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Automated design and STEP-NC matching of impellers.

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

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

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

2. Design calculation of impellers

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

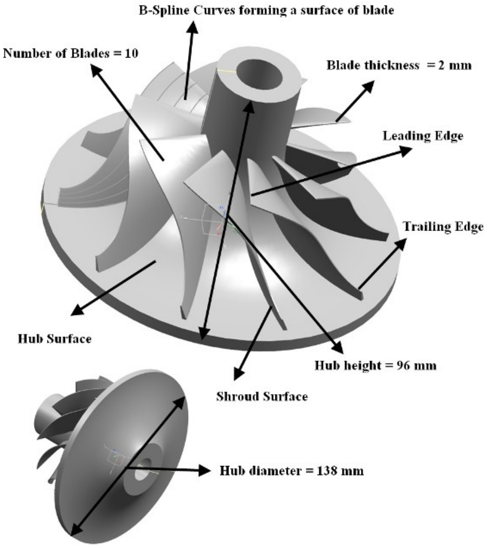


Fig.1(a). Radial Impeller cross section

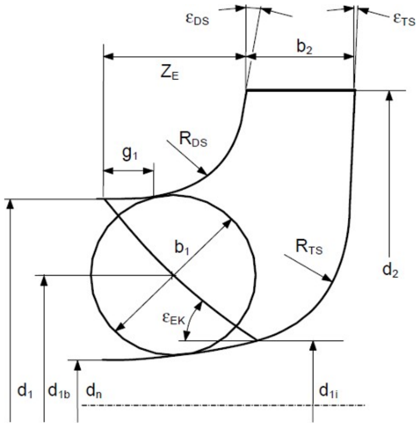


Fig.1(b). Meridional view of radial impeller

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 if shown in Fig. 1(b). It consists of parameters namely (i) b_1-impeller inlet width (leading edge) = ½ (d_1- d_n); (ii) b_2- impeller outlet width (trailing edge); (iii) d1-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) ε_{DS}-angle of front shroud; (xi) ε_{TS}-angle of rear shroud or hub; (xii) ε_{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) β_{1B} -Impeller blade inlet angle;

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

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

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

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

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

$$z_E = (d_{2a} - d_1)\left(\frac{n_q}{n_{q,Ref}}\right)^{1.07} \quad \begin{array}{l} R_{Ds} = (0.6 \text{ to } 0.8)\ b_1 \\ b_1 = ½\ (d_1 - d_n) \\ n_{q,Ref} = 74 \end{array} \qquad \text{Eq. (4)}$$

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

$$\beta_{1B} = \beta'_1 + i_1 = \arctan\frac{c_{1m}\,\tau_1}{u_1 - c_{1u}} + i_1 \qquad \text{Eq.(6)}$$

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

$Q_{La} = Q_{opt} + Q_{sp} + Q_E = 10.8\ m^3/s$; d_1 – based on Eq.1 =0.241m; $d_{1,opt}$ – based on Eq.1 = 1.30m; d_1 – based on Eq.2 = 0.0893m; z_E – based on Eq.4 = 0.684; R_{DS} – based on Eq.4 = 0.84m ; After making all the basic calculations the "Meridional Section" is drawn using UG NX software. The 3D representation is also drawn in the UG- NX software from the 'Meridional section' by adopting a similar set of calculation.

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 added to the model. Then drawing sheets associated with the parts are manually generated and checked.

Step2: Using UG/UFUNC functions extract the geometrical and topological data of the model.

Sub step2.1: Ask the tag (number) of part (specific to UG)

Sub step2.2: Using the tag, cycle all the objects in the part and count the number of features/ objects.

Sub step2.3: Get the ID's of all features/objects

Sub step2.4: Extract the data and store it in a text file. **Explanation to Step2/Sub steps 2.1-2.4:** Generally, a UG part model will have a single tag in the form of a number. This is extracted and the tags of various sub features / objects are found by cycling the part model through a UG/UFUNC function"UF_OBJ_cycle_objs_in_part". Using these tags the geometry and topological data of the sub features / objects are extracted which is used to find the closeness index with Bezier /B-Spline curves. Some of the other used functions are: (i) UF_CURVE_ask_spline_data (ii) UF_CURVE_edit_spline_feature(iii) F_b_curve_bezier_subtype.

Step3: Match the data with the basic B-Splines / Bezier curves / surfaces and calculate the closeness index **Explanation to Step3:** In this step, the extracted data is matched and a closeness index (CI) "0(0-not matching)- 10 (10-exact match)" is generated. It is done by calculating the control points, degree of meridional curve, and various parameters (as shown in Fig.1(b)) required for Bezier and uniform/ cubic/open/non-uniform B-Spline curves.

Step4: Calculate the blending functions and identify the machinable area of the impeller / blade features.

Explanation to Step4: After finding the closeness index blending functions are calculated using convolution theorem. Using the blending function data, the rough and finish cut machinable volumes are calculated.

Step5: Specify the process plan details and Adopt the Z- level contour area milling to generate tool paths **Explanation to Step5:** Here, ball end mill cutters with appropriate radius and length are used for machining.

Table 1. Process Plan details of the radial impeller

Roughing	Finishing
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

Appropriate process parameters for 5 axis contour area milling as shown in Table1 is adopted for machining.

The work piece is rotated to make cutting surfaces of tool tangent to ideal part features. Two methods namely

(i) fixed and (ii) variable contour machining methods are used to finish areas formed by free form surfaces. Intricate contours are machined by controlling tool axis & projection vector. A schematic representation of the impeller machining process is shown in Fig. 2. The tool path is simulated for both roughing & finishing operations and CL data is obtained after post processing.

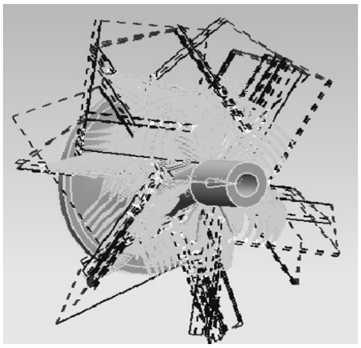
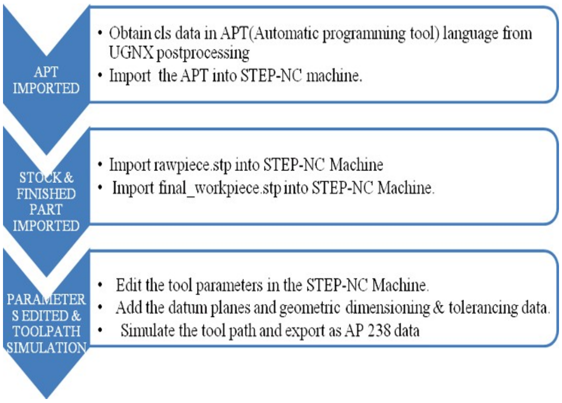


Fig.2 Tool paths simulated with GD&T data



- Obtain cls data in APT(Automatic programming tool) language from UGNX postprocessing
- Import the APT into STEP-NC machine.

- Import rawpiece.stp into STEP-NC Machine
- Import final_workpiece.stp into STEP-NC Machine.

- Edit the tool parameters in the STEP-NC Machine.
- Add the datum planes and geometric dimensioning & tolerancing data.
- Simulate the tool path and export as AP 238 data

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

<u>Step6:</u> 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^{2}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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