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Original Article

Feasibility studies for an enhanced flat bottom drill tool design considering modal and resonance using finite element methods

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ABSTRACT

The design of a cutting tool necessitates a comprehension of the applications and quandaries that may come across from manufacturing to the machining process. Developing technologies in components with complicated features and the competition among manufacturers in rapid and precision production leads to design and application of new types of cutting tools with sophisticated geometries. Besides sufficient cutting performance and dimensional accuracies, these tools are required to have setup rigidity, static and dynamic strength to prevent any damage to themselves, holders, and machine components. In this paper, flat bottom drills with various axial and radial rake angles have been designed and subjected to modal analyses using finite element methods. The first six natural frequencies, maximum total displacements, stiffnesses as well as the period of oscillation corresponding to the modes shape have been calculated for the designed tools. Based on the obtained results, it is seen that the designed flat bottom drills have acceptable stiffnesses and natural frequencies to be utilized in machining processes. Radial rake angle has a noticeable influence on the natural frequencies and stiffnesses of the system.

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INTRODUCTION

Drilling is one of the most commonly used operations for making holes for different purposes in various types of materials including metals, ceramics, composites, etc. Having a significant economic benefit in terms of rapidity, it contributes for 40–60% of the total material removal processes in industry [1]. In recent years, with the developing technology the interbedded and complex shapes of the designed components used in industrial applications require different types of cutting tools beyond the conventional twist drills one of which is the flat bottom drills. Flat bottom drills are used in making holes on the sloped surfaces, counterboring, thin plate, pre hole of blind tapping, cross hole, eccentric hole corrections, counterboring at deep hole position, deep half circle, continuous thin plates, deep position cross hole machining as demonstrated in Figure 1. The geometry of the designed cutting tools has a supreme influence on the chip morphology, cutting forces, workpiece quality, tool and machine components life cycle.

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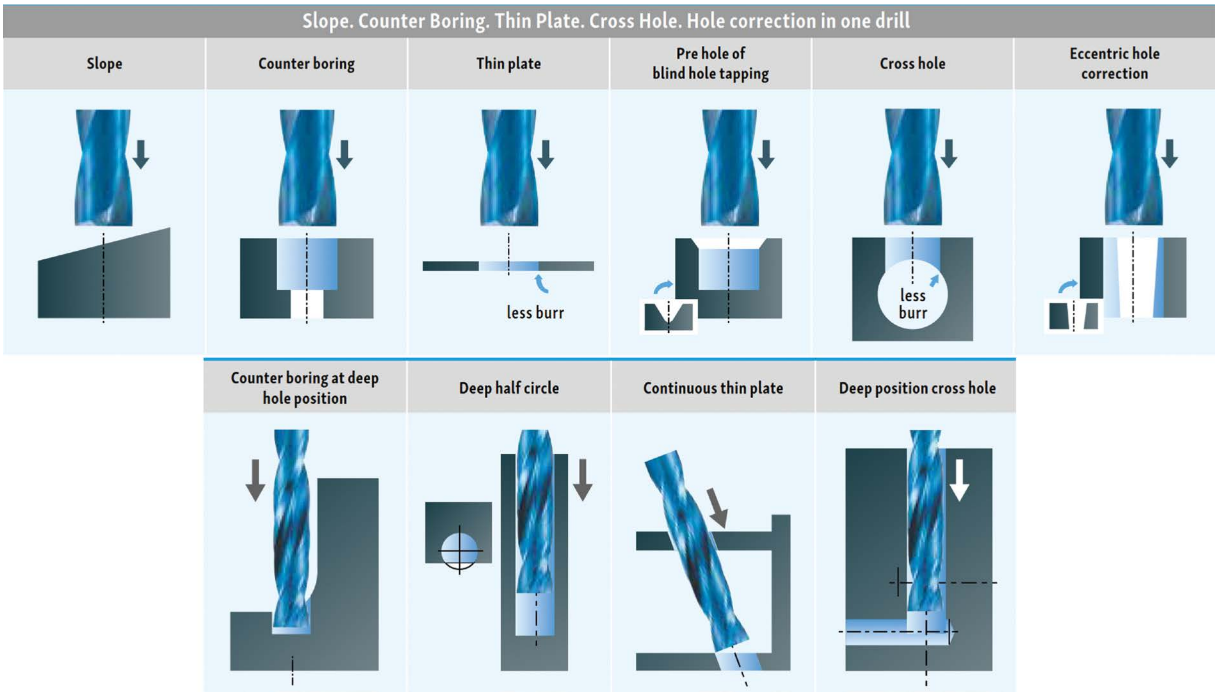


Figure 1. Various applications of flat bottom drills [2].

Table 1. Geometrical parameters of the designed cutting tools

Tool no.	Cuter diameter (mm)	Tool length (mm)	Helix angle (deg)	Relief angle (deg)	Flute radius (mm)	Core diameter (mm)	Axial relief angle (deg)	Radial rake angle (deg)	Axial rake angle (deg)
1								6	-2
2								6	0
3								6	2
4								8	-2
5	8	50	30	6	2	2.1	6	8	0
6								8	2
7								10	-2
8								10	0
9								10	2

Table 2. The calculated masses of the designed flat bottom drills

Tool no.	1	2	3	4	5	6	7	8	9
m (Kg)	0.266	0.268	0.269	0.266	0.267	0.269	0.265	0.267	0.268

Table 3. Technical specifications of the used carbide in the manufacture cutting tools

Grade	Classification	Co%	WC incl. doping	Density (g/cm^3)	Hardness HV30 (Kg/mm^2)	Tensile strength (MPa)	Fracture Toughness K_{IC}, (MPa.m$^{1/2}$)	Transverse rupture strenght (N/mm^2)	Average grain size (µm)
DK500UF	K20-K30	12.0	88.0	14.05	1690	550	10.4	4200	0.5

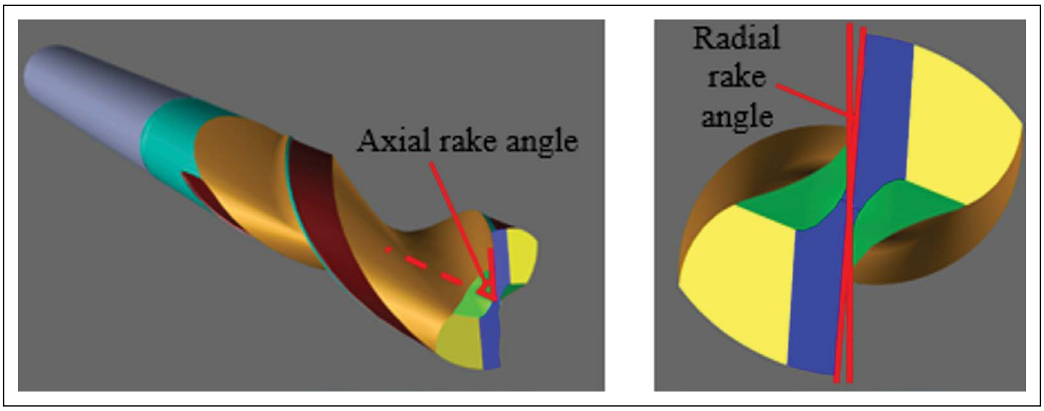


Figure 2. The studied geometrical parameters on the designed cutting tools.

Table 4. The calculated natural frequencies in different shape modes of the designed flat bottom drills

Mode no.	1	2	3	4	5	6
1	362.89	453.11	687.7	810.48	1019.8	1590.2
2	364.78	452.43	714.18	792.4	974.51	1586.2
3	363.65	448.87	722.97	784.12	953.09	1569.5
4	361.71	452.06	686.06	809.12	1019.4	1587.3
5	363.53	451.36	712.61	791.13	974.08	1582.2
6	362.38	447.77	721.52	782.93	952.67	1562.5
7	361.68	451.83	682.72	803.34	1007.7	1579.7
8	362.37	450.36	711.3	789.93	973.68	1581.3
9	361.2	446.74	720.28	781.63	952.26	1559.6

Table 5. The calculated total displacements in different shape modes of the designed flat bottom drills

Mode no.	1	2	3	4	5	6
1	1.182	1.248	1.016	1.28	1.207	1.003
2	1.404	1.362	1.02	1.138	1.199	1.002
3	1.29	1.227	1.022	1.1	1.209	1.002
4	1.179	1.244	1.017	1.288	1.208	1.003
5	1.398	1.368	1.02	1.142	1.199	1.002
6	1.294	1.231	1.022	1.103	1.208	1.002
7	1.211	1.282	1.018	1.247	1.202	1.003
8	1.392	1.373	1.021	1.146	1.199	1.002
9	1.299	1.234	1.023	1.105	1.208	1.002

Undesired vibrations are the dynamical phenomenon leading to experience an unstable cutting process [3]. Lateral chatter, torsional-axial chatter and whirling are three types of vibrations that arise in drilling [4]. Chatter vibrations evolve at tight range of frequencies of the cutting tool to the close natural ones. This type of vibration is generally

