Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-39927
www.engineeringscience.rs

Journal of Applied Engineering Science
Vol. 21, No. 2, 2023
Original Scientific Paper
Paper number: 21(2023)2, 1086, 418-427

PREDICTION OF GTE VANES DEFLECTION BY ANALYTICAL MODELS OF TECHNICAL AND GEOMETRIC INITIAL DATA IN CROSS LINE MILLING ON MULTI-AXIS CNC MACHINES

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In the process of milling the profile of the vanes of a gas turbine engine on multi-operational machines, a technological scheme of transverse line shaping is used. According to this scheme, the vane rotates around its own axis, it is machined with a mill with a spherical working surface, which performs rotation and interpolated axial movement. The required parameters of the surface quality of the vane airfoil profile (profile accuracy and surface roughness parameter) are provided by assigning a combination of controlled processing parameters. However, today there are no recommendations on the calculation and assignment of combinations of controlled parameters for the milling of complex-profile surfaces, which is the profile of the flow path of the GTE compressor vanes. For each line and angle of rotation of the vane, the accuracy of the vane profile will be determined depending on the amount of vane deformation, which should not exceed the tolerance for its manufacture. In the course of the analysis of geometric relationships in the contact zone of the curved profile of the flow part of the vane and the mill with a spherical working surface, dependences were obtained to determine the magnitude of the force component during milling and its projection on the Y axis, as well as the effective diameter of the mill, which are necessary to calculate the magnitude of the total deformation of the vane. A methodology is proposed and analytical models are obtained for determining and assigning a combination of controlled parameters of the milling mode that provide a given accuracy of the vane airfoil profile when developing a control program for the vane milling process on a CNC machine.

Keywords: vane deflection, vane profile milling, cutting forces, cutter effective diameter, contact arc length, parameters of the transverse line milling mode

1 INTRODUCTION

On multi-axis CNC machines, when shaping the profile of the flow path of the compressor vanes of a gas turbine engine (GTE), a technological scheme of transverse line milling is often used. According to this scheme, the vane rotates around its own axis, and the machined tool with a spherical working surface rotates and interpolates axial movement [1-4]. The specified quality indicators of the vane airfoil surface quality (profile accuracy and surface roughness parameter) [5-6] are provided by the assigned combinations of controlled parameters of the milling mode during processing on multi-axis CNC machines [7-9]. However, at present there are no recommendations on technical and geometric data for determining the amount of deflection of the vanes in various sections at different angles of their rotation.

2 THEORY

For each line and angle of rotation of the vane, the accuracy of the vane profile will be determined by the value of the total linear and angular deformations of the vane δi, which should not exceed the tolerance value for its manufacture (Fig. 1).

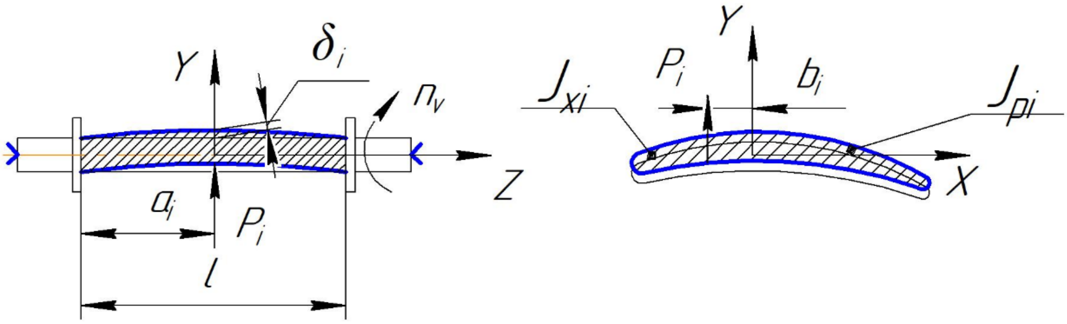


Figure 1. Scheme for calculating the magnitude of the vane deformation during transverse line milling: l- length of the vane feather; ai -coordinate of the line of the vane ; Pi - component of the milling force in the direction of the Y coordinate for each line and the angle of rotation of the vane; bi - arm of application of force Pi relative to the Z axis; δi - total deformation of the vane feather from bending and twisting under the action of force Pi for each line and angle of rotation, nv - vane rotation frequency

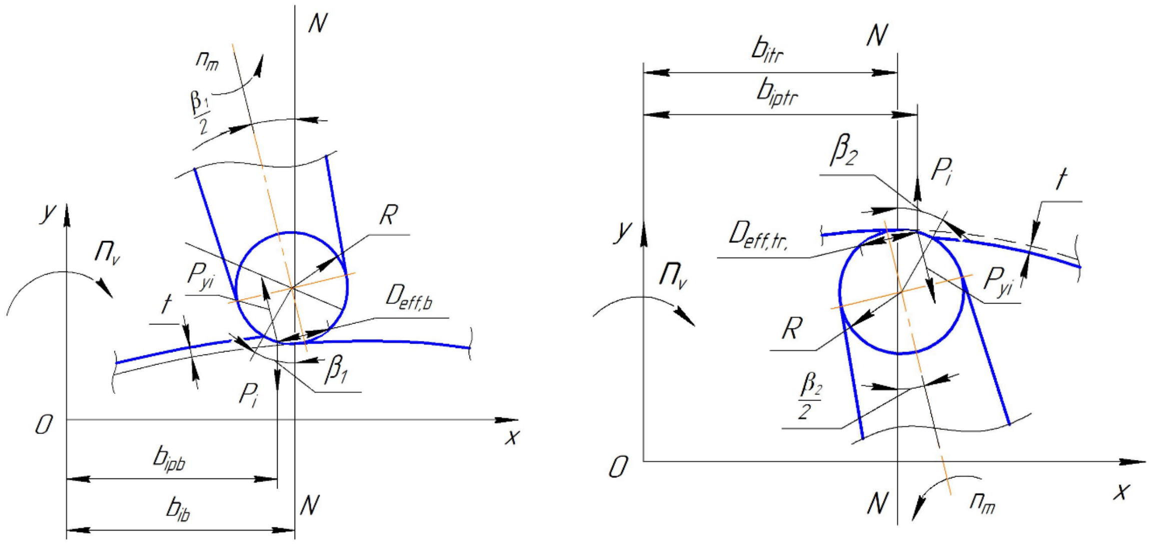
The value of the blade deflection δi is determined from the expression [9, 10]:

