# Investigation of a dynamics-oriented engineering approach to ultraprecision machining of freeform surfaces and its implementation perspectives

Cite as: Nanotechnol. Precis. Eng. **4**, 043002 (2021); https://doi.org/10.1063/10.0006388
Submitted: 04 February 2021 • Accepted: 10 August 2021 • Published Online: 07 October 2021

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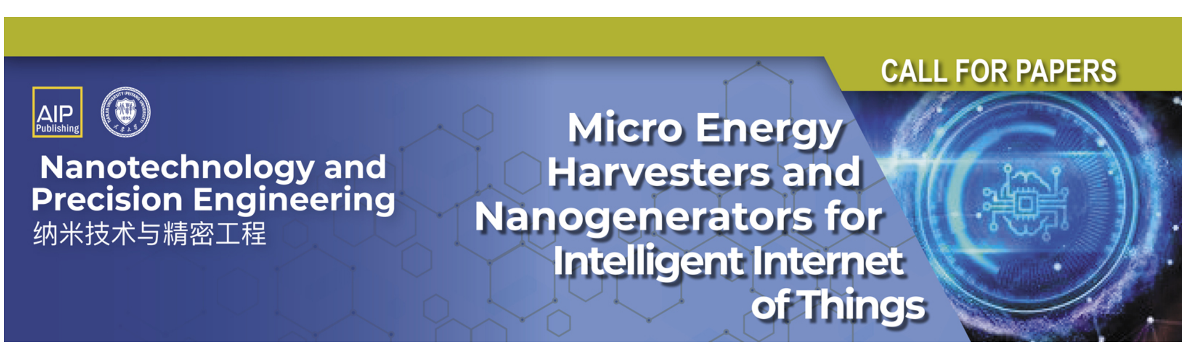

Nanotechnology and Precision Engineering | ARTICLE | scitation.org/journal/npe

# Investigation of a dynamics-oriented engineering approach to ultraprecision machining of freeform surfaces and its implementation perspectives

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Submitted: 4 February 2021 • Accepted: 10 August 2021 •
Published Online: 7 October 2021

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## ABSTRACT

In current precision and ultraprecision machining practice, the positioning and control of actuation systems, such as slideways and spindles, are heavily dependent on the use of linear or rotary encoders. However, positioning control is passive because of the lack of direct monitoring and control of the tool and workpiece positions in the dynamic machining process and also because it is assumed that the machining system is rigid and the cutting dynamics are stable. In ultraprecision machining of freeform surfaces using slow tool servo mode in particular, however, account must be taken of the machining dynamics and dynamic synchronization of the cutting tool and workpiece positioning. The important question also arises as to how ultraprecision machining systems can be designed and developed to work better in this application scenario. In this paper, an innovative dynamics-oriented engineering approach is presented for ultraprecision machining of freeform surfaces using slow tool servo mode. The approach is focused on seamless integration of multibody dynamics, cutting forces, and machining dynamics, while targeting the positioning and control of the tool–workpiece loop in the machining system. The positioning and motion control between the cutting tool and workpiece surface are further studied in the presence of interfacial interactions at the tool tip and workpiece surface. The interfacial cutting physics and dynamics are likely to be at the core of in-process monitoring applicable to ultraprecision machining systems. The approach is illustrated using a virtual machining system developed and supported with simulations and experimental trials. Furthermore, the paper provides further explorations and discussion on implementation perspectives of the approach, in combination with case studies, as well as discussing its fundamental and industrial implications.



**KEYWORDS**
**Ultraprecision machining, Freeform surface, Dynamics-oriented approach, Dynamic cutting force, Slow tool servo mode, Microcutting**

## I. INTRODUCTION

Ultraprecision machining of freeform surfaces through diamond turning in slow tool servo (STS) machining mode is becoming one of the most useful machining processes, since it can deliver high accuracy and efficiency by integrating distinct precision engineering techniques. Freeform surfaces are increasingly employed in precision engineering, including the automotive, optics, electronics, aerospace, and biomedical engineering industries.[1,2] The ultraprecision machining process chain normally starts by using a CAD/CAM tool to generate the toolpath trajectory. The toolpath generation can be based on the real form of the freeform surface and/or use the tool compensation trajectory to address surface form errors and apply corrections by modifying the final toolpath.[3,4] In ultraprecision machining components with nonuniform rational basis spline (NURBS) surfaces, the diamond tool has to move as a function of the spindle rotation and translation of the machine slide. This method differs from the use of tool servos to generate the tool motion.[5,6]

Moreover, the mechanism of material removal differs between STS mode and fast tool servo (FTS) mode, because of the dynamic effects associated with rapid acceleration. The achievement of good surface finish is challenging in ultraprecision machining in both STS and FTS configurations.[7,8] To fulfill the increasing requirements for high precision and productivity in ultraprecision machining of freeform surfaces, it is essential to have a scientific understanding of the underlying dynamics, ideally linked to the materials, mechanical stiffness, friction, tooling, servo system, and their collective effects, together with the precision engineering perspectives for the machining system.

The research presented in this paper is focused on a dynamics-oriented engineering approach for ultraprecision machining of freeform surfaces based on a scientific understanding of the underlying dynamics, the modeling of these dynamics, and the development of algorithms for implementation of the approach in precision engineering practice. The approach is centered on interfacial cutting dynamics at the tool and workpiece surfaces and dynamical interactions, with the tool and workpiece being supported by a chain of elements within the machining system. The implementation aspects of the approach are explored and discussed in the machining system domain, following precision engineering principles. The approach and implementation are further evaluated and validated through engineering case studies. To some extent, the paper also attempts in a holistic manner to bridge the gaps between engineering science fundamentals, precision engineering, and ultraprecision machining systems for high-precision machining of complex components and surfaces.

## II. DYNAMIC EFFECTS AND STS MODE ULTRAPRECISION MACHINING

STS can be directly applied on any modern diamond turning machine. It can achieve displacements of a few millimeters in nonrotational symmetric applications.[9] Unlike the FTS technique, STS does not require any additional axis for tool motions, since the tool sits directly on the slide to produce synchronized slide–spindle motions, thereby enabling the generation of freeform surfaces.[10] However, there is still substantial mileage to be gained in improving the dynamics of these synchronized motions. Furthermore, to enable the development of the next generation of ultraprecision machining systems with higher precision and manufacturing productivity, it is essential to have a scientific understanding of the dynamics chain supporting the interfacial interactions between the cutting tool tip and the surfaces generated.

### A. Dynamics specifications

Several key features need to be present to allow STS mode machining on a diamond turning machine, most of which concern friction-free linear and rotary axes. A control system with high-speed data processing capacity plays a key role in very accurately actuating the motors and all the direct drive axes. A number of key factors affecting precise positioning in the machining system should be fully taken into account, including encoder resolution, thermal stability, high-order trajectory generation, precision data acquisition methods, and system stiffness in the control loop. In-process analysis of the positioning loop and the loop dynamics is critical in STS mode ultraprecision machining, since the freeform surface topology has a direct effect on the cutting tool velocity and acceleration. The implementation of high positioning loop bandwidth is therefore also an essential requirement in STS. To maintain the appropriate bandwidth, evaluation of the actuation acceleration and velocity at the machining system must take account of the freeform surface curvatures and sagittal features Analysis of the freeform surface geometry in relation to the tool tip and workpiece interfacial surface is thus required to specify the dynamics in the system, rendered collectively by the mechanical structure, electrical actuation, in-process positioning feedback, and control algorithms, etc. The tool trajectory method for conventional ultraprecision toolpath generation is unable to effectively harness the system dynamics, such as the tool velocity and acceleration, tool friction, and surface contact force, which are affected by the freeform surface itself. Figure 1 illustrates the most characteristic elements maintaining the dynamic specifications in a typical ultraprecision machining system. Scientific understanding of the interfacial dynamics between the tool tip and workpiece surface, as well as the dynamics in the machining loop, is essential for developing future ultraprecision machining systems, particularly with regard to achieving higher precision and productivity.