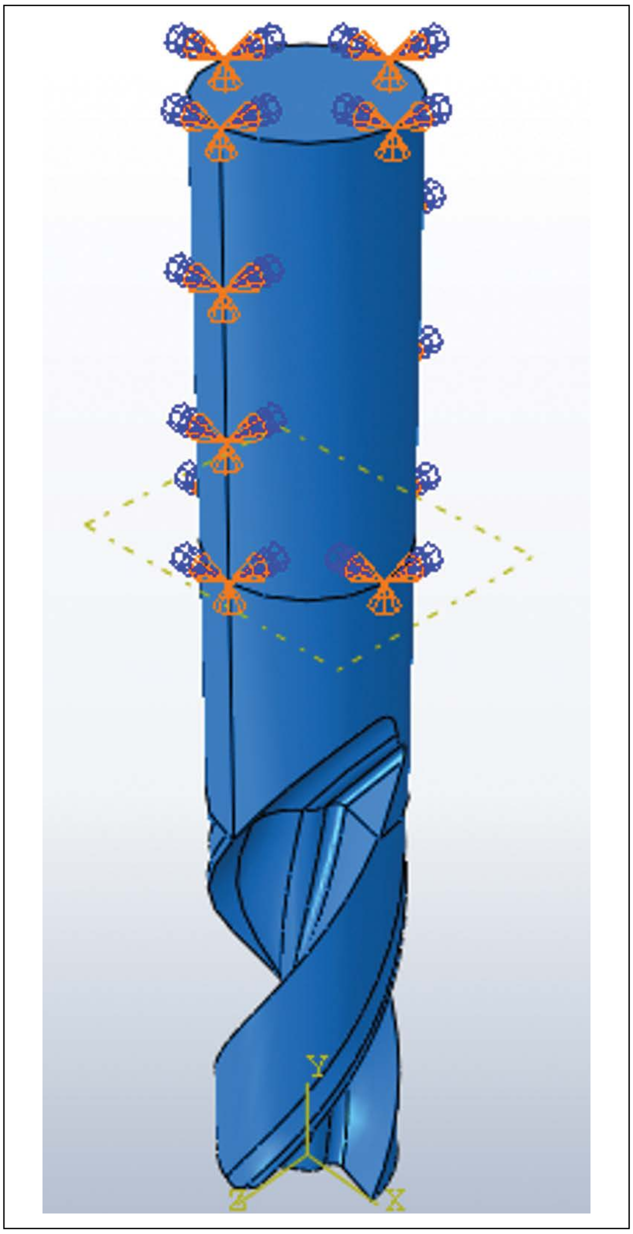


Figure 3. The applied boundary conditions to the cutting tools.

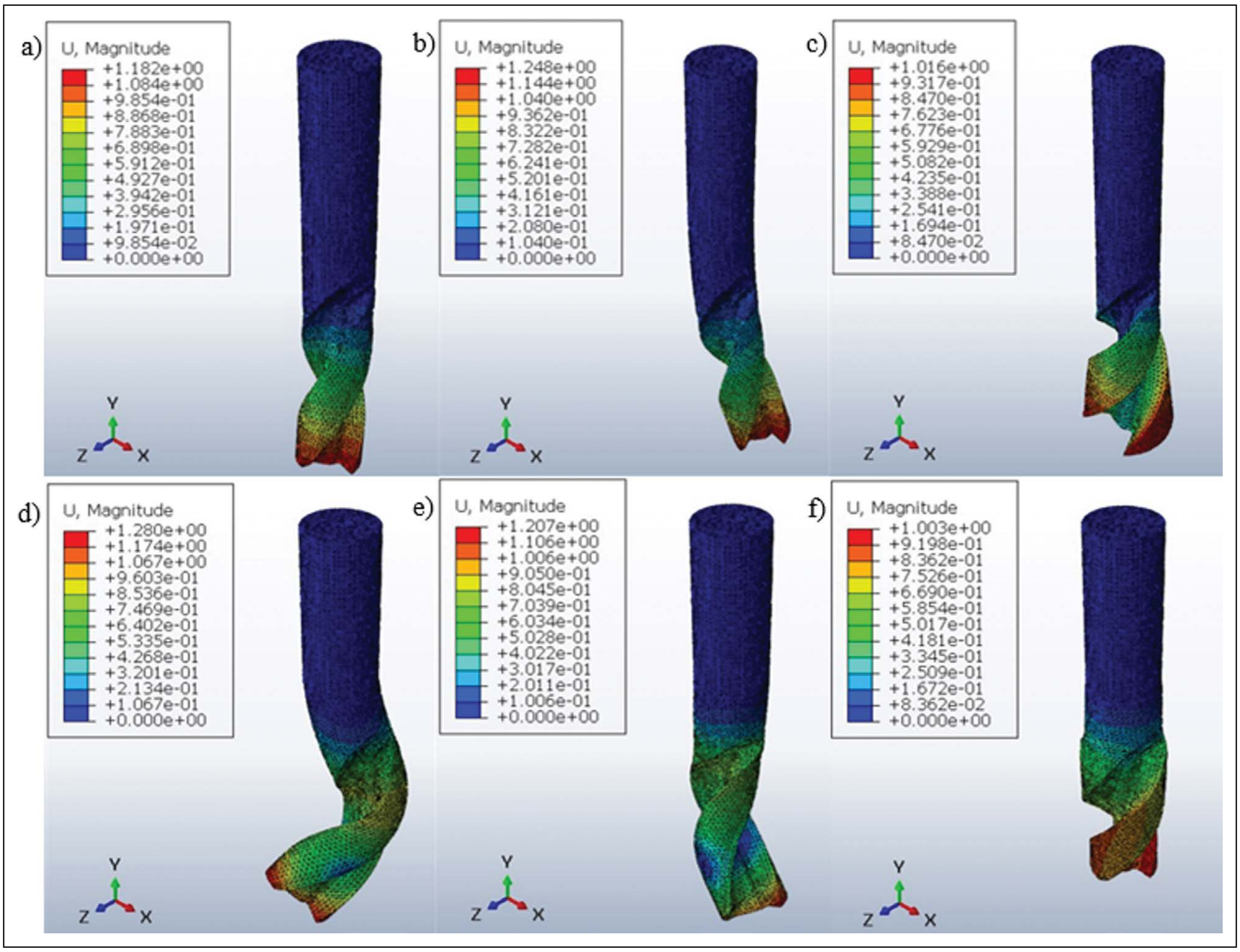


Figure 4. Modal analysis results for tool No. 1; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

Table 6. The calculated stiffness values for different shape modes of the designed flat bottom drills

Mode no.	1	2	3	4	5	6
1	1386037	2160887	4977632	6913681	10945982	26615107
2	1408092	2166066	5397396	6644432	10049432	26624705
3	1408477	2145970	5567024	6548587	9674986	26236456
4	1376464	2149988	4951857	6887629	10932843	26507080
5	1398062	2155222	5372170	6621276	10037723	26483094
6	1395757	2131039	5533223	6515193	9646425	25949051
7	1373529	2143577	4894116	6776224	10662314	26202227
8	1388943	2145357	5351623	6600201	10027956	26448952
9	1383903	2116995	5503170	6480562	9618810	25801010

Table 7. The calculated oscillation period time for different shape modes of the designed flat bottom drills

Mode no.	1	2	3	4	5	6
1	0.0028	0.0022	0.0015	0.0012	0.0010	0.0006
2	0.0027	0.0022	0.0014	0.0013	0.0010	0.0006
3	0.0027	0.0022	0.0014	0.0013	0.0010	0.0006
4	0.0028	0.0022	0.0015	0.0012	0.0010	0.0006
5	0.0028	0.0022	0.0014	0.0013	0.0010	0.0006
6	0.0028	0.0022	0.0014	0.0013	0.0010	0.0006
7	0.0028	0.0022	0.0015	0.0012	0.0010	0.0006
8	0.0028	0.0022	0.0014	0.0013	0.0010	0.0006
9	0.0028	0.0022	0.0014	0.0013	0.0011	0.0006

observed with dimensional accuracy error and tool failures. However, whirling occurs at the multiples of spindle frequency and uneccentric hole shapes, dimensions are representative of this type of vibration [4].

Ema et al. [5] investigated the frequency, amplitude, initiation boundary, and measured unstable range of chatter vibration at various cutting parameters for several drills with different overhang lengths and special drills

