CFD Based Added Mass Prediction in Cruise Condition of Underwater Vehicle Dynamic

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Abstract. One of the unsteady flow behavior on the hydrodynamic characteristics of underwater vehicle is the presence of added mass. In cruising conditions, the underwater vehicle may require the addition of speed or experience the disturbance in the form of unsteady flow so that cause the hydrodynamic interaction between the surface of the vehicle with the surrounding fluid. This leads to the rise of local velocity of flow and the great changes of hydrodynamic forces which are very influential on the stability of the underwater vehicle. One of the result is an additional force called added mass. It is very useful parameter to control underwater vehicle dynamic. This paper reports the research on the added mass coefficient of underwater vehicles obtained through the Computational Fluid Dynamic (CFD) simulation method using CFX software. Added mass coefficient is calculated by performing an unsteady simulation or known as transient simulation. Computational simulations are based on the Reynolds Average Navier-Stokes (RANS) equation solution. The simulated vehicle moves forward and backward according to the sinus function, with a frequency of 0.25 Hz, a 2 m amplitude, a cruising depth of 10 m below sea level, and Vcruise 1.54 m / s (Re = 9.000.000). Simulation result data includes velocity contour, variation of force and acceleration to frequency, and added mass coefficient.

Keyword: Underwater vehicle; Unsteady hydrodynamic; Transient simulation; added mass coefficient.

1. Introduction

Added mass is a physical phenomenon that arises from the acceleration of objects in the fluid. Research on added mass is still being done because of its many benefits in underwater vehicle development. In fluid mechanics, added mass or virtual mass is the additional mass and inertia to the system due to acceleration or deceleration. This causes the fluid traversed by the object to be moved away because the object can not be occupied in the same time and space simultaneously. The movement of objects will accelerate the surrounding fluid with varying magnitude. The coefficient matrix added mass is a dimensionless value which can be expressed in the added mass coefficient divided by the mass of the displaced fluid. The added mass coefficient represents a force and moment component which is proportional to the acceleration. In general, this coefficient is in the form of a second order tensor where the value of each component depends on the vector of acceleration and the geometry of the object. The force vector added mass is always opposite the acceleration vector of the object.
The first added mass began to be investigated in 1776 by Dubua using a spherical pendulum experiment. Today, there has been a lot of research on this subject. Chen, et al [1] conducted an analytical and experimental study of added mass and damping on the vibrating rod. K. Vikestad et al [2] has calculated the value of added mass by experiment with a lightly damped elastically mounted rigid cylinder subjected to constant flow velocity. The analysis of added mass and damping on the circular cylinder, which oscillates in an air numerically has been performed by Uchiyama [3]. Ghassemi and Yari [4] have carried out the added mass computation of sphere, ellipsoid and marine propellers using boundary element method. Similar research about mass coefficient on underwater vehicles has also been done by Eng, et al [5]. They used experimental methods with a sinusoidal motion approach of scaled vehicle in water, known as Free Decay Test. The result through this experiment then compared well with the simulation results obtained from well-established computational fluid dynamics (WAMIT Software). Thus, the proposed approach can be use to find the added mass for other underwater vehicles.

This paper presents the added mass coefficient of the underwater vehicle maneuver in cruise condition. The simulation is performed at a frequency of 0.25 Hz and at a reynold number of 9,000,000. To model the motion, the axial position of the object changes with respect to time and the path of motion according to a sinus function that has been set on CFX software. The flow model uses k-ε turbulence model. In addition, the computational domain around the underwater vehicle model has been made in multilayer domain to modeling simulated motion.

2. Computational Method

2.1 Geometry and Mesh Generation

Before perform the simulation, the definition of the computational domain, including the creation of the underwater vehicle geometry and mesh generation has to be carried out. The mesh generated in the computational domain has to accurately capture flow properties, such as velocity, pressure, and to properly model the underwater vehicle body. High quality (orthogonal) mesh is very important to prevent a negative volume during the simulation. For complex geometries such as the body, fin, and thruster of a vehicle, an unstructured mesh was created.

