Roughing an Impeller: A Review

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ABSTRACT

Impeller is a rotating device, which transforms fluid flow from axial to radial direction. It consists of several identical, twisted blades with ruled surfaces, which are attached to a hub surface. Commonly, impeller needs high-speed rotation in order to increase the pressure flow of a pump or turbine engine. High machining accuracy is vital in producing an impeller. In this sense, there are many issues in producing a high quality impeller. Not enough information has been provided to guide new researchers in this field in the meantime. To overcome this problem, therefore, this paper reviews existing researches associated with impeller machining, focusing on the roughing strategies. An extensive study covers the literature from 1970 to 2013, mapping out research issues regarding roughing strategy in details. This paper classifies the impeller roughing strategy issues in a chronological order according to the main idea and issues. A clear analysis of machining strategies provided by dividing them into 4 categories; (1) improving machining time, (2) avoiding tool collisions, (3) undercut avoidance, and (4) chatter avoidance. Critics on the existing work and research trends reported as discussions and conclusion.

1. INTRODUCTION

1.1. GENERALITIES

Impellers are widely used in the areas of aerospace [3-7], automobiles [8], ships' component parts [5, 8-10] and they are even used in jet engines [3, 10] and launch rockets [10]. Impeller is a high-speed rotating device, which transforms fluid flow from axial to radial direction under high speed, high pressure, and high temperatures. Impeller consists of multiple identical ruled surface blades, thus it must be balanced in terms of its weight and geometry, otherwise, while the impeller operates with high rotational speed, the imbalances will cause vibration and will result the impeller blades to fail and break [8, 10, 13]. The first impeller machining was reported by Kogan and Timoshenko [13] in 1971; where, at that time, the impeller was machined by only using turning operation. They experienced that the incorrect machining of the blanks (blanks preparation stage) of the impeller which caused the imbalances.

During 1970s and '80s, the trends of impeller machining only focused on machining issues, as at that time, only conventional 3-axis machines existed. The biggest challenge for impeller machining was designing the jigs and fixtures for supporting the machining activity. Because of the limitations at that era, such as, machine controller technology, cutting tools technology, computing and CAD/CAM technology [14], the most common methods for making impellers was by riveting and welding (joining method) the impeller blades [15]. In the late 70's, impellers were mostly made by casting with the lost-wax method [16]. In the '80s, Babichev et al. [16] machined an impeller with the help of fixtures which were powered by hydraulic drives, capable of rotary motion. Nevertheless, the limitations still exist on machining the blade. The fixture works efficiently with impeller of small diameter (between 40-50mm) with small blade width [16].

Recently, most of the impellers are machined by 5-axis CNC machine. The 5-axis machine offers the flexibility of the cutting tool orientation, by adding rotary and tilting movement to the worktable. For this reason, impeller with

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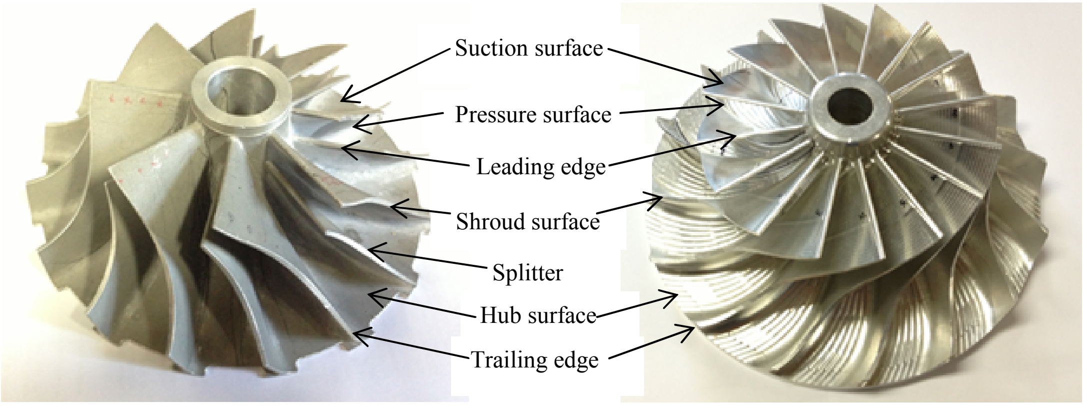
twisted ruled surface blades can be machined [1, 17, 18]. Even though current high technology promised a good result in impeller machining, there are still a lot of issues being raised such as difficulties to generate collision free tool-path, reducing the machining time and improving the machining strategies, etc.

