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CNC MILLING OF IMPELLER BLADE BY MACRO PROGRAMMING

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ABSTRACT

During machining of the curved profile, the tool path is converted into linear segments conventionally. It results in deviation of the tool path from the actual curved profile to be machined. MACRO programming technique for the parametric interpolation has been widely used due to its simplicity. Various programming methods, including conventional linear and circular interpolation as well as MACRO programming are studied in the present work. The geometry of impeller blade is studied as a curved tool path. Point cloud for the blade profile is scanned with needle scanner. These points are fitted to cut the blade with linear interpolation and obtained from series of arc of different radius. An inner surface and outer surface of blade profile are machined with Explicit, Implicit and Bezier spline function. In another approach, blade profile is segmented into three circular arcs to develop algorithms for MACRO programming.

Keywords: *Impeller blade, MACRO Programming, Tangent Arc method, Bezier Spline*.

1. Introduction

In the case of the curve or free-form machining process, there are no ready-made preparatory codes available. The entire curved profile is transformed into linear segments to be interpolated by cutter location points. Linear interpolation of the cutter location points on the tool path segments gives an approximation rather than accurate profile. While machining is done, the tool path is deviated from the ideal geometry and the generated work piece profile will be a series of facet instead of smooth profile. Line segments can be kept short enough to make the path as accurate as possible. But, each line segment corresponds to a block in the part program, increase the size of a part program as well as obstruct the cutting speed and hamper surface finish. Linear interpolation even occupies a major portion of memory storage. But, in case of MACRO programming, variables of parametric equation can be stored at a specific memory location. These memory addresses can be executed by assigning specific MACRO numbers. So, for MACRO programming, memory size depends upon the number of individual curve segments instead of linear segments. It avoids bottlenecks for memory and communication and favorable to achieve high accuracy with less memory size requirement, which results into feedrate fluctuation in case of MACRO programming may be lesser than linear interpolator. On the other hand, calculation time for linear interpolator is less than MACRO programming and even feasible when the computer was slower. But nowadays, computing speed is not a barrier to the implementation. As computing speed is considerably higher, larger tracking error is observed in case of the linear interpolator.

Literature has been presented after thorough research to improve surface quality to take impeller geometry as a case study. S. N. Al-Zubaidy determines overall dimensions of a centrifugal impeller using a single dimension to make modelling simple, considering basic physics of flow [1]. Yonglin Cai has developed an algorithm to generate tool path for impeller to reduce tool path length as well as machining time and the cutter can be proposed accordingly maximum curvature of the surface [2].Gang Zheng et al. have optimized the tool path for centrifugal pump impeller considering geometric errors. It leads to maximize cutter diameter and further increase material removal rate [3].Ernesto Benini et al. have developed an algorithm to machine centrifugal compressor impeller on the basis of CFD, considering pressure and jerk [4]. Chenggang Li et al. have designed an efficient impeller with Non Uniform Rational B spline for better surface accuracy by adjusting control points [5]. K. Sugimura et al. have designed a centrifugal impeller shape to improve the aerodynamic efficiency considering flow uniformity and stability [6]. H. T. Young et al. have recognized the rough machining as the most significant process influencing the machining efficiency.

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Based on the geometry model of the blade and hub of the impeller cutter location data are generated. Which is confirmed with the help of software simulation.[7].Chih-Hsing Chu et al. have subdivided a tool path for the boundary curve of the machined surface into segments. These segments can be represented as a guide curve. G_1 continuity between these curves is attained by newly developed algorithms, Cutter location data are generated with the help of the algorithm and machining deviation is approximated with generated cutter location data [8]. Senthilkumar et al. have suggested that optimization of cutting parameters can be optimize with the aim of minimizing the output responses like surface roughness. Surface reduces the quality of the component, which makes this study essential [9]. Parameshwari et al. have studied that optimization of CNC milling process parameters to provide better surface finish The surface finish has been identified as quality attribute and is assumed to be directly related to productivity. From the literature, it can be said that the efforts are carried out to get better surface quality of impeller profile.