2.1.1 Geometry

| Table 1. Underwater Vehicle Configuration |
|------------------------------------------|
| The length of the hull                   | 4.3 m                        |
| Capacity (driver)                        | 2 person                     |
| Maximum Payload                         | 50 kg                        |
| Dry Empty Weight                        | 1100 kg                      |
| Battery Capacity                        | 9 kwh                        |
| Thrust Engine                            | 182 kgf in bollard condition |
|                                          | 109 kgf for cruising speed of 3.08 m/s |
| Diving Method                            | Automatic Bouyancy System    |
| Cruise Depth                             | 10 m                         |
| Maximum cruise depth                     | 20 m                         |
| cruise speed                             | 1.54 m/s                     |
| Maximum cruise speed                     | 3.08 m/s                     |
The geometry was created using CATIA software. The design adopts an existing mini submarine with little improvement on the hull and fin shape.

![Geometry of Underwater Vehicle](image)

**Figure 1.** Geometry of Underwater Vehicle

### 2.1.2 Mesh Generation

Setting the size and quantity of elements and good mesh quality will improve the efficiency of the computing process. This process is performed using the Altair Hypermesh 13.0 software. Domain form that surrounds the object is cylinder-shaped with a diameter of 3.3 times the length of the object. The domain length in front of the nose is 2.1 times the length of the object, as well as the domain length behind the tail is 9 times the length of the object. In meshing process, the computational domain is divided into three parts, namely inner, outer, and downstream domains. Inner domain is the domain that directly interact with the vehicle, consisting of 3 parts namely the boundary layer, layer 1, and layer 2. For the outer domain is divided into 2 parts namely layer 3 and layer 4. The front size for the inner domain or layer 2 is 0.5 times the length of the object, the measured rear distance from the tail is 3 times the length of the object, while for the diameter of layer 2 is 4 times the width of the object.

Inner domain is defined as a domain that is move simultaneously with the vehicle while the outer domain is defined as a fixed or immovable domain. The division of move and fixed domains is to avoid the occurrence of folded mesh when the displacement of the object is considerable. This will cause a negative volume on the calculation results. For this downstream domain measuring 9 time the object body length. This section serves to capture the properties of the eddy flow that occur due to the movement of object, so that the results of the calculation is closer to real conditions.
Figure 2. Mesh generation for Underwater Vehicle

| Domain   | Nodes | Elements |
|----------|-------|----------|
| fluid 0 | 4171835 | 16650611 |

2.2 Motion Modeling

To obtain the added mass coefficient in cruise condition (axial direction), simulation is performed for one mode of motion. Therefore, simulation will be set so that the object moving back and forth or the position change on the positive and negative X-axis by time. The translational motion above is modeled by the following harmonic oscillation equation.

\[ X(t) = X_{\text{max}} \sin(2\pi ft) \]  

(1)

Figure 3. Motion illustration

| Xmax [m] | \( \omega \) [rad/s] | \( f \) [Hz] | \( \Delta t \) [s] | Total time Run |
|----------|---------------------|--------------|----------------|---------------|
| 2        | 1.57                | 0.25         | 0.05           | 10 [s]        |
3. Results and Discussions

(a) Time Domain Data

The calculation result of force and moment for each timestep, $\Delta t$ from the CFX is then plotted to see the resulting signal pattern. Below is presented plot of force and moment against time.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{force_moment_vs_time.png}
\caption{Time domain data for added mass force and moment}
\end{figure}

(b) Frequency Domain Data

The data set in point (a) is required as input data to be analyzed using fourier transforms. In its application, this fourier transform is already found in MATLAB software in the form of Fast Fourier Transform (FFT). Can be seen in Figure 4, the time-varying signal pattern of force and moment as a function of time is very complex, indicating that there are many combinations of harmonic wave with difference frequency and magnitude. Figure 5 show the result of the fourier transformation of added mass force and moment using Fourier Transform Method.
Figure 5. Frequency domain data for added mass force and moment
Figure 6. Velocity contour around the underwater vehicle
Top figure (x=0, t=4 s) dan bottom figure (upstroke, t=5 s)

Figure 7. Velocity contour around the underwater vehicle
Top figure (t=6 s, x=0) dan bottom figure (t=7 s, downstroke)