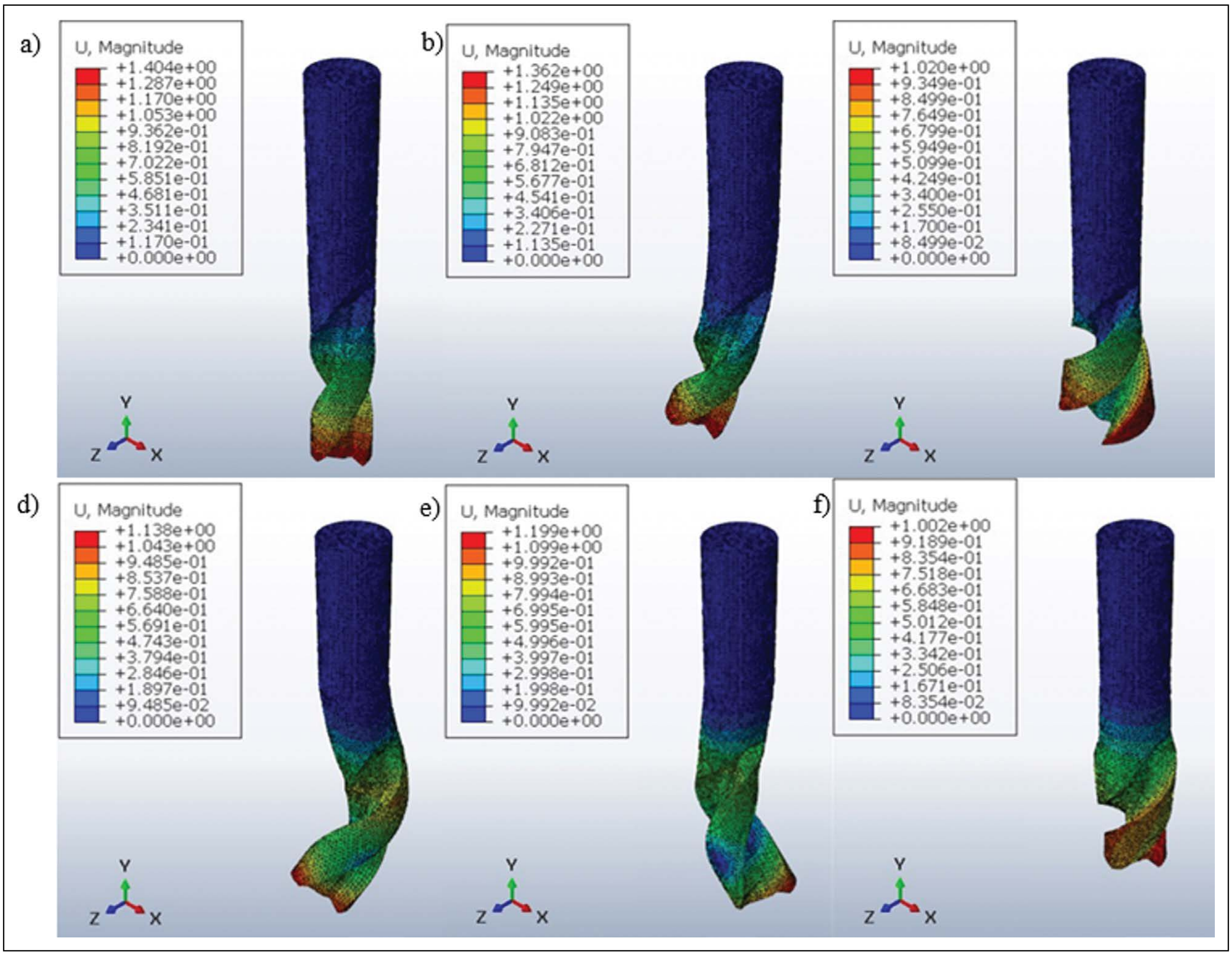


Figure 5. Modal analysis results for tool No. 2; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

Table 8. ANOVA results of first mode natural frequencies

Source	Sum of squares	df	Mean square	F-value	p-value	
Mode I	10.20	5	2.04	25.82	0.0114	Significant
A	6.14	1	6.14	77.74	0.0031	
B	0.1504	1	0.1504	1.90	0.2615	
AB	0.3844	1	0.3844	4.87	0.1145	
A^2	0.0983	1	0.0983	1.24	0.3460	
B^2	3.42	1	3.42	43.34	0.0071	
Residual	0.2370	3	0.0790			
Cor total	10.43	8				

with different pieces of additional masses. Their experimental results showed that the vibration is a regenerative chatter, and its frequency is equal to the bending natural frequency of the drill when the drill point is supported in a machined hole. Zhai et al. [6] studied different axial rake angle and radial rake angle combination under certain load deformation using finite element analysis for plunge milling cutters. Fujii et al. [7] studied the whirling vibrations in a workpiece with a pilot hole. In another work [8], they focused on the interactions between the effect of the drill geometry and the drill flank, in starting whirling. Tekinalp et al. [9] studied the dynamics of drill bits under different geometries, rotational speeds and boundary conditions using FEM (Finite Element Methods). Razika

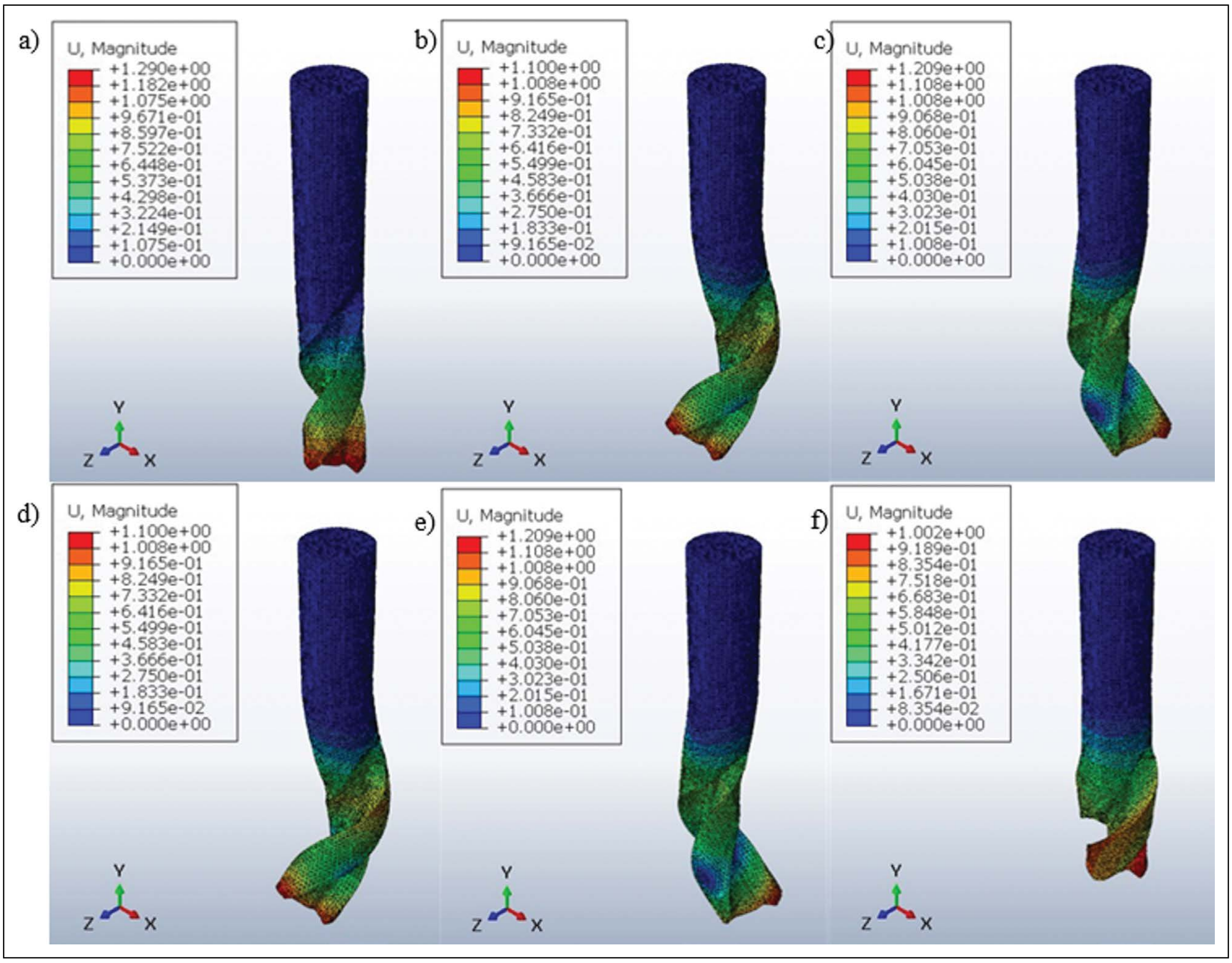


Figure 6. Modal analysis results for tool No. 3; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

Table 8. ANOVA results of first mode natural frequencies

Source	Sum of squares	df	Mean square	F-value	p-value	
Mode I	10.20	5	2.04	25.82	0.0114	Significant
A	6.14	1	6.14	77.74	0.0031	
B	0.1504	1	0.1504	1.90	0.2615	
AB	0.3844	1	0.3844	4.87	0.1145	
A^2	0.0983	1	0.0983	1.24	0.3460	
B^2	3.42	1	3.42	43.34	0.0071	
Residual	0.2370	3	0.0790			
Cor Total	10.43	8				

et al. [10] conducted a study of vibration and of deformation between a tool without defect and a tool with two cases of defects. These defects have a random shape (any form), and the contact length tool-work piece, is considered the length of defects as 1 mm and the height of wear has been studied for two cases: VB=0.1 and 0.2 mm. Ji et al. [11] performed a modal analysis using FEM for optimization of layer face milling cutting tool structural and analysis of restrain vibration. Kashyzadeh et al. [12] utilized computer simulation for identifying the effect of cutting tool construction and damping material on its natural frequency. Liu et al. [13] focused on the dynamic characteristics analysis and the stiffness contribution on a face-milling tool system by using Finite Element Modal