### B. Dynamic cutting forces

Based on the specifications and design of the freeform surface, the tool paths should be generated in the initial stage of the process. Machining process parameters based on both tool and surface geometry are selected to fulfill the targeted requirement while taking account of the dynamic cutting forces. Tool interference analysis needs to be carried out to check, identify, and eliminate overcutting between tool and surface. Tool axis motion analysis is also required for the toolpath generation process, from which numerical modeling is further developed to predict the theoretical surface generation and the features on which it relies. Tool compensation analysis is needed to make sure that the real surface profile and topography are achieved after machining. While the current toolpath generation method can provide a cutting tool path for freeform surfaces in ultraprecision machining, the dynamic and kinematic effects on the tool and surface features are not included. Therefore, in freeform surfaces ultraprecision machining, further research is needed to investigate the intrinsic relationship between these dynamic effects and surface finish, in particular in the context of achieving higher precision and machining efficiency.

### C. Tool geometry and surface characterization

Tool geometry has a significant role in undertaking successful STS mode ultraprecision machining. The selection of tool features relates directly to the topography of the freeform surface, such as curvature and sagittal elements. A freeform surface consists of various curvature features that need to be carefully taken into account in STS mode machining. Compatibility between the cutting tool nose radius and the maximum and the minimum curvatures of the surface is a key requirement to avoid any interference during the machining process. Furthermore, form error can

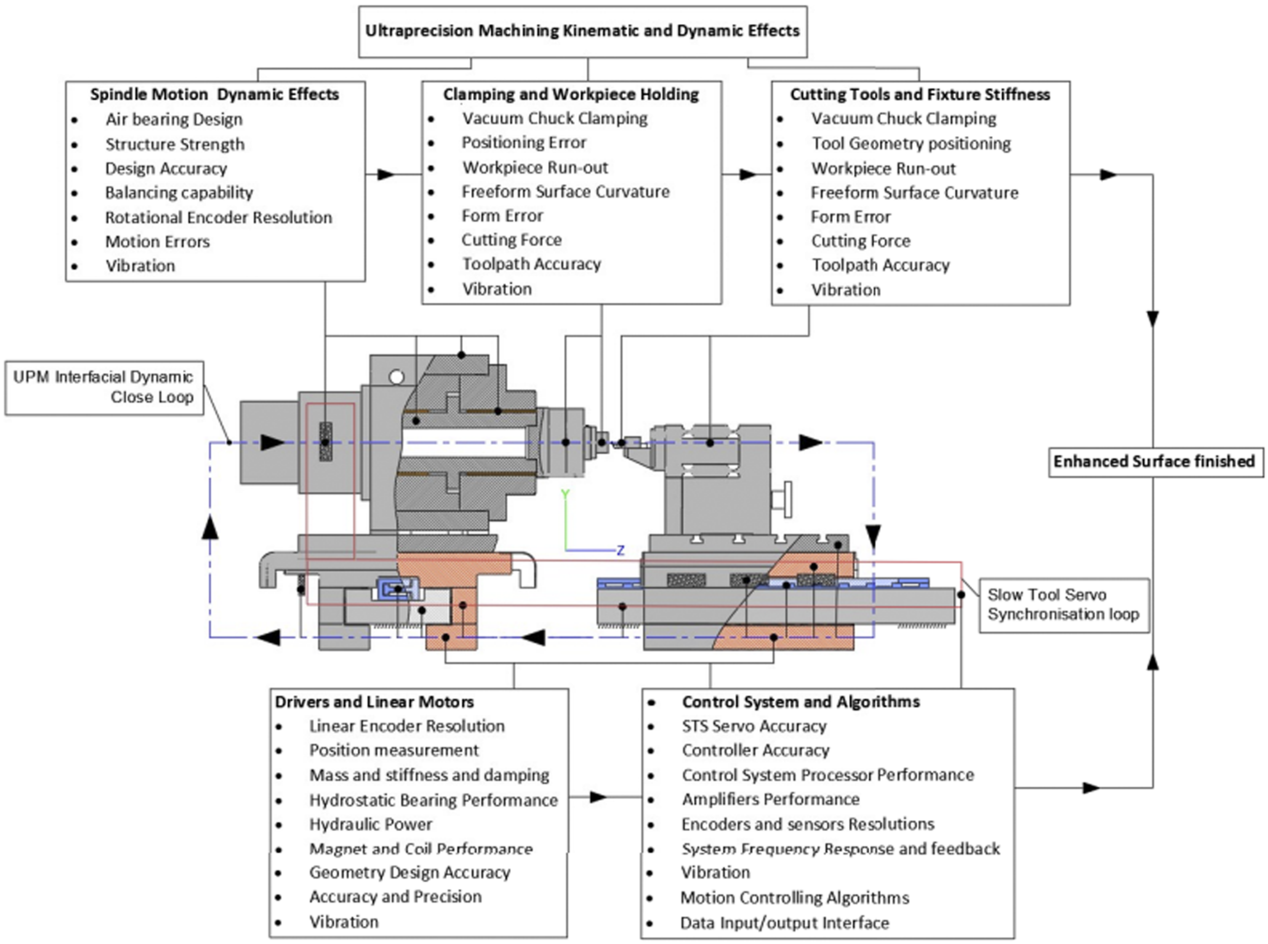



**FIG. 1.** Illustration of kinematic/dynamic characteristics in an ultraprecision machining system.

occur when the minimum surface curvature is less than that of the tool nose. The curvature of the surface 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. Dynamically, at the larger sagittal curvature of the surface, the tool acceleration and velocity are higher in STS mode machining. Therefore, the dynamic and kinematic effects of the tool on the surface geometry should be taken into account both qualitatively and quantitatively.

### D. Tool compensation

The basic geometry of a diamond tool nose is circular with a tilted clearance and can be defined as cylindrical or conical. Employing a suitable type of tool for STS mode machining depends on the freeform surface topology as discussed above. However, owing to the circular nature of the tooltip, the cutting edge can overcut on a finished surface with a higher sagittal feature. These overcuts can reduce the surface accuracy and final geometrical precision after machining such that the requirements for the proposed nominal surface are no longer met. A recently developed method to solve this problem in ultraprecision machining is to use a mathematical shifting algorithm to reposition the compensated points to the tangent point between the tooltip and the surface. However, there are issues in that the mathematical modeling cannot ideally compensate for the overcut with very complex freeform surfaces, and the machining process can fail owing to a lack of sufficient data generation points on the surface. The dynamic stiffness and dynamic cutting force are higher at the overcut positions, which can lead to a significant mismatch between the ideal and finished surface geometries.

