Unsteady Character and Flow Fields in an Axial Blood Pump under Pulsatile Pressure Boundary Condition

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Abstract. Blood pumps have been widely used as a temporary method for heart failure. In recent years, the challenging factors in design have generally concentrated on how to deal with the complicated time-dependent fluid dynamics. Therefore, this research studies the impact to flow field by pulsatile boundary condition with both steady and unsteady numerical simulations. For steady computation, total pressures of 20, 40, 60, 80, 100mmHg and an average pressure of 120mmHg were given at the inlet and outlet respectively, and an unsteady simulation was then conducted with the same fixed pressure of 120mmHg at the outlet but a periodical sinusoidal pressure within 20 and 100mmHg at the inlet. Compared with a single character line drawn through the steady points, the unsteady computation resulted in a closed elliptic character curve. In the whole range of operation of the unsteady condition, flow field showed a well-attached flow in rotor passage but a large area of recirculation in the second row of stator passages. By contrast, flow field in the first row of stator passages and the pressure on the surface of rotor blades were greatly impacted by the acceleration and deceleration of the flow rate, which can be well explained by the change of incidence. Besides, flow rate acceleration or deceleration exaggerated a non-uniform distribution of velocity, which can easily form a larger area of high scalar shear stress than the steady results. A special pressure distribution between rotors and stators was also observed in unsteady flow.

1. Introduction

Heart failure is a direct death threat to human beings all the time. To deal with that, blood pump was designed to augment output pressure and flow rate of the native heart [1].

As the working fluid of blood pump, blood contains many kinds of blood cells which requires more consideration of its identified property. High velocity gradient in pump may induce supra-physiological stress to the blood. Consequently, hemolysis and activation of platelet are determined by area of stress region and blood cells exposition time [2]. Another challenge is the formation of thrombosis induced by flow separation, stagnation or recirculation, which make blood clots deposit on the surface of pump and change its geometry [3]. Therefore, evaluation to the pump should focus on separation, recirculation and high stress regions inside the pump.

In common practices, design process and experimental verification of character and flow fields of blood pumps are only evaluated under steady conditions with a fixed physical value on pump’s inlet and outlet. However, with the effect by active heart contraction, the flow rate through the pump varies during the heartbeat, even while the pump is operating at a constant rotational speed. In contrast to
steady operation, a closed elliptic character curve instead of a line was observed in an animal experiment [4]. Similar loops were also observed in unsteady numerical computations [5],[6],[7] and mock heart-loop experiments [8],[9],[10], [11]. Using unsteady Computational Fluid Dynamics (CFD), Song [12] evaluated the change of character when boundary pressure varied with time after designing under steady conditions. Shu [9],[13] researched the influence to flow fields by flow acceleration or deceleration and related flow fields to two non-dimensional variables, that is, flow coefficient and flow acceleration coefficient. This article studies the impact to character and flow fields by a sinusoidal pulsatile boundary condition with both steady and unsteady numerical simulations.

2. Methods

2.1. Research model
The axial pump is composed of a row of rotor and stator, as shown in Figure 1 [14],[15]. In order to control flow separations, two splitters are employed in the latter half of the rotor, which have same profile with the main blades. In the stator row, tandem cascade is adopted with five upstream vanes and five downstream vanes to improve the pressure-rise capability. The detailed design parameters are listed in Table 1.

Table 1. Design parameters of the axial pump.

| Design parameters | Rotor | Upstream vane | Downstream vane |
|-------------------|-------|---------------|-----------------|
| Number of blades  | 2     | 5             | 5               |
| Number of splitters | 2   | 0             | 0               |
| Inlet hub/tip ratio | 0.32 | 0.83          | 0.80            |
| LE tip diameter   | 12.7mm | 12.7mm        | 12.7mm          |

Figure 1. Structure map of the research pump.

2.2. CFD Method
Both the steady-state and time-resolved flow fields were simulated using the 3-D RANS solver ANSYS 17.1. The Reynolds number is computed using:

\[ \text{Re} = \frac{V_D}{\nu} \]  

in which \( V_\infty \) (m/s) is the inlet free-stream velocity, \( D \) (m) the tip diameter at the rotor outlet, \( \nu \) (m²/s) the kinematic viscosity. The Reynolds number was computed to be around \( 1 \times 10^4 \) in the simulation. The turbulent Reynolds stress is treated employing the Shear Stress Transport (SST) model to have a good prediction both inside and outside the boundary layer. The computational domain includes the inlet tube, rotor, stator and the outlet tube, as shown in Figure 2. The whole passage meshes are used. O-grid topology was applied around the blade surface for good orthogonality and grid refinement was
carried out near walls. Both the steady and unsteady flow fields were predicted using whole-annulus meshes, and the total number of the mesh nodes is 4924546, with 3567186 in the rotor and 1357360 in the stator. The independence of mesh and the reliability of steady simulations compared with experiments have been verified in previous articles [16],[17], [18]. The computation was first run in steady mode using the mixing-plane model to transfer flow quantities between the rotor and stator rows. A set of total pressures (relative to atmospheric pressure) of 20, 40, 60, 80, 100mmHg were given at the inlet and a fixed average static pressure of 120mmHg at the outlet. The iterations proceeded until the average residual error dropped to $10^{-6}$. Considering the effects by the active heart contraction, an unsteady simulation was then conducted with the same fixed pressure of 120mmHg at the outlet but a periodical sinusoidal pressure within 20 and 100mmHg at the inlet. The steady result was used as the initial condition for the time-accurate mode with a transient interface model between the blade rows. The time-accurate simulation was run with 100 physical time steps per cycle and at least 5 inner iterations per time step. It took about 3 cycles for the simulation to converge to a periodic solution.