(c) Added mass coefficient

Table 2 below shows the value of added mass force and moment component due to axial acceleration.
Table 2. Added mass Force and Moment Component

| X\(\dot{u}\) [N] | Y\(\dot{v}\) [N] | Z\(\dot{w}\) [N] | K\(\dot{t}\) [Nm] | M\(\dot{r}\) [Nm] | N\(\dot{p}\) [Nm] |
|----------------|----------------|----------------|----------------|----------------|----------------|
| -1714.70       | -5.32          | -252.12        | -9.55          | -897.03        | -2.33          |

Based on reference [6], due to port and starboard symmetry of vehicle geometry, the added mass force in lateral direction (y-axis) can also be assumed zero. Similarly, added mass moment in x and z axis for this vehicle can also be assumed zero. According to Table 2, there is still a value of force and moment in this axis but relatively small, so it can be ignored. This is due to the computational error on ANSYS CFX. Based on table 2, the significant added mass forces and moment are X\(\dot{u}\), Z\(\dot{w}\), dan M\(\dot{r}\). The total added mass force and moment for vehicle with port and starboard symmetry expressed in equation 2 [6].

\[
\begin{align*}
X_{AM} &= -A_{11}\ddot{u} - A_{13}\ddot{w} - A_{15}\ddot{q} - A_{31}U_{0}\ddot{q} \\
Y_{AM} &= -A_{22}\ddot{v} - A_{24}\ddot{p} - A_{26}\ddot{r} - A_{11}U_{0}\ddot{r} + A_{31}U_{0}\ddot{p} \\
Z_{AM} &= -A_{33}\ddot{u} - A_{35}\ddot{w} - A_{37}\ddot{q} - A_{11}U_{0}\ddot{q} \\
K_{AM} &= -A_{42}\ddot{v} - A_{44}\ddot{p} - A_{46}\ddot{r} + A_{51}U_{0}\ddot{r} - A_{31}U_{0}\ddot{v} \\
M_{AM} &= -A_{51}\ddot{u} - A_{53}\ddot{w} - A_{55}\ddot{q} + A_{31}(U_{0}^{2} + 2U_{0}\ddot{u}^{*}) + (A_{33} - A_{11})U_{0}\ddot{w} + A_{35}U_{0}\ddot{q} \\
N_{AM} &= -A_{62}\ddot{v} - A_{64}\ddot{p} - A_{66}\ddot{r} - (A_{22} - A_{11})U_{0}\ddot{r} - (A_{24} + A_{51})U_{0}\ddot{p} - A_{26}U_{0}\ddot{r}
\end{align*}
\]

The component of added mass and Moment due to only axial acceleration shows in table 3.

Table 3. Added Mass Component Due to Axial Acceleration (\(\ddot{U}\))

| \(m_{11}\) [Kg] | \(m_{21}\) [Kg] | \(m_{31}\) [Kg] | \(m_{41}\) [Kgm] | \(m_{51}\) [Kgm] | \(m_{61}\) [Kgm] |
|----------------|----------------|----------------|----------------|----------------|----------------|
| 349.65         | 1.08           | 51.41          | 1.95           | 182.92         | 0.48           |

\(\ddot{U} = 4.90 \text{ m/s}^2\) (obtain from FFT)

Value of \(m_{21}\), \(m_{41}\), and \(m_{61}\) is relatively small, so it can be neglected and assumed to be zero magnitude. Added mass coefficient obtained from added mass component divided by mass displaced by the vehicle. The result shown in table 4.

Table 4. Added Mass Coefficient

| \(m_{11}\) | \(m_{21}\) | \(m_{31}\) | \(m_{41}\) | \(m_{51}\) | \(m_{61}\) |
|----------|----------|----------|----------|----------|----------|
| 0.095487 | 0.000296 | 0.01404 | 0.000887 | 0.083255 | 0.000216 |

\(\rho_{\text{sea water}} = 1020 \text{ kg/m}^3\), Volume of the vehicle = 3.6 m³
4. Conclusions

In this paper, a transient simulation of unsteady flow around the underwater vehicle was presented. The results include time-dependent force and moment and unsteady flow behavior at upstroke and down-stroke of underwater vehicle motion. Based on the result on point 3(c), the significant added mass coefficient for cruise condition is \(A_{11}, A_{31}, \text{ and } A_{51}\) with the largest added mass value is the one with the acceleration of the object that is \(A_{11}\). This is appropriate with the existing reference below. The coefficient due to acceleration of direction \(x\), \(\ddot{u}\) can be seen in point 3(c).

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