$$\delta_i = \frac{P_i l^3}{3E\,J_x}\left[\left(2\frac{a_i^3}{l^3} - \frac{a_i^4}{l^4} - \frac{a_i^2}{l^2}\right) + \frac{3EJ_x}{GJ_{\mathrm{p}}}\cdot\frac{b_{\mathrm{ip}}^2 a_i}{l^3}\right], \quad (1)$$

where E is the modulus of elasticity of the processed material, N/m^2; G is the shear modulus of the material, N/m^2; J_x - moment of inertia of the cross-sectional area of the vane airfoil relative to the X axis, m^4; J_p - moment of inertia of the cross-sectional area of the vane airfoil during torsion along the Z axis, m^4.

The analysis of expression (1) showed that for the prediction and technological support of the required accuracy of the flow part of the vane airfoil profile, the values for each section of the dependences of the axial (I_x) and polar (I_p) moments of inertia, the arms b_{ip}, the application of force P_i on the angle of rotation of the section α_i and coordinates α_i of the length of the flow part of the vane are necessary. The dependences for I_x, I_p, and b_i were obtained based on the data that are shown on the drawings of compressor vanes in [11].

Let us obtain functional dependences for determining the value of P_i and the calculated value of the shoulder b_{ip} of its application in expression (1), from geometric relationships in the contact zone of the end mill with a spherical cutting part and the vane, shown in Fig. 2.



a b

Figure 2. Geometrical model of the contact of the mill with the spherical working surface of the back (a) and trough (b) of the vane during milling:

t is the depth of milling; n_v, n_m - respectively, the rotational speed of the vane and mill; R is the radius of the spherical cutting part of the mill; $D_{eff.b}$, $D_{eff.tr}$ - respectively, the average effective diameter of the cutting edge on the back and trough; $\beta_1/2$, /2 - respectively, the angle of rotation of the axis of the cutter from the normal *N–N* to the point of the milled profile on the back and trough; β_1, β_2 – angles of arcs (length B_b, B_{tr}) of the mill and vane contact zone; P_{yi} is the normal component of the milling force at the average effective diameter of the cutting edge; b_{ib}, b_{itr} –shoulders of N–N normals to the points of the milled profile, according to the drawing of the vane; b_{ipb}, b_{iptr}– current application shoulders of projections P_{yi} of normal components of the milling force P_i on the *Y* axis

The contact zone of the arc length *B* between the mill with a spherical working surface and the vane during transverse line milling, depending on the direction of the contour bypass, is shifted relative to the *N-N* normal to the points of the geometric model of the vane.

Let us establish a functional dependence for the calculated value of the shoulder b_{ip} of the application of the projection P_{yi} of the normal component of the milling force P_i on the *Y* axis from geometric relationships in the contact zone of the end mill with a spherical cutting part with the back and trough of the vane.

The current value of the shoulder b_{ip} of the center of pressure in the contact zone of the projection P_{yi} of the normal component of the milling force P_i relative to the axis of rotation of the vane is determined from the expressions [12, 13]:

$$b_{i\mathrm{pb}} = b_{i\mathrm{b}} \pm R\cdot\sin\left(\frac{\beta_1}{2}\right), \quad (2)$$

$$b_{iptr} = b_{itr} \pm R\cdot\sin\left(\frac{\beta_2}{2}\right), \quad (3)$$

The increment (or decrement) sign used for b_{ip} in expressions (2, 3) is given in Fig. 3.

The direction of traversal of the stitch contour relative to the Z axis and the coordinate sign of X / The direction of rotation of the vane relative to the Z axis	Clockwise				Counterclock-wise			
	back of the vane	trough of the vane	back of the vane	trough of the vane	back of the vane	trough of the vane	back of the vane	trough of the vane
	Coordinate sign X							
	+	–	+	–	+	–	+	–
Clockwise	+	–	+	–	+	–	+	–
Counterclock-wise	–	+	–	+	–	+	–	+