Dimensions of impeller are determined with the minimum input variables; physics of flow (i.e. flow uniformity) is considered to develop impellor geometry to reduce geometric error. Reduction in the geometric error is resulting in the betterment of the machining parameter (i.e. higher Material removal rate, low jerk etc. while machining the impeller). Impeller surface can be interpolated with Non uniform Rational B spline for reduction in machining deviation. Algorithm is also developed to generate cutter location points with a purpose of reduction in machining time as well as reduction in tool path length. It is to be understood from the literature that conventional linear interpolation is not the suitable method to cut complex profile like impeller.

2. MATHEMATICAL MODELLING

In the present work, various algorithms are developed to cut the vane profile with the Implicit, Explicit and Bezier spline function. Equation driven MACRO programming is developed using these algorithms gives an additional feature of shape flexibility. Entire shape of the profile can be changed by changing equation variables. In addition, by increasing the number of loops in MACRO programming, number of cutter location points can be increased. Amongst all algorithm, actual CNC machining is conducted to cut vane profile fitted with the Bezier spline function to validate MACRO programming to taste the vane profile of the impeller of the centrifugal process pump (Model: 40x25x160).

Fig.1 Centrifugal pump impeller

The impeller is scanned by a needle scanner to generate cutter location point cloud as well as connected with conventional linear interpolation. In another approach, the curvilinear vane profile is segmented into known curve geometry. In which, inner blade and outer blade of vane profile are divided into three circular arcs. These circular arcs are fitted with Bezier spline, Implicit and Explicit function with MACRO programming methods. An actual vane profile fitted by the Bezier spline function is machined with the MACRO programming method.

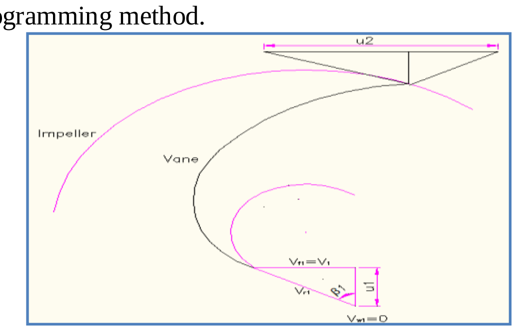

Fig 2. Vane Profile

In the present study, the case of one impeller blade is considered. The impeller vane size is calculated for the discharge 10 m^3/hr (2.78 lit/sec), specific speed of 2900 rpm and 30 meter of total head. The calculation of various parameters of the vane profile is explained [11];

Leakage loss is considered as 5 %,

$$Q_a = 1.05\times 10 \quad (1)$$
$$= 10.5 m^3/hr$$
$$= 0.00292\ m^3/sec$$

For calculation of eye diameter D_1, the value of actual discharge is taken from the equation (1) and put into the equation (2), assume nut diameter D_i is as 22 mm. The value of the radial component of velocity of flow at inletV_{f1} is preferably 2.5 m/sec, at the eye

$$Qa = V_{f1}\left(\frac{\pi}{4}\times D_1^2 - \frac{\pi}{4}\times D_i^2\right) \quad (2)$$
$$= 2.5\times\left(\frac{\pi}{4}\times D_1^2 - \frac{\pi}{4}\times 0.0245^2\right)$$

= 0.00292

D_1 = 0.0457m

From that, Radius of impeller eye, R_1 =22.85 mm

Tangential velocity at outlet U_2 is found from equation (3)

$$U_2 = (2 \times g \times H)^{0.5} \quad (3)$$

$$= (2 \times 9.8 \times 28)^{0.5}$$

= 24.25 m/sec

The value of tangential velocity at outlet U_2 from the equation (3) is to be put in equation (4) to calculate overall diameter of impeller disc D_2

$$U_2 = \frac{\pi \times D_2 \times N}{60} \quad (4)$$

$$24.25 = \frac{\pi \times D_2 \times 2900}{60}$$

D2 =0.160 m

So, Radius of impeller disc R2 = 80 mm. By putting the value of the eye diameter D1 from the equation (4), tangential velocity at inlet U1 can be obtained from equation (5).