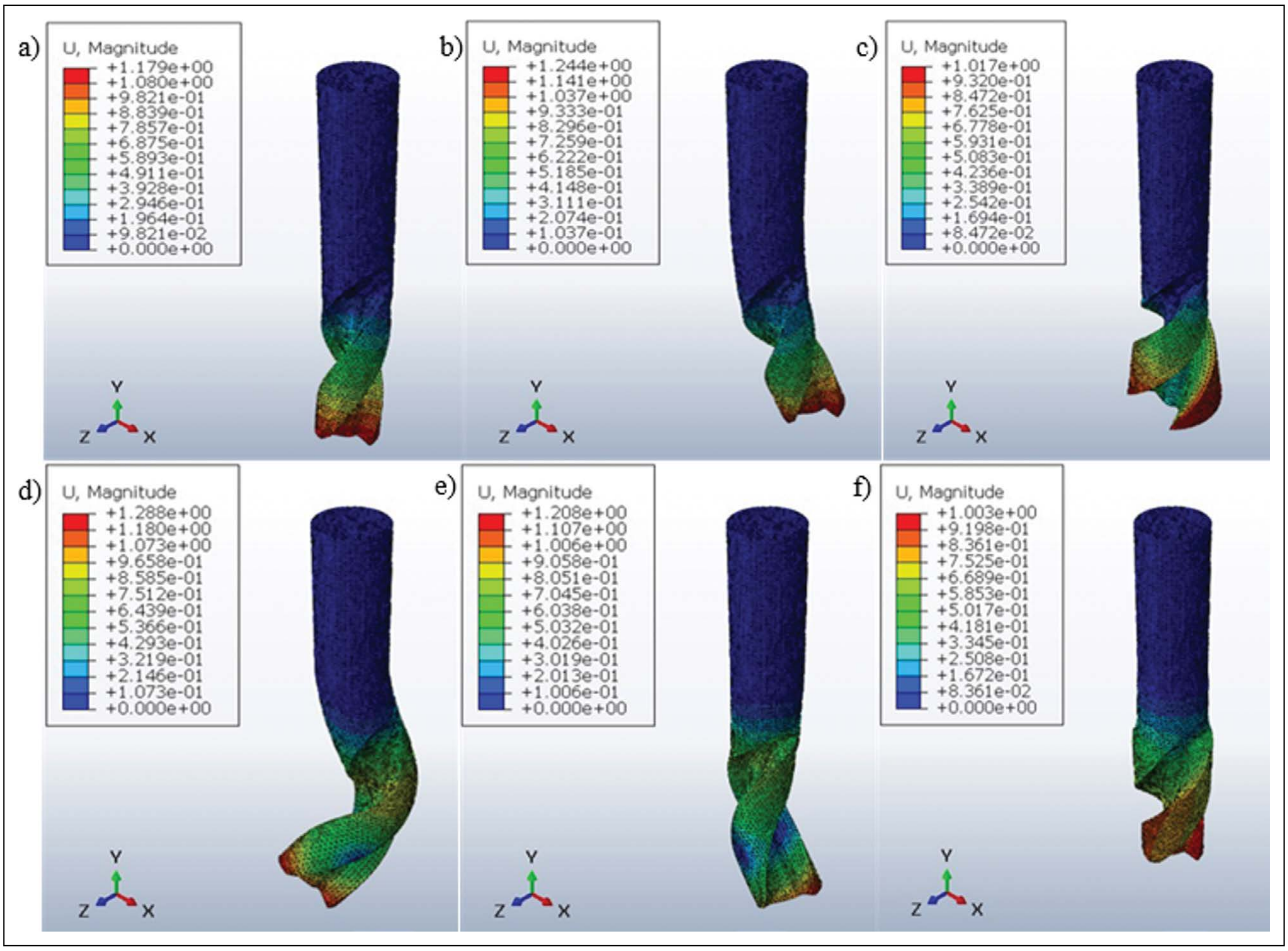


Figure 7. Modal analysis results for tool No. 4; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

Table 9. ANOVA results of second mode natural frequencies

Source	Sum of squares	df	Mean square	F-value	p-value	
Mode II	39.64	5	7.93	222.47	0.0005	significant
A	5.01	1	5.01	140.45	0.0013	
B	30.92	1	30.92	867.59	<0.0001	
AB	0.1806	1	0.1806	5.07	0.1098	
A^2	0.0512	1	0.0512	1.44	0.3167	
B^2	3.48	1	3.48	97.79	0.0022	
Residual	0.1069	3	0.0356			
Cor Total	39.75	8				

Analysis (FEMA). Tobias [14] investigated machine-tool dynamics. He reported that a certain type of chatter vibration which causes a relative displacement of the saddle in relation to the machine table may be observed only in certain speed ranges.

Considering the executed studies on literature, the importance of identifying the dynamic characteristics of the cutting tools is undeniable in order to minimize the trail, reworks and also scraps. Furthermore, it is seen that there is no available research paper on the newly developed cutters having different sorts of applications. Therefore, in this research it has been attempted to study various flat bottom drills' dynamic characteristics by focusing on the cutting tool design with combination of radial and rake angle. The natural frequencies, mode shape, displacements, rigidity, stiffness, oscillation periods of the designed flat bottom drills have been studied using finite element methods.

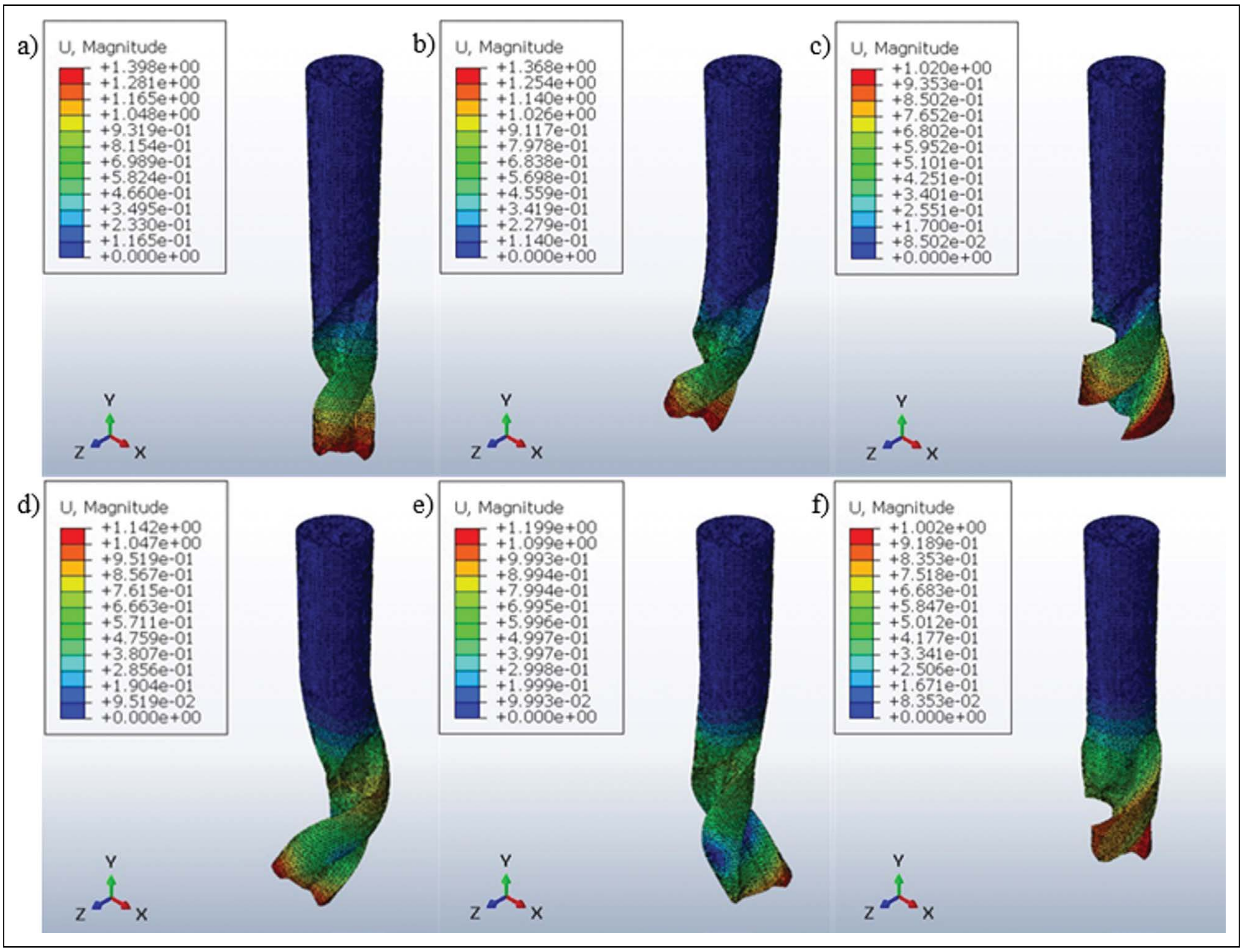


Figure 8. Modal analysis results for tool No. 5; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

Table 9. ANOVA results of second mode natural frequencies

Source	Sum of squares	df	Mean square	F-value	p-value	
Mode II	39.64	5	7.93	222.47	0.0005	Significant
A	5.01	1	5.01	140.45	0.0013	
B	30.92	1	30.92	867.59	<0.0001	
AB	0.1806	1	0.1806	5.07	0.1098	
A^2	0.0512	1	0.0512	1.44	0.3167	
B^2	3.48	1	3.48	97.79	0.0022	
Residual	0.1069	3	0.0356			
Cor total	39.75	8				

Modeling of the Flat Bottom Drills

The designed flat bottom drills with the illustrated geometrical parameters in Table 1 have been modeled in Solidworks 2021 as depicted in Figure 2. The mass and mechanical properties of the designed carbide cutting tools are given in Table 2 and 3, respectively. Thereafter, the feasibility of the designed tools has been studied considering the resonance and modal analysis properties for an enhanced drilling operation using Finite Element Methods. For this reason, the modal analyses of the designed flat bottom drills have been executed in Explicit solver of Abaqus 2017 program to improve cutting tool performance and capabilities, especially for vertical and inclined drilling operations of metallic materials. The tetrahedral element types were deployed for the meshing process. The element numbers for the designed tool were between 91610 and 92650. Since