## III. DYNAMIC ANALYSIS OF STS MODE ULTRAPRECISION MACHINING

### A. Dynamics and precision toolpath generation

The interfacial dynamics between the diamond tool and workpiece surface in ultraprecision diamond turning can be considered as a mass–spring–damper system working in a dynamic scenario.[11] As illustrated in Fig. 2(a), the workpiece mass $m$ is affected by the dynamic cutting force $\boldsymbol{F}(t)$, and supported with a damper $c$ and a spring $k$ in the $\boldsymbol{u}$ direction. The mass is permitted to have a displacement only in the $\boldsymbol{u}$ direction. Newton's second law applies to this dynamic system, whereby the dynamic cutting force is expressed as

$$m\ddot{\boldsymbol{u}}(t) + c\dot{\boldsymbol{u}} + k\boldsymbol{u}(t) = \boldsymbol{F}(t), \tag{1}$$

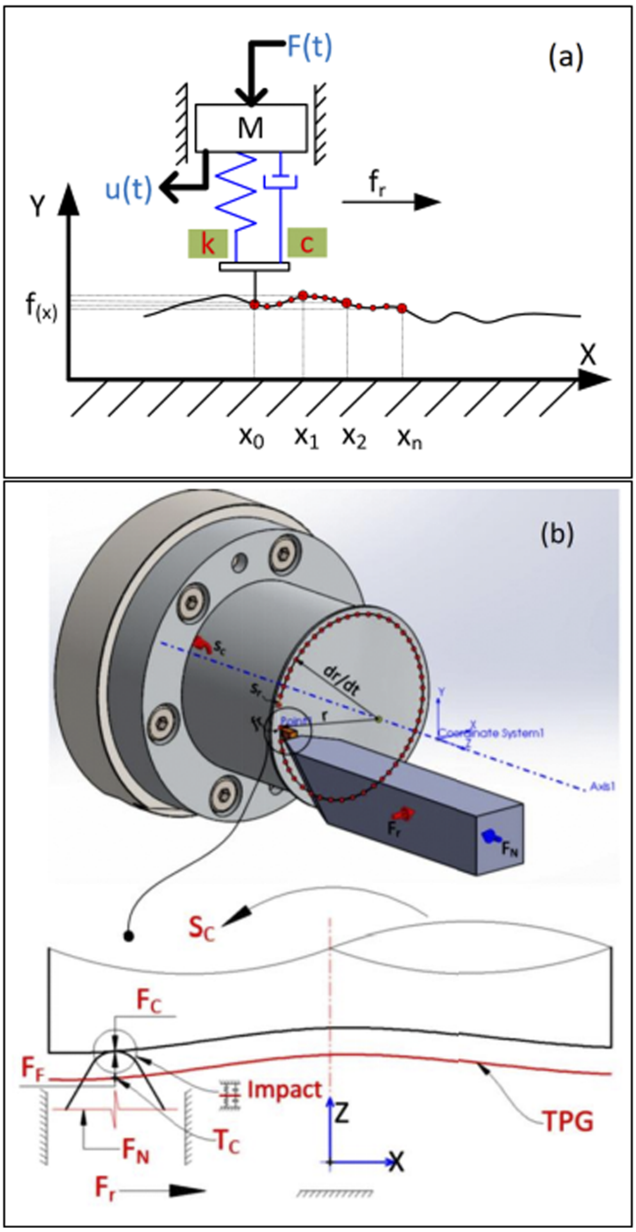



**FIG. 2.** ADAMS toolpath generation principle: (a) second-order mass–spring–damper system; (b) toolpath generation diagram via ADAMS/Solver.

where $m\ddot{\boldsymbol{u}}$ is the mass acceleration inertia at time $t$, $k$ is the stiffness constant, and $c$ is the damping constant. ADAMS/Solver is a method and tool that has robust algorithms to solve dynamics problems for multibody dynamic systems numerically. This method is employed in this study to generate the toolpaths for machining the freeform surface directly from a CAD model. It precisely generates the tooltip position coordinates as the output at each time step of the tool motion, while it is in 3D contact with the surface of the workpiece in the CAD model. ADAMS/Solver uses Newton's method to solve the nonlinear equations. The freeform surfaces can be recognized as a nonlinear system.[12] For a constrained multibody system, an additional equation is required to impose the condition of motion for the system. The generalized coordinates vector for the multibody system can be expressed as

$$q_{n\times 1} = [q_1, q_2, \ldots, q_n]^{\mathrm{T}} = \left[q_1^{\mathrm{T}}, q_2^{\mathrm{T}}, \ldots, q_N^{\mathrm{T}}\right]^{\mathrm{T}}, \tag{2}$$

where $\boldsymbol{q}_i = [x_i\ y_i\ z_i\ \alpha_i\ \beta_i\ \gamma_i]^{\mathrm{T}}$, $n$ is the number of generalized coordinates, and $N$ is the total number of bodies involved in the system. $x_i$, $y_i$, and $z_i$ are the coordinates of the $i$th body translation from the origin of the global reference frame to the origin of the $i$th body of the local reference frame. $\alpha_i$, $\beta_i$, and $\gamma_i$ are the Euler angles of the system. As a multibody dynamic system, the equation of motion with respect to Eq. (1) can be written as[13]

$$\boldsymbol{M}\ddot{\boldsymbol{q}} + \boldsymbol{\Phi}_q^{\mathrm{T}}\boldsymbol{\lambda} = \boldsymbol{Q}, \tag{3}$$

where $\boldsymbol{Q}$ is the generalized vector of forces, $\boldsymbol{M}$ is the inertia matrix, and $\boldsymbol{\Phi}_q^{\mathrm{T}}\boldsymbol{\lambda}$ is the generalized vector of reactions, in which $\Phi_q$ is the constraint Jacobian matrix and $\lambda$ is the Lagrange multiplier vector. Moreover, the constraint equations need to be satisfied by the generalized coordinates at the position level in each time step.

The Jacobian matrix equations can be used to represent and deduce the acceleration, forces, reaction forces, and positions within the machining system. For toolpath generation, the unknown positioning points are reevaluated for the Jacobian forces, taking account of the time and initial conditions, and the curve will be defined by integrating these points at each iteration. It can be assumed that the tool can be recognized as a high-resolution indicator that can be moved very smoothly across the freeform surface. Based on this phenomenon, as illustrated in Fig. 2(b), a normal force $\boldsymbol{F}_{\mathrm{N}}$ is applied to the tool, which has a tangential constraint associated with the freeform surface and works as an indicator on the $Z$ axis. On the $X$ axis, a linear motor with driving force $\boldsymbol{F}_{\mathrm{r}}$ provides the feed rate. The angular velocity $\boldsymbol{S}_{\mathrm{c}}$ defines the spindle speed. As noted in Sec. II, the system is dynamically fully constrained, and thus the contact friction between the tooltip and the freeform surface needs to be defined. A dynamic friction $\mu_{\mathrm{k}}$ and static friction $\mu_{\mathrm{s}}$ have been included in the system.

