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# Automated design and STEP-NC machining of impellers

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**Abstract.** This paper presents the four stage approach followed for automated design and STEP-NC based machining of impellers. In the first stage, the design calculations are performed to construct the 'Meridional representation' of the radial impeller. Then 3D curves are projected from the 'Meridional representation' and 3D model is generated using UG-NX software. In the second stage, the process planning activities including tooling & setup plan are completed. Here, ball end mill cutters with suitable diameter and length are selected and appropriate process parameters as suited to 5 axis milling are considered. In the third stage, the tool path data based on contour area milling is generated and verified in the UG NX software. Finally, in the fourth stage, the model with the complete data is imported to STEP-NC software and the AP-238 format is generated. In this article the design procedure adopted for construction of 'Meridional Section' of a radial turbine is discussed with the general methodology to automate the process planning and tool path generation. A test case of radial impeller is presented with the results obtained by adopting STEP-NC format.

**Keywords:** Impellers / Blades, Modelling & Automation, CAPP, STEP-NC Integration

## 1. Introduction

Automated design & STEP-NC machining of impellers is considered to be a crucial task as it involves integration of complex design procedures and 5 axis manufacturing process plan data. Impellers which are free form in nature are adopted to pump the flow of gas or fluid in centrifugal & axial compressors/turbines/pumps belonging to oil and gas (O&G), aviation and power generation domains. Generally, these are first casted and then finish machined using a 5 axis milling machine and sometimes completely milled in a 5 axis milling machine. In either case, a manufacturing drawing sheet must be generated from a parametrically strong and geometrically precise 3D CAD models. These 3D CAD models are designed by sweeping the basic curves namely (i) B-Spline and (ii) NURBS which follows recursive blending mathematical representations. The construction procedure of these curves and surfaces are well known [1] and implemented in many CAD/CAM packages. From an automated manufacturing point of view, these 3D CAD models should contain error free feature data, as even a minor change leads to improper process plan and tool paths. Further, process plan independent CL data generated from these models consumes more time for post processing in a CNC machine. In the present scenario, CL data alone is not sufficient to go ahead with the machining process. Addition details such as tooling, setup and fixture is required to proceed with a robust machining. As regards, researchers adopt STEP/STEP-NC technology owing to the advantage of integrating product life cycle and manufacturing process planning data. Also, it reproduces error free 3D CAD models and reduces the transfer time to a major extent. Even though there are many advances in this domain, automated design and STEP-NC machining of impellers needs attention owing to the complexity encountered while automatic feature recognition, design calculations and generation of process plan with tool paths. HT Young et al. [2] generated tool paths for rough machining centrifugal impeller using a five axis milling machine. They introduced two concepts namely (i) residual tool path and (ii) cutting tool path for removing the material which are closer and away

