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Exploring the Application of 5-axis CNC Machining for the Fabrication of an Impeller for Single Suction Centrifugal Pump

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Abstract

This study delves into the practical application of 5-axis machining for the fabrication of an impeller for a single suction centrifugal pump. It explores the integration of CNC machining and CAD as a crucial aspect, highlighting the synergy between design and manufacturing. The efficiency and performance of the pump are greatly influenced by the impeller, an important part of pump design. Impellers made using traditional manufacturing techniques frequently have intricate designs and complicated geometries that are difficult to precisely manufacture. Using 5-axis CNC machining and other advanced manufacturing technologies presents a viable way to overcome these obstacles. By focusing on applications and the intricate interplay between machining and CAD, this research contributes to the advancement of 5-axis machining technology for precise and efficient complex component manufacturing.

Keywords: 5-axis machining, complex components, axis definition, machine-tool axes, CNC machining, CAD integration, manufacturing efficiency, Impeller, production process.

INTRODUCTION

Computer Numerical Control is one of the advances in technology which has led to minimal tool change time, increased the efficiency of machining and accuracy in the production of machine components (Apro, 2008) [1]. The introduction of 5-axis machining began in the 1990s and thereafter other kinds of multiple axis machining such as the 9-axis machining for the production of machine tools (Rauch and Xu, 2010) [2].

It motions are aligned to have three linear axes X, Y and Z plus two rotary axes (Rauch and Xu, 2010) [2]. Although there are several configurations to this motion, but in this article only the classifications proposed by Makhanov and Anotaipaiboon (2007) [3] in (Rauch and Xu, 2010) will be considered (Figure 1). This classification is based on either the number of work piece and tool carrying axes, or the location of the rotational axes by using the notation of m/n, where m is the number of axis on the table and n is the number of axis on the tool:

a *5/0 machine:* All axes are on the table; the tool is fixed in space (suitable for small work pieces).
b *4/1 machine:* Four axes on the table and one on the tool (usually the spindle).
c *3/2 machine:* Three axes on the table and two on the tool.
d *2/3 machine:* Two axes on the table and three on the tool (very efficient for large work pieces).
e *1/4 machine:* One axis on the table and four on the tool.

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f *0/5 machine:* The table is fixed in space; all the axes are on the tool – an ideal situation for heavy work pieces. However, the accuracy of the machine tool can sometimes suffer from this configuration.

According to Apro (2008) [1], multiple axis CNC machines are made of this three essential parts which are;

a. *Physical Properties of the Machine:* This encompasses how the axes are stacked, the rigidity and flexibility of the structure, spindle motor specifications (horsepower, torque, maximum RPM), and the quality of guides/slides and rotary bearings.
b. *CNC Drive System:* Representing the machine's muscles, this system includes servo motors, drive components, ball screws, control and monitoring of positioning, as well as rapid-traverse and feed capabilities.
c. *CNC Controller Capabilities:* Serving as the brain of the machine, the CNC controller manages data handling, onboard memory size, and controls dynamic rotary synchronization (Figure 2).

According to Jun et al. (2003) [4], 5-axis machining is generally used in the production of automotive, aircraft, turbines, propellers and impellers etc. thus this paper seeks to address its possible application in the production of impellers for single suction centrifugal pump applications.

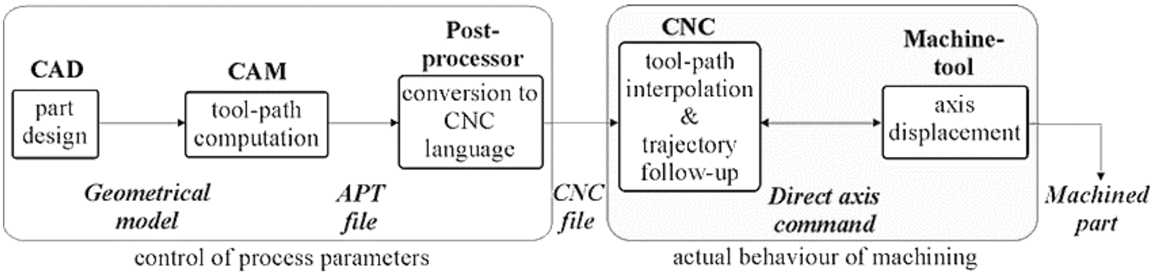

Figure 1. Generalized process of Multiaxis Machining.