The impact stiffness, damping, and a penetration constraint are also needed in the computation of the displacement at the next time step based on the physical contact and interaction between the tool and the workpiece surface. As illustrated in Fig. 2(b), after the solver has been run, the angular velocity of the spindle and linear motor are time-dependent. Both linear and angular velocities and the initial conditions are computed by ADAMS using the Newton–Raphson method. The next position is computed at each cycle per second.[14] The so-called indicator is in contact with the freeform surface in the $Z$ direction on the $X$–$Z$ plane. The position of the tool on the $Z$ axis is generated based on the geometric shape of the freeform surface and in synchronization with the rotational displacement of the $C$ axis, and the velocity and linear feed rate on the $X$ axis are generated from the origin coordinates. According to the equations of motion, as the C axis rotates, the linear motor moves toward the center of the workpiece. At each time step, the mass–stiffness–damping matrix equations are calculated, and the coordinates of the point are recorded. The arc distance of $S_r$ is defined by differentiation of the polar coordinate of $r$ with respect to time as $dr/dt$. According to Eq. (1), toolpath generation will be computed based on the input parameters. As described above, the system is nonlinear owing to the freeform nature of the surface and the complexity and nonlinearity of the machining system. The customized ADAMS/Solver is fully capable of resolving and computing such unknown outputs of the system.

### B. Implementation aspects

Conventional tool path generation (TPG) methods are based on map-to-map point projection, and so major problems arise when they need to be compiled in a real machining process or environment. Owing to contact and friction forces between the tooltip and the freeform surface, most of the generated points are correlated with errors on the final finished surface and are ultimately unable to provide high performance, accuracy and robust resolution. Multibody dynamics-oriented TPG aims to reduce the level of such errors by taking account of the friction and contact forces in the system and outputting the computed TPG points in light of the dynamic equations of motions. Figure 2(b) also illustrates a diagram of the forces that are included to generate points that can be integrated to shape the final toolpath on the surface. This is unlike conventional methods, which can only cope with map-to-map point projection onto the surface. On running the system simulation, as previously discussed, the contact between the tooltip and surface is subject to impact stiffness and damping forces, denoted by $\boldsymbol{F}_{\mathrm{C}}$, and a friction force $\boldsymbol{F}_{\mathrm{F}}$. The impact rules and equations are computed for the initial conditions on the basis of the ADAMS equations, and the position of the tool center $\boldsymbol{T}_{\mathrm{C}}$ is recorded.

The main disadvantage of using ADAMS toolpath generation is that a greater number of single points are generated in high-precision models, and there is a limit on the number of points that can be generated when larger parts are required. Thus, the efficiency of this method is currently not robust enough, and further investigation and development still need to be undertaken in this area. Nevertheless, the method is able to generate very precise toolpaths for tools working with extra information in association with complex machining conditions, such as force friction and dynamic cutting forces.

## IV. HIGH PRECISION AND ASSOCIATED IMPLEMENTATIONS

For modern ultraprecision machine tools and machining practices, positioning and motion control of machine actuation systems, such as the slideway and spindle, rely heavily on the use of linear and rotary encoders. However, the positioning control is quite "passive" in terms of not directly monitoring and controlling the tool and workpiece positions in the dynamic machining process, under the assumption that the machining system is rigid and the cutting dynamics stable. Such machine design configurations and other existing issues are hindering progress in ultraprecision machining toward higher precision (e.g., pico-precision[15]), and they need to be addressed, although this is likely to require a process of step-by-step innovation.

### A. Multibody dynamics in ultraprecision machining system

Three-axis ultraprecision machining can be represented as a rigid-body sliding wedge with a preloaded spring following a freeform trajectory. Motor loads and actuation are normally under preloaded magnetic forces, and the point of contact between the tooltip and the workpiece surface can therefore be identified as a spherical joint, with the resultant forces varying depending on the curvature of the workpiece freeform surface. Figure 3(a) shows a multibody diagram of three-axis ultraprecision machining of a freeform surface. Individual points of the toolpath are taken as the input for the controller, through which the servo motors driving the $X$ and $Z$ and $C$ axes are synchronized and close the loop of the STS mechanism.

Figures 3(b)–3(d) illustrate the multibody linkages of the resultant vectors and simplified system mechanism diagrams from the starting point to the semi-end and end positions, respectively, acting on the linear and rotary motors. From the point of view of dynamics, as shown in the diagrams, it is found that each point at the toolpath trajectory has a different resultant vector that represents the linear motions of the linear motors, which generate nonlinear reaction forces at the movable

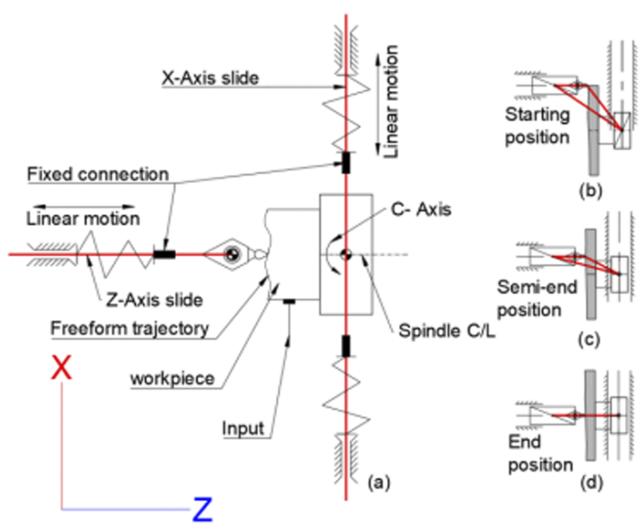



**FIG. 3.** Multibody diagram vectors for ultraprecision machining: (a) three-axis ultraprecision machining diagram; (b) starting position; (c) semi-end position; (d) end position.

bodies in the system during the cutting process. The reaction forces have characteristic effects on the precision positioning of the tool.

The coordinates and notational system used to specify the linear drive acting forces and their distribution are illustrated in Fig. 4 specifically for the ultraprecision machining scenario discussed here. As can be seen, the system consists of three major force vector components, with the resultant force $\boldsymbol{F}_{\mathrm{R}}$ always acting from the centers of mass of the slides, COM$z$ and COM$x$, respectively, and vice versa. Each moving slide (carriage) is identified as a rigid body carrying six degrees of freedom (DOF) at the center of mass, i.e., including three translational and three rotational components. The rotational components are the pitch, yaw, and roll in the $X$, $Y$, $Z$ directions in the Cartesian coordinate system.

The contact point between the tooltip and the workpiece surface is also subjected to a varying interfacial force $\boldsymbol{F}_{\mathrm{C}y}$ along its $X$ and $Y$ directions. The resultant of this interfacial force is translated through the component force vector of $\boldsymbol{F}_z$ and $\boldsymbol{F}_x$.

With regard to the force $\boldsymbol{F}_{\mathrm{C}y}$, it is envisaged that the freeform surface workpiece is subjected to varying reaction forces at the individual interfacial points in the machining process due to varying curvature. The behavior of the reaction forces at the center of the slide mass can be nonlinear. This highlights the fact that the cutting forces at the contact point between the tooltip and workpiece surface always affect the performance of the moving slides, which should not be neglected. Furthermore, the ability to measure the forces at each individual point of the toolpath can improve the capability of the control system by shifting it from semi closed-loop to full closed-loop control, i.e., the interfacial forces can be used as feedback to monitor and control the dynamics of the slide and the spindle in a direct and robust way. Sections IV B and IV C will describe and explore the mutual impact of the interfacial forces on the hydrostatic linear slideways and the air-bearing spindle.

