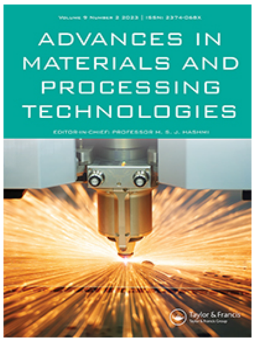

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On modelling and analysis of voxel-based force prediction for a 3-axis CNC machining

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ABSTRACT

Determination of cutting forces is the main requirement for understanding the machining process and optimising its parameters for achieving higher productivity and surface finish. This paper presents an exploratory study and the development of a model to estimate cutting forces for a 3-axis CNC milling process using a voxel-based CAD model. The developed algorithm takes the NC code, workpiece/tool material properties, and the tool geometry data as inputs. The cutting tool engagement with the workpiece is computed using a discretized (voxelized) model. The calculated voxel engagement was finally used to calculate the cutting forces using the analytical method. The algorithm was implemented and tested for various case studies and the in-house experimental data for different types of end mill tools. Finally, the effect of variation in the size of the voxel and the number of flutes was studied. The model showed a good correlation and was found to be accurate (~80%) and robust.

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KEYWORDS
Process modelling; 3-axis CNC machining; force prediction; Voxelization

1. Introduction

Multi-axis CNC machines are widely used to produce complex parts in the automotive, aerospace, and domestic product industries. Much of the research and development efforts in CNC technology have been focused on strategies for tool path planning, which is often disjoint from the real machining issues, such as machine dynamics, cutter deflection, tool breakage, surface integrity, etc. It ultimately affects productivity and part quality. These issues can be controlled using in-process parameters of machining, viz. feed rate, speed, and depth of cut. To optimise these parameters, cutting force calculation is necessary. The prediction of cutting forces is, thus, a fundamental issue in process modelling (Figure 1).

The force prediction models for 3-axis CNC machining have been studied over the years to achieve two main objectives, viz., the accuracy of prediction and efficiency. Yang and Park [1] developed a cutting force prediction model for the ball-end milling. They converted the cutting edge into a series of tiny elements that helped analyse the force generation. Fontaine et al [2]. also decomposed the cutting edge into small segments to

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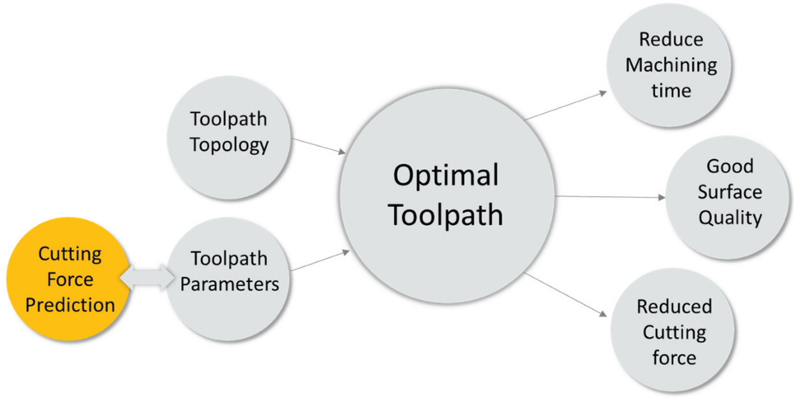


Figure 1. Importance of Cutting force prediction model.

model cutting forces for ball-end milling. They predicted cutting force based on thermo-mechanical modelling for ball-end milling of wavelike surfaces. They [3,4] further studied the effects of the tool–surface inclination on force prediction. However, they were limited to the ball end mill tool. Karolczak [5] used discrete wavelet transform to analyse the cutting forces in Turning. Zeroudi et al [6]. calculated cutting forces using the thermomechanical and analytical approaches directly by reading the toolpath obtained from the CAM package. Kim et al [7]. suggested using the Z-map for evaluation of cutting force. However, the determination of cutter engagement using Z-map was computationally difficult.

For machining force prediction, the representation scheme should have a good generality as the shape of the in-process workpiece continuously varies during the machining [8]. The voxel-based representation could be a solution as it gives an easy way to define geometric models. The discretisation of the surface into small cubes enables faster parallel integer space calculations [9]. Voxel models are primarily used in gaming and for medical imaging. However, the advent of general-purpose computing on graphics processing units (GPGPU) has led to its adoption for applications like toolpath generation [10,11], machining simulation [12], and cutting force prediction. Yousefian et al [13]. presented a voxel-based method for the prediction of cutting forces. The algorithm used a voxelized cutter helix and the workpiece, and based on the intersections, it estimated the cutting forces. Their method was generic and could be applied to any cutting tool. Tarbutton et al. [14] developed a voxel-based machining model for parallel processors which was gouge-free and efficient. Wou et al. [15] presented a mechanistic model based on a voxel-based geometric representation and a ray casting technique for ball end milling. Work has been reported on sculptured surface machining [16–18] to predict the cutting force and for CNC tool path generation. However, they are limited to ball end mill.