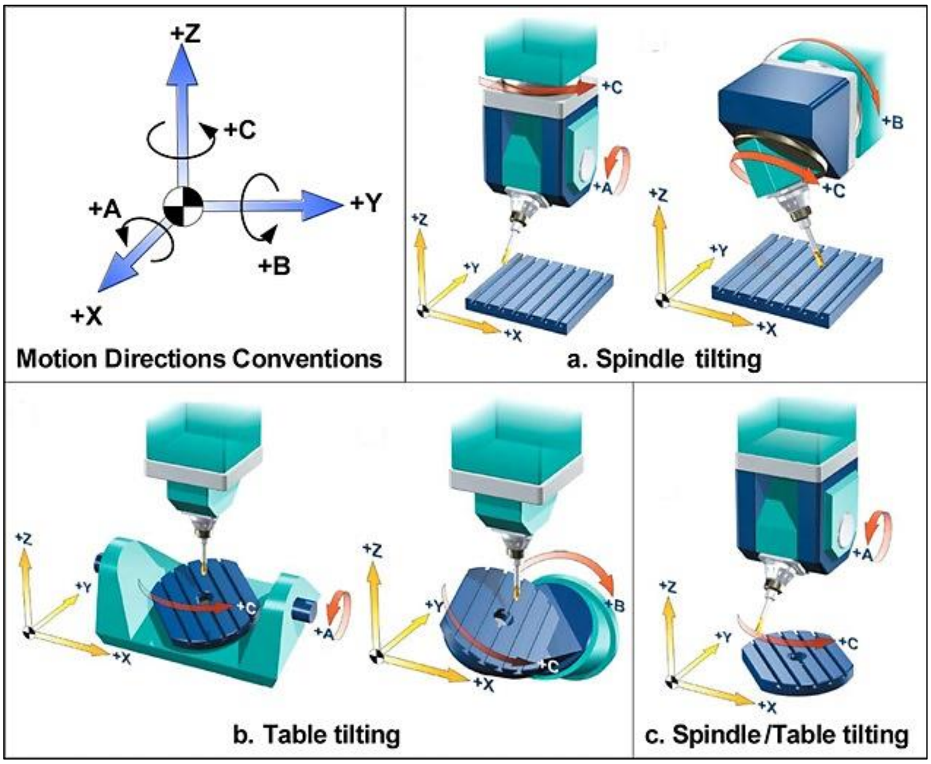

Figure 2. A typical 5-axis Motion Configuration. Rauch and Xu, 2010.

Statement of Problem

The manufacturing industries today is gradually adapting to the use of multiaxis CNC machine for production of complex parts that require simultaneous cutting motions which are not possible when using traditional CNC machines. However, there is a need to understand the working process and its full integration in order to reduce the challenges in the production process and improve the accuracy and efficiency of the production.

OBJECTIVES OF THE STUDY

Main Objective: To explore the practical application of 5-axis machining in the design and production of a single suction impeller for centrifugal pumps.

Objectives

1. To emphasize the importance of specialized models in enhancing precision and efficiency in 5-axis machining.
2. To explore the integration of CNC machining and CAD, highlighting the synergy between design and manufacturing in the context of 5-axis machining.
3. To contribute to the advancement of 5-axis machining technology for precise and efficient manufacturing of complex components.

Significance of the Study

This paper explores the practical integration of Computer aided design models with CNC machines for the design of complex models requiring simultaneous cutting motions which are not possible using traditional CNC machines. By the integration, this paper contributes to the advancement of 5-axis machining [5].

Scope and Limitations of the Study

This study explores the practical the practical application of 5-axis machining for the design of an impeller by integrating CAD models with CNC machines. However, limitations may arise in addressing all nuances of 5-axis machining, and the study acknowledges the dynamic nature of technology, anticipating future developments beyond the current research scope [6–7].

LITERATURE REVIEW

Karlo Apro (2008) [1] addresses misconceptions in multiaxis CNC machining operations and introduces 5-axis CNC machine. He makes clear distinction between the various multiaxis CNC classifications by defining axis and lists examples of multiaxis CNC machines configurations available.

It introduces the process of 5-axis machining with schematics and establishes a predictive model that can improve the actual feedback and efficiency of the 5-axis CNC machine by highlighting its kinematic behavior as a key through programmable solutions (Figure 3).

Rauch and Xu (2010) [2] highlights the benefits of 5-axis CNC machine over traditional CNC machine to include; tool life, flexibility in the length of tool, time saving, ease of drilling holes on work piece, reduced tool breakage and abilities to perform complex machining with one tool setup. The authors further explain 5-axis CNC machine tools structures and terminology, introducing diverse 5-axis CNC machining configurations, tool paths, tool positioning, tool orientation, tool path generation, 5-axis machine modelling techniques to include; tool path generation and optimization, process planning and virtual machining, geometric and kinematic and cutting force errors in 5-axis machining and solutions to the challenges encountered when operating 5-axis machining.

Jun et al. (2003) [4] develops an algorithm for optimization and control of 5-axis tool orientation for adequate efficiency and accuracy by considering the local gouging, rear gouging and the errors developed while machining sculpted surfaces.

