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KNOWLEDGE-BASED DESIGN OF AXIAL PUMP IMPELLER

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Abstract: *This paper presents a knowledge-based hydraulic numerical design process to determine the geometric and hydrodynamic properties of axial pump impeller. One of the final stages of the hydraulic design process is the generation of the impeller's blade CAD geometry based on the previously calculated profile sections. The 3D coordinates of impeller's blade profile sections are stored and available in data files. Using the modelling capability of Siemens NX PLM software and its knowledge-based design automation, the solid model of axial pump impeller's blade can be generated. The automated modelling algorithm allows to produce and compare design variants and select the optimum result.*
Keywords: *axial pump, impeller, knowledge-based design, KBD*

1. INTRODUCTION

When solving engineering problems the different modules of integrated CAE systems use information of computerised geometric design and its required data related analysis, tooling design, preparation of manufacturing and production. Solution of the tasks may became separated from each other, thus accelerating the design processes and reducing resulting costs due to the extended design time. Further options are provided to reduce the design time by applying automatable algorithms. One of the largest advantage of the application of integrated CAE systems is that the required operations for the product design can be performed inside the given software, the particular specialized modules are capable to share the geometric information and other attributes using the software internal data format. Further advantage of integrated CAE systems that product data management (PDM) is also become manageable, if managing of the entire product life cycle is required, this demand can be realized by using the appropriate PLM system. Development of CAD systems can be observed in various fields, which is basically defined by customer demands and feedback. These fields are the geometric modelling (e.g. solid and surface modelling), specialized modules for problems of particular engineering fields (e.g. sheet metal, tool design and cable routing design modules), various engineering analysis (e.g. thermal and flow analysis, finite element methods) and recently the development of production support at a faster rate (e.g. 3D-5D milling, robot motion control, NC code post processing of CNC machine tools, manufacturing simulation, collision detection, optimising of production times).

2. KNOWLEDGE-BASED DESIGN PROCESS OF AXIAL PUMP IMPELLER

The parametric feature based design is a modelling method which enables the expressions of parameters, features, constraints and dimensions driven modification. The knowledge-based design methods and tools can include rigid or variable geometry data, the integration of calculation and simulation procedures into the design process, or the application of problem-oriented software solutions that can be integrated into the design environment. Modelling and analysis of complex geometries (i.e. surfaces in hydrodynamics) requires large and high level computations [1], [2]. To simulate the results, a complex CAD geometry has to be modelled. The conventional techniques are time-consuming solutions, thus more efficient method is required. Integrate the high-level computations and the feature based modelling and analysis into a knowledge-based algorithms an expressions and rules driven application can be developed [3], [4], [5], [6].

Modifications of the geometry can be performed by reusing the previously defined numerical computations and establishing the desired rules and decisions during the design procedure. The presented work in this paper focuses on the knowledge-based 3D design of axial pump impeller.

2.1. Computing of profile section coordinates

Hydraulic computations precedes the axial pump impeller 3D geometric modelling. The following initial parameters are needed to perform the hydraulic design of an axial flow water pump impeller [7]:

Table 1: Main input parameters

Designation	Symbol	Unit
Total head at the operation point of best efficiency	H	[m]
Flowrate at the operation point of best efficiency	Q	[m^3/s]
Pump rotational speed	n	[min^{-1}]
Density of fluid	ρ	[kg/m^3]
Specific speed	n_q	-
Total efficiency	η	[$\%$]
Tip diameter	D	[m]
Hub diameter	d	[m]
Number of blades	N	-

The main dimensions can be determined by numerical processes and empirical relations. The number of blades (N) and the hub-tip ratio (μ) has to be determined after defining the initial data system. Furthermore, we must choose different values of the radius of the cylinder sections where we would like to determine the coordinates of the impeller's blade sections with the calculation. In order to determine the impeller's blade surface the hydro-dynamical singularity method has to be used [7]. Through the design method the emerging spatial flow in the flow field is divided into several sub channels by means of cylindrical surfaces as approximate stream-surfaces. The two-dimensional flows are tested when they emerge in the centre of the cylindrical surfaces of the given sub channels. The sections of the impeller's blade surface can be defined as the relative streamlines of the flow emerging in the sub channels. The three-dimensional flow emerged in the flow field is accordingly led back to solve a two-dimensional flow task carried out on the middle cylindrical surfaces of several part channels. After determining the emerged flows in each sub channels, the geometrical features of the blade sections given on the central cylindrical surfaces of the sub channel can be calculated, and then the velocity and pressure distribution on the surface of the impeller's blade can be calculated as well. The calculation has to be done for each sub channel, and then the spatial model of the impeller's blade can be produced with the full knowledge of the blade sections in the middle surfaces of sub channels.

