Effect of viscosity on dynamic stability of an AUV in CFD studies

Chutturu Nikhil Vinay, Pooja Biswas

***Abstract*— Dynamic stability of an AUV determines how the vehicle behaves when disturbed while initially travelling on a straight course with no control input. The hydrodynamic analysis is conducted on an AUV to predict the effects of viscosity on dynamic stability in CFD studies comparing the degree of stability at various velocities. The hydrodynamic coefficients are calculated using numerical approach of Computational Fluid Dynamics (CFD) study using ANSYS Fluent 15.0 a non commercial software. The CFD studies which have to be conducted using viscosity effects require high performance computers and are slightly labor intensive (e.g. k-∈ and k-ω models) than inviscid model. By avoiding the usage of viscous models the CFD analysis can be completed quite efficiently with minimum computational requirements. The current paper investigates the need of whether to consider the effects of viscosity or not in order to produce the required analysis in a shorter time. So the main aim of the paper is to demonstrate two different model tests numerically, drift angle and rotating arm tests through which a stability margin is calculated to find out whether the AUV is directionally stable or not. The tests are repeated at various velocities in both viscous as well as no-viscous models, so as to clearly note down the difference. By the end of the paper, we would try and suggest as to in which operating velocities (whether high or low) it is necessary to consider the viscous effects.**

***Index Terms*—Dynamic stability, CFD, drift angle test, rotating arm test.**

I. INTRODUCTION

Autonomous underwater vehicles have been used for a limited number of tasks dictated by technology available. With the development of more advanced processing capabilities and high yield power supplies, AUV's are now being used for more and more tasks, with roles and missions constantly evolving. The oil and gas industry uses AUV's to make detailed maps of the seafloor before they start building subsea infrastructure, pipelines and subsea completions can be in the most effective manner with minimum disruption to the environment.

Fig 1. Autonomous underwater vehicle

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Scientists use AUV's to study lakes, the oceans, and the ocean floor. A variety of sensors can be affixed to AUV's to measure the concentration of various elements or compounds, the absorption or reflection of light, and the presence of microscopic life. Military applications include intelligence, surveillance, reconnaissance, mine countermeasures, anti submarine warfare, inspection and identification (search & rescue), navigational network nodes and payload delivery in critical times of warzone.

The dynamic stability of an AUV determines how the vehicle behaves when disturbed while initially travelling on a straight course with no control plane input. Using only linear terms, solutions to the sway and yaw equations provide linear transfer functions permitting the review of the stability of motion. The condition for stability is simply

$$\frac{N'_r}{(Y'_r-\Delta')} - \frac{N'_v}{Y'_v} > 0 \qquad (1)$$

To know the hydrodynamic coefficients Y_v, N_v, Y_r and N_r there are various methods like experimental, computational methods. Although experimental methods are quite accurate, it becomes a second choice for the designers with the advent of computers because experimental methods are costly and time consuming whereas computational results are reliable and can be easily achieved. [1]

In this work the dynamic stability of AUV is found out using two different viscous models (k-∈ and inviscid)at various speeds to find the appropriate speeds at which k-∈ should be used so as to reduce computational time of the analysis.

II. OVERVIEW

A. Model Description

The model used here is a prolate spheroid. The curvature of profile is taken in 2-d form and it is rotated about the centerline axis in AutoCAD to obtain the 3-d form. Length (L) of model is 2.04m and the diameter(D) is 0.4 m. Fins have been attached at the aft to simulate realistic flow around the AUV. Fin geometry is obtained by extruded aerofoil section NACA (0019). The span of fin is 0.4 m.

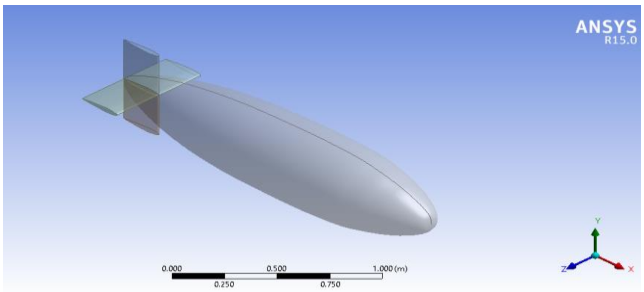

Fig .1. AUV model

B. Computational domain (Boundary Conditions)

The important aspect while generation of domain is to ensure that the walls have little effect on disturbance of flow around the hull.