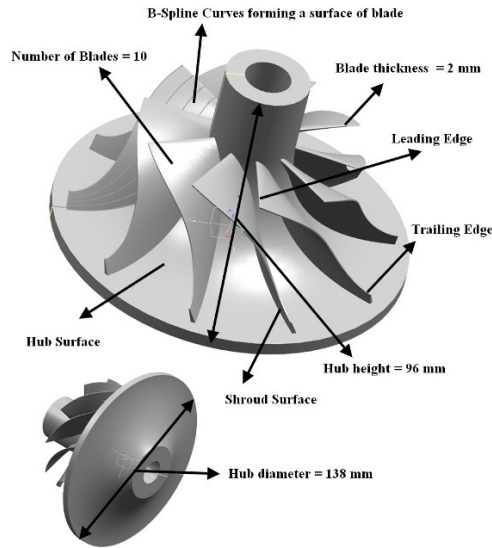
53 from the blade tip. Pyo Lim [3] presented an approach to optimize the rough cutting factors of  
54 impeller with a 5 axis machining using 'response surface methodology'. In his work, the  
55 roughing operation is divided into five portions to machine the fillets between blade surfaces  
56 and hub surfaces. Julien Chaves-Jacob et al. [4] presented an optimal strategy for finish  
57 machining the impeller blades by adopting a 5 axis milling machine. Here, point milling and  
58 flank milling strategies are developed to reduce the machining time. Li- Chang Chuang & Hong-  
59 Tsu Young [5] presented an integrated rough methodology to manufacture centrifugal impeller.  
60 While rough machining constant scallop height is maintained to improve the quality of machining  
61 process. They analyzed a theoretical model and developed process plan for machining the part  
62 in a 5 axis milling machine. Toh [6] developed a strategy for cutter path calculation in high-  
63 speed milling process. He focused on rough machining of moulds and tested the tool paths using  
64 a vertical high-speed-machining centre. An algorithm for parametric tool path correction in a 5  
65 axis machining has been proposed by Gabor et al. [7]. In their approach, machine dependent  
66 and independent data is developed to store the prescribed tool path. A machining strategy for  
67 milling a set of surface which is obtained by the technique of cross sectional design is performed  
68 by Sotiris & Andreas [8]. The surfaces are formed by sliding the Bezier Curve (Profile curve)  
69 along another Bezier Curve (Trajectory) and tool-paths are  
70 generated by offsetting the boundaries of the profile curve matching with the trajectory curve.  
71 He used data point models and produced LOD models and obtained adaptive rough-cut and  
72 finish cut tool-paths. Brecher et al. [9] tested STEP- NC program and inspected the feed back  
73 in a closed loop CAPP/CAM/CNC process. In their work, they modelled the component in a CAD  
74 package and generated the process planning details and validated in a STEP-NC based milling  
75 machine. A frame work to interpret the data in AP-238 is done by Liu et al. [10]. In their work,  
76 a PC based STEP-NC prototype for STEP compliant CNC is developed to interface and to extract  
77 the details required for processing the AP-238 format. After analyzing the literatures, the  
78 following points are noticed:

- 79 • Machining is conducted without addressing the design calculation of impellers
- 80 • 5- axis milling ignores the integration of process planning and tool path data in a single  
81 format
- 82 • There is still a complexity on roughing out the excess material in between the blades.
- 83 • While machining, there is a necessity for most efficient tool path, where the tool spends  
84 only a minimum amount of time in air.
- 85 • The tool length needs to be kept to the minimum to avoid vibration and to prolong tool  
86 life
- 87 • Focus must be given for integration of tooling, setup and fixturing aspects
- 88 • STEP-NC integration focuses on simple rotational, prismatic and sheet metal parts and not  
89 for impellers

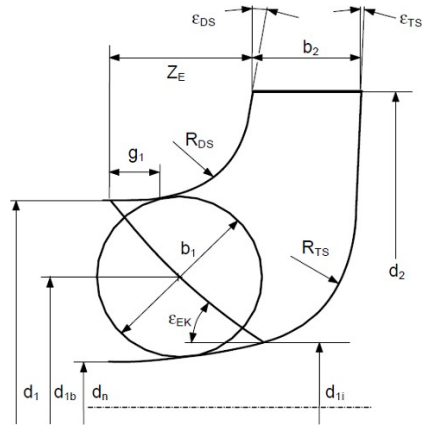
90 Based on the above points, it is decided to proceed with an automated design and STEP-NC  
91 machining of impellers. As the first step, the design procedures adopted in impellers are  
92 analysed. It is noticed there are more than 20 design parameters involved in impeller design  
93 process. The next section presents the design calculation and its automation carried out in this  
94 research.

## 97 **2. Design calculation of impellers**

98  
99 The design of an impeller is considered to be most complicated and crucial as there are more  
100 than 20 design parameters. These parameters are related to various flow parameters of  
101 compressor/pumps and is to be checked in accordance with the desired output. Fig.1(a) shows  
102 an impeller with few basic parameters namely (i) a leading edge-as pointed at its top (ii) trailing  
103 edge-as pointed at its end; (iii) hub diameter (iv) hub height (v) shroud (vi) hub & shroud  
104 surface and (vii) blade thickness.