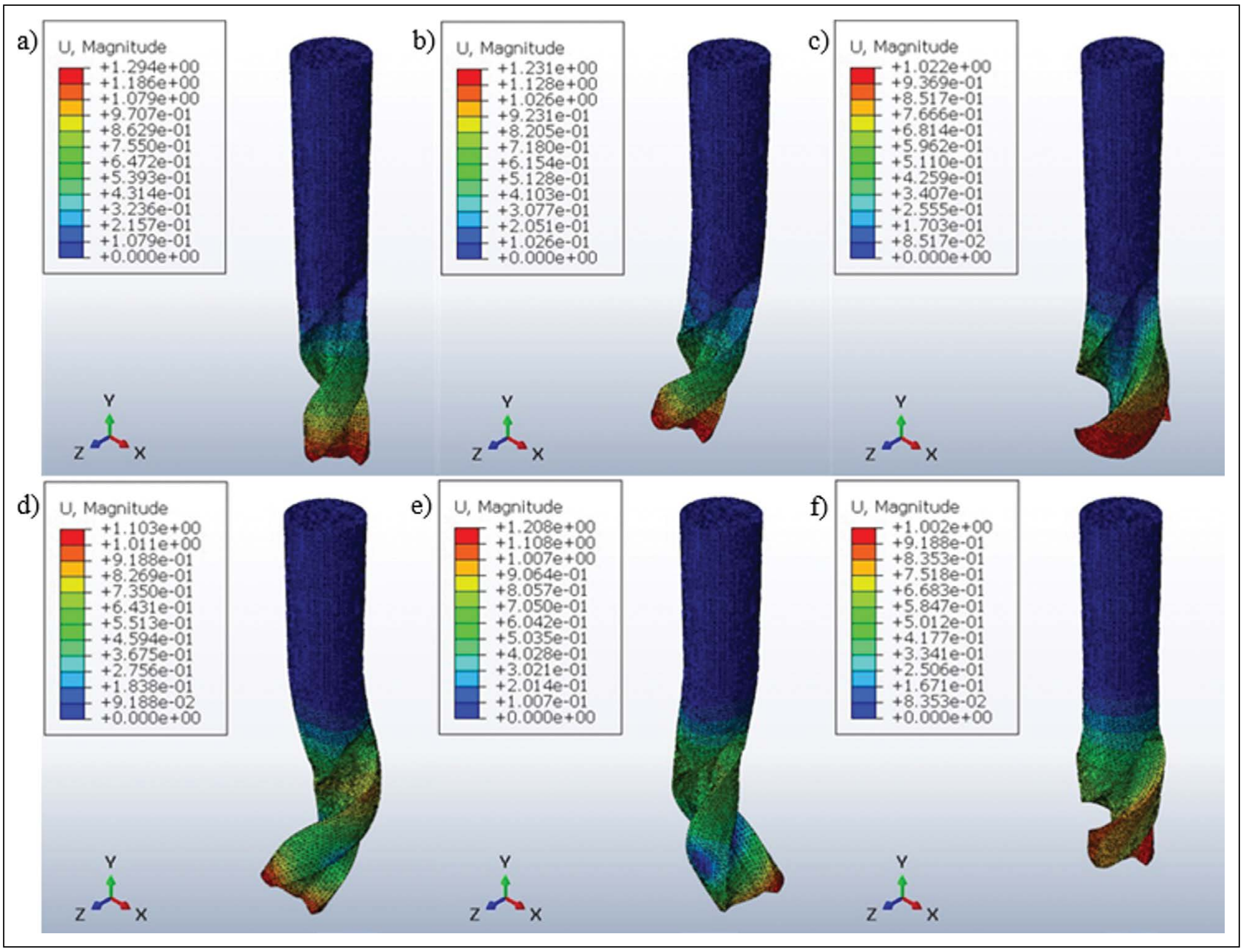


Figure 9. Modal analysis results for tool No. 6; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

Table 10. ANOVA results of third mode natural frequencies

Source	Sum of squares	df	Mean square	F-value	p-value	
Mode III	2142.03	5	428.41	1784.42	<0.0001	Significant
A	18.55	1	18.55	77.27	0.0031	
B	1954.45	1	1954.45	8140.83	<0.0001	
AB	1.31	1	1.31	5.46	0.1015	
A^2	0.0841	1	0.0841	0.3501	0.5957	
B^2	167.63	1	167.63	698.22	0.0001	
Residual	0.7202	3	0.2401			
Cor total	2142.75	8				

cutting tool design necessitates an understanding of the application challenges that can be experienced during the machining process, counting; setup inflexibility – critical to dimensional accuracy and finish quality of the part, in order to have an actual close condition to industrial applications, U1=U2=U3=RU1=RU3=0 boundary conditions have been applied to the shank of the flat bottom drills as tool holder assembled simulation as demonstrated in Figure 3.

RESULTS AND DISCUSSIONS

Finite Element Analysis

Modal analysis was carried out by considering the boundary conditions described in the previous section. The obtained analyzes outcomes for the designed cutting tools are shown from Figure 4 to Figure 12. The results of six natural frequencies, maximum total displacements,

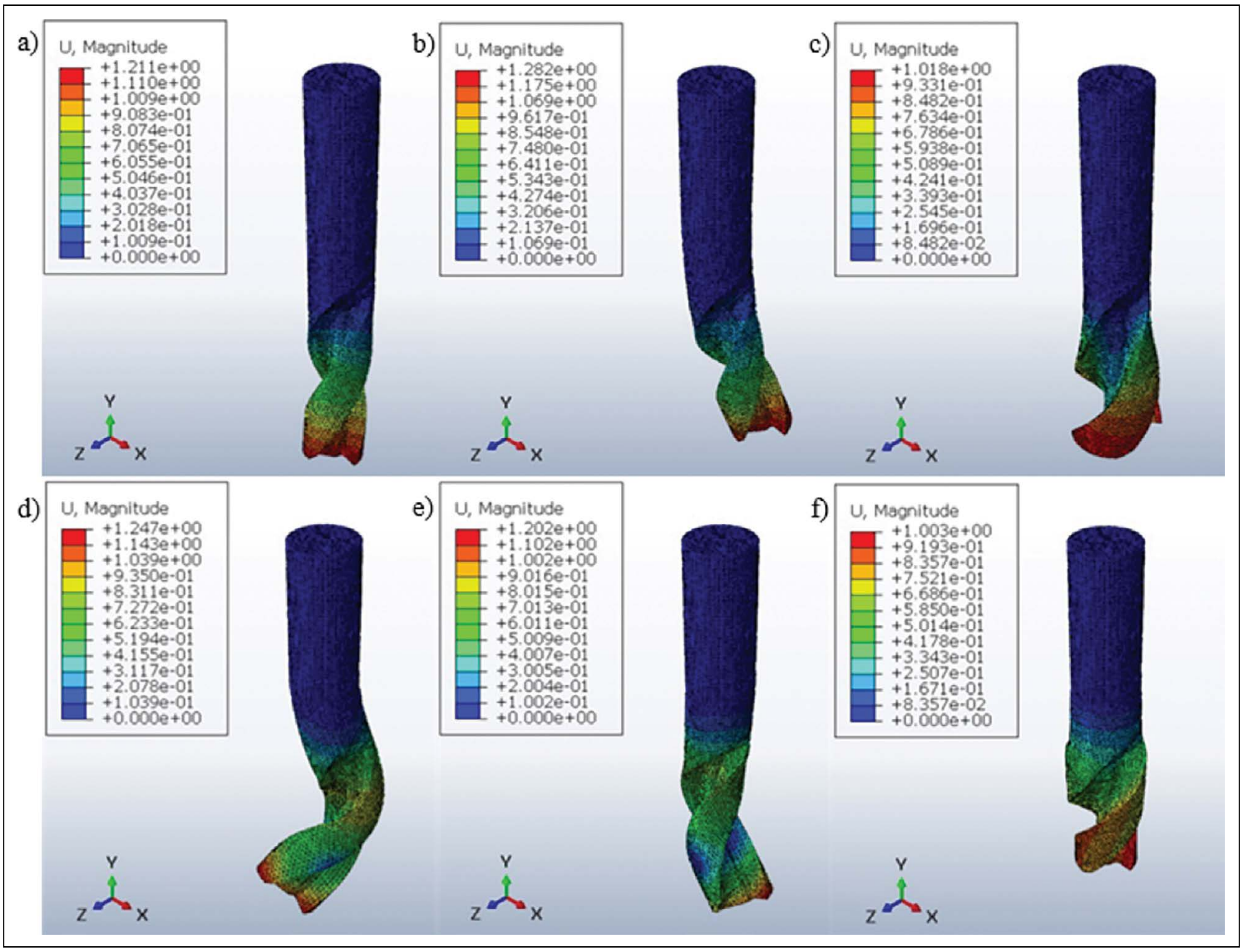


Figure 10. Modal analysis results for tool No. 7; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

Table 11. ANOVA results of fourth mode natural frequencies

Source	Sum of squares	df	Mean square	F-value	p-value	
Mode IV	2142.03	5	428.41	1784.42	<0.0001	Significant
A	18.55	1	18.55	77.27	0.0031	
B	1954.45	1	1954.45	8140.83	<0.0001	
AB	1.31	1	1.31	5.46	0.1015	
A^2	0.0841	1	0.0841	0.3501	0.5957	
B^2	167.63	1	167.63	698.22	0.0001	
Residual	0.7202	3	0.2401			
Cor total	2142.75	8				

and mode shapes of the flat bottom drill tools are given in Table 4, 5, respectively. The stiffness of the system in each frequency has been calculated by the below given expressions.