The literature documents that most of the approaches for cutting force prediction are devised for ball end mill and are often difficult to implement for other types of cutting tools. Also, parametric or vector-based models are generally used to represent the workpiece, which has inherent limitations. Scant work is done to estimate cutting forces using a voxel model. Therefore, a thorough investigation is required in this regard. This paper presents the development of a cutting force prediction method using a voxel-based model. It further explores the effect of voxel size and the number of flutes on the estimated value of cutting force. The system modules, algorithm, and results are discussed at length in the sections to follow.

2. Methodology

The system is divided into four functional modules (as shown in Figure 2): NC code Interpreter for Cutter location (CL) data, Voxelization module, cutter contact determination module, and the cutting force prediction module. These system modules are explained one by one.

A generic regular expression (RegEx) based NC code interpreter developed in this work reads the input part program to find the CL points. It gives the location of the cutting tool in the cartesian space. The paths between the CL points are discretized to obtain intermediate positions of the tool, which facilitates the determination of the cutter engagement for generating continuous force readings. The next step is to voxelize the workpiece and tool.

2.1. Voxelization

A voxel is a three-dimensional cubic volume element. The tool and workpiece are voxelized in the proposed system using the Ray casting approach [19]. The size of the voxel is related to the feed per tooth. For preliminary case, a cuboidal voxel size of 80 microns (for an overall part size of 100 × 100 × 100 mm) is chosen in the present study. It is envisaged that the workpiece engagement occurs at the helix of the tool. Thus, the voxels corresponding to the tool helix are identified by overlapping the helix onto the voxelized tool termed as cutting voxels. Only the cutting voxels are considered for engagement detections and force calculations, which significantly reduce the computational cost. For calculating the cutting voxels, the helix equation (Equation. 1) is used [13].

$$x = R_t \times \cos\left(\frac{t}{a} + i \times \psi_p\right) \quad 0 < t < L \tag{1}$$

$$y = R_t \times \sin\left(\frac{t}{a} + i \times \psi_p\right) \quad i = 1, 2, 3, \ldots N \qquad z = t$$

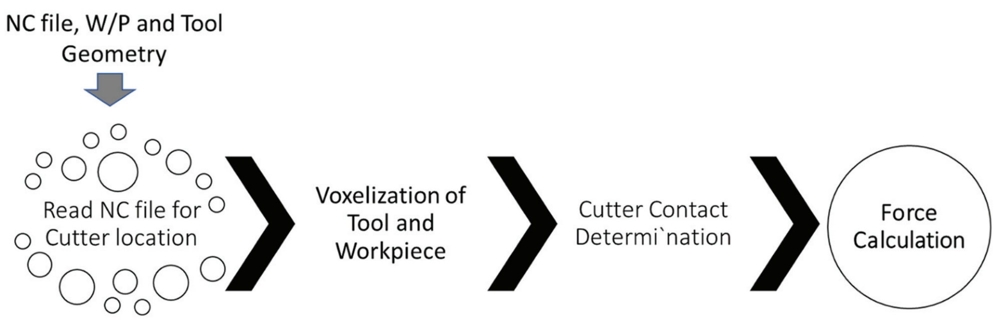


Figure 2. Modular Diagram of the system.

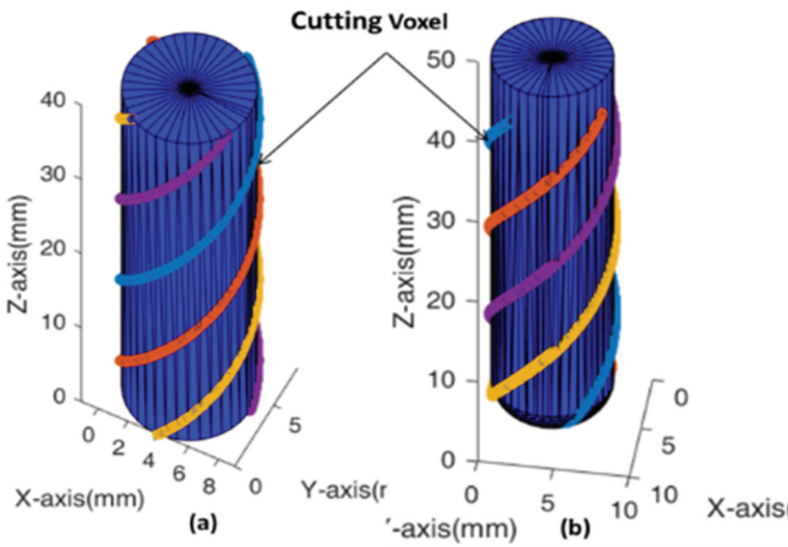


Figure 3. Identification of cutting voxels (a) 4 Fluted Flat End Mill (b) 4 Fluted Ball End Mill.