For these reasons, impeller machining is a topic that attracts researchers' attention. As the technological development boosts, many facilities support and ease the research concerning impeller machining. The word “impeller machining” was searched in article titles, abstracts or keywords in a Scopus® [19] database with total of 51 publications. The first research in impeller machining was reported in 1970, and it continues for a forty-three-year period and increasing until now.

1.2. IMPELLERS

Impeller machining is a complicated machining process because it consists of blades with twisted ruled surfaces. Figure 1 shows two different types of centrifugal impellers, which are splitter type and non-splitter type. The main difference between these two impellers is the design of the blades. The non-splitter type impeller has identical design for all blades; the splitter type impeller has smaller size blades alternating with the main blades. A typical impeller has as much as 16 identical twisted ruled blades and a hub surface. The geometry of the blades consists of suction surface, pressure surface, leading edge, trailing edge and shroud surface.

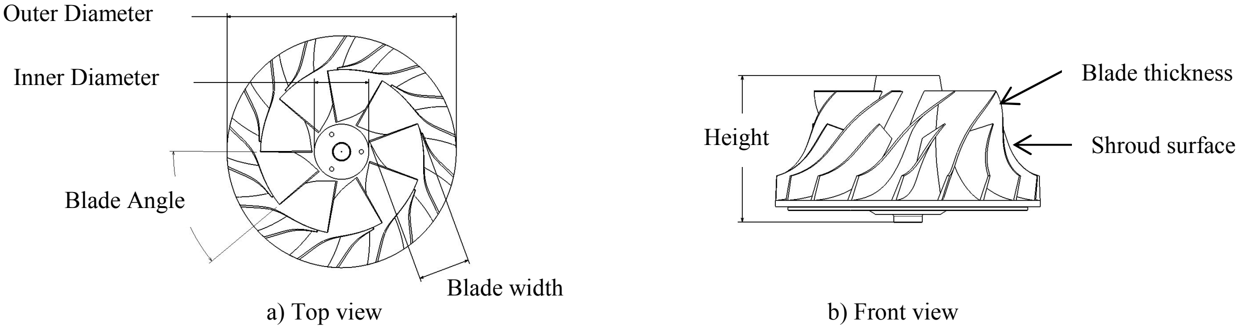


(a) Splitter Type

(b) Non-Splitter Type

Figure 1. Types of a typical centrifugal impeller; (a) Splitter type (b) Non-splitter type.

Figure 2 shows a geometrical view of an impeller. It includes impeller inner diameter, outer diameter, blade width (also known as leading edge), blade angle (360° divide by the number of blades), blade thickness, and impeller height.



a) Top view

b) Front view

Figure 2. Geometrical view of an impeller; (a) Top view (b) Front view.

Generally, in order to perform impeller machining. First, a cylindrical bar with a diameter similar to the outer diameter of the impeller has to be prepared according to the impeller height (Figure 3a). Then, to form an impeller stock, the cylinder bar is machined by lathe in order to form the shroud surface as shown in Figure 3b.

(a) Cut the cylinder bar to impeller height (b) Perform turning for shroud surface (impeller stock)

Figure 3. Preparing the impeller stock.

2. PREPARING THE STOCK

The quality of the stock material will affect the quality of the impeller. As mentioned before, the stock is prepared from a cylinder bar and will be machined in a lathe to form the shroud surface of an impeller. According to Kogan, et al [13], improper turning operation will result to undesired impeller stock. Thus, they suggested that the unbalance of the stock bar and the eccentricity of working surface should not exceed 1.5-100 g.cm and 0.025-0.075 mm, respectively. Failing to meet the requirements, will generate vibrations and errors while turning operations. Machining the unbalanced bar will cause errors related to unstable cutting force, centrifugal force, inertia and gyroscopic effect.