$$\omega = \sqrt{\frac{k}{m}} \quad (rad.s^{-1}) \tag{1}$$

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (Hz) \tag{2}$$

$$T = \frac{1}{f} = \frac{1}{2\pi}\sqrt{\frac{m}{k}} \quad (s) \tag{3}$$

$$N = f \times 60 \tag{4}$$

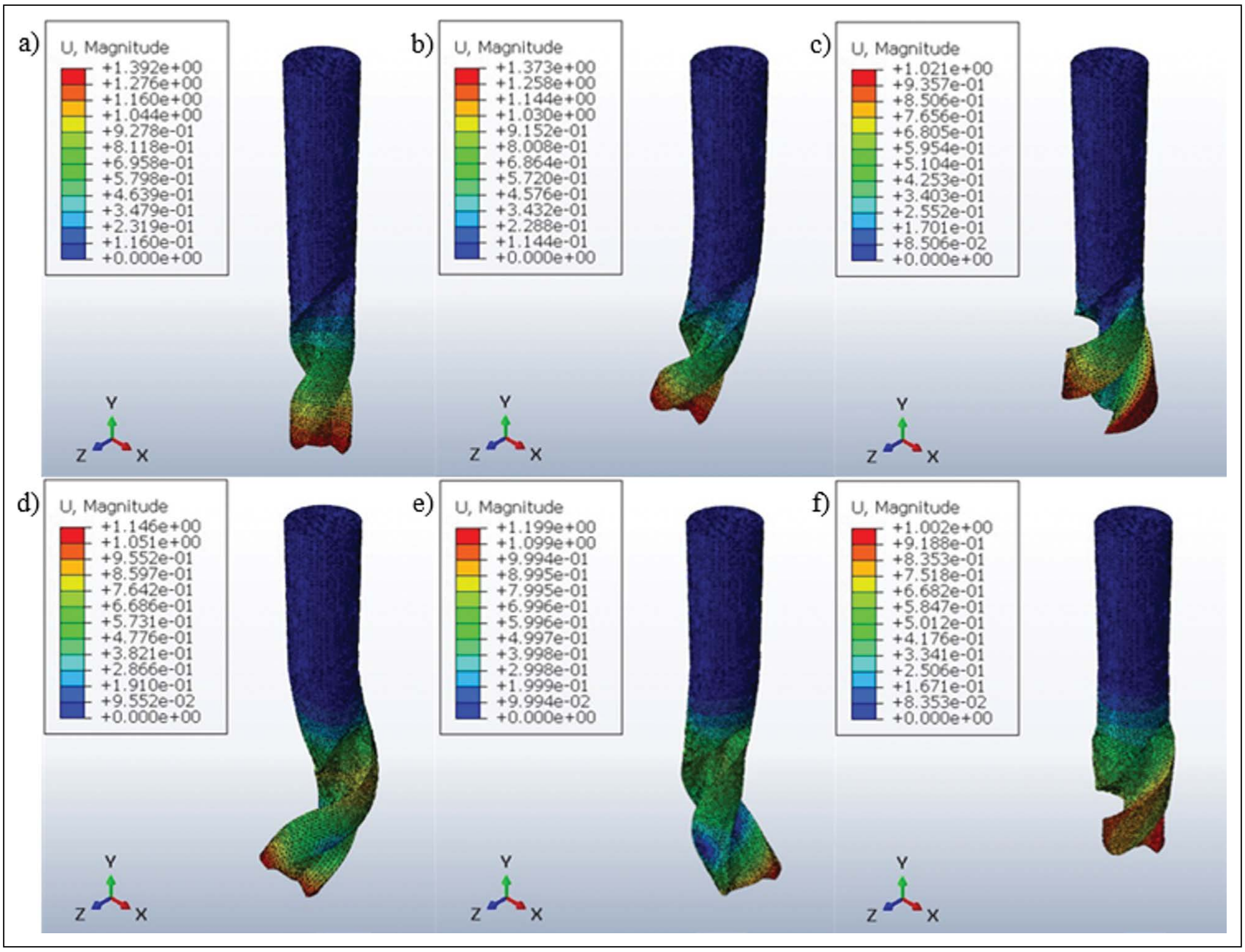


Figure 11. Modal analysis results for tool No. 8; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

Table 12. ANOVA results of fifth mode natural frequencies

Source	Sum of squares	df	Mean square	F-value	p-value	
Mode V	2142.03	5	428.41	1784.42	<0.0001	Significant
A	18.55	1	18.55	77.27	0.0031	
B	1954.45	1	1954.45	8140.83	<0.0001	
AB	1.31	1	1.31	5.46	0.1015	
A^2	0.0841	1	0.0841	0.3501	0.5957	
B^2	167.63	1	167.63	698.22	0.0001	
Residual	0.7202	3	0.2401			
Cor Total	2142.75	8				

where; ω, f are the angular and natural frequencies for the mode shape., m, k, T and N represent the mass, stiffness, oscillation period, and rotational speed in rpm, respectively.

The lowest natural frequency has been calculated as 361.20 Hz for tool number 9 at first mode. However, the highest one was for tool number 1 with 1590.20 Hz at sixth mode. It must be noted that the metallic materials are being machined using carbide tools at maximum 20000 rpm in industrial applications. Ideally, the calculated natural frequencies for the tools are higher than the industrial application conditions and also tool manufacturers' recommendations which is an implicant of a sufficient cutting tools design considering the modal dynamic analyses and can be used with no failure or damages to the framework such as machine tools. The calculated stiffness and oscilla-

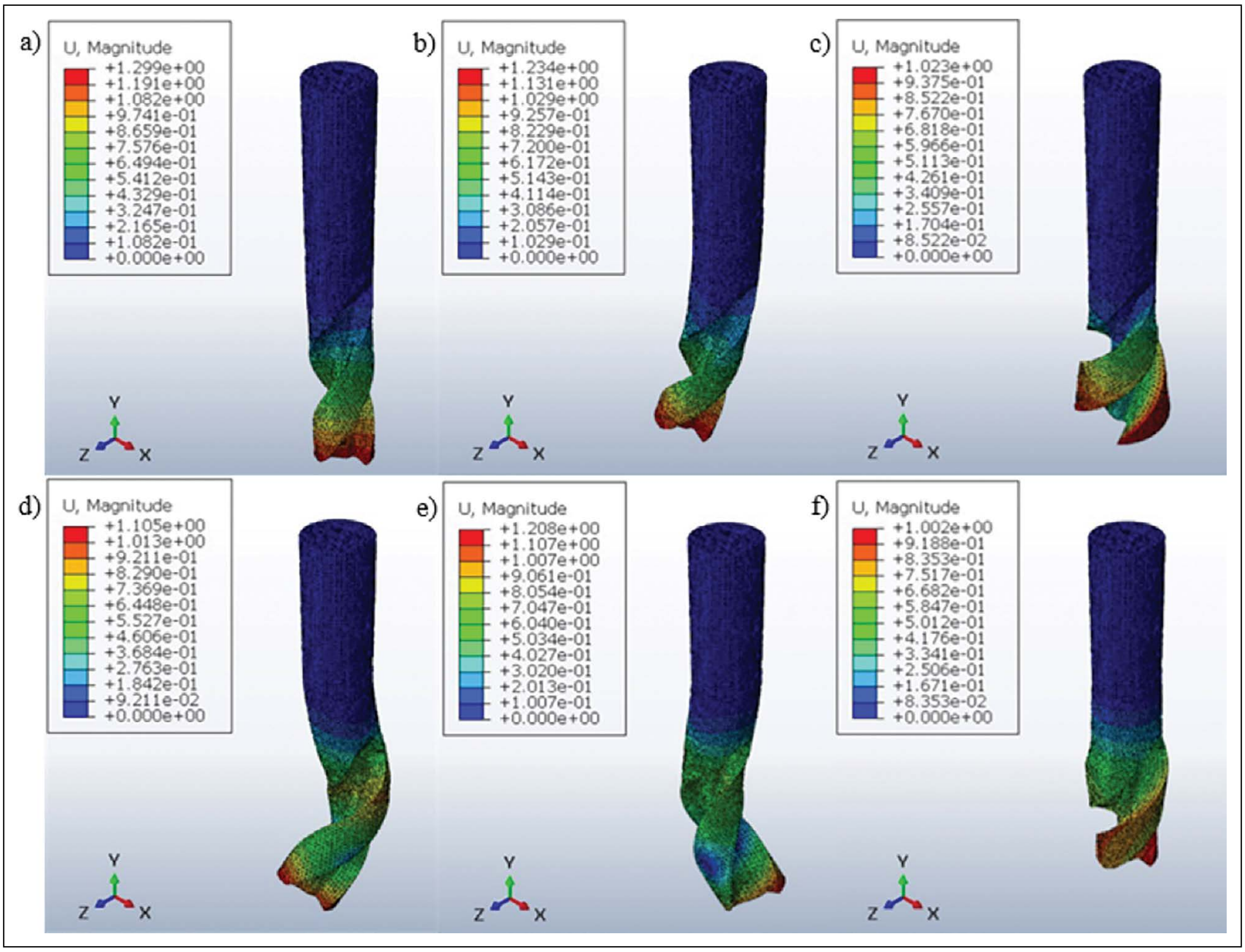


Figure 12. Modal analysis results for tool No. 9; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

Table 13. ANOVA results of sixth mode natural frequencies

Source	Sum of squares	df	Mean square	F-value	p-value	
Mode VI	2142.03	5	428.41	1784.42	<0.0001	Significant
A	18.55	1	18.55	77.27	0.0031	
B	1954.45	1	1954.45	8140.83	<0.0001	
AB	1.31	1	1.31	5.46	0.1015	
A^2	0.0841	1	0.0841	0.3501	0.5957	
B^2	167.63	1	167.63	698.22	0.0001	
Residual	0.7202	3	0.2401			
Cor total	2142.75	8				

tion period for the mode shapes of the designed flat bottom drills are exposed in Table 4, 5, respectively. The stiffness values for each mode shape expresses the ability of the tool against elastic deformation in order to provide an accurate cut. Meanwhile, the machining power is transmitted by this property [15]. The higher value of stiffness leads the framework to lower elastic deformations or faster stop of the oscillation.