Where L is the length of the cutter flutes, Rt is the radius of the cutter at each depth t, N is the number of flutes, and ψp is the angle between flutes given 2π/N and a is given by Rt/tan(α), where α is the helix angle.

The helix is generated for two typical tool geometries (a flat end mill and a ball end mill) and imposed on the voxelized cutter tool model. All the voxels that contain the helix points are marked as the cutting voxels. The identified cutting voxels are shown in Figure 3.

2.2. Cutter contact determination

After the identification of the cutting voxels, the next step is to determine the engagement of tool with workpiece, which is quantified in terms of the number of voxels. These are the part voxels that come in contact with the cutting (tool) voxels during machining. Steps to find out the cutter contact voxels are as follows:

(1) Calculate the rotation angle and translation distance of the cutting tool in the workspace based on the CL points.
(2) Find out the position of the cutter voxels and spindle speed, a new discrete location of the voxels on the cutting edges in terms of X–Y–Z global coordinates by rotating and translating the voxels from one CL to the other.
(3) Find the cutter contact area with the workpiece using the depth and width of the uncut workpiece in front of the tool. The instantaneous contact of the workpiece and the tool at each of the cutter voxels are determined based on the start (sØ) and exit angles (eØ) of the tool engagement (Figure 4).

Steps 1–3 are repeated for all the tool positions as it moves based on CL data.

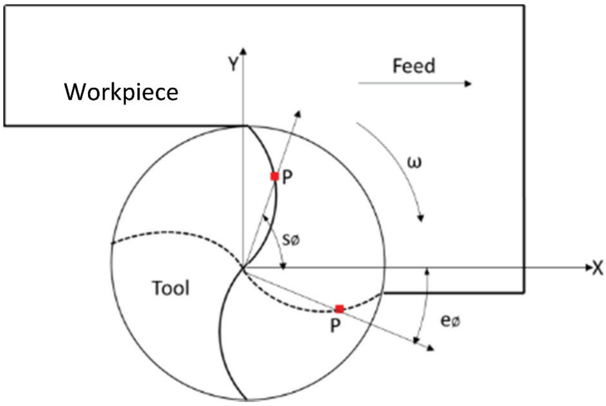


Figure 4. Start & Exit Angle for Voxel at Point P.

The rotational matrix and translation matrix are used to represent the rotation and translation of the tool in the feed direction. The movement of the tool by one step is given by Equation. 2.

$$P' = P \times R \times T \tag{2}$$

$$R = \begin{bmatrix} cos(\theta) & -sin(\theta) & 0 \\ sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$T = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \Delta x & \Delta y & 1 \end{bmatrix} \tag{4}$$

Where, P shows the location of a specific cutter voxel, R is the rotation matrix (Equation. 3), T is the translation matrix (Equation. 4), and P' shows the new location of a cutter voxel after the movement of the tool by one grid. θ represents the angle by which the tool has rotated and Δx, Δy represents the increments for new tool location. The voxels which are obtained from the cutter-workpiece engagement (cutting voxels) at each CL point are further analysed for the force calculation.

2.3. Force prediction module

A discrete analytical model is used to calculate the force exerted on the cutting tool during machining. For each cutting voxel, two angles are computed, viz. an axial angle (k(z)), and radial angle (θ) as shown in Figure.5(a). The radius of the cutter voxel at a height z is r(z) and is used to calculate k(z). The angle (θ) that the voxel makes with the Y direction is used to calculate the start and exit angle to give the engagement of the tool and workpiece.

The three components of cutting forces viz. Axial (Fa), Radial (Fr), and Tangential (Ft) are calculated for each CL point as per by Equation. 5 [21].

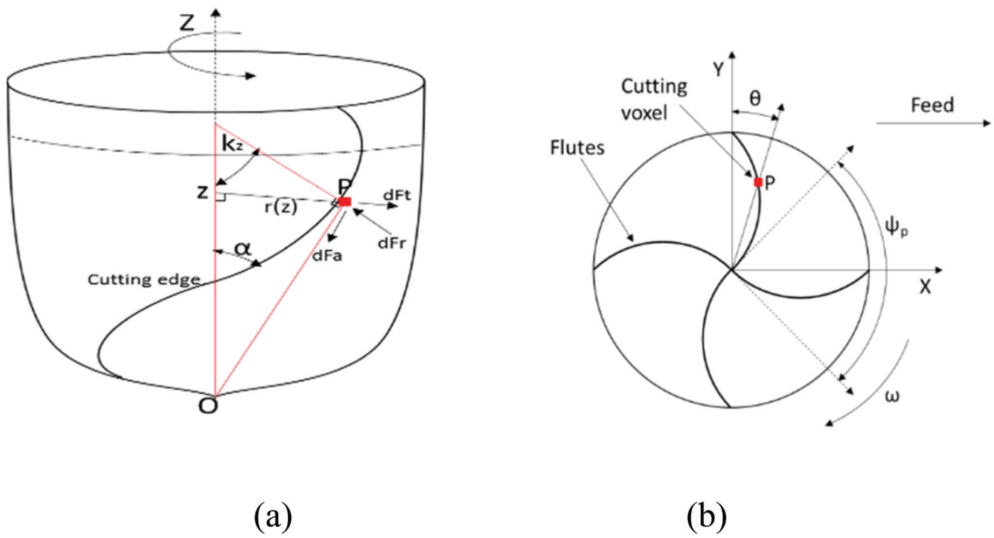


Figure 5. (a) Axial Immersion for Voxel at Point P [20] (b) Cross-Section Of Cutting Tool (4 Flutes) with Cutting Voxel Position [21]

