SOFTWARE SOLUTIONS FOR NUMERICAL MODELLING OF THE FLUID FLOW IN HALF BODY TURBOMACHINERY

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ABSTRACT

The paper presents a software solution for numerical modelling of the fluid flow in turbomachinery. From the known expression of the velocity potential function and the stream function, the flow pattern of the potential lines and the streamlines will be plotted. The program, PFSim_2 can perform the analysis of different types of axis symmetrical fluid flows: axial, radial-axial and radial turbomachinery; Pelton nozzle, as well as bulb, Francis and Kaplan turbines. The PFSim_2 program allow a high interactivity level, the user can adjust both the parameters that define the fluid flow characteristics, but also the parameters that define the plotting and visualization conditions.

KEYWORDS
Flow pattern, turbomachinery, numerical modelling, software solution.

NOMENCLATURE

Subscripts and Superscripts

\[ \text{min} \] minimum condition
\[ \text{max} \] maximum condition
\[ L \] refer to a distributed source
\[ P \] refer to a point source
\[ S \] refer to a stagnation point

1. INTRODUCTION

A graphical user interfaces which can perform the analysis of most important types of two-dimensional potential fluid flows (one-dimensional fluid flow, fluid flow between two plane walls, source and sink systems, vortex systems, source and vortex systems, the fluid flow generated by the doublet, the fluid flow around an open half body, the fluid flow generated by two parallel rows of vortices) has been previously developed [3]. Also for the axial flow turbomachinery (only) another program has been presented [2].

In order to perform more specialized numeric simulation of different types of the turbomachinery half bodies, a new program, PFSim_2 (Potential Field Simulation), has been developed. This paper presents the PFSim_2 program mainly, but also the basic relationship, as well as some representative flow patterns that have been obtained using the above mentioned software solution.

The basic relationship used to obtain flow patterns for the turbomachinery half bodies has been summarized in section 2. The PFSim_2 program description, the most important program facilities developed for improving the computation and the visual quality of the flow pattern, as well as the application windows for the flow pattern analysis has been presented in section 3. The paper conclusions are summarized in section 4.
2. BASIC RELATIONSHIP

The flow pattern for axial turbomachinery can be obtained by superposition of an uniform flow with velocity \( U \) with a point source with positive discharge \( Q_p \) and a distributed source with negative discharge \( Q_l \) and positive length \( L \), see Figure 1.

![Figure 1. Flow structure for axial turbomachinery.](image1)

The following relationship for the velocity potential function and the stream function has been obtained:

\[
\begin{align*}
\varphi &= U \cdot z - \frac{Q_p}{4\pi R} + \frac{Q_l}{4\pi L} \ln \left( \frac{R + R_l + L}{R + R_l - L} \right) \\
\psi &= U \cdot \frac{r^2}{2} - \frac{Q_p}{4\pi} \left( 1 + \frac{z}{R} \right) + \frac{Q_l}{4\pi} \left( \frac{R - R_l}{L} + 1 \right) 
\end{align*}
\]

(1)

In order to obtain another flow pattern for axial turbomachinery the superposition of three positive length distributed sources, two positive and the last negative has been used, see Figure 2 and Eq. 2.

![Figure 2. Flow structure for axial turbomachinery.](image2)

\[
\begin{align*}
\varphi &= U \cdot z - \frac{Q_{l1}}{4\pi L_1} \ln \left( \frac{R_1 + R_2 + L_1}{R_1 + R_2 - L_1} \right) - \frac{Q_{l2}}{4\pi L_2} \ln \left( \frac{R_2 + R_3 + L_2}{R_2 + R_3 - L_2} \right) \\
&\quad + \frac{Q_{l3}}{4\pi L_3} \ln \left( \frac{R_3 + R_4 + L_3}{R_3 + R_4 - L_3} \right) \\
\psi &= U \cdot \frac{r^2}{2} - \frac{Q_{l1}}{4\pi} \left( 1 + \frac{z}{R_1} \right) + \frac{Q_{l2}}{4\pi} \left( \frac{R_1 - R_2}{L_1} + 1 \right) \\
&\quad - \frac{Q_{l3}}{4\pi} \left( \frac{R_3 - R_4}{L_3} + 1 \right) + \frac{Q_{l4}}{4\pi} \left( \frac{R_4 - R_3}{L_3} + 1 \right) 
\end{align*}
\]

(2)

The flow pattern for radial-axial turbomachinery can be obtained by superposition of an uniform flow with velocity \( U \) with a point source with negative discharge \( Q_p \) and a distributed source with positive discharge \( Q_l \) and negative length \( L \), see Figure 3 and Eq. 3.

![Figure 3. Flow structure for radial-axial turbomachinery.](image3)

\[
\begin{align*}
\varphi &= U \cdot z + \frac{|Q_p|}{4\pi R} - \frac{Q_l}{4\pi L} \ln \left( \frac{R + R_l + |L|}{R + R_l - |L|} \right) \\
\psi &= U \cdot \frac{r^2}{2} + \frac{|Q_p|}{4\pi} \left( 1 + \frac{z}{R} \right) + \frac{Q_l}{4\pi} \left( \frac{R - R_l}{|L|} - 1 \right) 
\end{align*}
\]

(3)

The flow pattern for Pelton nozzles can be obtained by superposition of an uniform flow with velocity \( U \) around a sphere with radius \( R_0 \) and a distributed source with negative discharge \( Q_l \) and positive length \( L \), see Figure 4 and Eq. 4.