![Figure 2](image_url). The blade-to-blade view of the computational domains.

3. Results

3.1. Steady and unsteady character
The pressure rises over outlet and inlet and flow rates through the pump in steady numerical computation converge to separated character points on Figure 3, which can be fitted to a single line. By contrast, character of the unsteady result with pulsatile boundary shows in Figure 3 is a closed elliptic character curve. The transient character point rotates in anti-clock direction with a higher pressure rise in the deceleration of flow rate and a lower in acceleration, and the flow range of unsteady operation was totally located in that of the steady conditions with the same pressure rises. Three groups of points with same pressure rise were compared in following content. Group I is the highest boundary of unsteady character with a pressure rise of 100mmHg and flow rates of 3.278 and 3.426 L/min on steady and unsteady character respectively. Group II is the lowest boundary with a pressure rise of 20mmHg and flow rates of 5.000 and 4.865 L/min on steady and unsteady character respectively. Group III contains points near the maximum flow rate difference of unsteady character with a pressure rise of 60mmHg and flow rates of 4.292 L/min on steady line and 3.998, 4.439 L/min on unsteady loop.
3.2 Differences on flow fields
Flow fields on 0.5 span of the blades shown in Figure 4 are examined as the average behavior of the three-dimensional flow. In both steady and unsteady results, there exists no area of separation or recirculation in rotor, but a large area in second row of stator. However, flow fields in first row of stator was influenced more by acceleration and deceleration of flow rates. In Group I, flow rate of unsteady is bigger than that of steady, which means a more negative incidence on stator in unsteady result. What makes it surprised, the separation points near the trailing edge (TE) differ little between both results. Due to a higher flow rate, the unsteady separation influences a larger region than steady, which even extends to the second row of stator and impacts more. Things turn more reasonable in Group II when unsteady flow rate is smaller than steady. The more negative incidence of steady stator induces a larger separation area on its pressure side. In Group III, there is no obvious separation in steady stator, but separations occur on blade’s suction and pressure side in unsteady low and high flow rate point respectively, due to the change of incidence.

![Figure 3. Steady and unsteady character.](image)
3.3. Scalar stress analysis

In order to describe the impact to cell rupture by shear stress, a scalar stress [19] is defined as,

\[
\sigma = \frac{1}{6} \sum (\sigma_i - \sigma_j)^2 + \sum \sigma_i^2 \overline{\bar{c}}
\]  

As shown in Figure 5, on blade-to-blade surface of 0.5 span in Group I, higher stress shows in unsteady rotor passage than steady because of less uniformity of velocity distribution circumferentially. Besides, larger velocity gradient near the TE of first stator row in unsteady result creates a high stress region which extends to second blade row. Higher stress also shows in unsteady rotor passage of in Group II, while a smaller high stress region on pressure side of unsteady stator, with consistency to previous analysis on flow field, is shown compared with steady result. In Group III, higher stress also shows in unsteady rotor passage compared with steady result. High unsteady flow rate point creates a high stress region in pressure side of stator. Due to the velocity gradient, a lower stress region is shown near the TE of unsteady stator even though the separation point in this case locates anterior to steady result, which is consistent with previous analysis.
3.4. Blade load and pressure rise of rotor

A more non-uniform circumferential velocity distribution in unsteady rotor passage caused by rotor blade load and pressure rise are compared with steady results. On 0.5 span of rotor blades, as the tangent velocity in rotor is much higher than axial velocity, the incidences of steady and unsteady rotor are almost the same, so the differences are mainly located in latter part of rotor. Figure 6 compares surface pressure of rotor in each group. In Group I, pressure on unsteady rotor surface is bigger than steady, while it turns reversely in Group II. In Group III, pressure on pressure side of steady rotor is larger than that in unsteady lower flow rate and smaller than that in unsteady high flow rate, while the sequence of pressure value changes differently on suction side of rotor. However, what is in common with all three groups is that steady rotor has the largest pressure difference between its pressure and suction side, and has the lowest pressure rises.

Figure 5. Scalar stress distribution in steady and unsteady results (top: Group I; middle: Group II; bottom: Group III).
4. Conclusion

The conclusion is as following,

1) In the whole range of operation of the unsteady condition, flow field showed a well-attached flow in rotor passage but a large area of recirculation in the second row of stator passages. By contrast, flow field in the first row of stator passages were greatly impacted by the acceleration and deceleration of the flow rate, which can be well explained by the change of incidence.

2) In low flow rate, even when separation point on stator’s suction side is posterior, higher velocity gradient and larger stress area may occur near the TE.

3) Generally, flow rate acceleration or deceleration exaggerated a non-uniform distribution of velocity; which can easily form a larger area of high scalar shear stress in rotor passage than the steady results.

4) A special pressure rise distribution between rotor and stator was also observed in unsteady flow. Compared with unsteady results, the pressure difference between pressure and suction side of rotor blades is larger in steady results.

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