### B. Freeform curvature and dynamic cutting forces

The resultant interfacial force at the contact point between the tooltip and workpiece surface varies owing to the surface curvature and topology. This has a significant impact on the surface finishing of the workpiece. As illustrated in Fig. 5, in ultraprecision machining of a freeform surface, the chips formed in the process are produced by three-zone material removal that varies coherently with changes in surface curvature. These zones are characterized as flowing, normal, and fracturing. Chips are produced in the flowing zone when the tool approaches part of the surface that has a large curvature angle. During the cutting process, when the tangential plane of the curvature is perpendicular to the tooltip, there is a normal force distribution on the cutting chip.

As the cutting process continues, and when the tool approaches part of the surface with a tight curvature angle, the greatest resultant forces are generated and act on chip fracture. This influences the dynamics of the machining system, particularly through the impact force on the hydrostatic-bearing-supported slideways and the rotational air-bearing spindle. Therefore, understanding and predicting the interfacial forces acting at the tooltip–workpiece surface interface are important for further increasing the dynamic capacity and performance of ultraprecision machining systems.

Figure 6 highlights the major dynamic effects and factors that need to be considered in dynamic monitoring and control of tool and workpiece positioning. Although the resolution of currently employed encoders in ultraprecision machining systems is high enough for kinematic positioning control of the slide and spindle elements, it is still far from full closed-loop control in which account is taken of the dynamic interfacial interactions of the tooltip and workpiece surface as feedback input. Nevertheless, full closed-loop control incorporating the dynamics

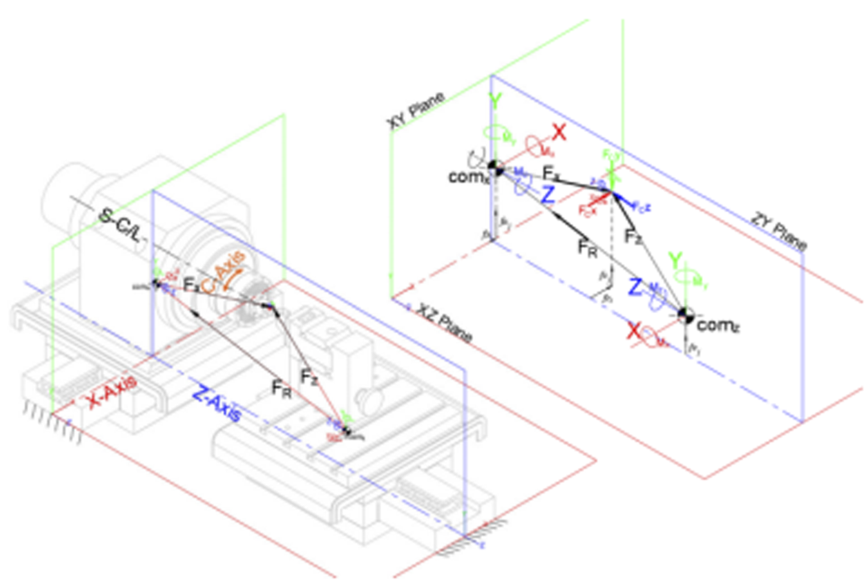



**FIG. 4.** Three-dimensional diagram illustrating the linear drive acting forces and their distribution in the ultraprecision machining scenario.

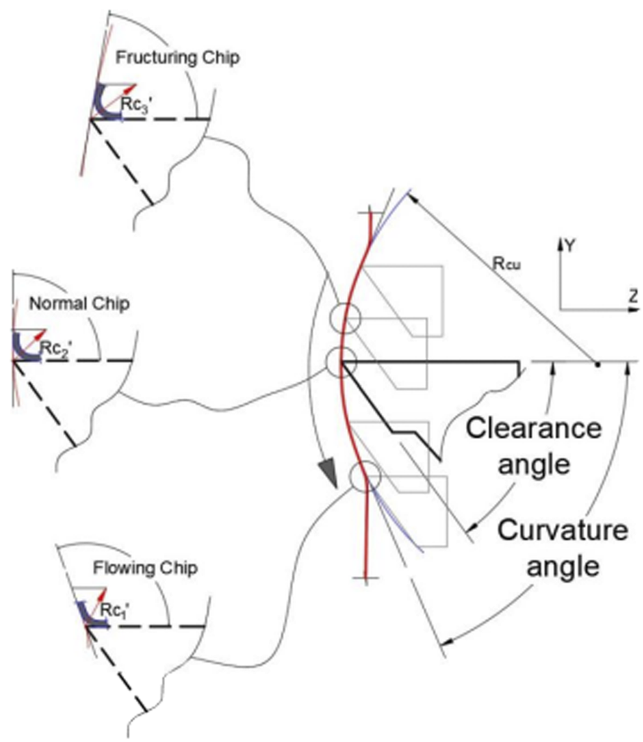



**FIG. 5.** Curvature and dynamic cutting force effects on the freeform surface.

and interfacial interactions of the tooltip and workpiece surface is essential for the next generation of ultraprecision machining system, particularly with regard to the achievement of even higher precision.

## C. Dynamic effects on hydrostatic linear slideways

Hydrostatic bearing supported slideways are often used in ultraprecision machining systems for maintaining high stiffness and loading capacity. As illustrated in Fig. 7, the loading $\boldsymbol{F}_{\mathrm{v}}$ includes all resultant forces from cutting forces, static loading, and damping in the machining process transferred onto the constraining planar joints between the stationary and movable parts. The pressure of the hydraulic flow through the orifices has a gradient and varies with the mass flow rate of the oil. Despite the fact that hydrostatic-bearing-supported slideways have been used in precision machines for a few decades, very few investigations have been carried out on the influence of the system dynamics on the hydrostatic bearing system in STS mode ultraprecision machining of freeform surfaces.

In hydrostatic bearing design specifications, the dimensions of the oil orifices or constraint slot entries to the hydrostatic bearing are in the range of 10–20 $\mu$m, depending on load capacity and stiffness requirements, which are fundamentally subject to the dynamics and kinematics associated with motion displacement, velocity, and acceleration between the rail block and carriage in the constraint plane. A second-order mass–spring–damper model is appropriate, since a Newtonian fluid forms the pressure zone and the force distribution around the constraint pockets is horizontal for $\boldsymbol{F}_{\mathrm{hh}}$ and vertical for $\boldsymbol{F}_{\mathrm{vh}}$. Therefore, in machining freeform surfaces, the resultant vectors $\boldsymbol{F}_{\mathrm{hc}}$ and $\boldsymbol{F}_{\mathrm{vc}}$ respectively determine the nonlinear force curves in the constraint plane acting against the pressurized fluid flow through the constraint orifice or slot entries. Those forces influence the dynamics and dynamic performance of the hydrostatic bearings and the slideway.