2.2. Modelling the impeller's blade geometry

The blade geometry is modelled from the previously determined profile sections data points. An automated algorithm had been developed in Siemens NX PLM system in VB programming language, which generates the section curves. Most CAD system uses non-uniform rational B-splines (NURBS) to generate freeform parametric curves.
These NURBS curves can be defined as

$$\mathbf{P}(t)=\frac{\sum_{i=0}^{n} w_i \mathbf{P}_i N_{i,p}(t)}{\sum_{i=0}^{n} w_i \mathrm{N}_{i,p}(t)},\ t\in\left[t_0,t_{n+p+1}\right] \qquad (1)$$

where $\mathrm{N}_{i,p}(t)$ functions are the basis of degree p of the B-spline curve, $\mathbf{P}_i$ is the i^{th} control point, w_i is the weight associated with the control point $\mathbf{P}_i$, and $n+1$ is the total number of control points. In case of all $w_i=0$, then the NURBS curve is not rational, however a B-spline curve because the basis functions in the denominator of Eq. 1 is equal to one. The basis functions of degree p can be determined recursively as

$$N_{i,p}(t)=\frac{(t-t_i)}{t_{i+p}-t_i}N_{i,p-1}(t)+\frac{(t_{i+p+1}-t)}{t_{i+p+1}-t_{i+1}}N_{i+1,p-1}(t) \qquad (2)$$

and

$$\mathrm{N}_{i,0}\left(t\right)=\begin{cases}1, \text{ if } t_i \le t \le t_{i+1}\\0, \text{ otherwise.}\end{cases} \tag{3}$$

The number of elements in knot vector is $n+p+2$ and t_i knots in Eq. 2 and Eq. 3. can be computed by

$$t_i=\begin{cases}0, \text{ if } i < p+1,\\ i-p, \text{ if } p+1 \le i \le n,\\ n-p-1, \text{ if } i > n,\end{cases} \tag{4}$$

which formulate the so called standard clamped uniform knot vector with these conditions. Applying Eq. 1. with $w_i=1$ an interpolating closed B-spline curve can be generated through the profile section points. Producing appropriate number of profile section closed curves a surface can be generated through them.

The surface generation through the profile sections can be produced by different methods. A *ruled surface* is a linearly interpolated surface on two curves (sections). A sequence of curve sections can be skinned by computing ruled surfaces between adjacent pairs of curves, thus *skinning* is the operation of constructing a surface that interpolates a number of user specified curve sections. Skinning is often referred to as *lofting*, a technique whereby curved lines are generated, to be used in plans for streamlined objects such as aircraft and boats. When a skinned or lofted surface is interpolated on a sequence of section curves the interpolating surfaces satisfy specified derivative conditions along the curve sections [8]. If the skinned surface is generated by ruled surfaces between adjacent pairs of sections, the resulting surface meet with only C^0 continuity. For smooth lofted surfaces G^i, $i=1...3$ continuity is required.

The profile sections are interpolated by B-spline curves, a lofted surface is generated across the sections to form an open B-spline surface. In this process, the number of control points of the B-spline curves must be kept identical across sections. In addition, the polynomial order of the basis functions and knot values of the B-spline curves must be identical in all sections. The lofted B-spline surface equation is then described by

$$\mathbf{S}\left(u,v\right)=\sum_{i=0}^{m}\sum_{j=0}^{n}\mathbf{P}_{i,j}N_{i,p}\left(u\right)N_{j,q}\left(v\right),\ \left(u,v\right)\in\left[u_p,u_{k-p}\right]\times\left[v_q,v_{l-q}\right], \tag{5}$$

where $N_{i,p}\left(u\right)$ the B-spline basis functions of degree p with knot vector $u_0, u_1,\dots, u_k$, and $N_{i,q}\left(v\right)$ the B-spline basis functions of degree q with knot vector $v_0, v_1,\dots, v_l$. $\mathbf{P}_{i,j}$ are control points of B-spline surface, and $0 \le i \le m = k-p-1,\ 0 \le \mathrm{j} \le n = l-q-1$. The resulting B-spline surface continuity conditions depends on the degrees of basis functions in both u- and v-parametric directions.