Harik et al. (2013) [8] explores the application of 5-axis flank milling to the production of automotive and aircraft parts by the analysis the its diverse tool orientation and tool trajectory on iterative surfaces.

Ozturk and Budak (2007) [9] examines the geometric analysis of the 5-axis CNC milling processes by defining the geometry of the tool at different positions using a mathematical calculations methodology for improvement.

MATERIALS AND METHODS

Design Model of Impeller on Computer Aided Design Software

The impeller design is created using CAD software based on specific calculations from the expected output of the pump (Figures 4, 5).

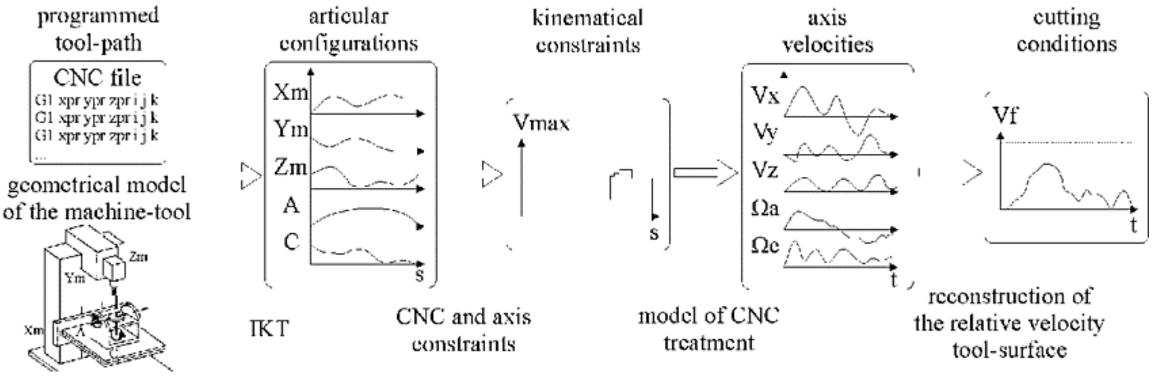

Figure 1. CNC Predictive Model.

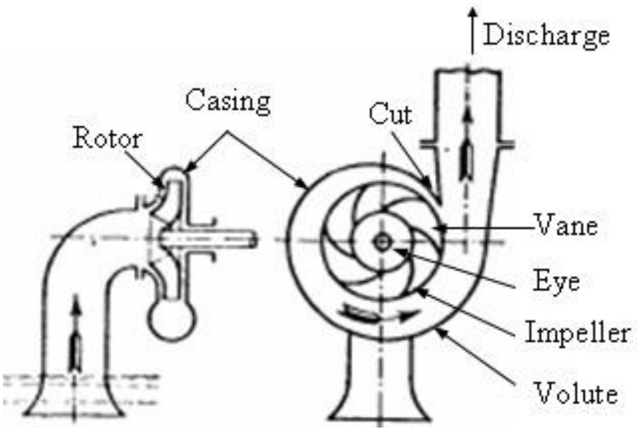

Figure 2. Components Diagram of a Single Suction Centrifugal Pump. Aung et al., 2019 [10].

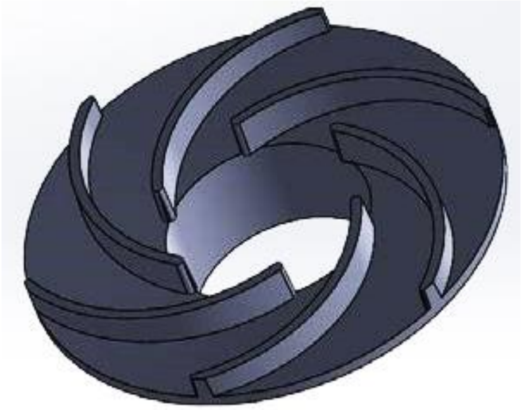

Figure 5. 3D CAD of an Impeller. Aung et al, 2019 [10].