$$\begin{cases} F_t = \text{Voxel Size} \times [K_{tc} \sum_{\mathrm{i}=1}^{\mathrm{n}} C_{th}(\theta_{\mathrm{i}})] + K_{te} \\ F_r = \text{Voxel Size} \times [K_{rc} \sum_{\mathrm{i}=1}^{\mathrm{n}} C_{th}(\theta_{\mathrm{i}})] + K_{re} \\ F_a = \text{Voxel Size} \times [K_{ac} \sum_{\mathrm{i}=1}^{\mathrm{n}} C_{th}(\theta_{\mathrm{i}})] + K_{ae} \end{cases} \tag{5}$$

where Kae, Kre, and Kte, are the edge constants, and Kac, Krc, and Ktc, are the cutting force coefficients in axial, radial, and tangential direction, respectively. These coefficients are taken from the approach proposed by Schmitz and Smith [22]. n is the total number of the voxels engaged in cutting for a specific CL. The uncut chip thickness $C_{th}(\theta)$ is given by Equation.6, which depends on the position of the voxel in the cutting helix (Equation. 6) [20].

$$C_{th}(\theta_{\mathrm{i}}) = f_t \times \sin\theta_{\mathrm{i}} \times \sin(k(z)) \tag{6}$$

where θi is the angle that a cutting voxel makes with the positive Y-axis, k(z) is the immersion angle and ft is the feed/tooth.

The axial (Fa), radial (Fr), and tangential (Ft) forces calculated above needs to be transformed to get forces in X, Y, and Z directions (Equation. 7).

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = [\mathrm{T}] \times \begin{bmatrix} F_t \\ F_r \\ F_a \end{bmatrix} \tag{7}$$

Where T is the transformation matrix and is given by,

$$\mathrm{T} = \begin{bmatrix} -\cos(\theta) & -\sin(\theta) \times \sin(\mathrm{k}) & -\sin(\theta) \times \cos(\mathrm{k}) \\ \sin(\theta) & -\cos(\theta) \times \sin(\mathrm{k}) & -\cos(\theta) \times \sin(\mathrm{k}) \\ 0 & -\cos(\mathrm{k}) & -\sin(\mathrm{k}) \end{bmatrix} \tag{8}$$

The algorithm therby calculates the cutting forces (Fx, Fy, Fz) in all three (X, Y, Z) directions.

3. Simulation and experiment results

The system was implemented in MATLAB 2015b on a system with 4GB RAM and Core (TM) i5-2450 M, 2.50 GHz processor. It was tested using various case studies and compared with the experimentally measured data for different types of tools (Ball end, Flat end). The voxel size for all the cases is taken as 80 μm. The effect of varying the voxel size and the number of flutes on the cutting force is demonstrated in section 3.2.

3.1. Model experimental validation

In this case study, the predicted force values were compared with the experimental results. The experiments were performed on a 3-axis Vertical CNC Machine to validate the developed force prediction model. The force was calibrated on Kistler Type 9257A Dynamometer having amplifier Type 5017. The sampling frequency of the reading was taken as 10 kHz using MyDaq® acquisition tool. The signals from the Mydaq was finally recorded using LabVIEW 2014. Figure 6(a) shows the experimental setup used for the measurement of cutting force, and Figure 6(b) shows the tested aluminium workpiece. Different tests were carried out with various cutting tools. The machining parameters chosen were: Spindle Speed: 1200 rpm, Feed rate: 120 mm/min, Depth of cut:1.5 mm, Workpiece: 6061 Aluminium. The cutting tool used for Test 1 and Test 2 were 8 mm Flat-end mill (Four flutes) and 8 mm ball-end mill (Four flutes), respectively.

Figure 7 shows the results obtained for Test1 and Test2. As evident, the predicted force agrees reasonably well with the experimental results (Fx, Fy) for both the test. The peak errors were found to be below 20% for both Test1 and Test2. Although certain regions show abrupt changes in the simulated values, it can be attributed to the fact that our model does not consider the vibrations and other cutting conditions on the machine. Nonetheless, the overall trend matches well with the experimental results. Next, the effect of varying voxel size on the prediction of force is studied.