For *DRIFT ANGLE TESTS:* A cuboidal domain whose dimensions are 60 m x 24 m x 24 m respectively was created in ANSYS design modeler. Front face, upper face, lower face and side faces are constrained at 12×L distance from model while back face is constrained at 25×L distance from model. The head of AUV hull is placed at 10 m from the inlet. [5]

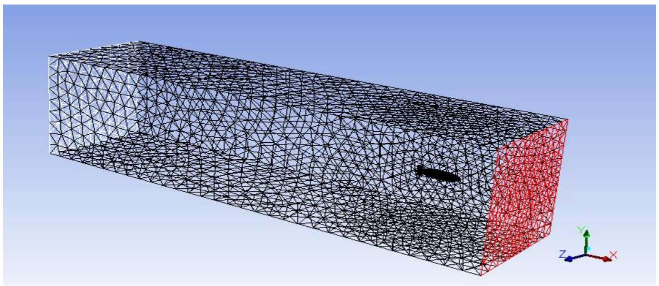

Fig .2. Meshed domain for drift angle tests

For *ROTATING ARM TESTS:* Flow domain is defined as a semi-cylinder with a hole at the center. The radius of hole is equal to L, cylinder radius is equal to 8×L and height of cylinder is equal to 3×L.The AUV hull is placed at varying radius so as to alter the angular velocity.

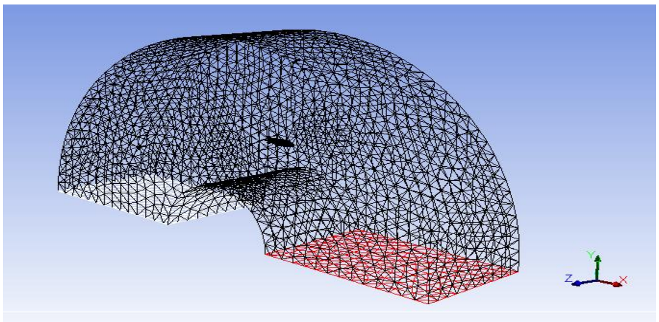

Fig .3. Meshed domain for rotating arm tests

Table 1.boundary conditions of computational domain

Boundary	*Type*
Inlet	Velocity inlet
Outlet	Outflow
AUV hull	No slip wall
Remaining sides	No slip wall

C. Meshing

Ansys Mesh tool is used for the meshing of computational domain. Non Uniform unstructured mesh elements have been used to divide the domain into small control volumes. Mesh structure has been designed denser in the vicinity of the model and gradually the elements size increases as it moves away from it. Such an approach enables simulations run economically. The analysis is done using Ansys Fluent 15.0 software. Flow domain is defined large enough to minimize flow effects between model and boundaries.

D. Solver model description

All the analysis is done using Ansys FLUENT 15.0 software. In this study, straight-line towing and Rotating Arm tests are simulated by using CFD methods. FLUENT code is used as flow solver. FLUENT solves mass and momentum conservation equations for all flow problems. In this study fluid is water so that it is assumed that flow is incompressible and there is no heat transfer. [2]

All the tests are performed using two models, Standard k-ϵ model and inviscid model. The incompressible, isothermal Reynolds Averaged Navier Stokes (RANS) equations are solved in order to determine the Cartesian flow field (u_i =u,v,w) and pressure (p) of the water around the AUV hull

$$\frac{\partial \overline{U_\iota}}{\partial x_1} = 0$$

$$\frac{\partial \overline{U_\iota}}{\partial x_t} + \frac{\partial \overline{U_i U_j}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial P}{\partial x_J}\{v\left(\frac{\partial \overline{U_\iota}}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\} - \frac{\partial \overline{u_\iota' u_J'}}{\partial x_j} + f_i \tag{2}$$

By time averaging the Navier Stokes equations to generate the RANS equations, 6 further unknowns have been created, termed the Reynolds stresses:

$$\frac{\partial \overline{u_\iota' u_J'}}{\partial x_j} \tag{3}$$

Various turbulence models are used to provide solutions to the Reynolds Stresses in terms of known quantities to allow closure of the RANS equations. The k-ϵ model is a commonly used turbulence model for engineering simulations due to its robustness and application to a wide range of flows. Along with these, inviscid tests are conducted using inviscid flow model, which involves removal of viscous terms from the governing equations.