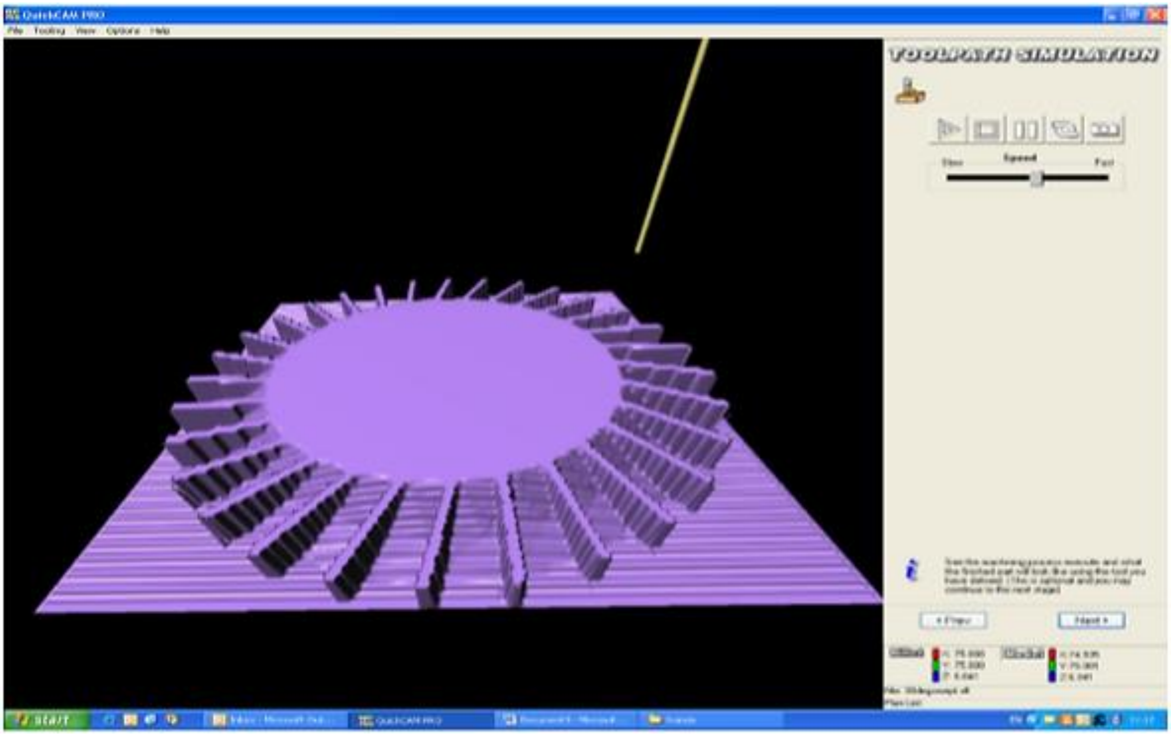

Figure 6: Virtual Tool path plot of Impeller. Quail et al. (2010) [11].

Tool Paths for 5-Axis Machining

The tool path is an essential determinant in the production process as these defines the most appropriate tool-path pattern to link the obtained tool positions and orientations. There are two tool paths for 5-axis machining which are the end-milling and flank milling (Figure 6). For the simplicity of the production, flank milling tool path will be considered as its operations are usually employed with CAD models (Rauch and Xu, 2010) [1].

Pump Specifications

The impeller design for a single-suction centrifugal pump involves selecting velocities, vane angles, and impeller layout based on pump specifications, including head, discharge, rotational speed, and water density. The specific speed is a crucial criterion for impeller shape determination.

Manufacturing

In the exploration of manufacturing methods, 5-axis CNC machines offer enhanced capabilities by incorporating two additional axes (XYZAB), where the fifth axis (B axis) controls the tilt of the cutting tool itself. Although 4-axis CNC machines allows for rotation of machine parts during machining there are challenges in the setup and fixture complexities, especially when dealing with intricate impeller geometries featuring overhangs and interior volumes. This requires the need to turn and remix the impeller for symmetric machining introduced repeatability and alignment issues, leading to increased manufacturing time and potential errors. The preferred production method involves leveraging the precision and versatility of 5-axis CNC machining. The impeller fabrication process begins with drawing a 3D model, followed by creating intricate patterns using 5-axis CNC milling. This step involves detailed specifications such as tool path, diameter, depth of cut, and operation time for each impeller pattern. Subsequently, the manufacturing process continues with mold making and sand casting, ensuring accurate reproduction of the impeller design. Moving to the foundry process, cast iron is melted in a cupola-type furnace, forming the raw material for the impeller. The final step involves machining the cast impeller on a lathe machine to meet specified dimensions. This comprehensive approach, centered around 5-axis CNC machining, ensures the production of high-quality impellers with intricate geometries [12].

Sample G-code

A simplified G-Code which includes the common commands required for machining a workpiece using 5-axis CNC machine.

```
G90 G94 G17 G40 G49 G54 (Initialization)
(Machine Home and Tool Change)
(Milling Operation)
T1 M6 (Tool change to Tool 1)
S10000 M3 (Spindle start, clockwise rotation)
G54 (Work coordinate system)
G0 X0 Y0 Z50 A0 B0 (Rapid positioning to start point)
G43 H1 Z5 (Tool height offset)
G1 X10 Y10 Z2 A45 B30 F500 (Linear move with feedrate)
G1 X20 Y10 Z-5 A90 B45 F500
G1 X20 Y20 Z-10 A135 B60 F500
G0 Z50 (Rapid retract)
M5 (Spindle stop)
G91 G28 Z0 (Return to home position)
G90 M30 (Program end)
```

