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Science - Research Article

A Numerical Investigation on the Roll Damping Coefficient of a Typical Airship based on the Computational Fluid Dynamics

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Nonsingular terminal sliding mode (NTSM) guidance for intercepting the desired line of sight (LOS) angle in terminal phase is proposed in this paper. In order to satisfy the predefined LOS angle and to intercep into target, a nonsingular terminal sliding variable is introduced. In reaching phase, in the presence of uncertainties such as target maneuvers, robust NTSM guidance law is designed in order forzeroing the sliding variable in finite reaching time. Then, in sliding phase, due to introducing nonsingular terminal sliding variable, finite time stability of line of sight angle and line of sight angular rate is granteed without singularity in commanded acceleration as control signal Numerical simulations are presented to illustrate the potential of the proposed guidance law.

Keywords: : *Guidance law; Impact angle, NTSM control, Parallel navigation.*

Introduction

It is disputable fact that flight simulation of the flying objects applied in autopilot design, navigation systems, guidance algorithms, fault analysis and collision accuracy, requires a thorough aerodynamic analysis. In order to perform an accurate aerodynamic analysis for each flying body it is necessary to have aerodynamics coefficients including static coefficients and dynamic coefficients. The more accurate these coefficients are used in flight path calculations as well as projectile collision error analysis, the more accurate and realistic simulation results leading to the optimal design of the aircrafts. In addition to the geometry of the aircraft, these coefficients are a function of various flight parameters such as speed, altitude and angle of attack, so the calculated coefficients are wide and require lots of calculation.

There are three pivotal methods for calculating aerodynamic coefficients, both static and dynamic including analytical methods, experimental methods such as wind tunnels or flight tests and the numerical methods.

In previous studies, the experimental methods have been used as a common procedure of calculating the dynamic coefficients of the flying objects. In subsequent decades, with the development of wind tunnels, these measurements will be based on wind tunnel tests. However, with the development of numerical and analytical methods and also the high cost of experimental tests, experimental methods are not usually used in the initial design phase of the product. Analytical methods can often be used with assumptions and are not acceptable accuracy for complex geometries and certain conditions, and the results will be very different from the actual results. For example, one of the engineering codes that can calculate the dynamic

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coefficients of projectiles and missiles analytically is the MD code.
This code calculates the aerodynamic coefficients including dynamic and static ones of missiles and projectiles in specific situations and can only be used in conceptual design due to the accuracy of the results. With the increasing development of computers and the development of numerical methods in recent years, the ability to analyze aerodynamic problems using computational fluid dynamics methods has increased significantly. Numerical methods have the ability to simulate different problems in a variety of conditions and compared to analytical methods can analyze a wider range of problems and they also have higher speed and much lower costs than experimental method. Therefore, among these methods, the numerical method is more powerful for analyzing flows and consequently calculating aerodynamic coefficients. Today, many numerical analyzes are performed to calculate aerodynamic coefficients. A number of these analyzes have been mentioned in the following.