2.3. Flow of design procedure

The axial pump impeller design process can be divided into two phase. In the first phase the hydraulic design process has to be proceeded to generate the profile sections coordinates in 3D. This procedure uses the so called hydro-dynamical singularities method. The second phase of the design process is the 3D axial pump impeller's blade solid model generation. The knowledge-based design process executes the following main steps:

Step 1: Get input parameters (defined in Table 1.) by the user.

Step 2: Compute 3D profile section coordinates by hydro-dynamical singularities method. This routine calculates the required number of profile section points for geometric modelling.

Step 3: Call the impeller wizard journal from Siemens NX to process the profile section points. Generate the interpolating B-spline curves (as described in subsection 2.2.) with the predefined degrees.

Step 4: Generate the lofted surface as an interpolating surface on the previously generated B-spline curves. Create the solid model of the axial pump impeller by closing the lofted surface. In this design process the closing surfaces at the inner and outer diameters are spheres, trimmed by the boundaries.

Step 5: Check the impeller geometry for degenerated result. If undesired results are produced, change the input parameters at the hydraulic process (main input parameters), or redefine the interpolation parameters at the CAD modelling process.

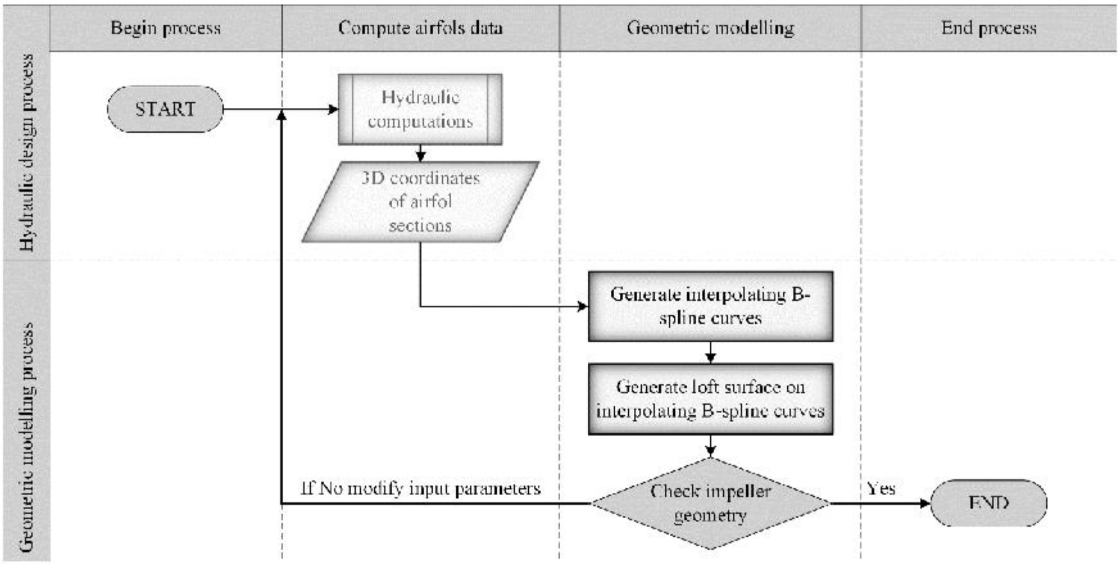

Figure 1: Flow of design process of axial pump impeller

Figure 1 shows the main parts of the axial pump impeller design process. A more detailed presentation of the design process is described in the next section.

3. CASE STUDY OF AXIAL PUMP IMPELLER KBD PROCESS

In this section an axial flow pump impeller hydraulic and knowledge-based feature design is presented on an AXP1 type pump. The main input parameters for the numerical computations:

– Total head per stage at the operation point of best efficiency:	H=6 [m],
– Flowrate at the operation point of best efficiency:	Q=1.15 [m^3/s],
– Pump rotational speed:	n=720 [min^{-1}],
– Density of fluid:	ρ=1000 [$kg/m3$],
– Specific speed:	n_q=201,
– Tip diameter:	D=0.6 [m],
– Hub diameter:	d=0.3 [m],
– Number of blades:	N=4.