3. ROUGHING OPERATIONS

Rough cutting is a very important operation in impeller machining, as it will affect the productivity and the finishing process [1, 9, 20]. Rough cutting strategy's main objective is to remove as much as possible unnecessary stock material to form the desired shape of the final product. In rough cutting an impeller, most of the unwanted material stock exists between the impeller blades. Up to 70% of unwanted stock material has to be removed by rough machining [1]. According to Heo et al. [8], it takes more than 60% of the overall machining time to rough-cut an impeller. Thus, it is very important to determine the efficient cutting strategies and produce an optimal cutting tool-path for impeller machining.

3.1. IMPROVING MACHINING TIME

As mentioned earlier, most of the machining time is spent on roughing operation. In the sense of creating efficient cutting strategies, research conducted by [8, 12, 17, 18, 20-25] aims to reduce the roughing time. Koichi Morishige and Yoshimi Takeuchi [12] proposed an algorithm for efficient tool-path to reduce machining time. They created the algorithm that eliminates cutting tool retraction for roughing the material between the impeller blades. The method introduces two types of roughing strategies; rough cutting in reciprocating mode and rough finishing in contouring mode. Heo et al. [8], suggested that the rough machining area of an impeller should be partitioned into several unit machining regions (UMR) to eliminate the cutter locations that need to be controlled by the 5-axis machine controller. The authors used this approach so that the cutter location for the complete rough cutting process will be generated based on the 3-axis machining plan at each UMR. Generally, the more cutter axis locations the machine controller has to read, the slower it takes to machine the impeller [23]. Later on, Kim et al. [22] improved the works of Heo et al. [8] by considering the surface quality of the rough machined areas that affect the finishing process. The authors introduce a hybrid rough-cut machining plan (H-RMP). By this new improved method, acceptable rough-cut surface quality for final finishing is achieved. In the same sense, Kim et al. [17] proposed that the roughing strategy should be integrated by 3-axis and 5-axis machining strategy. The authors aim to minimize the 5-axis cutting tool-path in order to improve the total roughing time. Thus, the authors introduce 3-axis roughing strategy that enables the removal of more than 40 percent of the stock material before it will be processed by the 5-axis machining strategy. With this method, the total machining time of an impeller was improved by 19 percent. Young et al. [18, 25] described a method on flank milling the blades of the impeller for rough cutting. They developed a module using C++ language that can automatically generate the tool-path of an impeller. Using the same strategy, Chuang et al. [20] improved the idea of Young et al. by applying a different flank milling tool-path. The authors introduced a different machining strategy on the hub surface, which resulted in a zig-zag pattern. In a different approach, Tsay et al. [24] proposed a flank milling strategy by applying the B-spline curve interpolation on the ruled surface of the blade, and at the same time by means of coordinate transformations the authors calculate the corresponding rotating and tilting angle of the tool axis. So et al. [23] optimized the factor influence of the 5-axis machining operation. According to the authors, the most effective factors that influence machining speed is the step length, the block processing time, and the ratio between the rotational motions of 5-axis machining. These factors were optimized and the authors reported that the method improved the machining time by 25 percent. Yonglin Cai et al. [21] presented an approach with a modified cutting tool, named a drum-taper cutter. With the proposed design of cutting tool, the authors claim that the new design-cutting tool leads to reduction of tool-path length, as a result improving the machining time.

