UNMANNED MINE-CLEANING UNDERWATER VEHICLE NUMERICAL DRAG PREDICTION

NUMERYCZNA PROGNOZA CHARAKTERYSTYKI OPOROWEJ BEZZAŁOGOWEGO, PRZECIWMINOWEGO POJAZDU PODWODNEGO

Maciej Kaczmarczyk¹, Jacek Jachowski²

¹ Gdansk University of Technology ² Gdynia Maritime University

e-mail: ¹ mmkaczmarczyk@o2.pl ² jjachowski@o2.pl

Abstract: At the beginning of the XXI century unmanned underwater vehicles such as ROV or AUV became common in use around the world. They are useful, practical and helpful in many underwater works. Moreover, in many cases they can be a good replacement for men. But to secure good man-machine cooperation or substitution high reliability is required as well as safety in everyday use – especially in the Navy. Therefore, beyond functionality, these two main factors are the most important in designing and then operating such vehicles. It can be achieved in many different ways, but one of the most sensitive and prone to damage elements is vehicle propulsion system. Commonly in use bare propellers are in danger of being damaged by many different things floating under the surface. To try to avoid such situation and find an alternative solution, there was an idea to design and build the ROV powered by a waterjet drive. This paper focuses on numerical drag prediction for underwater vehicle with two different propulsion systems. The pros and cons for each solution are also presented.

Keywords: propulsion system, underwater vehicle, ROV, AUV, waterjet, CFD

Streszczenie: Na początku XXI bezzałogowe pojazdy podwodne stały się powszechne w użyciu, a ich wykorzystywanie w różnych typach prac nikogo już nie dziwi. Bez względu na to, czy mamy do czynienia ze zdalnie sterowanymi ROV, czy pływającymi swobodnie AUV są one bardzo praktyczne i pomocne w pracach na dowolnych głębokościach, czy wielkich obszarach, jak morze, czy ocean. Z powodzeniem współpracują z człowiekiem lub, niejednokrotnie, są w stanie zastąpić go całkowicie, czy wykonać pracę dla niego niedostępną. Jednak warunkiem dobrej kooperacji jest niezawodność oraz bezpieczeństwo użytkowanego urządzenia. Poza funkcjonalnością, wspomniane dwa czynniki wydają się być kluczowe dla procesu projektowania, a następnie użytkowania pojazdu. Można to zrealizować na wiele sposobów, jednak jednym z kluczowych elementów, bez wątpienia, jest napęd. Powszechnie stosowane śruby są niestety bardzo podatne na różnego rodzaju uszkodzenia mechaniczne, dlatego podjęto próbę znalezienia rozwiązania alternatywnego, jakim okazać się może napęd strugowodny. W poniższym artykule przedstawiono prognozę oporową dla pojazdu podwodnego wyposażonego w dwa różne typy napędu, a następnie porównano je przedstawiając wady i zalety obu rozwiązań.

Słowa kluczowe: systemy napędowe, pojazdy podwodne, ROV, AUV, waterjet, napęd strugowodny, CFD

1. Introduction

The last ten, twenty years of rapid technological development made many new possibilities. One of them is an opportunity to substitute man by a machine in most of underwater works. Moreover, using remotely operated vehicle sometimes enables performing the task at all, or makes it easier and cheaper. These submersible robots are divided into two main categories: AUV – an autonomous underwater vehicle and ROV – remotely operated vehicle. The first one is an independent vehicle executing previously programmed tasks. The second, connected with the surface via tether, is controlled live. They may divide in shape, sizes and functions, but what they all have in common is their propulsion system based on traditional propellers. And omitting other potential sources of problems this seems to be the gravest one from operator's point of view. Whether or not there is any protection propellers are in hazard of being damaged by anything floating in the water. It is important for small vehicles operating in restricted areas such as docks, lakes, rivers etc. especially. Even a small thing can cause serious mechanical damages. It hampers work schedule, complicates task and in an extreme situation can lead to a loss of a vehicle. It generates financial losses too. So, regardless of who operates the vehicle and what type of work performs, it is crucial to develop reliable device that secures safe work.