RESULTS

Impeller Design

Specification of the Pump

Pump head, H = 25 m also, 82 ft

Discharge, Q = 1.2 m^3 /min

Rotational speed, n = 2000 rpm

Density of water, ρ = 1000 kg/m^3

Pump Specific Speed

$$n_s = \frac{\text{rpm}\times\sqrt{\boldsymbol{Q}}}{H^{\frac{3}{4}}} = \frac{2000\times\sqrt{\mathbf{1.2}}}{25^{\frac{3}{4}}} = \frac{2190.9}{25^{\frac{3}{4}}} = 196$$

Figure 7 show the pump efficiency graph

Selection of Vane Number and Discharge angle

To obtain the best efficiency pump(BEP) with a desired head rise, the impeller should be designed with six equally spaced vanes having a discharge angle of 25°(Figure 8).

Impeller Diameter

Figure 9 show the head constant graph and Figure 10 show the capacity constant graph

Head constant, K_u = 0.94 (Figure 9)

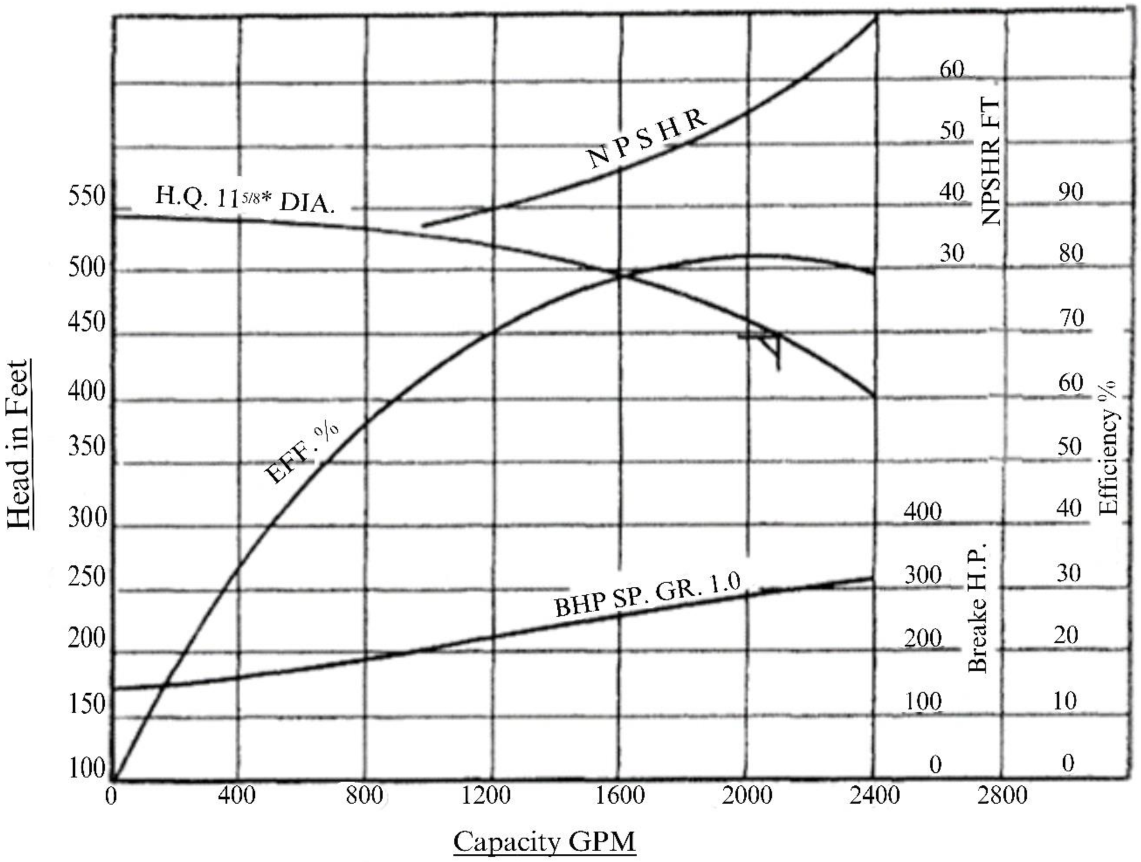

Figure 7. Pump Efficiency Graph. Lobanoff and Ross, 1992 [13].