3.2. TOOL COLLISION

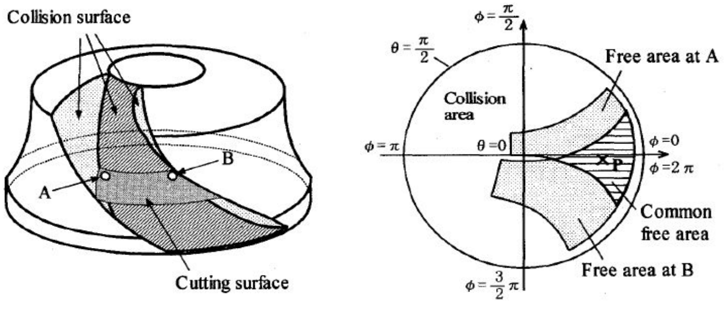
Avoiding tool collision is a very challenging issue in impeller machining. Due to the flexibility of the 5-axis machine orientation, yields to higher degree of collision occurrence probability. There are two types of tool collisions: local gouging between the bottom surface of the cutting tool and the target location of the workpiece, and global gouging between the tool holder with the workpiece or worktable [8]. Due to the twisted ruled surface of the impeller blades, both types of collisions may occur. Thus, tool collision is necessary to take into consideration prior to generating a cutting tool path. Due to this challenging issue, plenty of research is conducted in avoiding and improving tool-path generation. In the year 1997, Koichi Morishige and Yoshimi Takeuchi [12] proposed a method to detect the existence of tool collisions by 2-dimensional configuration space (C-Space). By applying this method, the authors map out the relationship between the tool postures inspecting for any existence of collision as shown in Figure 4. However, according to Young et al. [18], with this method, serious collisions will not be totally avoided, if the blades are extremely twisted and closely overlap each other. Later, Heo et al. [8] partitioned the rough machining area into several unit machining regions (UMRs), so that machining will occur only at certain setup posture of worktable. As a result, the tool collision can be avoided between the blades. Later on, Kim et al. [22] developed further the works of Heo et al. [8] by considering the tool information (tool diameter) that usually is available in the shop floor and the geometric configuration of a blades (blade angle, blade thickness and twisting angle). Ruolong et al. [1] studied on how to avoid tool collision in flank milling for roughing strategies. The authors realized that to avoid tool collision, interpolation method could be used in the realization of NC movement in tool-path planning. By this sense, for roughing a layer of a blade, the vectors of notching are interpolated by the vectors of flank milling giving the equation:

$$T_i^0 = \frac{T_i^1 + T_i^2}{2} \qquad (1)$$

where T_i^0 is the vector of the CL point *i* in notching, and T_i^1 and T_i^2 are the vectors of CL point *i* in flank milling on adjacent blades. Thus, to avoid tool collision with the blade, the vectors of the blade are calculated, so that the tool axis vector magnitude performed cannot exceed the blades vector magnitude. The algorithm for calculating the vector:

$$T_{j,i}^e = \begin{cases} T_i^0 + \frac{j}{N_1}(T_i^1 - T_i^0) \\ T_i^0 + \frac{j}{N_2}(T_i^2 - T_i^0) \end{cases} \qquad (2)$$

where $T_{j,i}^e$ is the expanding notch vector of the CL point *i* in the tool-path *j* at one side of notching. The authors verified the algorithm with the splitter and non-splitter type impeller. The authors reported that no collision occurred during verification operation. Chu et al. [26] proposed the tool collision avoidance by 3-stages approach, correcting tool axis at each cutter location with minimal change in tool orientations. Wu et al. [27], studied the impeller machining by using non-orthogonal 4-axis machine instead of 5-axis machining. The authors believed that, their research would help small enterprises to reduce equipment cost instead of having the 5-axis machine at the shop floor. Thus, the approach on avoiding tool collisions is different, because it is based on 4-axis non-orthogonal machining strategies. The authors proposed collision elimination by rotating the ellipse, which is the intersection of the offset plane of the machine table and the cutter.



(a) (b)

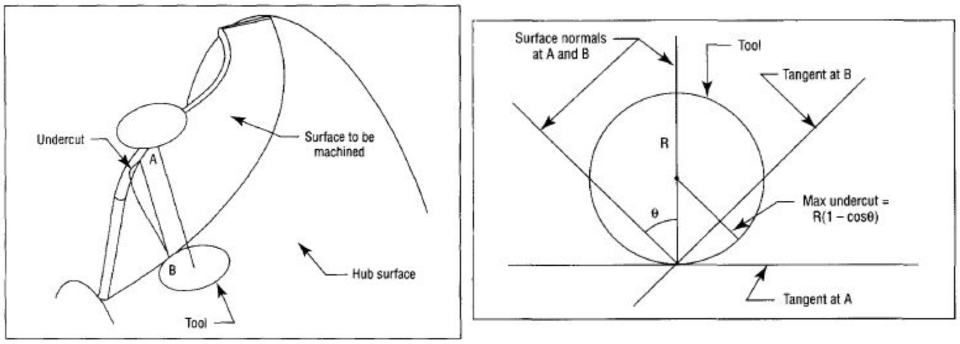
Figure 4. Tool posture; (a) two points where 2-dimensional C-Space is generated, (b) common free area and collision area. [12]