III. TEST PROCEDURE

A. Drift Angle Tests

In actual practice the model is towed at various angles of attack, measuring sway forces and yaw moment. The sway velocity is $= U \sin \beta$, where U is the steady state inlet velocity and β is the angle of attack. The sway forces and moments are plotted against the sway velocity, the slope of curve at zero angle determines Y_v and N_v respectively. Similar procedure is followed by varying the angles of attack of AUV model (i.e, 0,3,6,9 and 12 degrees) about the Z axis. For each inlet velocities, k-ϵ and inviscid models are used. The tests are conducted at 0.5m/s, 2 m/s and 5 m/s.

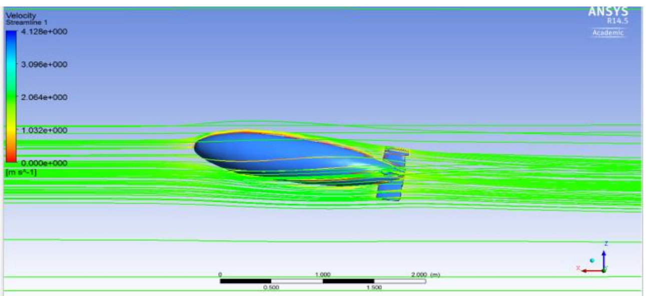

Fig .4.Flow visualization in drift test

B. *Rotating Arm Tests*

The Rotating Arm Technique measures the rotary derivatives, or more specifically the Yr and Nr on the models, which is a specially arranged towing tank and apparatus. The model is being fixed to the end of a radial arm and an angular velocity is applied on it by rotating the arm through a vertical axis fixed in the tank. The orientation of the model is such that its x-axis and z axis is kept normal to the radial arm and is attached to the arm at the model's mid-length. As a result of this orientation, when the model revolves about the axis of the tank, it rotates at the rate r. At this point however, the transverse velocity component v of the model is always zero (yaw angle of attack β=0) and the axial velocity component u1 is same to its linear speed. The model is constantly rotated at a constant linear speed and various radii R. [4]

Experimental rotating arm tests have some limitations, i.e., they require large specialized facilities. In order to determine the values of Y_r and N_r as r→0 the radius(R) should be large in relation to the AUV length (L) and the model must be accelerated and tests performed within a single revolution to ensure the vessel is not disturbed by its own wash, this limits the duration of each run. By performing virtual tests in a numerical towing tank these limitations can be overcome.

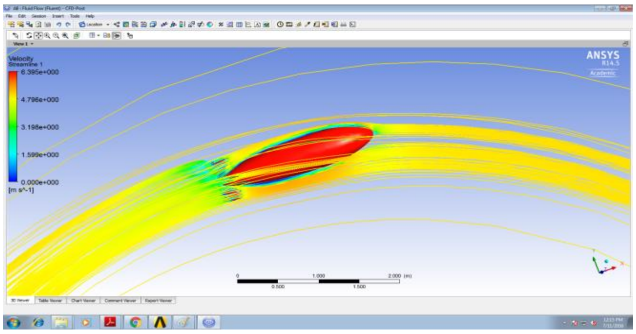

Fig .5. Flow visualization in rotating arm test

IV. CALCULATING DYNAMIC STABILITY

The numerical tests conducted are by fixing the controls, i.e., open loop stability which is studied only in horizontal plane. Only the linear terms are sufficient to review stability of motion. For the vessel to be stable, the horizontal velocity component v' and yaw angular velocity component r' should approach to zero as time increases to large value. [3]

$$v' = V_1 e^{\sigma_1 t} + V_2 e^{\sigma_2 t} \qquad (5)$$

$$r' = R_1 e^{\sigma_1 t} + R_2 e^{\sigma_2 t} \qquad (6)$$

The simultaneous solution of these two equations for v' and r' yields a second order differential equation which leads to dynamic stability criteria. e = 2.718, V_1, V_2, R_1 *and* R_2 are constants of integration; σ_1 *and* σ_2 are stability indices. The relationship between the stability indices and stability derivatives is

$$A\sigma^2 + B\sigma + C = 0$$

Where

$$A = n'_z \Delta \dot{y}$$
$$B = -n'_z Y'_v - \Delta_y N'_r \qquad (7)$$
$$C = Y'_v N'_r - (Y'_r - \Delta')N'_v$$