$$U1 = \frac{\pi \times D_1 \times N}{60} \quad (5)$$

$$= \frac{\pi \times 0.0457 \times 2900}{60}$$

=6.9364 m/sec

The value of tangential velocity at inlet U_1obtained from the equation (5) is to be put in equation (6) to calculate inlet vane angle β_1.

$$\tan\beta_1 = \frac{v_{f1}}{U_1} \quad (6)$$

$$\tan\beta_1 = \frac{2.5}{6.9364}$$

$$\beta_1 = 19.81^0$$

After determining the dimensions using the above set of equations, the next step is to construct the vane shape. The tangent circular arc method is used to construct the vane profile.

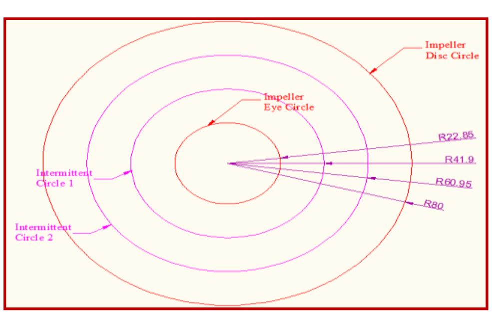

Fig 3. Intermittent circles

The Circular arc of the vane profile is needed to divide into the number of segments to attain smooth profile shape. In the present case, the vane profile is divided into three segments arbitrarily. For that, as described in figure 3, two concentric intermittent circles with radii 41.9 mm and 60.95 mm are constructed at equidistance from the eye circle and impeller disc circle. As per tangent circular arc method, vane angle is to be varied from the inlet vane angle β1 to the outlet vane angle β2 linearly with respect to changes in the radius of the circle. Outlet vane angle β2is always preferred to be greater than the inlet vane angle β1 to make outlet flow radially to the impeller disk. Here, the outlet vane angle β2 is assumed 30^0.

Table 1. Linear interpolation of Vane angle β with respect to Radius R

	Radius R (mm)	**Vane angle β** (Degree)
Eye circle	22.85	19.81
Intermittent circle 1	41.9	23.21
Intermittent circle 2	60.95	26.60
Impeller disc circle	80	30.00

Table 1 suggests that inlet vane angle (β_1) is equal to 19.81^0 for the radius of the impeller eye circle (22.85 mm) from the calculation done as per equation (2). Similarly, outlet vane angle (β_2) is equal to 30.00^0 for the radius of the impeller disc circle (80 mm) from the calculation done as per equation (4). Corresponding vane angle (β) will be calculated considering linear interpolation with radius (R) as 23.21^0 for the radius of intermittent circle1 and vane angle will be 26.60^0 for the radius of intermittent circle 2.

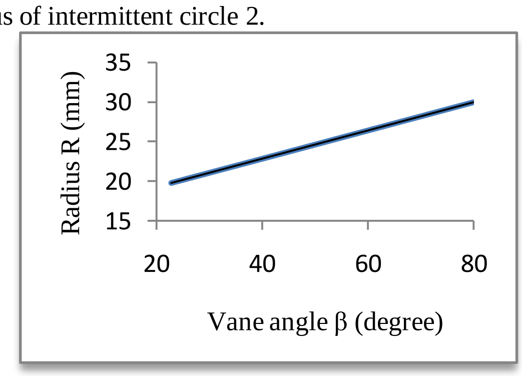

Fig 4. Linear development of vane angle β with respect to Radius R

Figure 4 shows that as the radius is changed from the eye circle radius R_1 (22.85 mm) to the impeller disc radius R_2 (80 mm), vane angle is to be varied linearly from the inlet vane angle β_1(19.81^0) to the outlet vane angle β_2 (30.00^0).

$$\rho = \frac{R_2^{\ 2} - R_1^{\ 2}}{2 \times (R_2 \cos\beta_2 - R_1 \cos\beta_2)} \qquad (7)$$

Equation (7) gives radius (ρ) of the circular arc segment of the vane profile using the value of the radius of impeller eye R_1 and radius of impeller disc R_2.