Obviously any drive failure is unacceptable. And the number of unpleasant experiences gained in practice (see *Fig. 8*) forced a search for a new, alternative solution. Bare propellers and ducted propellers used so far proved to be to prone. Admittedly developing a propellers guard (see *Fig. 1* and *Fig. 9*) improved propeller safety significantly, but in the same time decreased efficiency heavily. Hence there was an urgent need of finding an alternative solution to currently in use standard propellers. In search for potential solution among available designs – including design changes – and after detailed theoretical analysis of the problem ^{[1], [2], [3]} and scrutiny of the work of other scientists and engineers ^{[4], [5], [6], [7], [8], [9]}, the choice fell on waterjet drive.

Fig. 1. Currently in use ROV with mesh-guarded propellers.

The main waterjet drive advantage is the fact that, in its basic configuration, it has no protruding elements and the propeller (rotor) is fully covered by propulsion tunnel (see *Fig. 2*). This protection seems to be enough against most of possible threats. Additionally, using a steering box fixed at the outlet nozzle may increase

vehicle manoeuvrability. The general scheme of a standard waterjet drive is presented in the Fig. 3. Its principle of operation is similar to the air jet engine and the only differences are impellent and the range of flow velocities.

Fig. 2. One of the investigated waterjet drives fixed to the vehicle. No protruding elements at the rear end.

Fig. 3. Longitudinal section of an exemplary waterjet propulsion. Description: 1 inlet, 2 rotor, 3 stator, 4 outlet nozzle, 5 pump, 6 steering box; the blue arrows stand for impellent flow direction (water).

Of course the risk of sucking in numerous tiny things during operation (such as tether, strings, plastic bags, pieces of rags and any other debris) still exists, but is much smaller than previously.

As it can be seen in the figures above, waterjet propulsion aft is also much smoother than the standard one and carries no mesh-guard. Therefore another big gain is expected in vehicle resistance.

2. Vehicle drag prediction with a use of Computational Fluid Dynamics

The aim of this analysis was to estimate vehicle drag force for three different configurations:

- bare propellers
- propellers with mesh-guard
- waterjet drive

As it was mentioned earlier, the biggest and the most urgent problem in everyday use was sucking in numerous things – the tether especially. It led the vehicle to stop many times. And because no serious changes in vehicle design were possible

it was necessary to introduce efficient modification or alternative solution. The simplest one was to fix propellers covering mesh. It was not perfect, but gave basic protection and reduced number of incidents. But before the propellers guard and the waterjet were developed detailed analysis was performed.

The CFD simulations presented in this paper contained turbulence mathematical model selection, mesh settings validation, prediction and correction. Below, all of the stages were presented and short comments added.

Simulation settings validation via experimental results

Basing on empirical results for ROV powered by standard, bare propellers the mathematical model of turbulence was chosen. The experiments were performed at unlimited water (Jeziorak Lake in Hawa). Such data are more valuable than experimental tank ones, because they were obtained in an environment representing the operating area.

The Reynolds Averaged Navier–Stokes Equations choice was obvious as it is less demanding than Direct Numerical Simulation. And among the models available it was decided to use a simple, two-equation $k-\omega$ model. Such two-equation models are very common and widely used, because they offer well balanced compromise between numerical effort and computational accuracy. "One of the advantages of the $k-\omega$ formulation is the near wall treatment for low-Reynolds number computation. The model does not involve the complex nonlinear damping functions required for the $k-\varepsilon$ model and is therefore more accurate and more robust."^[10] A low-Reynolds number flow areas in $k-\varepsilon$ formula require greater mesh density near the wall. In practice, where complex-shape geometry is analysed, satisfying, high resolution for $y+$ factor might be impossible to achieve.