## D. Encoder resolution for high precision and dynamic effects

As discussed in the preceding subsections, positioning accuracy in ultraprecision machining is strongly affected by

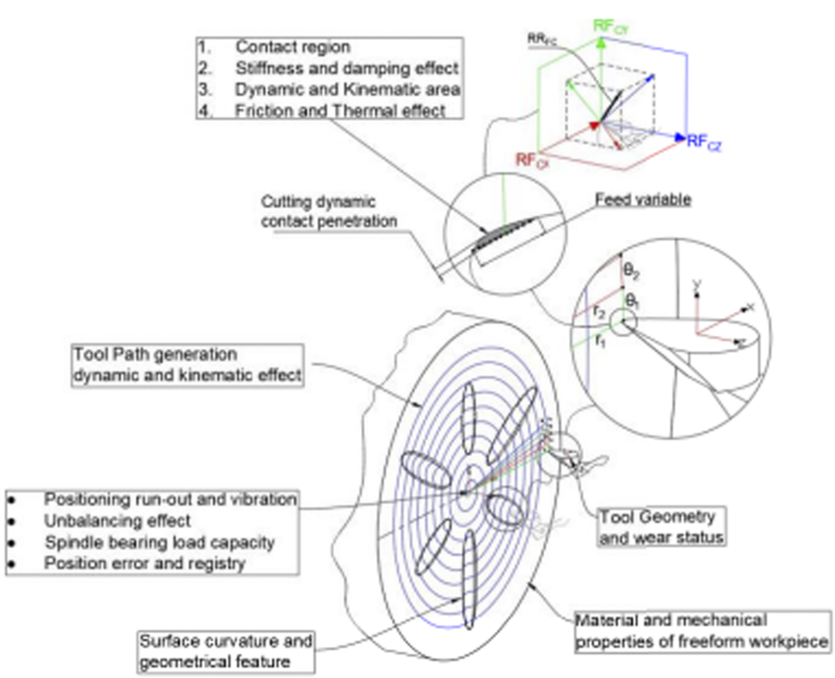



**FIG. 6.** Dynamic effects and factors in positioning control of the tool and the workpiece.

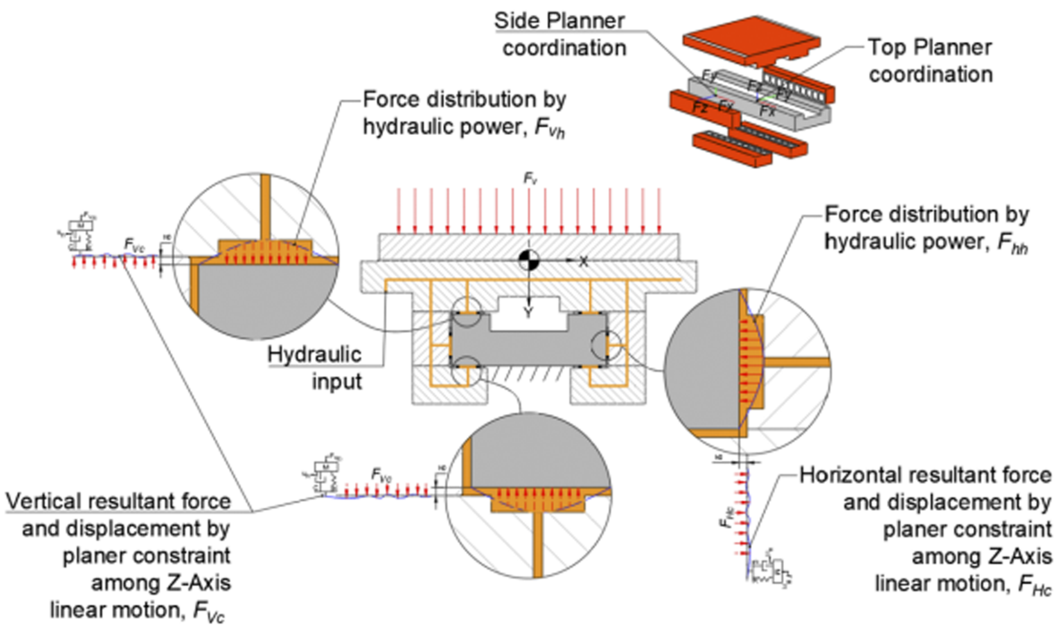



**FIG. 7.** Dynamic effects on a hydrostatic-bearing-supported linear slideway.

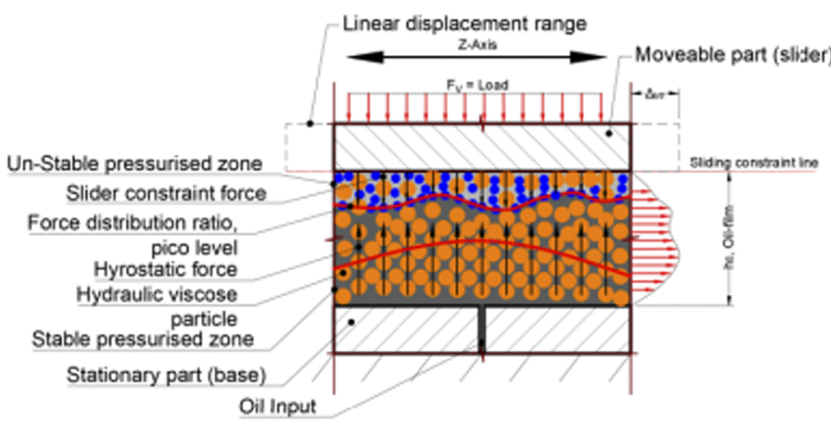



**FIG. 8.** Graphical illustration of intrinsic linkages and dynamic effects in the hydrostatic oil-film layer.

machining dynamics, and there is therefore a need for simultaneous consideration of dynamics and positioning accuracy. Among the dynamic parameters, the interfacial cutting force in particular should be linked with the positioning control in STS mode machining of freeform surfaces, since it has a direct impact the finishing of the surfaces. Figure 8 shows a graphical illustration of the effects of the dynamic forces, including the interfacial cutting force, and the intrinsic linkages between them in the pressurized oil-film layer of thickness $h_0$. During the cutting process, it is assumed that two different zones, stable and unstable, occur in the film gap.

The stable pressurized zone lies in the area between the stationary and movable parts, where the hydrostatic oil is affected by its viscosity (stiffness) and damping coefficient. In the unstable zone, the interfacial resultant forces caused by the workpiece surface curvature are transferred through the movable slider constraint forces into the stable pressurized zone. The force ratios and distribution are quite small; however, they are vary depending on the linear displacement range $\Delta\mu_s$ of the slider. Existing encoders, even with high resolution, are still unable to capture the uncertainties in the dynamic displacement and the dynamic forces on the constraint line, since they are not designed and configured for full closed-loop control of the machining system.

## V. DYNAMIC SIMULATIONS AND EXPERIMENTAL TRIALS: RESULTS AND DISCUSSION

Numerical simulations on a typical ultraprecision machining system are performed using algorithms for multibody dynamics implemented in the ADAMS/Solver environment.

As illustrated in Fig. 9(a), a 3D model of a typical ultraprecision machine is established and integrated with the ADAMS multibody-dynamics-based simulations. Figure 9(b) shows a workpiece with multicurvature freeform surfaces integrated with a flat surface base, which is delicately designed for capturing the distribution and variation of the forces in the machining system.