Figure 3. Increment sign (decrease sign) b_{ip}

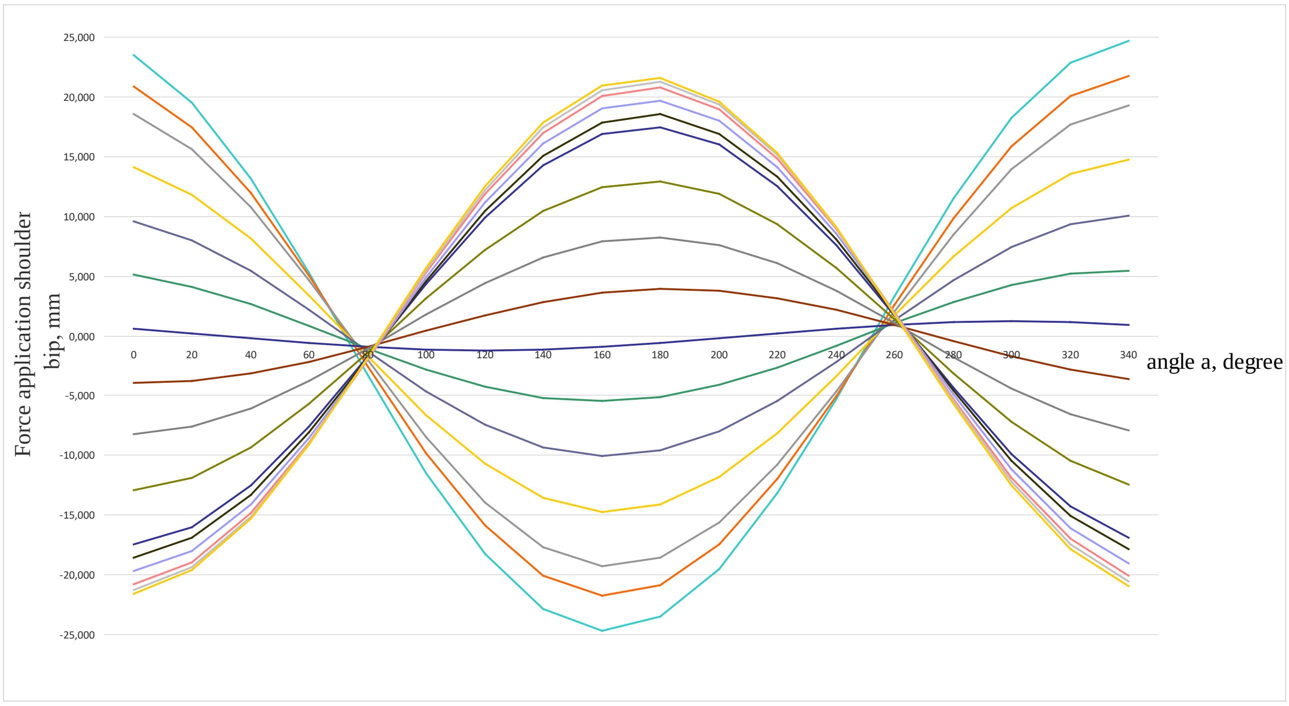
Taking into account the sign of the increment (decrease) of the coordinate $X(\Delta b_{ip})$ Fig. 3, approximated power-law functional dependences were obtained for calculating Δb_{ip} at each point of the section A_4-A_4 of the working vane of the IV stage of the GTE, with a flow path length of 151.63 mm, the result is given in Table. 1.

Table 1. Dependencies for calculating the value of the shoulders b_{ip} for each point in the section A_4-A_4