3.3. UNDERCUTS AVOIDANCE

In impeller machining operations, usually undercut is a recess in a convex narrow edge between the blades and the hub surface. Undercut happens because of inappropriate tool orientation angle or application of tool geometry. Undercut is the most popular issue in flank milling strategy research area. Numbers of research was conducted on undercut avoidance in flank milling roughing strategy. In 1997, Bohez et al. [2] studied the avoidance of undercuts on the blade surface and hub surface. The authors divided the undercut problem into two parts. The first part is; undercut occurs at line AB that is offset to the ruled surface of the blade (see Figure 5a). This happens due to the tool orientation and the twisting of the ruled blade surface. Thus, the authors introduced an equation for calculating maximum undercut that might occur at the AB line as shown in Figure 5b:

$$\text{Maximum undercut} = \mathrm{R}(1 - \cos\theta) \qquad (3)$$

where, R is the tool radius and θ is the angle between surface normal at each end of the iso-parametric line. They found that, undercuts could be reduced by using smaller diameter cutting tools or by reducing the angle θ. The second part is; the authors considered that if the tool is made tangent to the ruled surface at point P and the tool axis is parallel to the drive surface, the maximum undercut that might occur could be reduced to $\mathrm{R}(1 - \cos\theta/2)$. However, other problems arise. Undercut then appears on both hub and blade surface. The authors solve this problem by creating a number of iso-parametric lines, which depend on the number of tool path. By this strategy, the angle θ becomes very small, and leaves very small undercuts on both surfaces. Later on, Young et al. [18, 20, 25] applied one of the methods of Bohez et al. [2] by positioned the tool tangent to the blade ruled surface. The authors took an advantage of the idea of Bohez et al. by creating a residual thickness at the edge connecting the blade and the hub surface. This residual thickness will affect the final finishing stage. Thus, they modified the tool position, so it would help to prevent undercut and would create a layer of residual thickness.



(a) (b)

Figure 5. Undercut on the blade surface; (a) isoparametric line AB, (b) tool cross-section (maximum undercut). [2]

Chu et al. and Chen et al. [11, 28] still focus on the maximum undercut issue raised by Bohez et al. [2]. In their research, they avoid the undercut by modifying the method of Bohez et al. The authors suggested that the triple scalar product of the two tangent vectors of the blade surface and the ruling vector $A'(w) - B'(w)$ should be equal to zero (see Figure 6):

$$A'(w) \times B'(w) \cdot [A(w) - B(w)] = 0 \qquad (4)$$

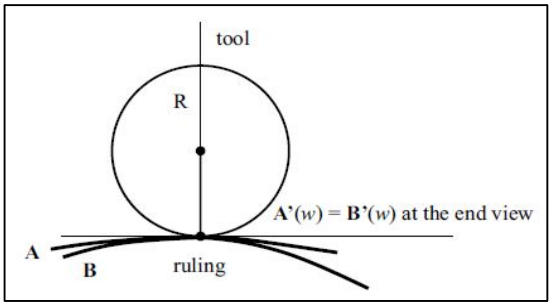


Figure 6. Elimination of the undercut. [11]

In this way, a better position of the tool axis is defined which results in the minimization of the undercut. Hu Gong et al. [29] proposed three points offset method to avoid undercut on the blade surface. First, the authors use three points at different ruling lines of the blade's ruled surface and offset a distance equal to the cutting tool radius. Then, they defined the undercut-free tool axis orientation by joining the three lines defined by the offset points. Kuan-Hung Chen [30] investigated the optimal tool orientation for flank milling blades of an impeller. First, the author derived a mathematical formula, which includes cutting tool and curve surface parameters for calculating the tool orientation. Then, the results from the derivation are plot into the CAD system for checking tool interference with the blade surface. The orientation was modified and calculations were made to obtain the optimal tool orientation without any interference with the blade surface.