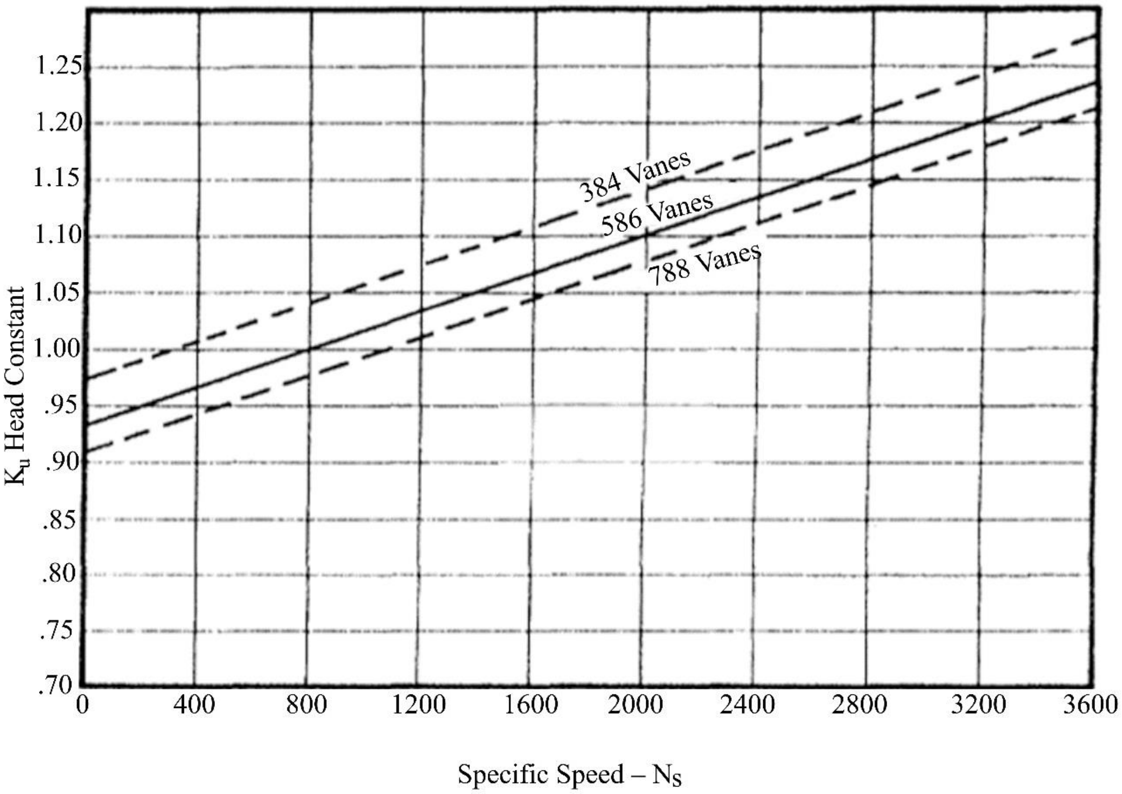

Figure 8. Percent head rise Graph. Lobanoff and Ross, 1992 [13].