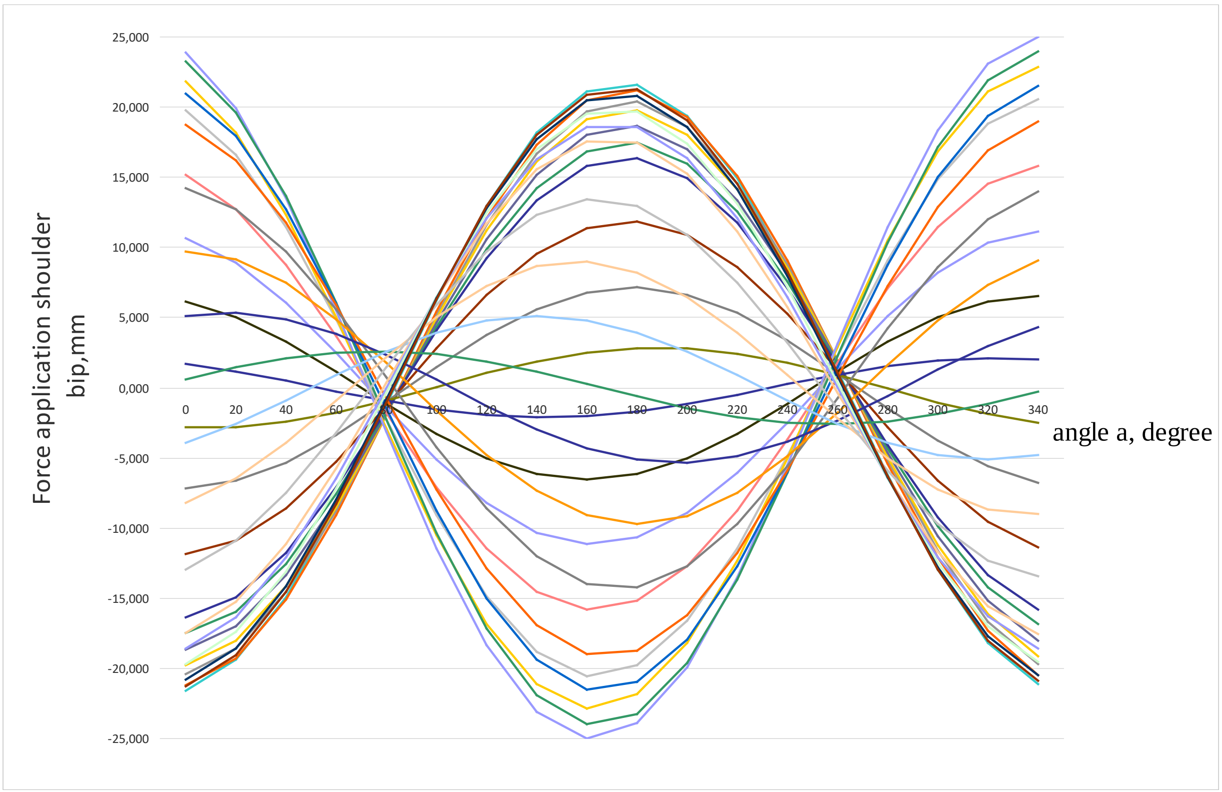
№ point	$b_{ip} = b_i \pm R \cdot \sin(\frac{\beta}{2}),$
1	$b_{ip} = -4 \cdot 10^{-5} \cdot \alpha^6 + 0.0022 \cdot \alpha^5 - 0.0412 \cdot \alpha^4 + 0.2081 \cdot \alpha^3 + 0.683 \cdot \alpha^2 - 0.7072 \cdot \alpha - 21.094$
2	$b_{ip} = -4 \cdot 10^{-5} \cdot \alpha^6 + 0.0022 \cdot \alpha^5 - 0.0398 \cdot \alpha^4 + 0.1982 \cdot \alpha^3 + 0.6798 \cdot \alpha^2 - 0.6357 \cdot \alpha - 20.572$
3	$b_{ip} = -4 \cdot 10^{-5} \cdot \alpha^6 + 0.0021 \cdot \alpha^5 - 0.0385 \cdot \alpha^4 + 0.1888 \cdot \alpha^3 + 0.6755 \cdot \alpha^2 - 0.569 \cdot \alpha - 20.054$
4	$b_{ip} = -3 \cdot 10^{-5} \cdot \alpha^6 + 0.002 \cdot \alpha^5 - 0.0359 \cdot \alpha^4 + 0.1711 \cdot \alpha^3 + 0.6637 \cdot \alpha^2 - 0.4486 \cdot \alpha - 19.016$
5	$b_{ip} = -3 \cdot 10^{-5} \cdot \alpha^6 + 0.0019 \cdot \alpha^5 - 0.0332 \cdot \alpha^4 + 0.1539 \cdot \alpha^3 + 0.6475 \cdot \alpha^2 - 0.3376 \cdot \alpha - 17.931$
6	$b_{ip} = -3 \cdot 10^{-5} \cdot \alpha^6 + 0.0017 \cdot \alpha^5 - 0.0307 \cdot \alpha^4 + 0.1377 \cdot \alpha^3 + 0.6311 \cdot \alpha^2 - 0.2338 \cdot \alpha - 16.887$
7	$b_{ip} = -2 \cdot 10^{-5} \cdot \alpha^6 + 0.0012 \cdot \alpha^5 - 0.021 \cdot \alpha^4 + 0.0777 \cdot \alpha^3 + 0.5418 \cdot \alpha^2 + 0.1106 \cdot \alpha - 12.564$
8	$b_{ip} = -1 \cdot 10^{-5} \cdot \alpha^6 + 0.0007 \cdot \alpha^5 - 0.0112 \cdot \alpha^4 + 0.0223 \cdot \alpha^3 + 0.4211 \cdot \alpha^2 + 0.3782 \cdot \alpha - 7.9516$
9	$b_{ip} = -6 \cdot 10^{-5} \cdot \alpha^6 + 0.0003 \cdot \alpha^5 - 0.0026 \cdot \alpha^4 - 0.0222 \cdot \alpha^3 + 0.2871 \cdot \alpha^2 + 0.5456 \cdot \alpha - 3.6344$
10	$b_{ip} = 2 \cdot 10^{-5} \cdot \alpha^6 - 0.0002 \cdot \alpha^5 + 0.006 \cdot \alpha^4 - 0.0634 \cdot \alpha^3 + 0.126 \cdot \alpha^2 + 0.6514 \cdot \alpha + 0.9617$
11	$b_{ip} = 1 \cdot 10^{-5} \cdot \alpha^6 - 0.0007 \cdot \alpha^5 + 0.0143 \cdot \alpha^4 - 0.0985 \cdot \alpha^3 - 0.0579 \cdot \alpha^2 + 0.6814 \cdot \alpha + 5.6457$
12	$b_{ip} = 2 \cdot 10^{-5} \cdot \alpha^6 - 0.0011 \cdot \alpha^5 + 0.0222 \cdot \alpha^4 - 0.1267 \cdot \alpha^3 - 0.2685 \cdot \alpha^2 + 0.6231 \cdot \alpha + 10.434$
13	$b_{ip} = 3 \cdot 10^{-5} \cdot \alpha^6 - 0.0016 \cdot \alpha^5 + 0.0296 \cdot \alpha^4 - 0.1468 \cdot \alpha^3 - 0.5101 \cdot \alpha^2 + 0.4621 \cdot \alpha + 15.344$
14	$b_{ip} = 4 \cdot 10^{-5} \cdot \alpha^6 - 0.0021 \cdot \alpha^5 + 0.0366 \cdot \alpha^4 - 0.1601 \cdot \alpha^3 - 0.7792 \cdot \alpha^2 + 0.2131 \cdot \alpha + 20.38$
15	$b_{ip} = 4 \cdot 10^{-5} \cdot \alpha^6 - 0.0023 \cdot \alpha^5 + 0.0401 \cdot \alpha^4 - 0.1663 \cdot \alpha^3 - 0.9154 \cdot \alpha^2 + 0.0831 \cdot \alpha + 22.904$
16	$b_{ip} = 5 \cdot 10^{-5} \cdot \alpha^6 - 0.0025 \cdot \alpha^5 + 0.0432 \cdot \alpha^4 - 0.1719 \cdot \alpha^3 - 1.0324 \cdot \alpha^2 - 0.0267 \cdot \alpha + 25.082$
17	$b_{ip} = 4 \cdot 10^{-5} \cdot \alpha^6 - 0.0025 \cdot \alpha^5 + 0.0415 \cdot \alpha^4 - 0.1531 \cdot \alpha^3 - 1.078 \cdot \alpha^2 - 0.2313 \cdot \alpha + 24.929$
18	$b_{ip} = 4 \cdot 10^{-5} \cdot \alpha^6 - 0.0022 \cdot \alpha^5 + 0.0373 \cdot \alpha^4 - 0.1432 \cdot \alpha^3 - 0.9303 \cdot \alpha^2 - 0.1143 \cdot \alpha + 22.041$