**Fig.1(a).** Radial Impeller cross section



**Fig.1(b).** Meridional view of radial impeller

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In order to draw a 3D impeller it is indeed necessary first to draw the section through the impeller called 'Meridional Representation'. Basically, the leading and trailing edges of a blade are projected into the drawing plane through 'circular projection' and the initial blade profile is drawn [12]. A 'Meridional representation' with various basic parameters required for construction is shown in Fig. 1(b). It consists of parameters namely (i)  $b_1$ -impeller inlet width (leading edge) =  $\frac{1}{2} (d_1 - d_n)$ ; (ii)  $b_2$ - impeller outlet width (trailing edge); (iii)  $d_1$ -Impeller inlet diameter ; (iv)  $d_2$ -Impeller outer diameter ; (v)  $d_{1i}$ - Blade inlet diameter at the inner streamline; (vi)  $d_{1b}$ - stream line diameter; (vii)  $R_{DS}$ -Radius of curvature - front shroud = (0.6 to 0.8)  $b_1$ ; (viii)  $R_{TS}$ -Radius of curvature - rear shroud or hub; (ix)  $Z_E$ -Axial Extension; (x)  $\epsilon_{DS}$ -angle of front shroud; (xi)  $\epsilon_{TS}$ -angle of rear shroud or hub; (xii)  $\epsilon_{EK}$ -axial inlet angle; (xiii)  $d_n$  - Hub diameter; (xiv)  $g_1$ - Short section length = (0.2 to 0.3)  $b_1$ ; (xv)  $e$ -Blade thickness; (xvi)  $d_w$ - Shaft diameter; (xvii)  $Z_{La}$ - Impeller blade number; (xviii)  $\beta_{1B}$  -Impeller blade inlet angle;

125 (xix)  $\beta_{2B}$  - Impeller blade Outlet angle and ; (xx)  $A_{1q}$ -Throat area.

126 Further to the above design formulas the following points are also considered: (i) In order to  
 127 achieve a flatter pressure, the radius  $R_{DS}$  should not be tangent to the point defined by  $z_E$ , but  
 128 a short section  $g_1 = (0.2 \text{ to } 0.3) \times b_1$  should be introduced with only a minor increase in radius  
 129 (ii) For short axial extension of the impeller, smaller values are selected for  $z_E$  and  $R_{DS}$  than  
 130 calculated from Eq. (1) (iii) Specific speed is used to find the angle  $\epsilon_{DS}$  (iv)  $\epsilon_{DS}$  is increased to  
 131  $15$  to  $20^\circ$  with higher specific speeds (v) Positive or negative angle for  $\epsilon_{TS}$  can be chosen and  
 132 (vi) The outer streamline is drawn with  $d_2$ ,  $b_2$ ,  $d_1$ ,  $z_E$   $g_1$ ,  $\epsilon_{DS}$  and  $R_{DS}$  defined by a free curve or  
 133 assembled from straight lines and circular arcs or by Bezier functions. To proceed with the  
 134 calculation of the basic parameters namely,  $d_1$ ,  $d_2$ ,  $d_{1opt}$ ,  $z_E$  etc. the Equations from Eq.1 to Eq.6  
 135 are adopted.  
 136

$$d_1 = 2.9 \sqrt[3]{\frac{Q_{La}}{f_q n k_n \tan \beta_1} \left(1 + \frac{\tan \beta_1}{\tan \alpha_1}\right)} \quad \text{Eq. (1)}$$

$$d_2 = \frac{60}{\pi n} \sqrt{\frac{2g H_{opt}}{\Psi_{opt}}} = \frac{84.6}{n} \sqrt{\frac{H_{opt}}{\Psi_{opt}}} \quad \text{Eq. (2)}$$

$$d_w = \left(\frac{16P_{max}}{\pi \omega \tau_{al}}\right)^{\frac{1}{3}} = 3.65 \left(\frac{P_{max}}{n \tau_{al}}\right)^{\frac{1}{3}} \quad \left\{ \begin{array}{l} P_{max} \text{ in W} \\ n \text{ in rpm} \\ \tau_{al} \text{ in N/m}^2 \end{array} \right. \quad \text{Eq. (3)}$$

$$z_E = (d_{2a} - d_1) \left(\frac{n_q}{n_{q,Ref}}\right)^{1.07} \quad \left\{ \begin{array}{l} R_{DS} = (0.6 \text{ to } 0.8) b_1 \\ b_1 = \frac{1}{2} (d_1 - d_n) \\ n_{q,Ref} = 74 \end{array} \right. \quad \text{Eq. (4)}$$

$$d_{1,opt} = \sqrt{d_n^2 + 10.6 \left(\frac{Q_{La}}{f_q n}\right)^{\frac{2}{3}} \left(\frac{\lambda_c + \lambda_w}{\lambda_w}\right)^{\frac{1}{3}}} \quad \text{Eq. (5)}$$

$$\beta_{1B} = \beta_1' + i_1 = \arctan \frac{c_{1m} \tau_1}{u_1 - c_{1u}} + i_1 \quad \text{Eq. (6)}$$