On one hand using computational fluid dynamics methods to obtain static coefficients is not difficult and several studies have been conducted in this field. On the other hand, very few references are available regarding the calculation of dynamic coefficients using computational fluid dynamics methods. Unfortunately, general information and results obtained in them are provided and how to calculate these coefficients is not discussed. In simulating the flight of flying objects, the calculation of dynamic coefficients such as Clp and $Cm\dot{\alpha}+Cmq$ is very important, and in the present study, full details of a method for calculating roll damping coefficient using computational fluid dynamics (Fluent software) is presented.
Calculating these coefficients is necessary for simulation of the oscillating movements of the flying geometry and MRF is used for this purpose. In the present paper, firstly, total steps of this procedure are mentioned and then the dynamic coefficients for a specific projectile with a certain geometry are calculated.
In order to validate the process proposed in the present study, the obtained results are compared with the results of a valid data [1] that shows a good agreement and this agreement indicates the appropriate accuracy of the proposed method for calculating dynamic coefficients.
Recently, several studies have focused on computing dynamic coefficients of flying objects. Sepahvand et al. [2] worked numerically in the field of calculating the dynamic coefficients of roll dumping and pitch dumping of a projectile in different flight conditions. They used dynamic mesh method to model the flight condition and then introduced their method to calculate dynamic coefficients results. Craig et al. [3] using numerical methods calculated the static coefficients of a small projectile in Mach 1.1, which is the transition region. They sought to find the effect of the height of the bullet from the ground on the aerodynamic coefficients and tried to obtain a height from which the static coefficients of the bullet did not change significantly. Disperito and Silten [4] calculated the derivatives of stability, roll damping coefficient and pitch damping coefficient for a simple geometry similar to a rocket with a method based on steady state solution. Their work compared to the results of experimental tests in the supersonic regime, had appropriate answers and in the subsonic regime had large differences. Howell et al. [5] performed the aerodynamic coefficients of a 5.56 mm bullet using flight test and model X-ray and infrared imaging. Sahu [6] used a combined method to simultaneously use the equations of rigid body dynamics and computational fluid dynamics to calculate the flight path of a rotating projectile. Saho's goal was to calculate the aerodynamic coefficients with appropriate accuracy. Silten [7] analyzed a standard projectile and calculated static coefficients and roll damping coefficient numerically.
Okay et.al [8], used a method based on computational fluid dynamics and of course creating an unorganized mesh and using a numerical code, analyzed the flow around a rocket and were able to calculate the dynamic coefficients of roll damping and pitch dumping. In their work, a numerical code is used and the flow is analyzed in a non-viscous manner based on Euler equations. Kaiser [9] and his colleagues also calculated the same coefficients for the same geometry using the flight test method. Sivan and Jeremy [10] extracted the aerodynamic coefficients of a 155 mm cannonball using the wind tunnel test method.
Experimental and numerical study of the effect of oscillating parameters on dynamic stability derivatives of Airfoil NACA0012 is another example of in-house work done by Dr. Shojaei-Fard [11] and his students that focuses on the calculation of stability derivatives.
Rathi et al. [12] have also conducted research on the longitudinal dynamic derivatives of an airfoil under two torsional oscillations and transmission oscillations in the wind tunnel with the aim of finding the range of transmission oscillations before the instability of the airfoil.

The related equations

It is evident that, to analyze airship aerodynamic, flow equations should be solved by CFD method. The Navier Stokes equations are used to solve the aerodynamic problem. The differential momentum equation for a Newtonian fluid with constant density and viscosity are as follows [13]:

$$\rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) = \rho\frac{du}{dt} \quad (1)$$

$$\rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) = \rho\frac{dv}{dt} \quad (2)$$

$$\rho g_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) = \rho\frac{dw}{dt} \quad (3)$$

The lift and drag forces are two important parameters that are extracted from CFD solution. The drag, the lift and the moment coefficients are shown below:

$$c_D = \frac{2F_D}{pv^2 s} \quad (4)$$

$$c_L = \frac{2F_L}{pv^2 s} \quad (5)$$

$$c_M = \frac{2F_M}{pv^2 s} \quad (6)$$

At this stage, after solving the solution, obtain the value of the momentum coefficient in the direction of the longitudinal axis and place it as $C_l - C_{l\varphi}\varphi$ in the following relation to obtain the value of the desired dumping coefficient of the roll [8].

$$C_{lp} = \frac{2M_\infty(C_l - C_{l\varphi}\varphi)}{p'} \quad (7)$$

$$p' = \frac{pd}{a_\infty} = 2M_\infty k \quad (8)$$

$$k = \frac{pd}{2V_\infty} \quad (9)$$

Geometry and meshing

In the present article, in order to study aerodynamic coefficients of the airship, the geometry is simplified to a rigid body which is shown in the Fig. 1. It should be noted that the plus (+) configuration is used for four separate fins. Table 1 shows the dimension of this airship (Skyship-600).

