COMPUTATIONAL FLUID DYNAMICS SIMULATIONS OF ENERGY-SAVING VORTEX RING THRUSTER USING COANDA EFFECT

YOUNGMIN HEO¹, WOOCHAN SEOK², SHIN HYUNG RHEE³
¹Seoul National University, Seoul, Korea, heoym1@snu.ac.kr
²Research Institute of Marine Systems Engineering, Seoul National University, Seoul, Korea, swc@snu.ac.kr
³Seoul National University, Seoul, Korea, shr@snu.ac.kr

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One of the jet propulsion systems, a Vortex Ring Thruster (VRT), has better propulsion performance than other propulsion systems at low speeds. It is also economical in terms of cost and relatively small volume, making it suitable for unmanned underwater vehicles (UUVs) (Mohseni, 2006).

The VRT is a piston-cylinder mechanism, as shown in Figure 1. Various studies using such a piston-cylinder mechanism have been conducted. Gharib et al. (1998) conducted experiments about the vortex ring, which occurs in piston shapes with a diameter of D and a length of L. The vortex ring was observed by setting the ratio of piston length to diameter, dubbed stroke ratio, and various ranges. It was confirmed that a leading vortex ring was clearly observed in the wake region, and the trailing jet did not occur in the range of stroke ratio less than 4. Rosenfeld et al. (1998) carried out computer fluid dynamics (CFD) simulations to investigate the generation and evolution of vortex rings. For the evaluation of the propulsion performance of VRT, Zhang et al. (2020) systematically studied the generation and evolution of vortex rings and the propulsion efficiency using a piston-nozzle computational model.

The governing equations are the continuity equation and Navier-Stokes equation for incompressible, which was expressed as follows:

\[ \nabla \cdot \mathbf{u} = 0 \]  
\[ \frac{\partial u_i}{\partial t} + (u_i \cdot \nabla) u_i = -\nabla p + \nu \nabla^2 u_i \] (2)

where \( u_i \) is velocity in three-axis directions (\( i = x, y, z \)), \( \nabla \) is divergence operator, \( \nabla^2 \) is Laplacian, and \( \nu \) is the fluid kinematic viscosity. The second-order implicit scheme was used for temporal discretization, and the second-order central finite difference scheme was used for spatial discretization. Dynamic mesh techniques were used to control piston motion. The PIMPLE algorithm was applied for the pressure-velocity coupling, which is a combination of both the semi-implicit method for pressure-linked equations (SIMPLE) and the pressure implicit with the splitting of operators (PISO) algorithm (Chen et al. 2014).

The main purpose of this study was to design a more propulsion-efficient VRT than a conventional VRT, using the Coanda effect. Numerical simulations were conducted on two VRT: VRT, which has only a primary jet, and VRT, which has a primary jet with a Coanda jet. The computational domains and boundary conditions of the conventional VRT and VRT considering the Coanda effect (hereafter referred to as CVRT) are shown in Figure 2. Dimensions of the piston and nozzle were exactly the same as experiments of Gharib et al. (1998). The whole computational domains were axisymmetric. The diameter (D) of the nozzle is 0.0254m, and the total length of the piston is 0.4m. The computational domain size is 20D × 3D in the x-, y-directions, respectively.

Figure 1 Schematic of the piston-cylinder mechanism

Figure 2 Domain dimensions and boundary conditions of conventional VRT and CVRT
For numerical validation, CFD simulations of the conventional VRT were carried out and compared with the previous numerical simulation results (Rosenfeld et al. 1998; Zhang et al. 2020) and experimental data (Gharib et al. 1998). Formation time $t^*$ and stroke ratio $T^*$ are non-dimensional times that represent total piston moving time and the piston moving time, respectively. They were defined as follows:

\[ t^* = \frac{L}{D} = \frac{U_p t}{D} \]  
\[ T^* = \frac{L_T}{D} = \frac{U_p T}{D} \]  

where $L$ is the distance of piston motion, $L_T$ is piston stroke and $D$ is the inner diameter of the nozzle.

In this case, piston velocity $U_p$ is a uniform discharge program, which is 0.1524 m/s. Figure 3 presents the non-dimensional circulation change with the formation time $t^*$ for stroke ratio $T^* = 6$. Total circulation and vortex ring circulation are in good agreement with the previous study.

\[\text{Figure 3 Comparison of total circulation and vortex ring circulation}\]

For the evaluation of propulsion performance for the VRT and CVRT, the thrust and propulsion efficiency were used, and this expression was proposed by Zhang et al. (2020). The thrust $F_T$ and propulsion efficiency $\eta$ were defined as follows:

\[ F_T = \rho \int u_s dA + \int (p - p_0) dA \]  
\[ \eta = \frac{\int_{1}^{T^*} F_T dt}{\int_{1}^{T^*} (F_p U_p + F_e U_e) dt} \]

where $A$ is the area of the piston exit-surface, $p_0$ is the ambient pressure, $F_p$ and $F_e$ are the pressure force on the piston of the primary jet and the Coanda jet, respectively.

In the future work, the propulsion performance of the CVRT would be evaluated comparing to that of the VRT using equations (5) and (6). In addition, the formation and evolution of vortex ring generated from the CVRT and VRT would be analysed.

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