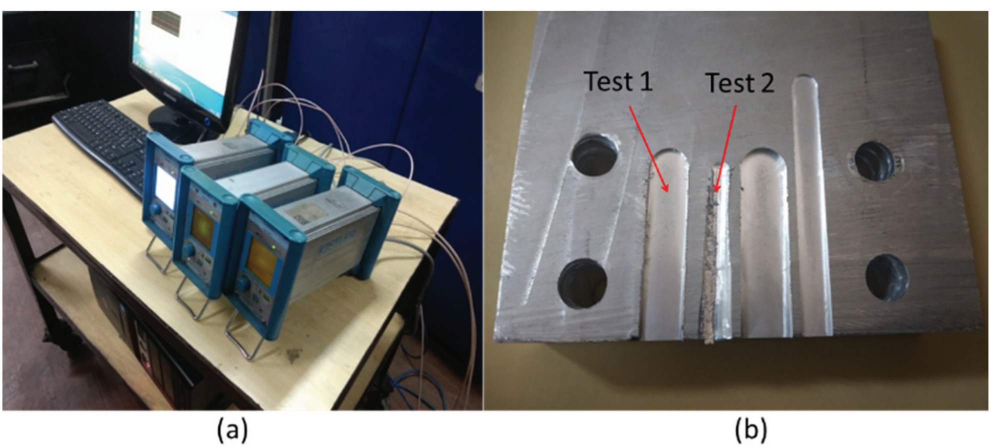


Figure 6. (a) Experimental Setup; (b) Aluminium Cutting Test Specimen

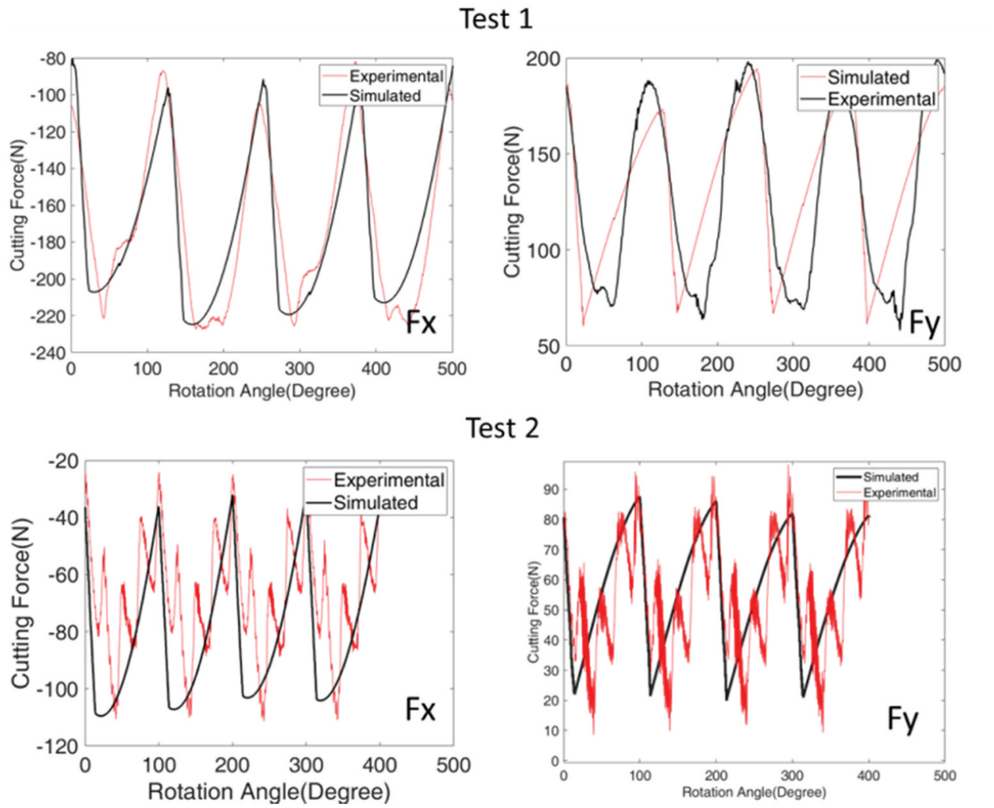


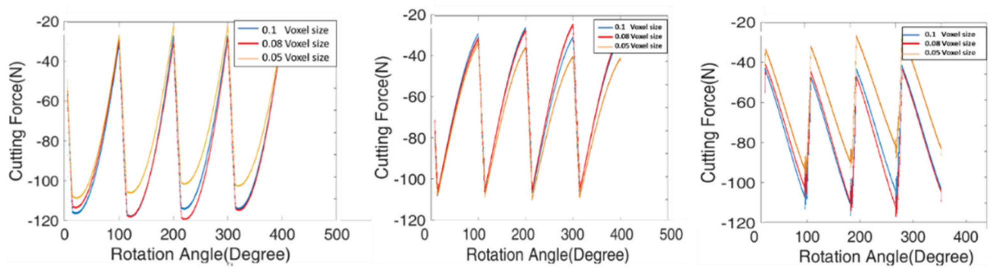
Figure 7. Simulated and Experimental Force Data Comparison.