3.4. CHATTER AVOIDANCE

Machining vibrations, also called chatter, are the result of forced and self-excited vibrations that occur during machining operations [31, 32]. In roughing operation, chatter avoidance is a very important issue for high quality impeller and better tool life. Due to the high cutting force, continuous variations of tool orientation and depth of cut occur, which may introduce chatter. Numbers of researcher addressed this issue in their publications. To avoid chatter in impeller machining, Koichi Morishige and Yoshimi Takeuchi [12] planned the tool-path strategy by setting machining layers, which will start from top to bottom of an impeller. The authors claim that by this strategy, the stiffness from the cutting force while machining operation could be recessed. Young et al. [18] and Chuang et al. [20] planned their rough machining strategy in such a way that would allow the residual material of certain thickness always be left on the bottom between two neighbouring blades. The authors believed that, the residual material provides an extra support to the blades during machining operation. However, there is no evidence of scientific findings that supports all the strategies that were mentioned above. They just claim that, by applying their strategy, no chatter occurs while observing the verification operations. On the other hand, Budak et al. [33] focus their study on avoiding chatter for machining titanium based impellers. The authors focus on flank milling strategy, which involves high cutting force and large depth of cut. Thus, the authors proposed the idea of using variable pitch cutter and variable cutting force using adaptive control (developed by Altintas et al. [34]) and force modeling to reduce chatter. First, from the experiments, they found that, by applying variable-pitch cutter with pitch angle (55, 57, 59, 61, 63, 65), chatter can be eliminated even at very slow spindle speed, 300 rpm. The proposed tool geometry also improved cutting tool life and resulted in high quality surface finish. Then, the authors proposed the idea of optimizing and increasing the feed-rate by controlling the milling force. The optimal feed-rate, $f_o$can be obtained as:

$$f_o = f_t \left(\frac{F_M}{F_{ref}}\right)^{\frac{1}{1-p}} \qquad (5)$$

where, $f_t$is the feed-rate used in the test, F_M and F_{ref} are the measured force and reference force from the adaptive controller, respectively. This approach offers reasonable accurate feed-rate to keep a constant force on the cutting tool and significantly reduce cycle times.

4. DISCUSSIONS

4.1. TREND OF RESEARCH FROM 1970 TO 2013

This chapter aims to give an overview of research trends that have been reported regarding impeller machining from 1970 to 2013. As mentioned in the introduction, in 1970s and ‘80s, the trends of impeller machining only focus mechanical issues. Because of the machine limitations, different approaches were taken in impeller manufacturing. The most common method of making impeller was by riveting, welding (joining method), and casting with the lost-wax method. Since its presence in the 1990s, the 5-axis CNC machine has been used extensively in the field of impeller machining. Figure 7 shows the percentage of the research area of impeller machining from 1990s to 2013. As it can be seen, improving machining time is the most common issue in machining an impeller. Whereas, there are still a lot of unresolved issues concerning process planning, chatter avoidance and finishing operation.