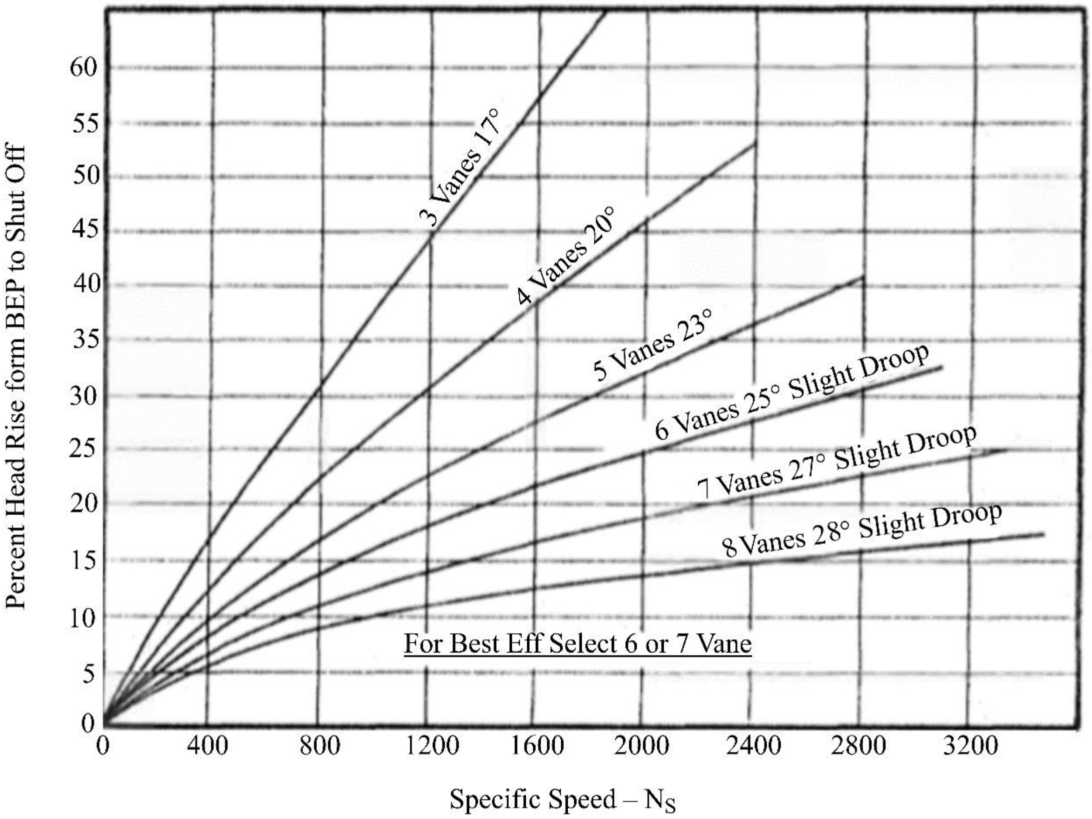

Figure 9. Head Constant Graph. Lobanoff and Ross, 1992 [13].

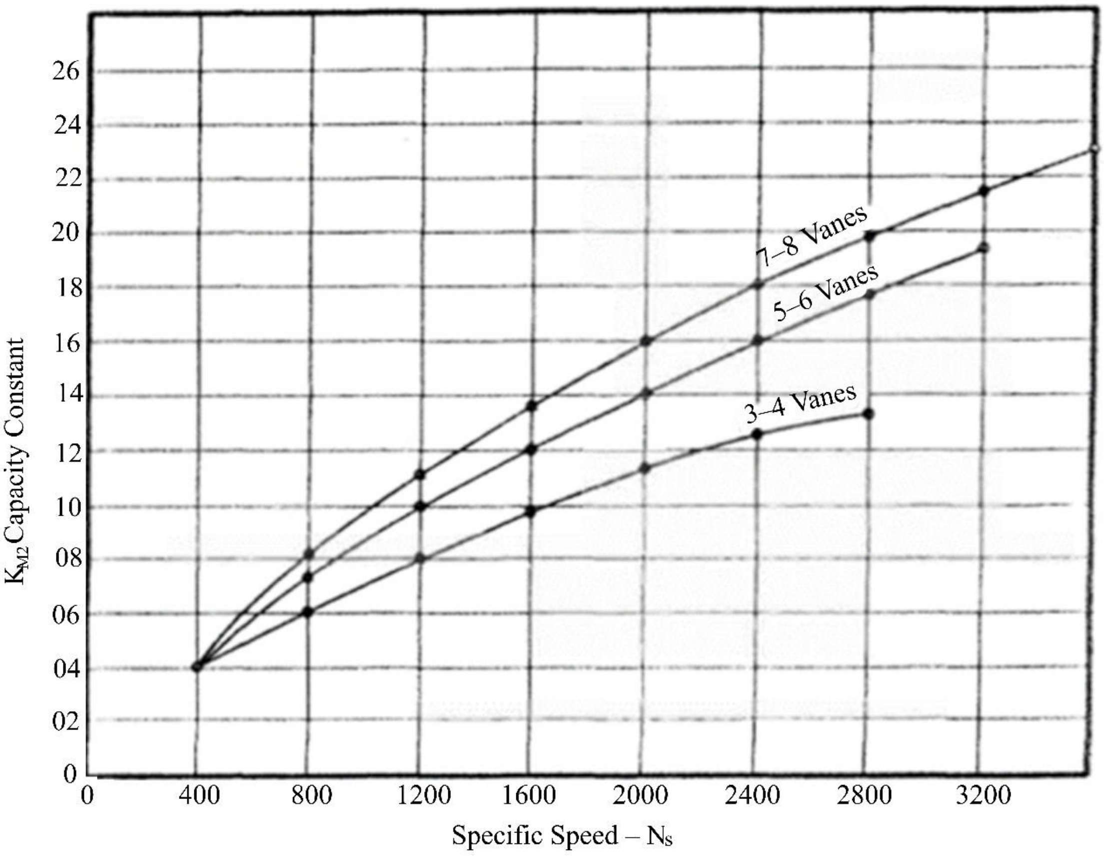

Figure 10. Capacity Constant Graph. Lobanoff and Ross, 1992 [13].

$$D_2 = \frac{1840 \times K_u \times \sqrt{\boldsymbol{H}}}{RPM}$$

$$D_2 = \frac{1840 \times 0.94 \times \sqrt{82}}{2000}$$

D_2 = 7.83 in (also, 19.89 cm)

Impeller Width

$K_{m2} = 0.02$

$C_{m2} = K_{m2} \times \sqrt{\boldsymbol{2gH}}$

$C_{m2} = 0.02 \times 170 = 3.4$ ft/s

$$b_2 = \frac{\boldsymbol{GPM} \times 0.321}{C_{m2} \times (D_2\pi - ZS_u)}$$

S_u is estimated to be $\frac{\boldsymbol{1}}{2}$ in.