3.2. Effect of varying voxel size

The machining parameters were kept the same as in Test 2. Figure 8 shows the simulated force results for voxel sizes viz. 50 μm, 80 μm, 100 μm in X, Y, and Z directions. It was observed that by increasing the voxel size, the amplitude of the forces (simulated) increases. As evident, by decreasing the voxel size the accuracy of force prediction increases. However, it also increases the computational cost. A trade-off is thus, required.

3.3. Effect of varying number of flutes

When choosing an end mill, one of the most important considerations is the number of flutes best suited for the job. Both material and application play an important role here. In this case study, a flat-end mill is used for the simulation process to predict the forces for the varying number of flutes. The cutting parameters were kept the same for all the simulations. Figure 9 shows simulated force results in X, Y, and Z directions for two, three, and four flute end mills, respectively. As expected, by increasing the number of flutes, the amplitude of the force decreases, and the operation becomes smoother. This is because of the increase in cutter engagement. Also, the periodicity of the curve increases as the periodic interval decreases with the number of flutes (reducing angular pitch between cutter teeth). Therefore, the developed system gives accurate force prediction trends.



(a) (b) (c)

Figure 8. Simulated Force Results for Varying Voxel Size (a) X-Axis, (b) Y-Axis, And (c) Z-Axis.

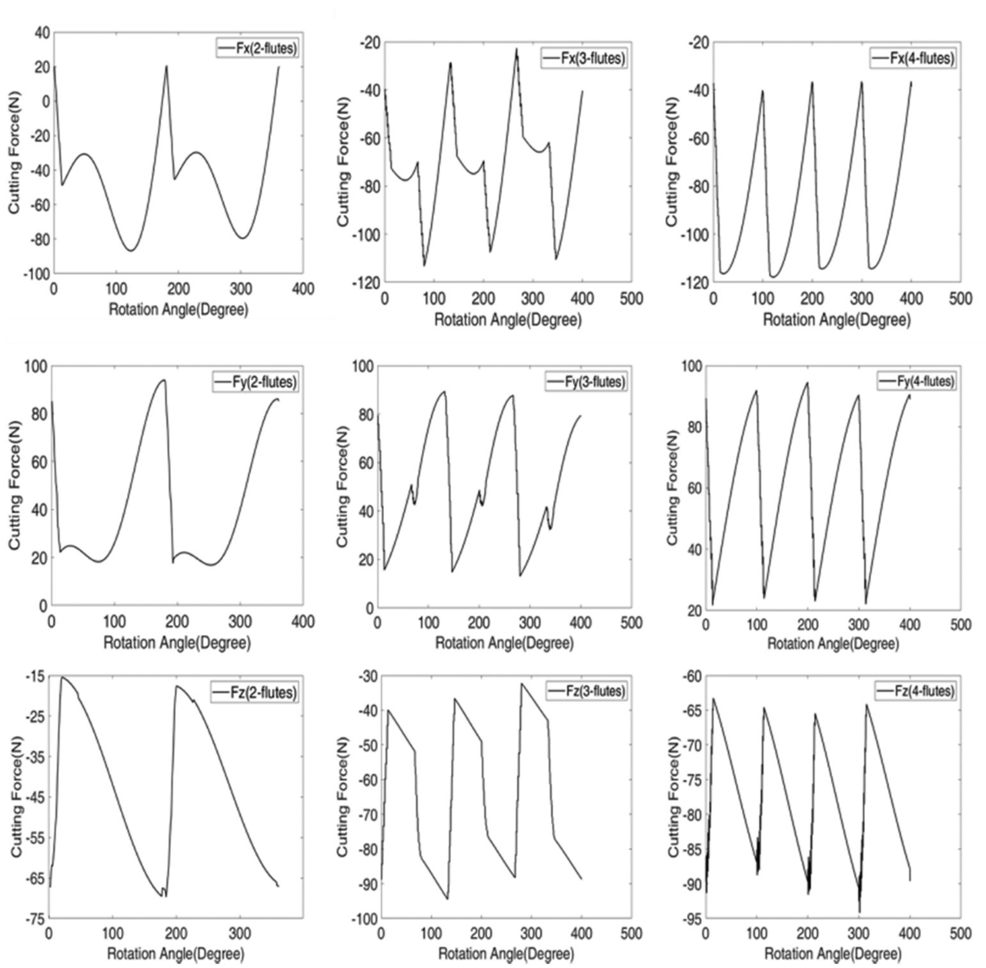


Figure 9. Simulated force results (Fx, Fy, Fz) for two, three and four flutes.