The roots of this quadratic equation should be negative for controls fixed stability; C is considered the discriminant of dynamic stability. The basic criterion for dynamic course stability can be expressed as

$$\frac{N'_r}{(Y'_r - \Delta')} - \frac{N'_v}{Y'_v} > 0 \qquad (8)$$

V. RESULTS AND DISCUSSIONS

A. *COMPARISION*

In this study, drift angle tests and rotating arm tests are performed at various inlet velocities 0.5,2 and 5 m/s using k-∈ and inviscid models.

Table 1. Stability derivatives using inviscid model

Velocity(m/s)	Y_v'	N_v'	Y_r'	N_r'
0.5	-0.0315	0.0505	0.0559	0.1001
2	-0.0331	0.0515	0.1429	0.1003
5	-0.0314	0.0671	0.1609	0.0980

Table 2. Stability derivatives using k-∈ model

Velocity(m/s)	Y_v'	N_v'	Y_r'	N_r'
0.5	-0.0243	0.0519	0.1954	0.0919
2	-0.0225	0.0503	0.1737	0.1164
5	-0.0337	0.0563	0.1780	0.1197

Tables 1 and 2 clearly demonstrate the differences in the non-dimensional stability derivatives. Upon substituting these values in the stability criterion, we can predict whether the vessel has initial dynamic course stability or not

Table 3. Dynamic stability at various velocities

Velocity(m/s)	*k-∈*	*inviscid*
0.5	stable	unstable
2	stable	stable
5	stable	stable

It is clear from above results that there is an effect of viscosity on dynamic stability at low speeds, whereas at high speeds of operation there is no significant effect.

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B. *Validation*

The CFD analysis performed in this study is validated with the IITC formula (1957) for skin frictional resistance.

$$C_F = \frac{0.075}{\log(\mathrm{Rn}-2)^2} \qquad (9)$$

The model is placed at an angle of attack of 0^0,and inlet velocities are 0.5, 2 and 5 m/s.

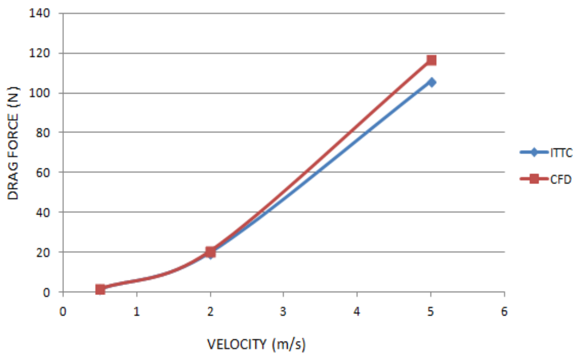

Fig .6. Drag force vs. Velocity

From the above graph it can be shown that, the methodology followed in this study is sufficiently accurate, because the difference is negligible.

VI. Conclusion

In this paper it is shown that there is an effect of viscosity on dynamic stability at low speeds, but the effect at high speeds is not considerable. So it is advisable to use viscous models while analyzing flow at low speeds. By using inviscid model at high speeds there is a considerable reduction in simulation time which is highly advantageous in low specification computers

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References

[1] Edward V. Lewis, “Principles of Naval Architecture second revision” vol . 3: Motion in waves and controllability, pp. 191-205.
[2] Ansys 15.0 fluent “Theory guide”, ch 4.3. Standard k-ϵ and inviscid model.
[3] O.Saout, P.Ananthakrishnan, “Hydrodynamic and dynamic analysis to determine the directional stability of an underwater vehicle near a free surface,” *Elseiver-AOR 2011*
[4] Alexander Phillips, Maaten Furlong and Stephen R Turnock, “The use of Computational Fluid Dynamics to determine the Dynamic Stability of an Autonomous Underwater Vehicle”, *CSIRO 2001*
[5] Mustafa Can, “Numerical Simulation of Hydrodynamic planar motion mechanism test for underwater vehicles”, *M.S. Thesis, Middle East Technical University*.
[6] Stavros I. Papanikolaou, “Parametrics of submarine dynamic stability In the vertical plane”, *NPG Thesis, California*.

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