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140 To find the various parameters initially, the values of the first 7 parameters are assumed. The  
 141 remaining are calculated accordingly with their specific formulas. Further, due to page restriction,  
 142 partial calculation is shown with the basic parameters assumed for few dimensional parameters.  
 143 The author can be emailed for the complete calculation part of the impeller. (i)  $d_n = 1.36$  m;  
 144 (ii)  $\alpha_1 = 60^\circ$ ; (iii)  $\alpha_2 = 35^\circ$ ; (iv)  $\beta_1 = 30^\circ$ ; (v)  $\beta_2 = 37^\circ$ ; (vi)  $\beta_1' = 45^\circ$ ; (vii)  $\beta_2' = 52^\circ$ ;  $i_1' = 15^\circ$ ;  
 145  $i_2' = \delta' = 10^\circ$ ;  $\beta_{1B} = i_1' + \beta_1' = 60^\circ$ ;  $\beta_{2B} = i_2' + \beta_2' = 60^\circ$ ;  $\delta = \beta_{2B} - \beta_2 = 25^\circ$ ;  $H_{opt} = 10$  m;  $n = 3000$   
 146 rpm;  $\lambda_c = 1.2$  to  $1.35$ ;  $\lambda_w = 0.42$ ;  $C_{1m} = Q_{La} / f_q A_1$ ;  $A_1 = (\pi/4 (d_1 - d_n)^2)$ ;  $C_{1u} = C_{1m} / \tan \alpha_1$ ;  $Q_{La}$   
 147 =  $Q_{opt} + Q_{sp} + Q_E$ ;  $Q_{opt} = 8.9$  m<sup>3</sup>/s;  $Q_{sp} = 1.9$  m<sup>3</sup>/s;  $Q_E = 0$ ;  $K_n = 0.2$ ; The calculated values are  
 148 given below:

149  $Q_{La} = Q_{opt} + Q_{sp} + Q_E = 10.8$  m<sup>3</sup>/s;  $d_1$  - based on Eq.1 = 0.241m;  $d_{1,opt}$  - based on Eq.1 = 1.30m;  
 150  $d_1$  - based on Eq.2 = 0.0893m;  $z_E$  - based on Eq.4 = 0.684;  $R_{DS}$  - based on Eq.4 = 0.84m ;  
 151 After making all the basic calculations the "Meridional Section" is drawn using UG NX software.  
 152 The 3D representation is also drawn in the UG- NX software from the 'Meridional section' by  
 153 adopting a similar set of calculation.  
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### 3. General methodology adopted in automation process

**Step1:** Design the radial impeller and model the part in UG NX CAD package

**Explanation to Step1:** In this step, the part is modelled and parameterized in the UG NX CAD package. Geometric dimensioning and tolerances (GD&T), information of datum's are

161 added to the model. Then drawing sheets associated with the parts are manually generated  
 162 and checked.  
 163 **Step2:** Using UG/UFUNC functions extract the geometrical and topological data of the model.  
 164 **Sub step2.1:** Ask the tag (number) of part (specific to UG)  
 165 **Sub step2.2:** Using the tag, cycle all the objects in the part and count the number of features/  
 166 objects.  
 167 **Sub step2.3:** Get the ID's of all features/objects  
 168 **Sub step2.4:** Extract the data and store it in a text file. **Explanation to Step2/Sub steps**  
 169 **2.1-2.4:** Generally, a UG part model will have a single tag in the form of a number. This is  
 170 extracted and the tags of various sub features / objects are found by cycling the part model  
 171 through a UG/UFUNC function"UF\_OBJ\_cycle\_objs\_in\_part". Using these tags the geometry  
 172 and topological data of the sub features / objects are extracted which is used to find the  
 173 closeness index with Bezier /B-Spline curves. Some of the other used functions are: (i)  
 174 UF\_CURVE\_ask\_spline\_data (ii) UF\_CURVE\_edit\_spline\_feature(iii) F\_b\_curve\_bezier\_  
 175 subtype.  
 176 **Step3:** Match the data with the basic B-Splines / Bezier curves / surfaces and calculate the  
 177 closeness index **Explanation to Step3:** In this step, the extracted data is matched and a  
 178 closeness index (CI) "0(0-not matching)- 10 (10-exact match)" is generated. It is done by  
 179 calculating the control points, degree of meridional curve, and various parameters (as shown  
 180 in Fig.1(b)) required for Bezier and uniform/ cubic/open/non-uniform B-Spline curves.  
 181 **Step4:** Calculate the blending functions and identify the machinable area of the impeller /  
 182 blade features.  
 183 **Explanation to Step4:** After finding the closeness index blending functions are calculated  
 184 using convolution theorem. Using the blending function data, the rough and finish cut  
 185 machinable volumes are calculated.  
 186 **Step5:** Specify the process plan details and Adopt the Z- level contour area milling to generate  
 187 tool paths **Explanation to Step5:** Here, ball end mill cutters with appropriate radius and  
 188 length are used for machining.