The variation of the natural frequencies for six modes of the designed flat bottom drills with radial and axial rake angles are demonstrated in Figure 13. The effects of these parameters on natural frequency are shown in Figure 14. It is seen that although small values, the natural frequencies of the cutting tool have decreased with increase in the radial rake angle for all of the shape modes. This can be attributed to the change in the cutting tool

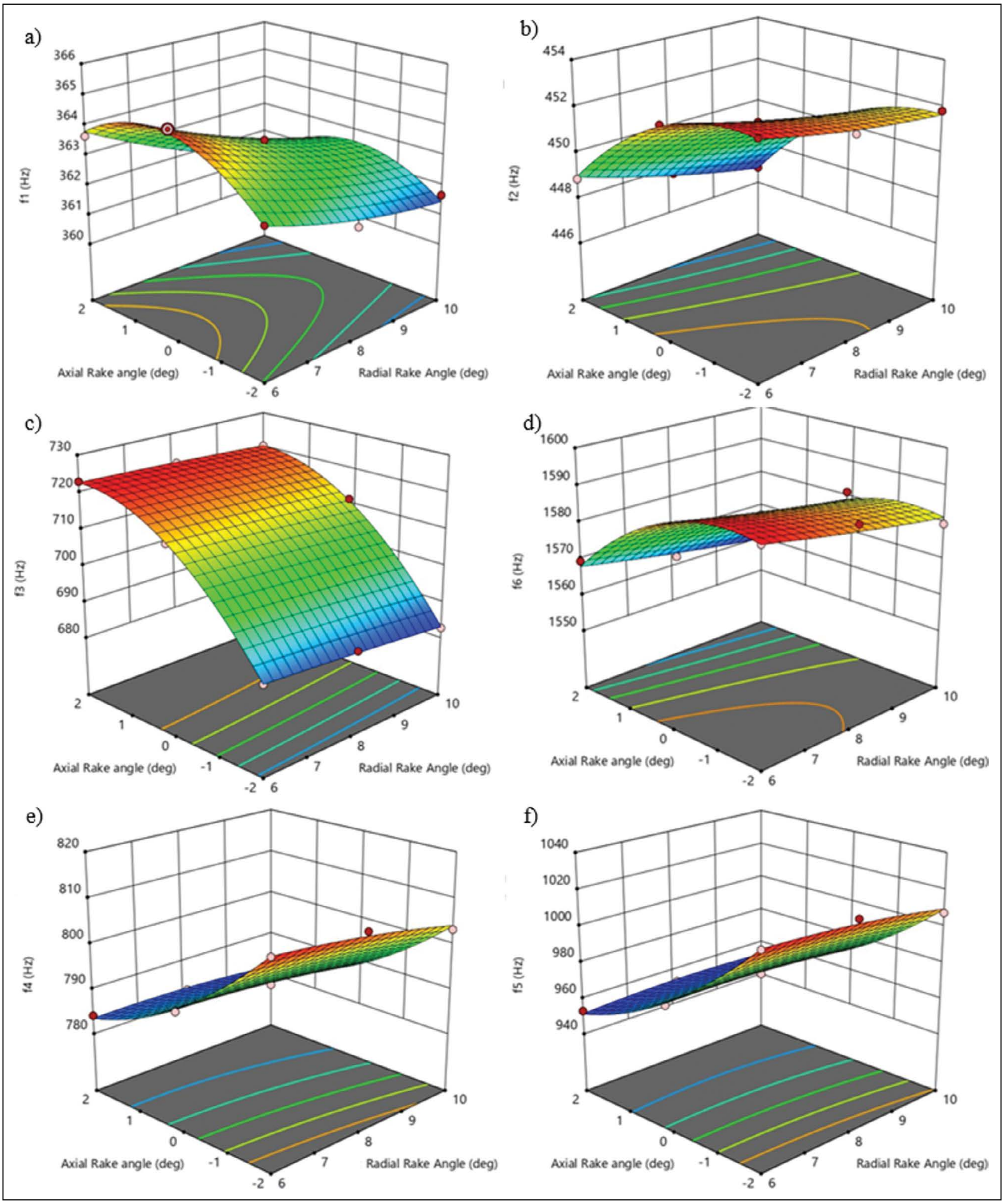
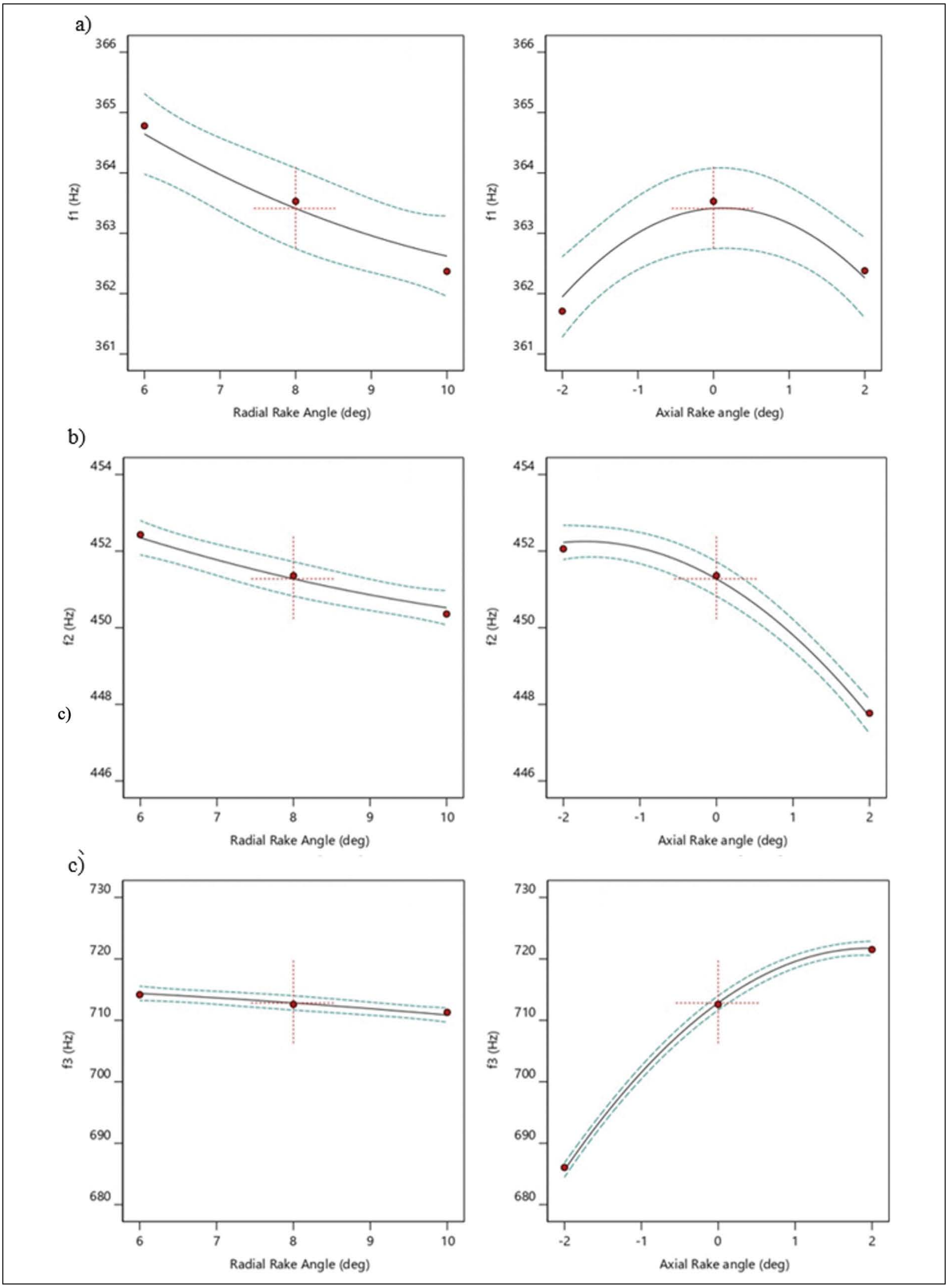


Figure 13. The variation of the natural frequencies with radial and axial rake angle of flat bottom drill; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

mass and stiffness. However, no dominant trends were observed for both natural frequencies and total maximum displacements with the change in the axial rake angle of the cutting tool. The effects of radial and axial rake angles on total maximum displacement are shown in Figure 15. In order to observe the influence of the cutting tool


a)
366
365
364
363
362
361
f1 (Hz)
6 7 8 9 10
Radial Rake Angle (deg)
-2 -1 0 1 2
Axial Rake angle (deg)
b)
454
452
450
448
446
f2 (Hz)
c)
6 7 8 9 10
Radial Rake Angle (deg)
-2 -1 0 1 2
Axial Rake angle (deg)
c)
730
720
710
700
690
680
f3 (Hz)
6 7 8 9 10
Radial Rake Angle (deg)
-2 -1 0 1 2
Axial Rake angle (deg)

