing the two results, it has been observed that the surface machined by the ADAMS toolpath has lower surface roughness due to the very precise generated points evaluated by Jacobean integration. Based on the results shown in Table2, it is evident that the maximum values of PV, Rms and Ra in the ADAMS tool path generation are less than when undertaken by the NanoCAM process.

Table2: Surface finish profile comparative data

Analysis data	**ADAM**	**NanoCAM**
PV (μm)	0.303	0.774
Rms (μm)	0.030	0.068
Ra (nm)	19.926	45.923

5 Conclusions

In this paper, an innovative toolpath generation approach for ultraprecision machining and the analysis of an ultraprecision machining system has been proposed based on multibody dynamics. It can be deployed for precision toolpath generation for ultraprecision diamond turning of freeform optic surfaces. It can overcome the issues currently existing with ultraprecision machining when using the conventional CAM system by direct linkage to the CAD model. It is considered that this methodology can be applied for in-line measurements of the freeform surface finishing, with the factors being of force, velocity and acceleration of each individual point calculated accurately. As a disadvantage point of view, the limitation of the generating points for larger parts and surfaces is identified in this approach. Also, the improvements shown in Table 2 lead to a quantified summary that this methodology can be integrated with conventional ultraprecision machining to achieve optimum freeform surface finishing.

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References

[1] L. Zhou and K. Cheng, “Dynamic cutting process modelling and its impact on the generation of surface topography and texture in nano/micro cutting,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 223, no. 3, pp. 247–266, 2009.

[2] D. Huo, K. Cheng, and F. Wardle, “A holistic integrated dynamic design and modelling approach applied to the development of ultraprecision micro-milling machines,” *Int. J. Mach. Tools Manuf.*, vol. 50, no. 4, pp. 335–343, 2010.

[3] D. W. K. Neo, A. Senthil Kumar, and M. Rahman, “CAx-technologies for hybrid fast tool/slow slide servo diamond turning of freeform surface,” *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 230, no. 8, pp. 1465–1479, 2016.

[4] H. Gong, Y. Wang, L. Song, and F. Z. Fang, “Spiral tool path generation for diamond turning optical freeform surfaces of quasi-revolution,” *CAD Comput. Aided Des.*, vol. 59, pp. 15–22, 2015.

[5] L. B. Kong, C. F. Cheung, and W. B. Lee, “A theoretical and experimental investigation of orthogonal slow tool servo machining of wavy microstructured patterns on precision rollers,” *Precis. Eng.*, vol. 43, pp. 315–327, 2016.

[6] O. Riemer, “Advances in Ultra Precision Manufacturing,” *Proc. JSPE Spring Meet.*, 2011.

[7] M. C. Liu, J. Q. Lin, and X. Q. Zhou, “Recent Advances in Ultraprecision Diamond Turning of Non-Rotationally Symmetric Optical Surfaces,” *Appl. Mech. Mater.*, vol. 110–116, pp. 3600–3607, 2011.

[8] F. Z. Fang, X. D. Zhang, A. Weckenmann, G. X. Zhang, and C. Evans, “Manufacturing and measurement of freeform optics,” *CIRP Ann. - Manuf. Technol.*, vol. 62, no. 2, pp. 823–846, 2013.

[9] D. Lutrell, “Innovations in Ultra-Precision Machine Tools: Design and Applications,” pp. 1–4, 2010.

[10] Y. E. Tohme and J. A. Lowe, “Machining of freeform optical surfaces by slow slide servo method,” *Proc. Am. Soc. Precis. Eng.*, pp. 3–6, 2003.

[11] C. W. Gear, “The Automatic Integration of Ordinary Differential Equations,” *Commun. ACM*, vol. 14, no. 3, pp. 176–179, 1971.

[12] M. Pękal and J. Frączek, “Comparison of Selected Formulations for Multibody System Dynamics with Redundant Constraints,” *Arch. Mech. Eng.*, vol. 63, no. 1, pp. 93–112, 2016.