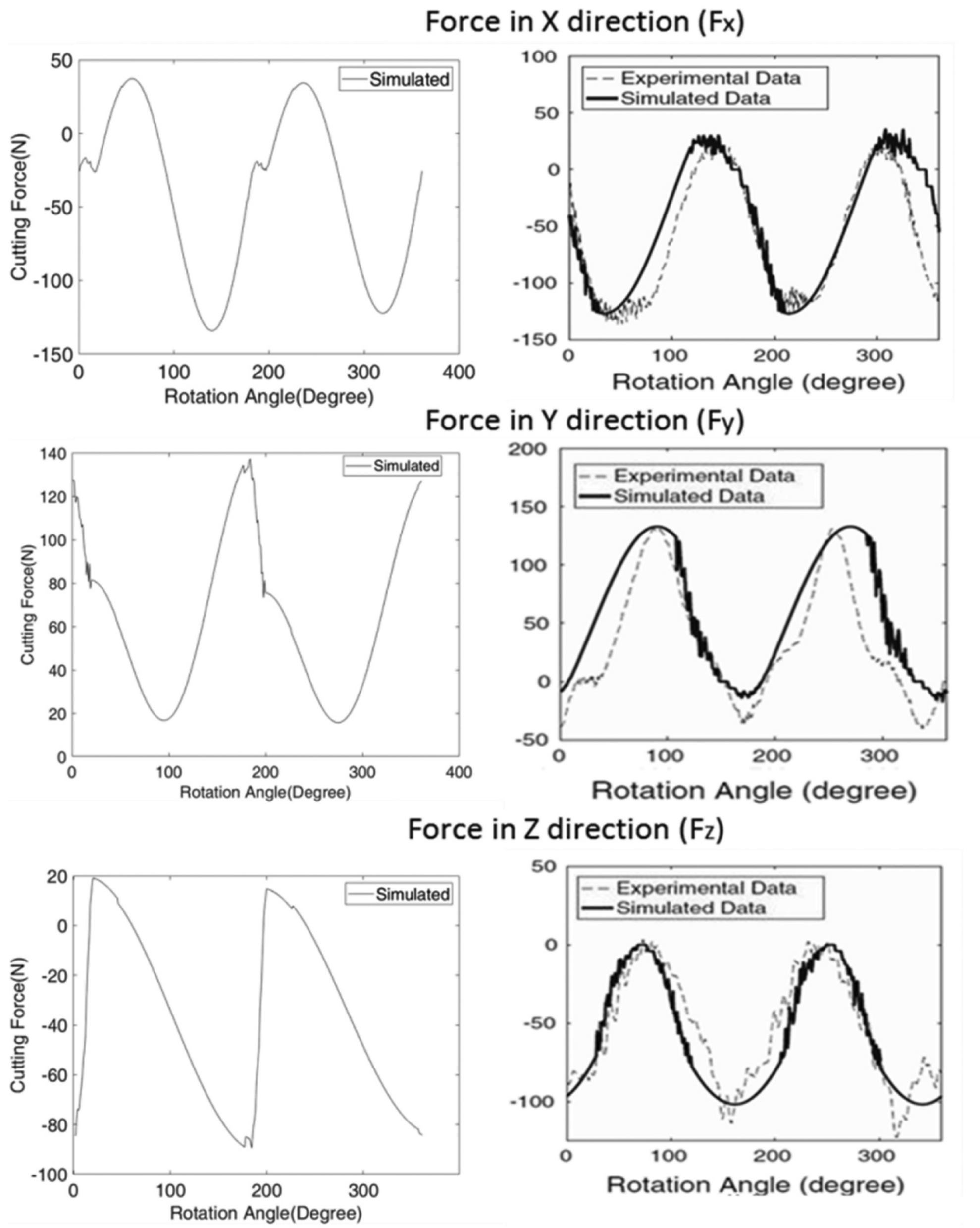


Figure 10. Comparison of forces predictions (a) Our model (b) Literature [13].

3.4. Comparison of force prediction results with the Literature

In this case study, the forces (in X, Y, and Z directions) which are predicted using our model are compared with the results reported in the literature by Yousefian and Tarbutton [13]. The cutting parameters chosen for simulation are as under:

- Depth of cut:1.27 mm,
- Spindle Speed: 2500 rpm

- Feed rate: 381 mm/min
- Tool: 6 mm Flat-end mill (Two flutes).
- Workpiece: 6061 Aluminium

Figure 10 shows the comparison between the results obtained by our model with those reported in the literature [13].

The simulated results by our model are seen to be matching well with the trends of results obtained from the literature [13] in terms of force amplitude. However, the force envelope is slightly shifted due to the phase angle difference, the negative value of the force indicating the direction of the force.

4. Conclusions

An exploratory study on cutting force prediction was carried out in this work. The employed technique uses a discretized voxel model for the representation of the tool and the workpiece. This approach is comparatively simple and achieves faster results than analytical models that use complex mathematical models. The developed system was tested using various case studies. The predicted value of cutting force agreed reasonably well with the experimental results and literature.