№ point	$b_{ip} = b_i \pm R \cdot \sin(\frac{\beta}{2}),$
19	$b_{ip} = 4 \cdot 10^{-5} \cdot \alpha^6 - 0.0019 \cdot \alpha^5 + 0.0335 \cdot \alpha^4 - 0.14317 \cdot \alpha^3 - 0.8117 \cdot \alpha^2 - 0.0478 \cdot \alpha + 19.553$
20	$b_{ip} = 3 \cdot 10^{-5} \cdot \alpha^6 - 0.0015 \cdot \alpha^5 + 0.0253 \cdot \alpha^4 - 0.0972 \cdot \alpha^3 - 0.6279 \cdot \alpha^2 - 0.0727 \cdot \alpha + 14.905$
21	$b_{ip} = 2 \cdot 10^{-5} \cdot \alpha^6 - 0.001 \cdot \alpha^5 + 0.017 \cdot \alpha^4 - 0.063 \cdot \alpha^3 - 0.4387 \cdot \alpha^2 - 0.0883 \cdot \alpha + 10.181$
22	$b_{ip} = 1 \cdot 10^{-5} \cdot \alpha^6 - 0.0005 \cdot \alpha^5 + 0.0086 \cdot \alpha^4 - 0.0267 \cdot \alpha^3 - 0.259 \cdot \alpha^2 - 0.1328 \cdot \alpha + 5.5088$
23	$b_{ip} = 1 \cdot 10^{-5} \cdot \alpha^6 - 0.00005 \cdot \alpha^5 + 0.0001 \cdot \alpha^4 + 0.0119 \cdot \alpha^3 - 0.0874 \cdot \alpha^2 - 0.2052 \cdot \alpha + 0.8627$
24	$b_{ip} = -7 \cdot 10^{-5} \cdot \alpha^6 - 0.0004 \cdot \alpha^5 - 0.0085 \cdot \alpha^4 + 0.0532 \cdot \alpha^3 + 0.0729 \cdot \alpha^2 - 0.3136 \cdot \alpha - 3.7308$
25	$b_{ip} = -1 \cdot 10^{-5} \cdot \alpha^6 - 0.0009 \cdot \alpha^5 - 0.017 \cdot \alpha^4 + 0.095 \cdot \alpha^3 + 0.2179 \cdot \alpha^2 - 0.4459 \cdot \alpha - 8.096$
26	$b_{ip} = -2 \cdot 10^{-5} \cdot \alpha^6 - 0.0014 \cdot \alpha^5 - 0.0263 \cdot \alpha^4 + 0.1439 \cdot \alpha^3 + 0.3626 \cdot \alpha^2 - 0.6327 \cdot \alpha - 2.796$
27	$b_{ip} = -3 \cdot 10^{-5} \cdot \alpha^6 - 0.0019 \cdot \alpha^5 - 0.0354 \cdot \alpha^4 + 0.1919 \cdot \alpha^3 + 0.5002 \cdot \alpha^2 - 0.8215 \cdot \alpha - 17.333$
28	$b_{ip} = -3 \cdot 10^{-5} \cdot \alpha^6 + 0.002 \cdot \alpha^5 - 0.0375 \cdot \alpha^4 + 0.2035 \cdot \alpha^3 + 0.5291 \cdot \alpha^2 - 0.8726 \cdot \alpha - 18.358$
29	$b_{ip} = -4 \cdot 10^{-5} \cdot \alpha^6 + 0.0021 \cdot \alpha^5 - 0.0398 \cdot \alpha^4 + 0.2152 \cdot \alpha^3 + 0.5659 \cdot \alpha^2 - 0.9152 \cdot \alpha - 19.521$
30	$b_{ip} = -4 \cdot 10^{-5} \cdot \alpha^6 + 0.0022 \cdot \alpha^5 - 0.042 \cdot \alpha^4 + 0.2257 \cdot \alpha^3 + 0.6035 \cdot \alpha^2 - 0.9463 \cdot \alpha - 20.633$
31	$b_{ip} = -4 \cdot 10^{-5} \cdot \alpha^6 + 0.0023 \cdot \alpha^5 - 0.0428 \cdot \alpha^4 + 0.2293 \cdot \alpha^3 + 0.6225 \cdot \alpha^2 - 0.9493 \cdot \alpha - 21.118$
32	$b_{ip} = -4 \cdot 10^{-5} \cdot \alpha^6 + 0.0023 \cdot \alpha^5 - 0.0434 \cdot \alpha^4 + 0.2307 \cdot \alpha^3 + 0.6421 \cdot \alpha^2 - 0.9344 \cdot \alpha - 21.505$

Graphs of the dependencies of the shoulder b_{ip} on the angle of rotation α are shown in Fig. 4 for section A_4-A_4.



a



b

Figure 4. Graphs of dependences of the value of the shoulder b_{ip} on the angle of rotation α for the section A_4-A_4; a - the back of the vane, b- trough of the vane

To calculate the magnitude of the cutting forces during milling, it is necessary to know the geometric parameters of the contact zone of the tool with a spherical working surface with a milled vane profile. These parameters are: R_b, R_{tr} – averaged radii of the back and trough of the vane sections, respectively, B_b, B_{tr} – lengths of arcs of contact of the tool with the back and trough of the vane, respectively, $D_{eff.b}$, $D_{eff.tr}$ – average effective diameters of the cutting edges of the tool, respectively, when milling the back and trough, β_1, β_2 are the angles of the arcs (length B_b, B_{tr}) of the contact zone of the mill with the back and trough, respectively.