The presented model was developed by Wilcox. It solves to transport equation where the k stands for turbulent kinetic energy and ω represents turbulent frequency.

k equation ^{[11], [12]}

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial U_i}{\partial x_j} - 0.09k\omega + \frac{\partial}{\partial x_j} \left[\left(\nu + 0.5 \frac{k}{\omega} \right) \frac{\partial k}{\partial x_j} \right] \quad (1)$$

ω equation ^{[11], [12]}

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \frac{5}{9} \frac{\omega}{k} \tau_{ij} \frac{\partial U_i}{\partial x_j} - \frac{3}{40} \omega^2 + \frac{\partial}{\partial x_j} \left[\left(\nu + 0.5 \frac{k}{\omega} \right) \frac{\partial \omega}{\partial x_j} \right] \quad (2)$$

where U stands for velocity, τ is molecular stress tensor (includes normal as well as shear components of the stress), ν represents water kinematic viscosity coefficient and x is an element location. Depending on the software the formulas can take various forms, but do not differ much from each other.

The satisfying prediction accuracy was assumed at $\pm 10\%$ level. It was motivated by relatively low forces that had to be measured in a real vehicle experiment. The numerical model convergence with experimental data for bear propellers configuration (without mesh-guard) reached 2% at the operating point. All of the results presented below refer to the operating point. It represents vehicle drag at a speed of 3 [m/s] ($R=100\%$) for each drive configuration.

Fig. 4. Experimental results compared to its CFD representation – numerical settings evaluation.

Predictions, validations and corrections

Subsequently series of numerical drag predictions for mesh-guarded propellers and waterjet powered vehicle were conducted. Simulations, in each case, covered velocity range $0.5 \div 3.0$ [m/s] with 0.5 [m/s] per step. One mesh was used in two successive steps, which resulted in three different meshes used at all in one case.

Later, when the real vehicle was investigated and numbers of tests were carried out, the results were compared.

The result convergence for mesh-added configuration fluctuates between positive 5% and negative 6% in all steps. It is regarded as an excellent result.

In case of waterjet propulsion convergence approached to 10% limit and extrapolation tendency suggests further divergence. However, as it was mentioned earlier, the key here was the operating point and all attention should focus on it. In order to improve relation between CFD analyses and the real experiments, after tests, another series of simulation was performed. It led to convergence improvement, but kept tendency to overestimate the drag force values.

3. Conclusion

The results obtained during numerical simulations correspond very well with the empirical ones. However, very careful approach is recommended if results for lower velocities were important – the extrapolation curve for the lowest velocities does not reflect the experimental tank results precisely.

The drag, as it was expected, was reduced significantly. The difference between protected propellers and waterjet drive reach 40%. It is a huge drop of resistance (see *Fig. 7*) and, if theoretical analyses were correct, it might pay off replacing standard propellers by waterjet propulsions.

In conclusion, the efficiency decrease due to propeller diameter reduction and a rise of velocities range might be covered and compromised by a vehicle drag reduction.

Fig. 5. Numerical drag prediction for mesh-guarded propellers compared to experimental results.

Fig. 6. Numerical drag prediction for waterjet powered vehicle. Prediction and post simulation results confronted with the experiment.

Fig. 7. The drag force for different vehicle configuration.

Fig. 8. Tangled tether on one of the previous vehicles.

Fig. 9. The first version of mesh-guard during tests.

4. References

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Maciej Kaczmarczyk (MSc. Eng.) graduated at Gdansk University of Technology (Faculty of Ocean Engineering and Ship Technology, Department of Theory and Ship Design) in small underwater vehicles control and drive systems. Then received a postgraduate degree (Faculty of Applied Physics and Mathematics) in numerical engineering simulations. Currently working on his Ph.D. thesis, which deals with a use of waterjet propulsion systems in small underwater vehicles.

Jacek Jachowski (MSc. Eng.), assistant at Gdynia Maritime University, specialization: safety of navigation and Computational Fluid Dynamics of three-dimensional and free-surface ship flows. Currently working on his Ph.D. thesis, which deals with modeling ship squat in shallow water using Computational Fluid Dynamic simulations.