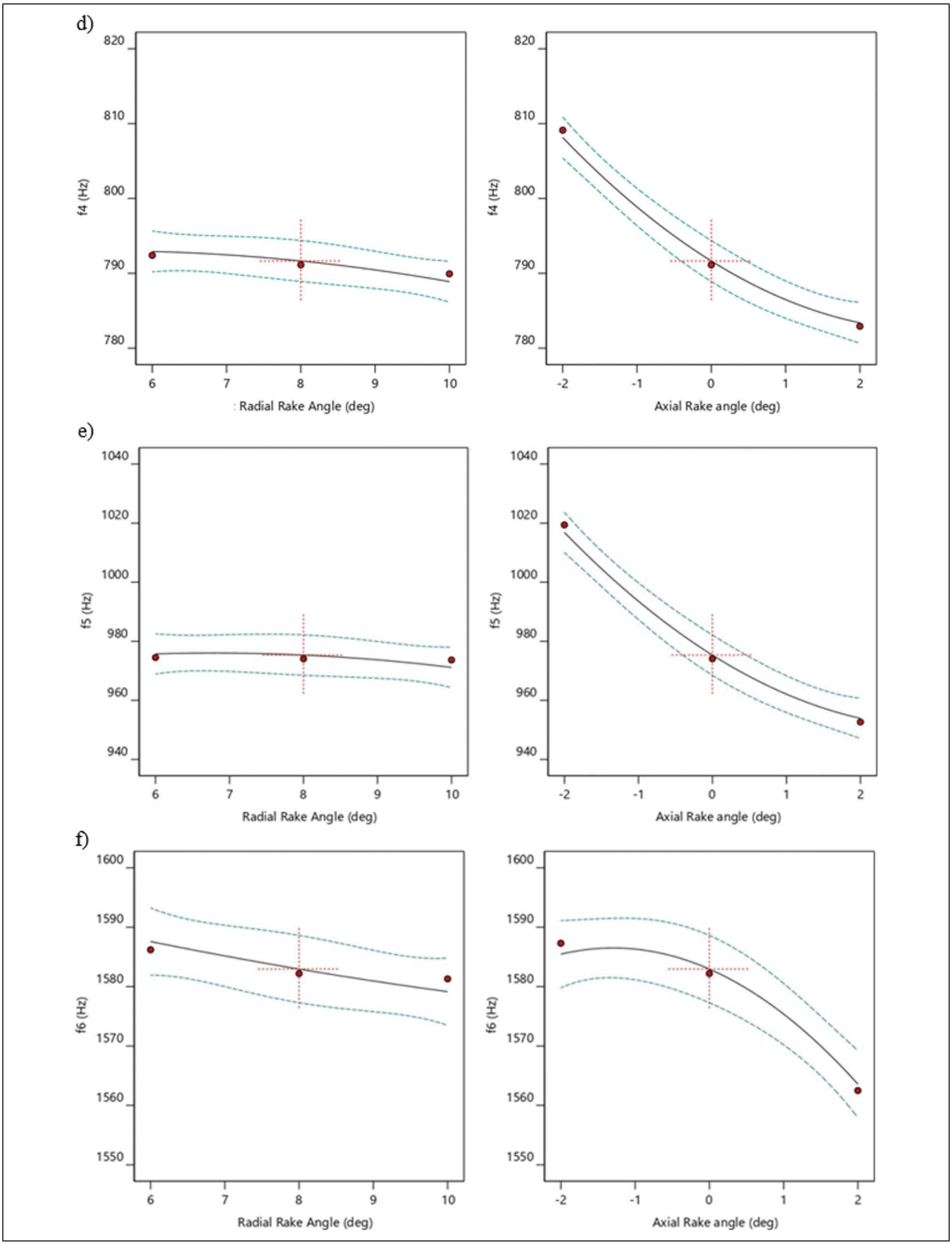


Figure 14. The variation of the natural frequencies with radial and axial rake angle of flat bottom drill; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes.

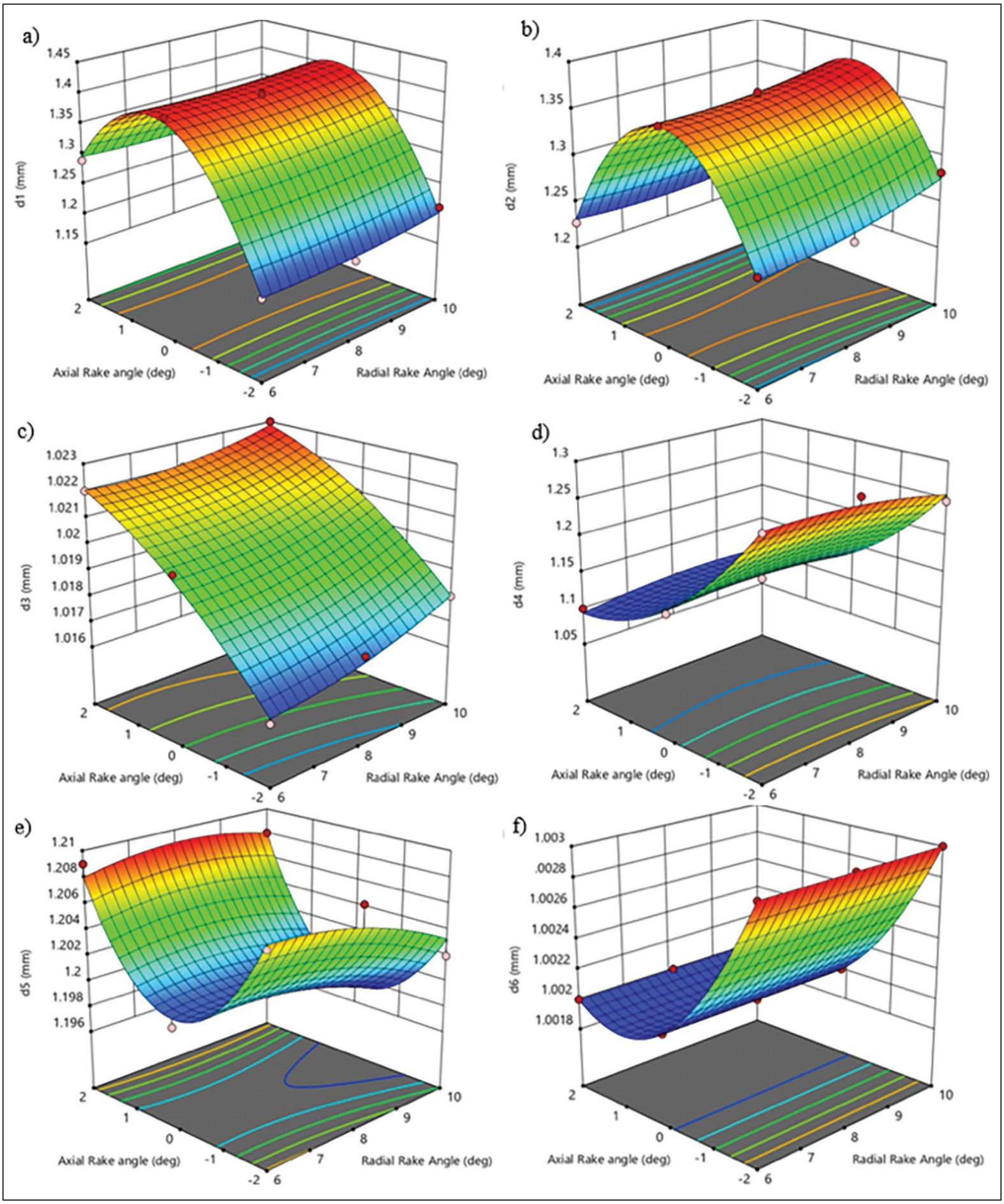


Figure 15. The variation of the natural frequencies with radial and axial rake angle of flat bottom drill; **(a)** first, **(b)** second, **(c)** third, **(d)** fourth, **(e)** fifth, **(f)** sixth modes..

geometrical design parameters on the natural frequencies for each mode shape, analysis of variance (ANOVA) as a statistical technique has been used. Statistical significance of the fitted model and terms was assessed by the P-values of ANOVA results. The analysis results are given in Tables 8 to 13 for six modes of natural frequencies, respective-

Table 14. The quadratic order developed regression model for different shape modes of the designed flat bottom drills

Mode No.	f1	f2	f3	f4	f5	f6
C	371.006	457.490	716.587	787.822	954.488	1606.489
A	-1.392	-1.097	-0.059	1.965	6.360	-3.775
B	0.699	-0.710	7.879	-8.513	-21.375	-5.767
AB	-0.078	-0.053	0.143	0.291	0.704	0.038
A^2	0.055	0.040	-0.051	-0.186	-0.469	0.104
B^2	-0.327	-0.330	-2.289	1.029	2.516	-2.108
R^2	0.939	0.993	0.999	0.989	0.989	0.954

ly. The A and B parameters stand for the radial and axial rake angles in the tables, respectively. For all the mode shapes, the high model F-values imply that the analyzes are significant. The chances of error due to noise are less than 1%. P-values less than 0.0500 indicate model terms are significant. Values greater than 0.1000 indicate the model terms are not significant.

In order to predict the natural frequencies for different shape modes of the designed flat bottom drills quadratic order regression models have been developed and illustrated in Table 14. The A, B, and R^2 parameters stand for the radial, axial rake angles and model accuracy, respectively.

CONCLUSION

In order to achieve a comprehensive knowledge on the cutting tool dynamics, modal analyzes of flat bottom drill with various geometrical parameters have been studied using finite element methods. The obtained conclusions from the simulation are mentioned in below:

- The Finite elements method analysis is a powerful and functional tool which provides the designers with realistic results for complex geometrical shapes.
- Modal analysis does not have any restrictions in definition of the angular frequencies. Therefore, it can be said that it is a universal and sufficient analysis method for definition of the natural frequencies.
- The result of modal analysis reveals that the calculated natural frequencies for the tools are higher than the industrial application conditions and also tool manufacturers' recommendations. Therefore, they can be used in metallic materials material removal processes.
- The natural frequencies for all the mode shapes intensify with increase in the radial rake angle.
- The stiffness, maximum total displacement and oscillation period has been calculated for each mode shape of the designed flat bottom drills.
- Regression models have been presented in order to predict the natural frequencies of the designed flat bottom drills with radial and axial rake angles as geometrical inputs. The accuracy of these models is higher than 93% and can be used for faster prediction.

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Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Nima Zoghipour: Cutting tool design, performing the finite element analysis, preparing the article.

Yusuf Kaynak: Supervisor.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

There are no ethical issues with the publication of this manuscript.

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