Functional dependencies for calculating R_b, R_{tr} for a vane of the IV stage with a length of 151.63 mm were obtained in [14] and are as follows:

$$R_b = 32.008 - 0.3029 \cdot a_i^2 + 16.869 \cdot a_i,$$

$$R_{tr} = 79.087 - 0.2732 \cdot a_i^2 + 60.358 \cdot a_i.$$

The calculated values of the radii for various combinations are given in Table 2.

Table 2. Radii values for vane length L=151.63 mm

Section number	Section coordinate z, mm	R_b, mm	R_{tr}, mm
3	7,87	54,09	136,58
4	16,85	60,61	161,75
5	34,82	76,75	251,66
6	52,79	91,12	320,74
7	70,76	109,39	390,85
8	88,73	126,64	420,41
9	97,72	134,41	490,85
10	106,70	149,84	530,29
11	124,67	160,09	600,57
12	142,64	170,05	664,39
13	151,63	179,2	708,26

Let us set the values of the remaining parameters when milling the section A_4-A_4 of the vane with the length of 151.63 mm with the following initial data:

t=0,5 mm; R=3 mm; R_b=60,61 mm; R_{tr}=161,75 mm; δ=0,1 mm (Fig.5).

Let us determine the angle β_1 of the arc B_b of the contact between the mill and the back of the vane.

According to the cosine theorem [15]:

$$\cos\beta_1 = \frac{OA^2 + OO_1^2 - AO_1^2}{2\cdot OA\cdot OO_1}, \quad (4)$$

where: $OA=R=3mm$,

$$OO_1 = R_b + \delta + R = 60.61 + 0.1 + 3 = 63.71mm,$$

$$AO_1 = R_b + \delta + t = 60.61 + 0.1 + 0.5 = 61.21mm,$$

Substituting the numerical values of the parameters into expression (4), we obtain cos(β_1)=0,8405, β_1=32°48', $\beta_1/2$=16°24'.

Let us determine the numerical values of the segments located on the normal N-N:

$$GH = R - R\cdot\cos(\beta_1/2) = R\cdot(1-\cos(\beta_1/2)) = 3\cdot 0.047 = 0.122mm,$$

$$DE = R - R\cdot\cos(\beta_1) = 3 - 3\cdot\cos(32°48')) = 0.0218mm,$$

$$DG = t - GH - DE = 0.5 - 0.122 - 0.0216 = 0.3562mm,$$

$$FG = \frac{R\cdot\sin(\frac{\beta_1}{2})}{ctg(\gamma_b)}.$$

Let us get analytical dependencies for segments *FM* and *KF*:

$$FM = \sqrt{FG^2 + (R\cdot\sin(\frac{\beta_1}{2}))^2},$$

$$KF = (R - GH - FG)\cdot\sin(\gamma_b) = (R - GH - R\cdot\sin(\frac{\beta_1}{2})\cdot tg(\gamma_b))\cdot\sin(\gamma_b).$$

According to the diagram in Fig. 5 we write the following expression:

$$\sin(\gamma_b + \frac{\beta_1}{2}) = \frac{FM + KF}{R} = \frac{\sqrt{FG^2 + (R\cdot\sin(\frac{\beta_1}{2}))^2} + (R - GH - R\cdot\sin(\frac{\beta_1}{2})\cdot tg(\gamma_b))\cdot\sin(\gamma_b)}{R}$$

Let us transform the last expression by substituting *FG*:

$$\sqrt{(R\cdot\sin(\frac{\beta_1}{2})\cdot tg(\gamma_b))^2 + (R\cdot\sin(\frac{\beta_1}{2}))^2} = R\cdot\sin(\frac{\beta_1}{2}) - (R - GH - R\cdot\sin(\frac{\beta_1}{2})\cdot tg(\gamma_b))\cdot\sin(\gamma_b),$$

Substituting the numerical values of *R*, *GH*, $\beta_1/2$ and sin($\beta_1/2$), we finally get:

$$0.717\cdot tg(\gamma_b))^2 + 0.717 - 9\cdot\sin(\gamma_b + 16.4)^2 + 6\cdot\sin(\gamma_b + 16.4)\cdot\sin(\gamma_b)\cdot(2.878 - 0.846\cdot tg(\gamma_b)) -$$
$$-(2.878 - 0.846\cdot tg(\gamma_b))^2\cdot\sin(\gamma_b)^2 = 0$$

Solving the last expression in Matcad we found that it is valid for any value γ_b in the range from 29°8' to 4°30'.