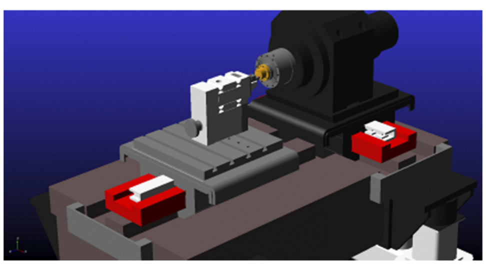
Table I lists the parameters used in the ADAMS simulations of the dynamic effects of the forces on the linear slides during STS mode ultraprecision machining. In these simulations, the toolpath is generated using the multibody dynamics method recently developed by the present authors.[14]

### A. Dynamic effects on toolpaths and interfacial dynamic forces

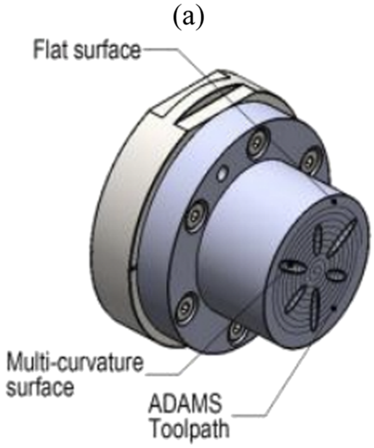
For validating the interfacial force affecting the toolpath, two different models are analyzed in the simulation, employing two different materials with different densities, namely, steel and a metal matrix composite (MMC). According to the simulation results, steel-based and MMC-based components in the slideway give significantly different dynamic responses in the system, and in the case of steel, the increased reaction forces at the tooltip increase the impact pressure in the toolpath. Figure 10 illustrates the differences in reaction forces due to the changes in surface curvature at the tooltip and the toolpath. It is found that the reaction forces $RF_{cx}$ and $RF_{cz}$ in the $X$ and $Z$ directions of the slides, respectively, are larger in the case of steel. It is also found that using the MMC with its lower mass results in a decreased pressure at the cutting toolpath and finally reduces the reaction forces at the tooltip during the cutting process. This further improves the dynamics and dynamic performance of the ultraprecision machining system and thus its machining accuracy and productivity.

**TABLE I.** Simulation analysis: parameters and data.

| Analysis data | Value |
|---|---|
| Workpiece speed $S_c$ | 60 rpm |
| Feed rate $f_r$ | 0.01 mm/rev |
| Initial force $F_N$ | 1 N |
| Dynamic friction contact $\mu_k$ | 0.25 |
| Static friction $\mu s$ | 0.3 |
| Elastic impact stiffness | $10^6$ N/mm |
| Maximum damping | 2000 N/(mm/s) |
| Penetration | 0 mm |
| **Integrator** | **Value** |
| Frames per second (time step) | 7200 |
| 3D contact resolution | High |
| Accuracy | $10^{-10}$ |
| Integrator type | WSTIFF |
| Maximum iterations | 25 |
| Initial integrator step size | 0.01 |
| Minimum integrator step size | $10^{-10}$ |
| Maximum integrator step size | 0.01 |
| Jacobian reevaluation | Every iteration |



(a)



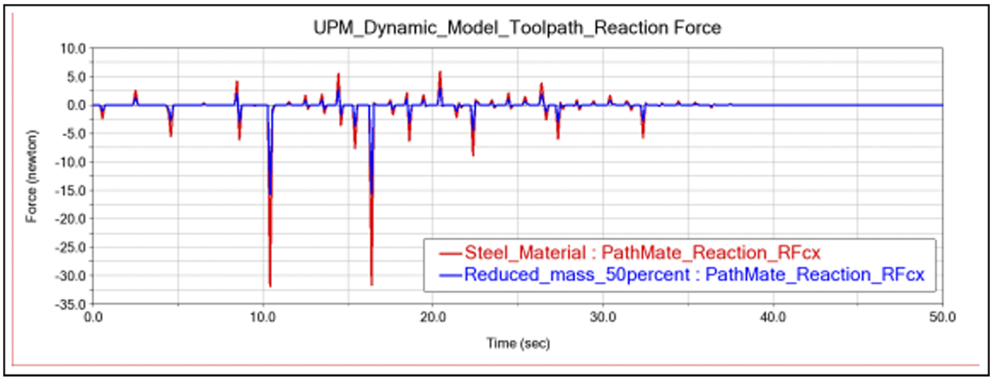

(b)

**FIG. 9.** Numerical simulations on a typical ultraprecision machining system using multibody dynamics algorithms in the ADAMS/Solver environment: (a) imported CAD model of the ultraprecision machining freeform surface; (b) workpiece toolpaths generated by ADAMS multibody dynamics.

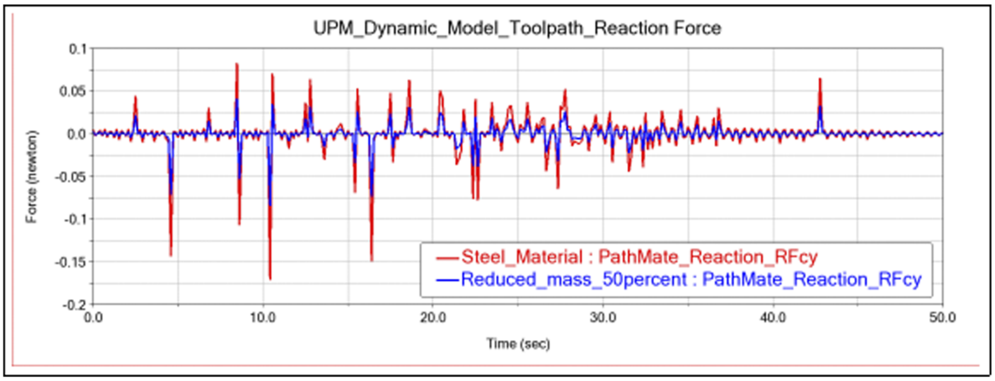
### B. Dynamic effects at slideways planar constraint

As discussed in Sec. IV, with regard to dynamic effects at the hydrostatic-bearing-supported linear slideway in STS mode ultraprecision machining, the loading $\boldsymbol{F}_v$ includes the cutting forces, interfacial forces, toolpath pressure, dynamic stiffness/damping, and contact forces, which are distributed along the constraint plane on both the top and side planar joints between the stationary base and the movable carriage. The reaction forces on those planes can be attributed to the multicurvature nature of the freeform surface. Based on the design configuration shown in Fig. 7, the current ADAMS model and simulation are integrated to evaluate the simulation parameters and their impacts on the planar joints in both the $X$ and $Z$ slideways. The results obtained from the constraint planes are further analyzed with regard to the dynamic performance of these two hydrostatic slideways.

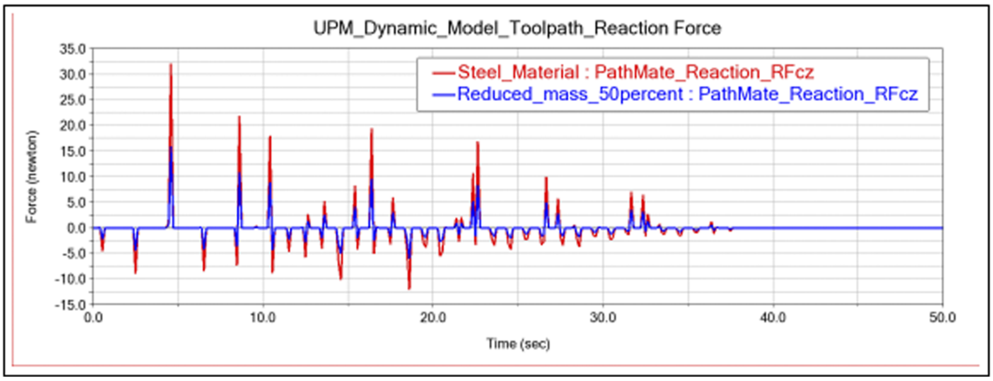
The joint coordination positions are illustrated in Fig. 11, which indicates the reaction forces in the Cartesian plane calculated from the position of the center of mass of each slide at the top and side planar joints. A comparative reaction force analysis for different materials at the planar connection joints is presented in Fig. 12.