Furthermore, prediction accuracy increases with the decrease in the voxel size. The effect of increasing the number of flutes on the cutting force was also demonstrated. As expected, the predicted force decreases with the increase in the number of flutes, enabling smoother cutting tool engagement. The current study thus reinforces the benefits of using a voxel-based approach for cutting force prediction.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

[1] Yang M, Park H. The prediction of cutting force in ball-end milling. Int J Mach Tools Manuf [Internet]. 1991;31:45–54. Available from. https://linkinghub.elsevier.com/retrieve/pii/089069559190050D
[2] Fontaine M, Devillez A, Moufki A, et al. Predictive force model for ball-end milling and experimental validation with a wavelike form machining test. Int J Mach Tools Manuf. 2006;46:367–380.
[3] Fontaine M, Moufki A, Devillez A, et al. Modelling of cutting forces in ball-end milling with tool-surface inclination. Part I: predictive force model and experimental validation. J Mater Process Technol. 2007;189:73–84.
[4] Fontaine M, Devillez A, Moufki A, et al. Modelling of cutting forces in ball-end milling with tool-surface inclination. Part II. Influence of cutting conditions, run-out, ploughing and inclination angle. J Mater Process Technol. 2007;189:85–96.

[5] Karolczak P. Application of discrete wavelet transform to analysis of cutting forces in turning of composites based on aluminium alloys reinforced with Al2O3 fibres. FME Trans. 2021;49:563–574.
[6] Zeroudi N, Fontaine M, Necib K. Prediction of cutting forces in 3-axes milling of sculptured surfaces directly from CAM tool path. J Intell Manuf. 2012;23:1573–1587.
[7] Kim GM, Cho PJ, Chu CN. Cutting force prediction of sculptured surface ball-end milling using Z-map. Int J Mach Tools Manuf. 2000;40:277–291.
[8] Li Y, Tang K, Zeng L. A voxel model-based process-planning method for five-axis machining of complicated parts. J Comput Inf Sci Eng. 2020;20:1–14.
[9] Kukreja A, Dhanda M, and Pande S. Voxel-based adaptive toolpath planning using GPU for freeform surface machining. J Manuf Sci Eng. 2021;144(1):011013–23 doi:10.1115/1.4051535.
[10] Kukreja A, Dhanda M, Pande S. Efficient toolpath planning for voxel-based CNC rough machining. Comput Aided Des Appl [Internet]. 2020;18:285–296. http://cad-journal.net/files/vol_18/Vol18No2.html
[11] Bhole KS, Kale B. Techniques to minimise stair-stepping effect in micro-stereolithography process: a Review. Adv Mater Process Technol. 2021;1–20. [Internet]. Available from.
[12] Jang D, Kim K, Jung J. Voxel-based virtual multi-axis machining. Int J Adv Manuf Technol Internet]. 2000;16:709–713. http://link.springer.com/10.1007/s001700070022
[13] Yousefian O, Balabokhin A, Tarbutton J. Point-by-point prediction of cutting force in 3-axis CNC milling machines through voxel framework in digital manufacturing. J Intell Manuf. 2020;215–226 [Internet]. Available from. doi:10.1007/s10845-018-1442-7
[14] Tarbutton J, Kurfess TR, Tucker T, et al. Gouge-free voxel-based machining for parallel processors. J Advan Manuf Techn. 2013;69(9–12):1941–1953.
[15] Wou SJ, Shin YC, El-Mounayri H. Ball end milling mechanistic model based on a voxel-based geometric representation and a ray casting technique. J Manuf Process. 2013;15(3):338–347.
[16] Wei ZC, Wang MJ, Zhu JN, et al. Cutting force prediction in ball end milling of sculptured surface with Z-level contouring tool path. Int J Mach Tools Manuf. 2011;51(5):428–432.
[17] Dhanda M, Kukreja A, Pande SS. Region-Based efficient computer numerical control machining using point cloud data. ASME J Comput Inf Sci Eng. 2021;21(4):041005.
[18] Dhanda M, Kukreja A, Pande SS. Adaptive spiral tool path generation for computer numerical control machining using point cloud. Proc Insti Mech Eng, Part C: J Mech Eng Scien. 2021;235(22):6240–6256.
[19] Patil S, Ravi B. Voxel-based representation, display and thickness analysis of intricate shapes. Proc - Ninth Int Conf Comput Aided Des Comput Graph CAD/CG 2005. 2005;2005:415–420.
[20] Engin S, Altintas Y. Generalized modeling of milling mechanics and dynamics: part i - helical end mills. Am Soc Mech Eng Manuf Eng Div Med. 1999;10:345–352.
[21] Lazoglu I. Sculpture surface machining: a generalized model of ball-end milling force system. Int J Mach Tools Manuf. 2003;43:453–462.
[22] Schmitz TL, Smith KS, Vaughn M. Machining dynamics: frequency response to improved productivity. 2008.