![Figure 4. Flow structure for Pelton nozzle.](image4)

\[
\begin{align*}
\varphi &= U \cdot z \left( 1 + \frac{R_3^2}{2R^2} \right) + \frac{Q_l}{4\pi L} \ln \left( \frac{R + R_l + L}{R + R_l - L} \right) \\
\psi &= U \cdot \frac{r^2}{2} \left( 1 - \frac{R_0^2}{R^2} \right) - \frac{|Q_p|}{4\pi} \left( R_l - R \right) 
\end{align*}
\]

(4)

The flow pattern for bulb turbomachinery can be obtained by superposition of an uniform flow with velocity \( U \) with three point source with discharges \( Q_{P1} > 0, Q_{P2} < 0, Q_{P3} > 0 \) and a distributed source with negative discharge \( Q_l \) and positive length \( L_4 \), see Figure 5 and Eq. 5.
The flow pattern for radial turbomachinery can be obtained by superposition of an uniform flow in front of a plane perpendicular on the symmetrical axis with a distributed source with positive discharge and negative length, see Figure 6 and Eq. 6.

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The flow pattern for radial turbomachinery can be obtained by superposition of an uniform flow in front of a plane parallel with the symmetrical axis with a distributed source with negative discharge and positive length, see Figure 7 and Eq. 7.

The flow pattern for Kaplan turbine can be obtained by superposition of an uniform flow in front of a plane parallel with the symmetrical axis with a distributed source with negative discharge and negative length and a point source with positive discharge, see Figure 8 and Eq. 8.

3. SOFTWARE SOLUTION

The main window of the PFSim_2 program is shown in Figure 9. From the main window, different types of turbomachinery can be selected by opening the appropriate windows.

From the known expression of the velocity potential function and the stream function [1], the flow pattern of the potential lines and the streamlines has been plotted. This will be the main task of the program. For example, in Figure 10 the application window (AxialTurbomachinery_1) of the
flow pattern analysis in axial turbomachinery (according with the first definition structure, see Figure 1 and Eq.1 is presented.

The program allow a high interactivity level, the user can adjust both the parameters that define the fluid flow characteristics, but also the parameters that define the plotting and visualization conditions. Thus, for the flow pattern shown is Figure 10, the user can adjust the point source discharge \( Q_p = 2 \), the distributed source discharge \( Q_d = -1 \), the velocity magnitude \( U = 1 \) and the length of the distributed source \( L = 0.5 \). Also, the fluid flow domain \([z_{min}, z_{max}] = [-1,+1]\) and \([r_{min}, r_{max}] = [-1,+1]\), as well as the matrix computation dimension \( n_z \times n_r = 200 \times 200 \) can be adjusted. The visualization of a certain fluid flow domain can be made using the zoom function by adjusting the zoom parameters in both \( z \) and \( r \) directions: \([z_{min}, z_{max}]_{zoom} = [-1,+1]\) and \([r_{min}, r_{max}]_{zoom} = [0,+1]\).

By changing the parameters above mentioned the flow pattern will be replotted accordingly.

The user can adjust also the number of the potential lines \( \phi = 250 \) as well as the number of the streamlines, both positive \( \psi^+ = 10 \) and negative \( \psi^- = 15 \) which will be plotted. Also, there is the possibility to draw the streamline which correspond to a given value of the stream function, by introducing its value (for example, \( \psi = 0.1 \)). The boundary streamline \( \psi = 0 \) is plotting by default.

The labelling process of the potential lines and the streamlines can be made automatically or manually.

In auto mode, all the plotted lines are labelled in three different conditions: first - only the potential lines, second - only the streamlines and third - the potential lines and the streamlines altogether. In the manual mode, the user can place labels only on certain potential lines or streamlines by direct selecting in the figure window with left click mouse on those lines. Then, pressing the Enter key, the labelling process will be complete.

Figure 11 shows the application window (Radial Axial Turbomachinery) for the flow pattern analysis in radial-axial turbomachinery according with Figure 3 and Eq. 3.

Figure 12 shows the application window (Pelton Nozzle) for the flow pattern analysis in a Pelton nozzle according with Figure 4 and Eq. 4.

Figure 13 shows the application window (Bulb Turbomachinery) for the flow pattern analysis in a bulb turbomachinery according with Figure 5 and Eq. 5.

Figure 14 shows the application window (Radial Turbomachinery) for the flow pattern analysis in radial turbomachinery according with Figure 6 and Eq. 6.

Figure 15 shows the application window (Francis Turbine) for the flow pattern analysis in a Francis turbine according with Figure 7 and Eq. 7.

Figure 16 shows the application window (Kaplan Turbine) for the flow pattern analysis in a Kaplan turbine according with Figure 8 and Eq. 8.
Figure 12. The application window for Pelton nozzle.

Figure 13. The application window for bulb turbomachinery.

Figure 14. The application window for radial turbomachinery.

Figure 15. The application window for Francis turbine.

Figure 16. The application window for Kaplan turbine.

4. CONCLUSIONS

The PFSim_2 program (Potential Field Simulation) represents a very useful tool in order to perform complex analysis of the flow pattern in different types of turbomachinery: axial, radial-axial and radial turbomachinery; Pelton nozzle, as well as bulb, Francis and Kaplan turbines.

The interactivity between user and the PFSim_2 program refer to the possibility of adjusting both the parameters that define the fluid flow structure (the discharge values for both the point and the distributed sources, the position of the point sources, the length of the distributed sources, the velocity magnitude, the fluid flow domain, the matrix computation dimension), but also the parameters that define the plotting and visualization conditions (the zoom function, the potential lines an the streamlines numbers, the labelling process).
The high interactivity level of the PFSim_2 program allows to obtain different flow patterns for the same fluid flow structure and to observe the just sense of changing of certain flow parameter.

REFERENCES