Table 2. Calculation of radius of circular arc

Radius R_1 (mm)	**Radius R_2** (mm)	**Vane angle β_1** (Degree)	**Vane angle β_2** (Degree)	**Radius of circular arc ρ** (mm)
22.85	41.9	19.81	23.21	36.26
41.9	60.95	23.21	26.60	61.29
60.95	80	26.60	30	90.83

The value of the radius of circular arc ρ is mentioned in table 2. As per example, for the segment of the circular arc, the value of eye radius R_1 and intermittent circle radius R_2 are equal to 22.85 mm and 41.9 mm respectively. For the same value of radii, inlet vane angle β_1 is equal to 19.81^0 and outlet vane angle $\beta_2$is equal to 30.00^0. By putting these values in equation (7), the radius of the first circular arc segment of vane profile will be 36.26 mm. Similarly, for second and third segments, the radii of the second and third segments will be 61.29 mm and 90.83 mm respectively.

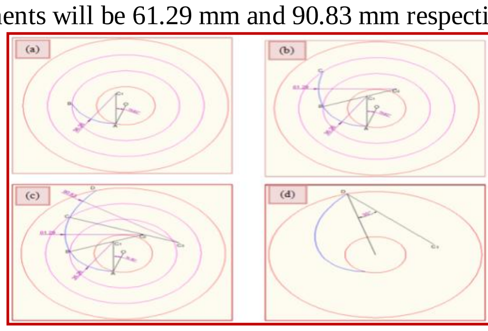

Fig 4. Construction of vane profile

Vane profile is constructed as shown in figure 5 as per tangent circular arc method. As shown in figure 5(a) line OA is drawn from the origin ‘O’ that intersects eye circle at point ‘A’. From the point ‘A’, line $AC_1$of length 36.26 mm (i.e. radius ρ of the first segment of the circular arc) is drawn at the angle 19.81^0 (i.e. the inlet vane angle β_1). By taking a center at ‘C_1’an arc is drawn with the radius 36.26 mm .This arc intersects the intermittent circle at point ‘B’. Figure 5 (b) depicts that line $BC_1$is drawn to connect point ‘B’ with center‘C_1’. Line BC_1 is extended to center‘C_2’ with the distance equal to 61.29 mm (i.e. radius ρ of the second segment of a circular arc). An arc BC is drawn with center ‘C_2’and radius equal to 61.29 mm. This arc meets the intermittent circle at ‘C’. Figure 5 (c) describes that from the point ‘C’, line CC_2 is extended up to ‘C_3’ with the distance equal to 90.83 mm (i.e. radius ρ of the third segment of a circular arc). An arc CD is drawn that intersect impeller disc diameter at ‘D’. The tangent circular arc ‘CD’ is the desired vane profile. Figure 5(d) mentions that an angle subtended at point ‘D’ with origin and centre point ‘C_3’ is equal to 30.00^0, that is equal to the value of outlet vane angle β_2.After plotting of vane shape, MACRO programming is generated for the same segment.

3. EXPERIMENTAL SET UP

Actual impeller is measured to machine vane profile. To determine vane coordinates, the impeller is measured by needle scanner. Each coordinate generated by needle scanner is stored for further analysis. Scanning entire impeller on needle scanner is a time consuming process. The data, to be analyzed are in bulk.