Performing the hydrodynamics singularities method the profile section coordinates are computed. In this part of process the number of generated sections is 10 with 802 x, y, z coordinates, thus the total number of coordinates for the geometric modelling is 8020. To perform the large number of section points, the automated KBD application is used in the CAD software. Following the procedure, the coordinates are read into the geometric modeller, which stored in an MS Excel file and the B-spline curves are interpolated on the points simultaneously In this example p=3, the degree of each interpolating curve, and the weights w_i=1 (see Eq. 1).

The impeller's blade geometry is generated by an interpolating B-spline surface in the CAD modeller using the *Trough Curve* command. The input parameters for the process are the interpolating B-spline curves and the resulting surface is a bi-cubic B-spline surface (p=3, q=3 in Eq. 5). At this step the impeller's blade geometry can be analysed and the surface checked for avoiding degenerate results.

The resulting B-spline surfaces of the impeller's blade are closed to form a solid geometry. For this the inner and outer boundary spheres are modelled according to the pump dimensions. To complete the surface modelling process all of the impeller's blade surfaces are sown together. The axial pump design is finalized by modelling its house and the impeller pattern according to the number of blades, and main dimensions.

Figure 2 shows the knowledge-based surface design of the axial pump impeller, using the interpolating B-spline curves of profile sections. The parameters of design process can be set by a user defined wizard application.

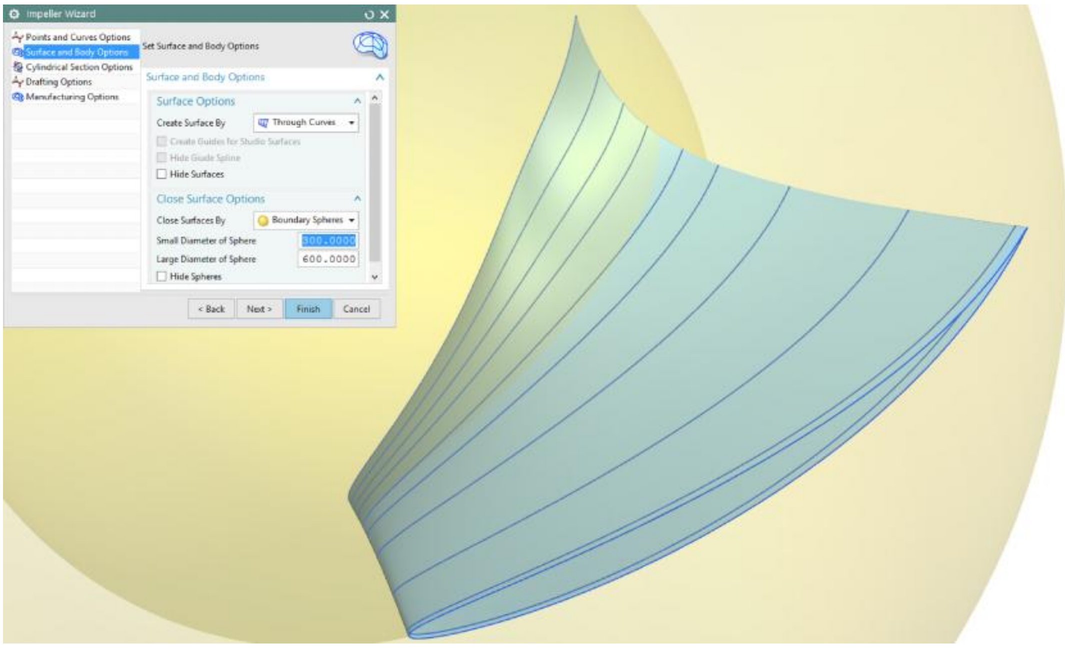

Figure 2: Generate the impeller's blade surface by KDB wizard

During the design process different variant can be produced depending on the hydraulic design input parameters. The results of the computations and the modelled geometries can be compared by the CAD software built in commands. Figure 3 shows the deviation between the different blade geometries. The interpolating B-spline surface parameters highly affects the computation time and the result. In this example one of the blade surface is interpolated by a bi-cubic B-spline surface, and the other surface is interpolated in u parameter direction by cubic, and in v parameter direction by quantic degree.