$$b_2 = \frac{317 \times 0.321}{3.4 \times (7.83\pi - 6 \times 0.5)}$$

$$b_2 = \frac{101.76}{73.44}$$

$b_2 = 1.39$ in

Impeller Eye Diameter

From Figure 11

$\frac{D_1}{D_2} = 0.25$

$D_1 = 1.96$ in

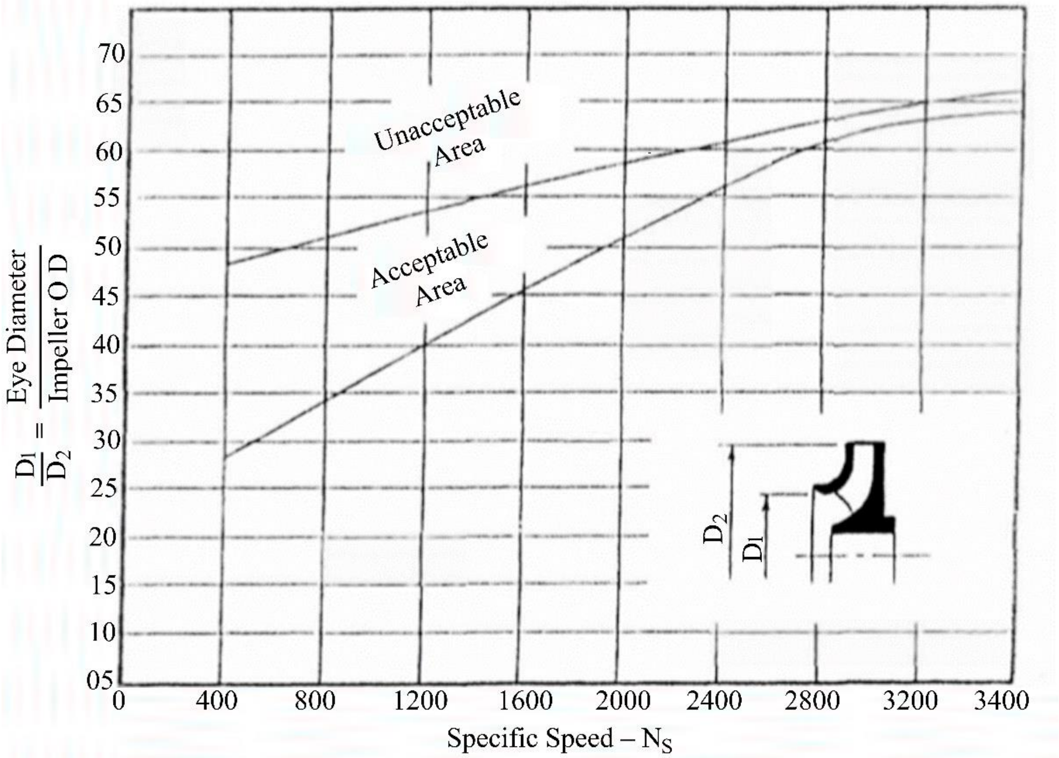

Figure 11. Impeller eye diameter/outside diameter ratio. Lobanoff and Ross, 1992.

Impeller tip speed

$U_2 = K_u \times \sqrt{2gH}$

$K_u = 0.94$

$U_2 = 21$ m/s

Figure 11 show the Impeller eye diameter/outside diameter ratio

$U_1 = \frac{\pi \times N \times D_1}{60}$

$U_1 = \frac{\pi \times 2000 \times 0.05}{60} = 5.23$ m/s

DISCUSSION

From the equations presented, design procedures can be commenced by assigning the calculated values to the CAD model such that the actual head calculated matches with the required pump head utilizing the integration of 5-axis CNC machining ensuring to positioning the tool and set its orientation and axis accurately.

CONCLUSION

This exploration deepens our understanding of 5-axis CNC machining processes and their application in fabricating a single suction impeller for centrifugal pumps. The practical relevance of 5-axis CNC machining extends to process simulation and optimization in the manufacturing industry. Its seamless integration into CAD/CAM programs allows for the consideration of cutting parameters, enhancing the precision and efficiency of 5-axis machining processes. This approach ensures that components, such as impellers for centrifugal pumps, are manufactured with a focus on quality and performance. This article further outlines detailed procedures for integrating CAD with a 5-axis CNC machine, offering valuable insights into the fabrication of single suction impellers. By delving into the specifics of CNC machining, this exploration provides a comprehensive understanding of the methodology and considerations involved in leveraging this technology for the production of intricate components in centrifugal pump applications.

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