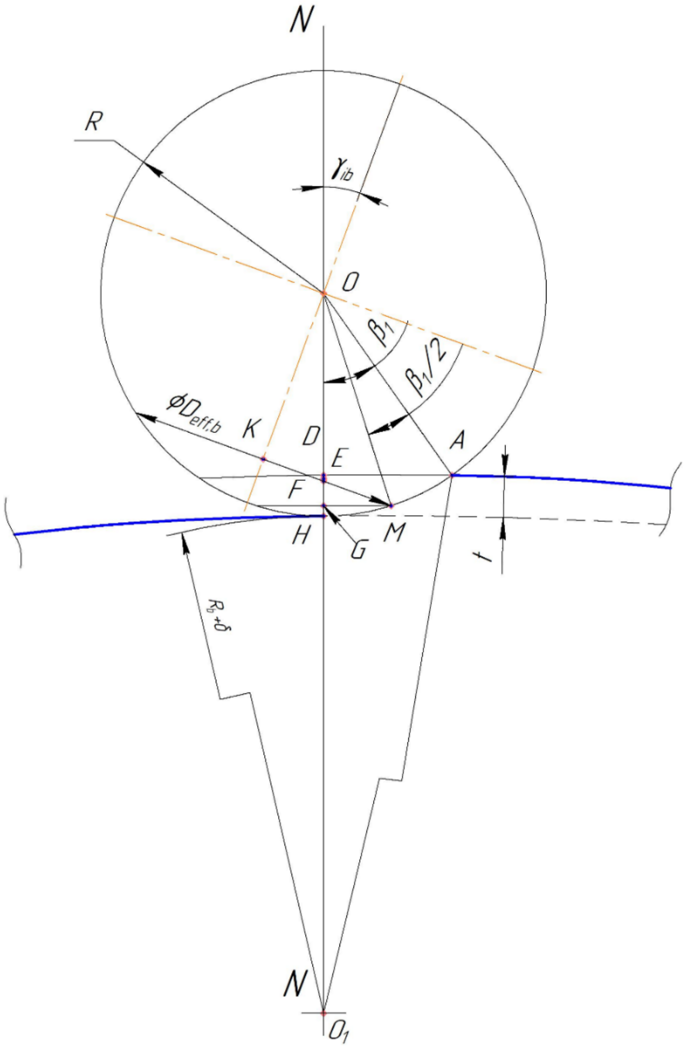


Figure 5. Geometric parameters of the contact zone of the mill with the back of the vane feather

In this regard, for subsequent design calculations, we will take the average value $\gamma_b = \frac{\beta_1}{2} = 16°24'$.

Having performed a similar transformation procedure for the contact of the mill with the vane trough, we obtain the following expression:

$$0.765 \cdot tg(\gamma_{tr}))^2 + 0.765 - 9 \cdot \sin(\gamma_{tr} + 16.95)^2 + 6 \cdot \sin(\gamma_{tr} + 16.95) \cdot \sin(\gamma_{tr}) \cdot (2.87 - 0.8748 \cdot tg(\gamma_{tr})) -$$
$$-(2.87 - 0.8748 \cdot tg(\gamma_{tr}))^2 \cdot \sin(\gamma_{tr})^2 = 0$$

Solving the last expression in Matcad we found that it is valid for any value γ_{tr} in the range from 29°25' to 4°18'.

In this regard, for subsequent design calculations, we will take the average value $\gamma_{tr} = \frac{\beta_2}{2} = 16°57'$.

Determine the length of the contact arc B_b и $D_{eff.b}$

$$B_b = \frac{\pi \cdot R \cdot \beta_1}{180} = \frac{3.14 \cdot 3 \cdot 32°48'}{180} = 1.718mm,$$

$$D_{eff.b} = 2R \cdot \sin \beta_1 = 3.25mm.$$

Let us determine the cutting speed when milling the back of the vane [4]:

$$V_{pb} = \frac{C_v \cdot D_{eff.b}{}^q}{T^m \cdot t^x \cdot F^y \cdot B_b^u \cdot z^p} \cdot K_V,$$

where Cv=35; q=0,6; m=0,35; x=0,3; y=0,3; p=0,2; u=0,2; Kv=1 - correction factor [16, 17]; T=15min; Deff.b=3,25mm; Bb=1,718mm; t=0,5mm; F=0,03 [18]; z=4.

$$V_{pb} = \frac{35 \cdot 3.25^{0.6}}{15^{0.35} \cdot 0.5^{0.3} \cdot 0.03^{0.3} \cdot 1.718^{0.2} \cdot 4^{0.2}} \cdot 1 = 65{,}97 m/\min.$$

The obtained value is close to the recommended ones [2], so we accept $V_{pb} = 70 m/\min.$

$$n_{m.b} = \frac{70 \cdot 1000}{3.14 \cdot 3.25} = 6859 rev/\min.$$

The process of milling with a ball nose is similar to milling with shaped cutters with a convex profile. The tangential component of the cutting force during milling P_{zb} is determined from the expression [16, 18]:

$$P_{zb} = \frac{10 \cdot C_p \cdot t^x \cdot F^y \cdot B_b^n \cdot z}{D_{eff.b}^q \cdot n_{m.b}^w} \cdot K_{pz}, \qquad (6)$$

where Cp - constant coefficient; t - milling depth; F_z - feed mill; B_b - milling width; $D_{eff.b}$ - effective mill diameter; z - number of mill tooth; n - mill rotation frequency, $K_{pz} = (\frac{G_b}{750}) = 1.15.$

The values of the coefficients and exponents for the formula for the cutting force P_z are [2]: C_p=12,5; x=0,85; y=0,75; n=1,0; q=0,73; w=-0,13;

$$P_{zb} = \frac{10 \cdot 12.5 \cdot 0.5^{0.85} \cdot 0.03^{0.75} \cdot 1.718^{1} \cdot 4}{3.25^{0.73} \cdot 6859^{-0.13}} \cdot 1.15 = 46.86 N,$$

The normal component P_{yib} is established from the ratio with the main component of the force P_{zb} [18]:

$$P_{yib} = (0.4 - 0.6) \cdot P_{zb}$$

Taking this relation into account, we transform formula (6) by multiplying the numerator and denominator by z^y:

$$P_{yib} = \frac{5 \cdot C_p \cdot t^x \cdot F_0^y \cdot B_b^n \cdot z^{1-y}}{D_{effb}^q \cdot n^w}.$$

where F_0 - mill feed per revolution.