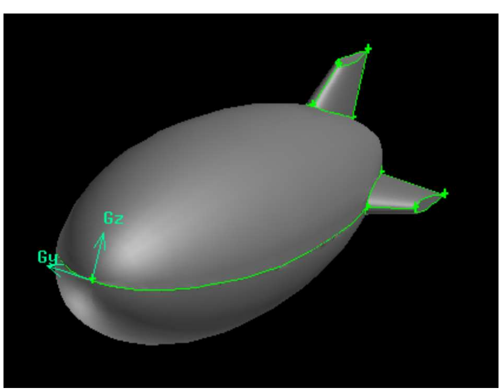

Fig. 1:The geometry of the airship

Table 1: The geometry characteristic of the airship

V	17500 m^3
L	81 m
L/D	3.88

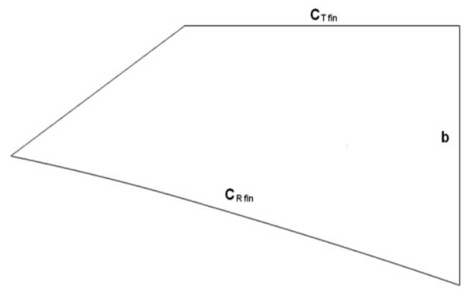

Fig. 2: The sectional view of a tail

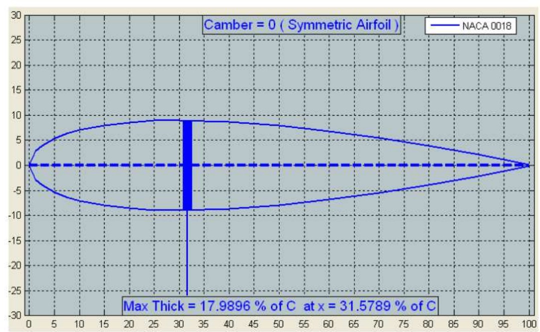

Fig. 3: NACA0018 airfoil

Table 2: The detail parameters of fins

Name	*(+) configuration*
Single fin area (s)	68.249
Tip chord (C_T)	8.400
Root chord (C_R)	14.354
Height (b)	7.534
Number (N_f)	4
Location (L_{ft}/L)	0.725

In the present work Pointwise is used to generate mesh. The height of the first layer in boundary layer with value of 0.27mm is used to provide appropriate Yplus parameter on the wall surface. The final mesh in the fluid domain and the surface of the airship are shown in Fig. 4 and Fig. 5.

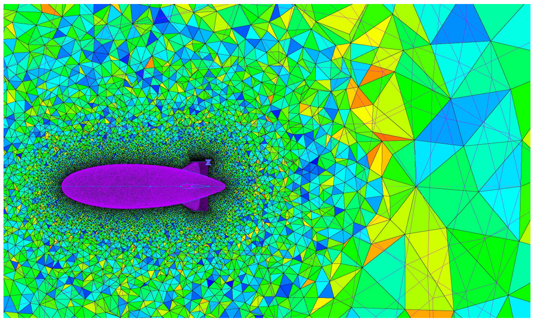

Fig. 4:Full domain mesh

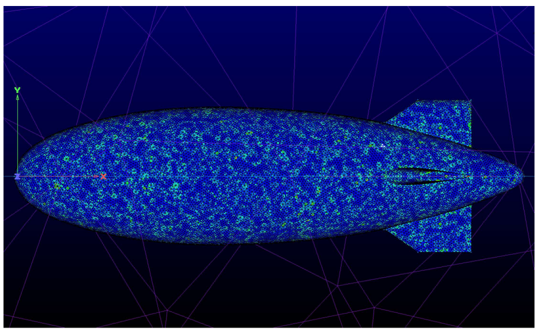

Fig. 5:The surface mesh of the airship

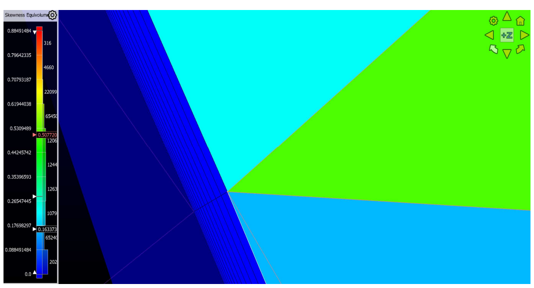

Fig. 6:close-up Boundary layer mesh

In this study in order to choose proper mesh, four different meshes are applied. Table 3 shows the mesh parameters and the Table 4 shows the results of the mesh study for four different meshes.

Table 3: The mesh study parameters

Mesh	*1*	*2*	*3*	*4*
No. of Boundary layer	12	12	12	12
Height of first layer (m)	0.00027	0.00027	0.00027	0.00027
Total meshes	949,127	2,456,054	2,541,648	4,160,974

Table 4: The results of static coefficients in different meshes

Mesh	*Angle Of Attack*	C_L	C_D	C_M
1	10	0.1861	0.0502	-0.09368
2	10	0.1907	0.0543	-0.08905
3	10	0.1852	0.0466	-0.0925
4	10	0.1868	0.0492	-0.0895

Therefore, according to the meshes created and the results related to their solution at an angle of attack of 10 degrees, it can be concluded that mesh number 1 has less solution time due to fewer elements and the appropriate answer, and therefore it is selected as a mesh to continue working in this study.

Numerical investigation

To calculate the moment coefficient, the center of gravity is selected as the reference point which is located 36 meters from the beginning of the body. The reference length for airship geometry is $V^{\frac{1}{3}}$ and the reference surface is $V^{\frac{2}{3}}$. In order to compute the aerodynamic coefficient, the CFD solution is done based on boundary conditions illustrated in Table 5.