(a)




(b)




(c)

**FIG. 10.** Effects of the reaction force and ultraprecision machining toolpath dynamics: (a) reaction force $RF_{cx}$; (b) reaction force $RF_{cy}$; (c) reaction force $RF_{cz}$.

The results provide strong evidence that the reaction forces at the planar joint vary with the curvature of the freeform surface. Furthermore, the results of the analysis show that the use of an MMC produces less reaction force and significantly reduces the positioning error at the linear slides, which can improve the dynamic performance of the machining system. A comparison of the reaction forces when steel and MMC, respectively, are used reveals that the maximum reaction forces are $\boldsymbol{F}_x$ in the top planar direction [as illustrated in Fig. 12(d)] and $\boldsymbol{F}_y$ at the side planar joint on both the $Z$ and $X$ slides. The most surprising aspect of the results can be seen in Fig. 12(a), where the reaction force $\boldsymbol{F}_x$ at the side planar joint has a very small value. To some extent, this indicates that the

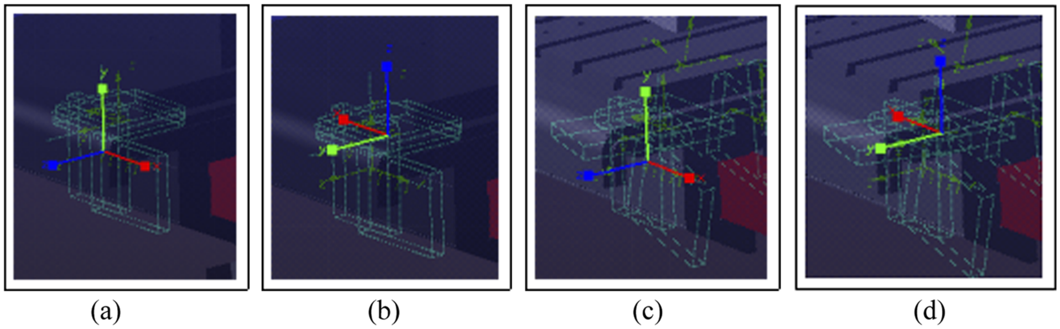



**FIG. 11.** ADAMS models and slideway coordination: (a) *X*-axis side planar; (b) *X*-axis top planar; (c) *Z*-axis side planar; (d) *Z*-axis top planar.

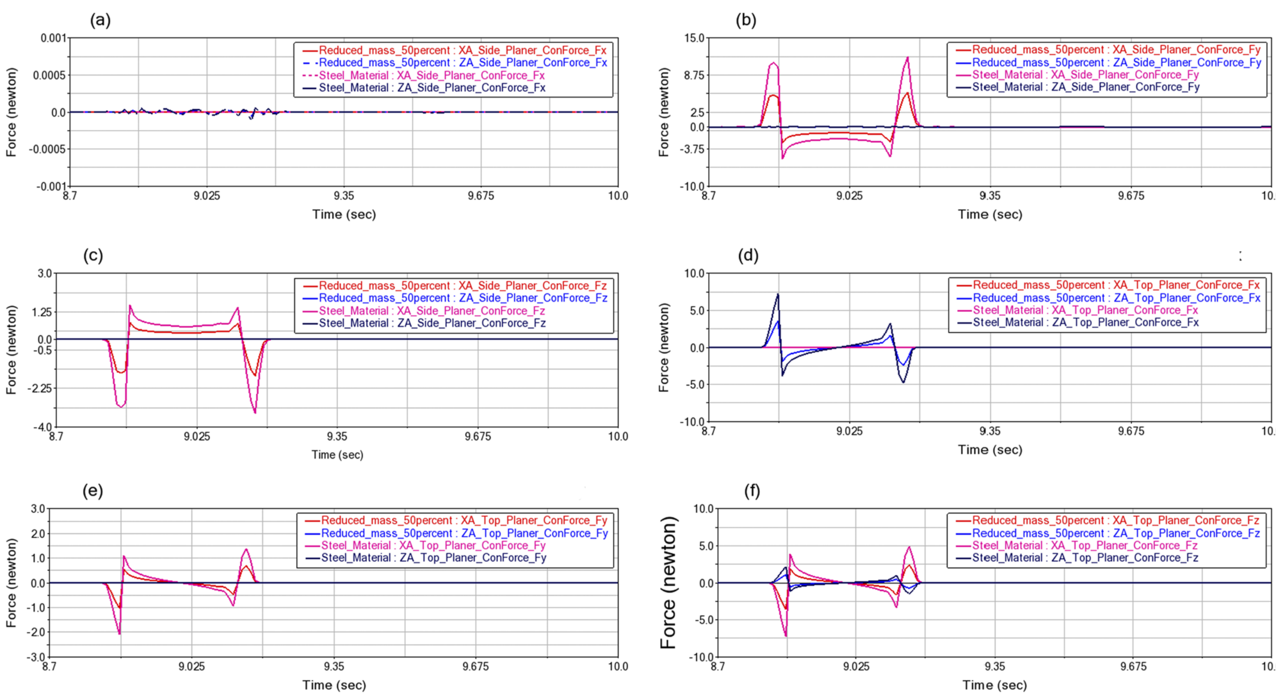



**FIG. 12.** Illustration of reaction forces at linear planar joints of hydrostatic bearing slideways.

use of MMC to fabricate hydrostatic bearing slideways can lead to substantially improved dynamics and positioning precision for the slideways and thus the machining system, although this still needs further experimental testing.

## VI. CONCLUSIONS

In this paper, an innovative precision engineering approach for ultraprecision machining of freeform surfaces has been presented based on modeling and analysis of dynamics. The aim of this dynamics-oriented approach is to achieve even higher precision in ultraprecision machining systems. The interfacial dynamic cutting forces at the tooltip and workpiece surface and the underlying dynamic interactions are at the core of this study and have been investigated through simulations of STS mode ultraprecision machining of freeform surfaces. The implementation of this approach has been discussed and analyzed in a dynamics-oriented holistic engineering approach, with particular attention being paid to interfacial microcutting dynamics, in-process monitoring using the interfacial microcutting forces and dynamics, application of MMC-based slideways, and dynamic control of the STS mode machining system. The conception, approach, and associated implementation have been further evaluated and validated by simulations and experimental case studies.

The results presented here, based on studies of ultraprecision machining NURBS-described freeform surfaces using existing ultraprecision machines at our Brunel University laboratory, are promising and encouraging. However, more research and development need to be carried out, particularly on the ultraprecision machining system that is being developed to machine generic freeform surfaces on any complex component, and results of such studies are expected to be reported in the future.

## ACKNOWLEDGMENTS

The authors are grateful for Ph.D. Scholarship funding support from Brunel University London and the UK EPSRC.

The authors declare no conflict of interest.

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