Then: $P_{yib} = 23.43 N$.

The projection of the normal component of the milling force in the direction of the Y coordinate for each line and the angle of rotation of the vane P_i can be determined:

$$P_{ib} = P_{yib} \cdot \cos(\frac{\beta_1}{2}).$$

$$P_{yib} = \frac{5 \cdot C_p \cdot t^x \cdot F_0^y \cdot B_b^n \cdot z^{1-y}}{D_{effb}^q \cdot n^w} \cdot \cos(\frac{\beta_1}{2}).$$

Having performed a similar calculation procedure for the contact of the mill with the vane trough, the following numerical values were obtained:

$$V_{ptr} = 68.99 m/\min.$$

Accepted value $V_{ptr} = 70 m/\min.$

$$P_{zitr} = 43.95 N$$

$$P_{yitr} = 22 N$$

$$P_{itr} = P_{yitr} \cdot \cos(\frac{\beta_2}{2}) = 21 N.$$

Contact arc length B_{tr} and D_{efftr}

$$B_{tr} = \frac{\pi \cdot R \cdot \beta_2}{180} = \frac{3.14 \cdot 3 \cdot 33°55'}{180} = 1.774 mm,$$

$$D_{eff.tr} = 2R \cdot \sin(\beta_2) = 3.54 mm.$$

The algorithm for generating the initial information to determine the value of the deflection of the vane profile is shown in fig. 6.

3 CONCLUSIONS

Analytical expressions of technical and geometric data are obtained for calculating the magnitude of the deflection of the vanes, which are the initial data for calculating and assigning combinations of controlled parameters for the vane airfoil profile milling mode when designing operations and developing a control program for multi-axis CNC machines that provide the required processing accuracy.

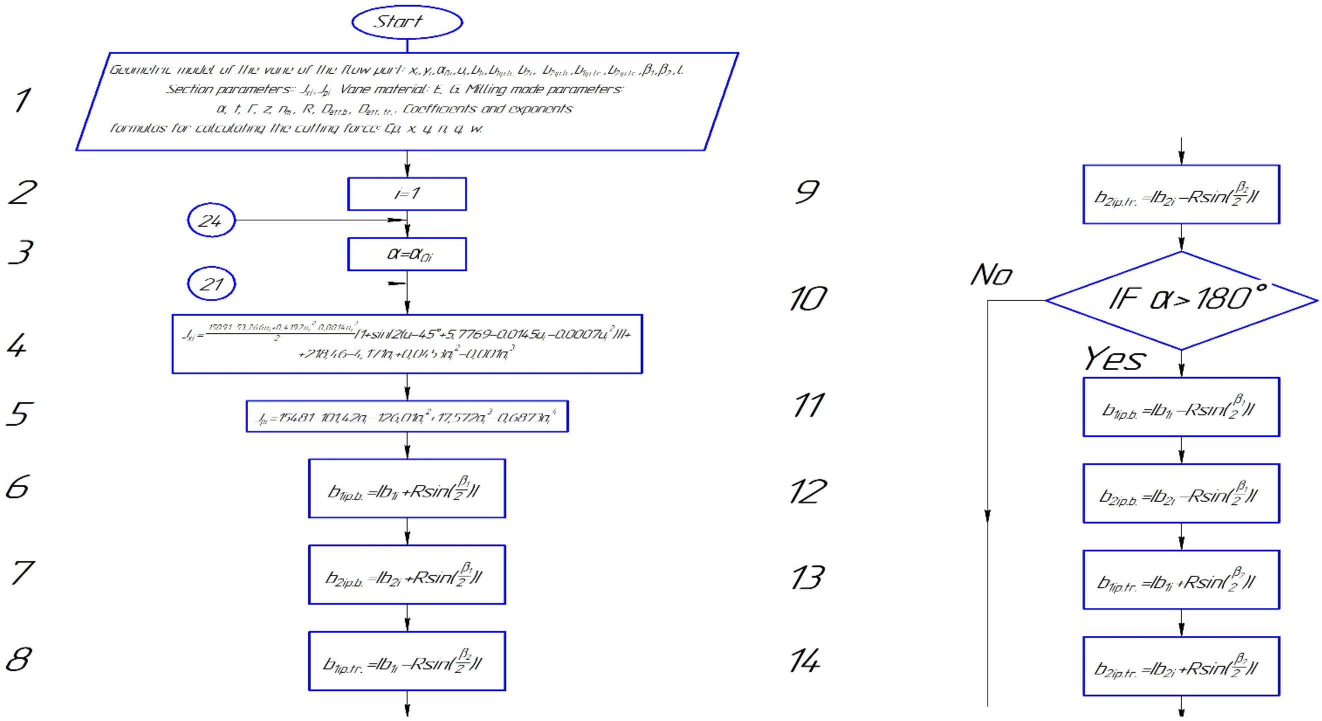


Figure 6. Algorithm for generating initial information for predicting the vane profile deflection

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Paper submitted: 02.09.2022.
Paper accepted: 01.06.2023.