So, it is decided to prepare a replica of a single vane and collect data for that vane only. Figure 4(a) shows the actual impeller of centrifugal process pump (Model: 40x25x160). The scanning of the impeller is done to generate point cloud as shown in figure 4(b). After scanning of the impeller, huge data are collected. This has resulted in excess of data and difficult to analyze. Hence, a replica of a single vane is made up as shown in figure 4 (c). The vane is scanned by the needle scanner. Point cloud of the single vane profile is collected as shown in figure 4 (d).

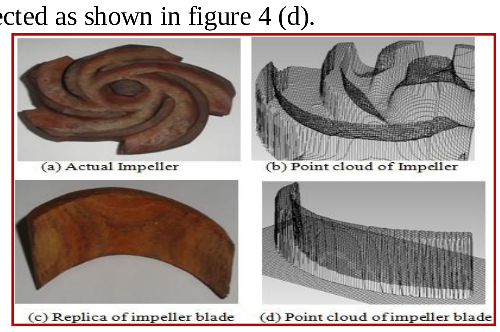

Fig 5. Measurement of impeller vane

These point cloud data consist of X and Y coordinate values of each point of the vane profile. The vane profile is machined with the linear interpolation of these points. The replica of impeller suggests that the height of the vane is more at impeller eye circle and gradually decreased while traveling from impeller eye circle to impeller disc circle. Depth of cut is adjusted as per the height of the vane profile during machining with a conventional program. In another approach, the vane profile is segmented into 3 circular arcs by circular tangent arc methods. These circular arcs are fitted with Bezier spline. MACRO programming is developed to machine Bezier splines to attain the shape of vane profile. The initial value of the depth of cut is stored as a variable at specific MACRO address. The height of vane profile is adjusted by the loop of the MACRO address that stored the initial value of the depth of cut. The MACRO program of all three segments of the vane profile is transferred to CNC milling machine.

4. RESULT AND DISCUSSION

Dimensions of vane profile are determined by the tangent circular arc method. Hence, vane profile is divided into three segments. Due to that, at a time of actual machining, all segments of curves are going to be machined separately as the vane profile consists the individual three segments. The Machine has to attain the home position to cut the single segment of vane profile every time due to different program zeroes for individual segments. This is very difficult to determine the center of the circular vane segment to store program zero by touching milling cutter of the diameter of 4 mm with an accuracy of a micron. The best solution is to calculate relative distance between the center of each segment with origin as shown in figure 5.

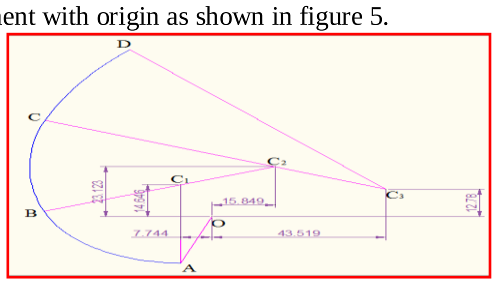

Fig. 5 Relative distance between center of arc with origin

The tool is offset as per the calculated relative distance. Vane profile is divided into the inner curve and an outer curve. Inner curve is further segmented into three parts. All three segments of inner curves are drawn in AutoCAD by tangent arc method. Figure 5 shows the relative position of first segment center C_3 with respect to origin O. Different algorithms are developed to machine vane profile. Bezier spline, Implicit and Explicit functions are employed for MACRO programming. Another approach is to fit the first segments of vane profile with conventionally G01 and G03 preparatory codes.

The first segment of the inner profile can be cut with above stated methods. Other two segments are programmed with different programming methods also. Similarly, all three segments of outer blades are programmed. After simulation of all programs, machining of the vane curve is done to collect shape accuracy of the profile. Figure 6 shows actually machining of vane profile.