190 **Table 1.** Process Plan details of the radial impeller  
 191

<b>Roughing</b>	<b>Finishing</b>
Ball End mill	Ball End mill
Diameter = 8 mm	Diameter = 5 mm
Length=75 mm	Length=75 mm
Flute length= 50 mm	Flute length= 50 mm
Feed rate	23 mm/min
Spindle speed	2500 rpm

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 195 Appropriate process parameters for 5 axis contour area milling as shown in Table1 is adopted  
 196 for machining.  
 197 The work piece is rotated to make cutting surfaces of tool tangent to ideal part features.  
 198 Two methods namely  
 199 (i) fixed and (ii) variable contour machining methods are used to finish areas formed by free  
 200 form surfaces. Intricate contours are machined by controlling tool axis & projection vector. A  
 201 schematic representation of the impeller machining process is shown in Fig. 2. The tool path is  
 202 simulated for both roughing & finishing operations and CL data is obtained after post processing.

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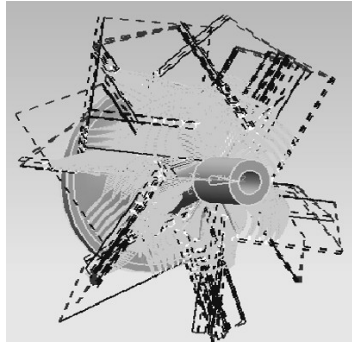


Fig.2 Tool paths simulated with GD&T data

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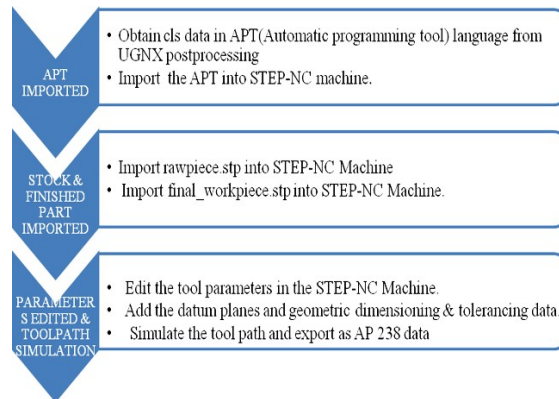


Fig.3. Steps followed to obtain a AP-238 data.

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**Step6:** Integrate and verify with STEP-NC format **Explanation to Step6:** Finally, the impeller is machined using standard method of tool path generation available in STEP-NC Machine as shown in Fig.3. The tool path is finally simulated & output file is obtained as AP238 format.

#### 4. Conclusions and future work

The whole process is automated through a software named Free\_Form\_Blades\_Impleller\_Automation F<sup>2</sup>BIM). It consists of four modules namely (i) Design Module (DM) (ii) Process Planning Module (PPM) (iii) Tool Path Generation Module (TPGM) and (iv) STEP-NC generation Module (STM). All these modules are linked with the main GUI of the software. A user can select/ modify various blades / impellers as suited for industrial needs and can generate the complete set of data required for machining. Presently, cross sectional details of 3 radial impellers are automated. Work is in progress to upgrade the whole software with more than 50 different types of profiles collected from various engineering domains.

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