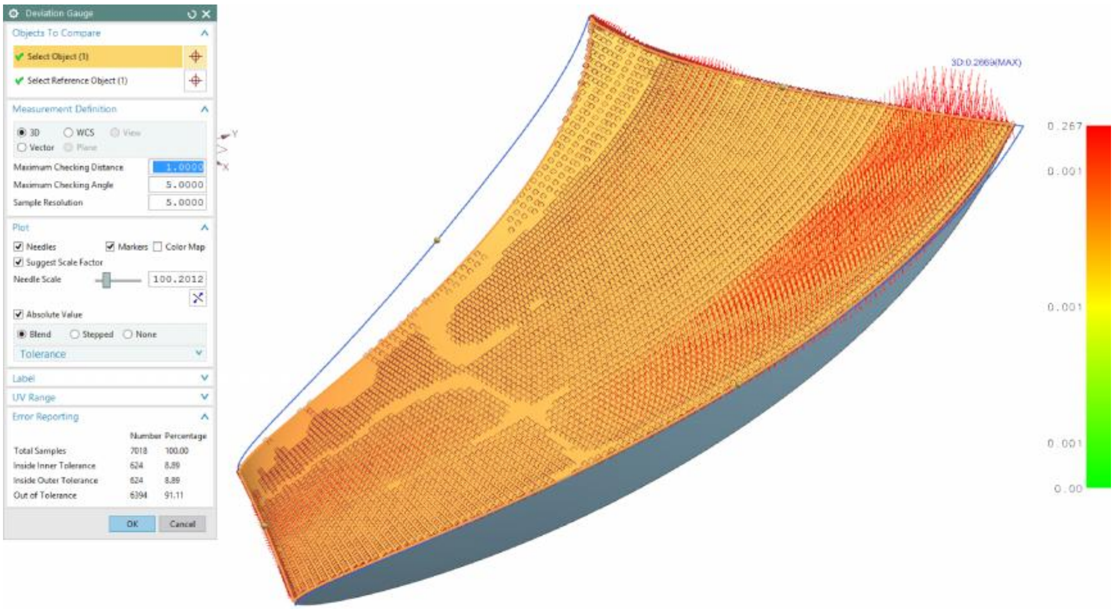

Figure 3: Result of surface deviation on different blade designs

The deviation between the two interpolating B-spline surfaces can be analysed, the maximum deviation in the direction of surface normal vector is 0.2669 *mm*. By using the CAD software analysis capabilities further tests can be applied on the computed geometries such as curvature, slope and surface continuities.

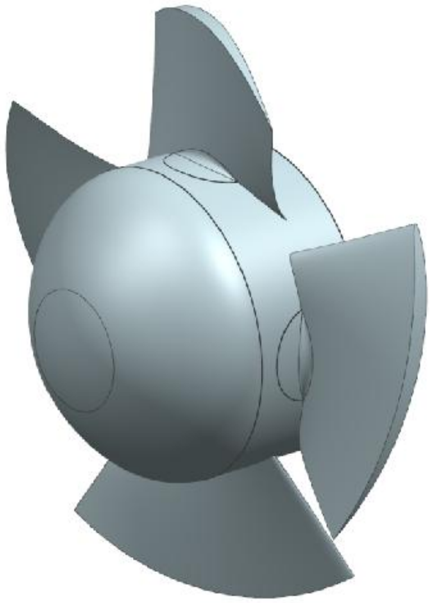

Figure 4: Knowledge-based design of an axial pump

Figure 4 represents a solid model of an axial flow pump designed by knowledge-based hydraulic computations and geometric modelling.

3. CONCLUSION

A knowledge-based design environment was presented on an axial flow pump according to hydro-dynamical singularities method and the geometric relationship of the pump impeller. The automated geometric modelling application was developed in Visual Basic language in Siemens NX software. The 3D coordinates of each profile section data file calculated by design program and directly read into the CAD environment. The solid geometry of pump impeller's blade was automatically generated. Due to the knowledge-based wizard the 3D geometric modelling of the impeller's blade is greatly accelerated and the development process highly reduced. The user developed application can be extended to perform further CFD analysis of the resulting geometry thereby increasing the quality and efficiency of the pump impeller.

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