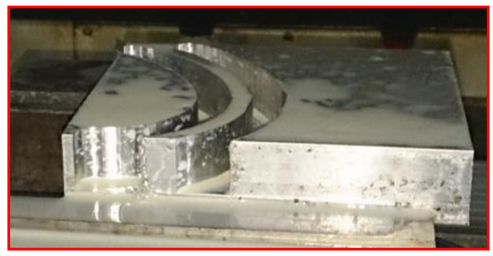

Fig. 6 Machined Vane profile

Length and size of programs are compared in Table 3 with consideration of feeding time and execution time. The length and size of the program are the least (112 words, 28KB) in the case of conventional programming method with the G03 preparatory code. Data input takes 231 seconds due to fewer data to enter for the same method. Program execution time is also less (161 seconds) due to less length of the program. The length and size of the program are the highest (739 words, 35 KB) in the case of conventional programming method with the G01 preparatory code.

Table 3. Various programming methods comparison

		Conventional		MACRO		
		G01	G03	Implicit	Explicit	Bezier spline
Length (words)		739	112	139	179	563
Size (KB)		35	28	28	28	31
Time (Sec)	Drawing	1681	284	0	0	0
	Data input	406	231	283	368	508
	Program execution	169	161	297	255	362
	Total	2256	676	580	623	870

Data input of the program takes 406 seconds due to fewer data to enter for the same method. Program execution time is also fewer (169 seconds). Program execution time for conventional method (G01) is quite less because there is no equation to be calculated by the processor. The MACRO programming method is less in program length and program size compared to the conventional method (G01). The data input time is 283 seconds, 368 seconds and 508 seconds in case of programming with Implicit, Explicit and Bezier spline function respectively. However, program execution time in each of three methods of is more. As, it has to undergo calculation at every block based on the parametric equation.

Program execution time for conventional method (G01/G03) is quiet less because there is no equation used to calculate the cutter location point. MACRO programming uses parametric equation to determine CL points. Program execution times for all the stated MACRO programming methods are more than conventional programming methods. There is no need to draw vane profile with the help of CAD software. This saves total time for machining the vane profile considerably. Implicit (i.e. $X^2+Y^2 = r^2$), Explicit (i.e. X=acosθ; Y=bsinθ) and Bezier spline (i.e. $P(u) = (1-t)^3P_{0u} + 3(1-t)^2t\ P_{1u} + 3(1-t)\ t^2\ P_{2u} + t\ ^3P_{3u}$) are used to cut circular arc of the vane profile. Bezier spline equation is the most complex compared to Explicit and Implicit function. Hence, Data input time for Bezier spline function is the highest in comparison to Implicit and Explicit function. Processor has to halt more for a moment while machining with Bezier spline function (rather machining with Implicit as well as Explicit function.

6. CONCLUSIONS

The following conclusions can be narrated from the present work:

- Vane profile of impeller is studied as a curved tool path. Cutter location points are to be collected by scanning the point cloud by needle scanner. Data are analyzed to determine the cutter location point and connected by linear interpolation. Which took less time for machining. But, the chances of human errors are there, as huge data are to be handled.
- Another approach is to calculate vane profile shape mathematically. From that, by using tangent arc method, vane profile can be segmented. The main advantage is that the profile can be cut with conventional circular interpolation. Circular interpolation requires least memory size andmachining time is also the lowest amongst all programming methods.
- Vane profile can be also fitted with Implicit, Explicit and Bezier spline function using MACRO programming. These methods are equation driven. By changing equation variables, the entire shape of the profile can be changed. It gives additional flexibility to the program. By increasing the number of loops in MACRO programming, a number of cutter location points can be increased. Actual CNC machining with curve fitting by Bezier spline function is done to validate MACRO programming method.

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NOMENCLATURE

Symbol	Meaning	Unit
Q_a	Actual discharge	m^3/s
D_1	Eye diameter	mm
U_1	Tangential velocity at inlet	m/s
U_2	Tangential velocity at outlet	m/s
β_1	Inlet vane angle	Degree
β_2	Outet vane angle	Degree
ρ	Radius of curvature	mm