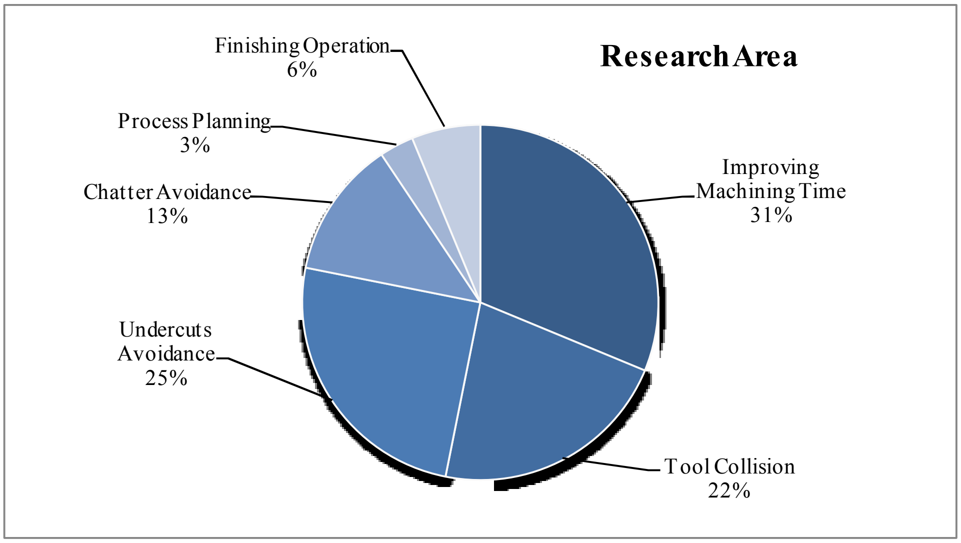


Figure 7. Percentage of research area of impeller machining from 1990s to 2013.

4.2. FEEDBACK AND CRITICS

In order to help new researchers even further, this paper attempts to give feedback and critics according to any irrelevant statements and negligence observed in the papers reviewed.

In 1997, Bohez et al. [2] did a very good review on geometrical modeling of an impeller. The authors described the geometry and the dimensions of an impeller by mathematical representations, in order to visualize the surfaces of the impeller. Besides that, they also introduced useful mathematical equations for evaluating maximum undercut on the blade surface, which has been cited and improved by Young et al. [18, 25], Chuang et al. [20] and Chu et al. and Chen et al. [11, 28]. Moreover, according to Scopus® database [19], the authors have been cited with a total of 55 citations from the year 2003 until 2012.

On the other hand, Chu et al. and Chen et al. [11, 28] presented their idea of eliminating tool interference. They modified Bohez et al.’s [2] method (see Figure 5b). The idea was to transform the boundary curves, $\mathbf{A}(w)$ and $\mathbf{B}(w)$, of a ruled surface so that the tangent vectors of the boundary curves ($\mathbf{A}'(w)$ and $\mathbf{B}'(w)$) and the ruling vector ($[\mathbf{A}(w) - \mathbf{B}(w)]$) will become coplanar (see Figure 6). The authors’ idea in solving the problems in tool interference required some revision. If the three vectors mentioned previously (boundary curve tangents and ruling surface vector) become coplanar, then the blade cannot be twisted anymore. The main idea should be to eliminate undesired tool interference with the twisted impeller blade and not create a new geometry for the blade. Nevertheless, this approach is very helpful for developing a parametric representation of a non-twisted blade.

4.3. RECOMMENDATIONS FOR FURTHER RESEARCH

Due to the complexity of the impeller geometrical shape, there are still many issues to be discussed and improved in order to machine an impeller more efficiently. In coming years, in order to cope with the advance of technology, the design of an impeller would be more complicated. There are still a lot of issues to discuss regarding impellers with the ruled blade surface. Besides the issues in roughing operation, there are still unresolved issues concerning finishing operations for impeller machining. In addition, the issues such as machining time, surface quality and chatter avoidance could be interesting for the future researcher.

However, to increase the performance of the impeller itself, an impeller with non-uniform blade surface has to be considered. Further challenging issues will arise in machining those types of impeller. Further research on the machining of impellers with non-uniform blade is highly recommended.

5. CONCLUSION

This paper reviews a great amount of literature concerning impeller machining from 1970 to 2013. The review summarizes the main ideas and issues regarding roughing strategy of impeller machining. This paper divides the main issues into 4 categories as such:

1) Improving machining time
2) Tool collisions
3) Undercut avoidance
4) Chatter avoidance

Furthermore, this paper describes the research trend, provides feedback and critics, and recommendations for further research in the area of impeller machining. The main objective of this paper is to give clear view and guidance to new researchers regarding machining an impeller, focusing on rough machining strategies.

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