Table 5: The boundary conditions used in this study

Altitude	20 **km**
Temperature	216.65 k
Pressure	5474.89 Pa
Density	0.0880349 $\frac{kg}{m^3}$
Speed of sound	295.07 $\frac{m}{s}$
Free flow speed	15 $\frac{m}{s}$
Reynolds	$2 \cdot 39 \times 10^6$
Turbulence method	Kw-SST
inlet	Velocity inlet
outlet	Pressure outlet

Validation

In this section the results of the numerical investigation including the static and also roll damping coefficients are presented.

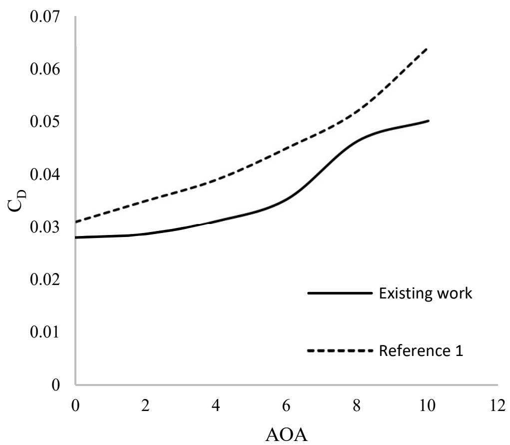

Fig. 7:The result of drag coefficient

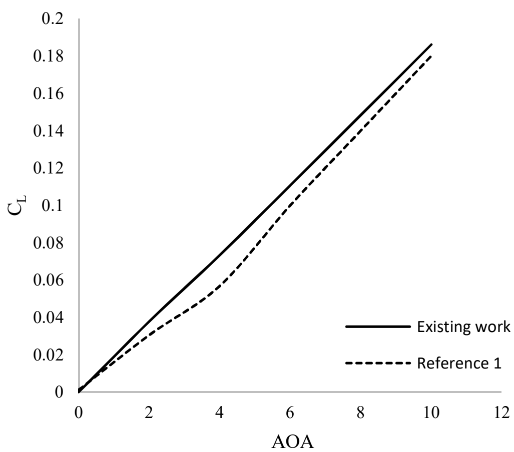

Fig. 8:The result of lift coefficient

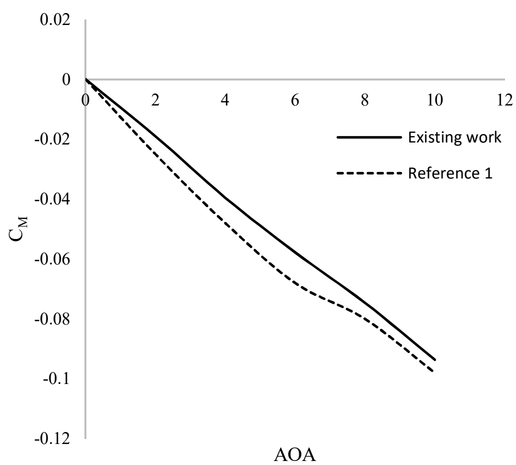

Fig. 9:The result of pitch moment coefficient

As it is showed in Fig. 7. to Fig. 9. the results of the existing work are very close to the results of reference [1] So selected this type of mesh and the solution method for the static part. In order to validate our method in dynamic part, In order to validate our method, we used another geometry presented by Sepahvand et al [2]. They used a simple projectile to compute its dynamic coefficient including pitch and roll damping coefficients. Fig. 10. shows the geometry and the mesh used in their work.

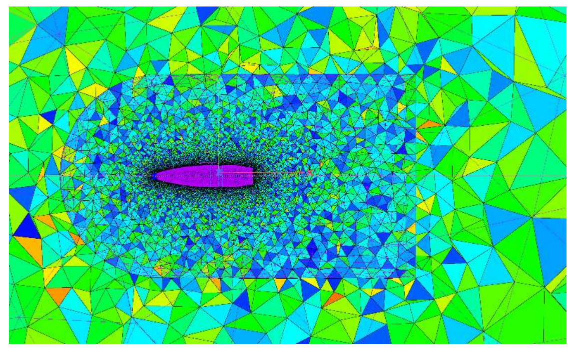

Fig. 10:The geometry and mesh of projectile [2]

Now we should compare the result of MRF method (present method) against the dynamic mesh method [2].

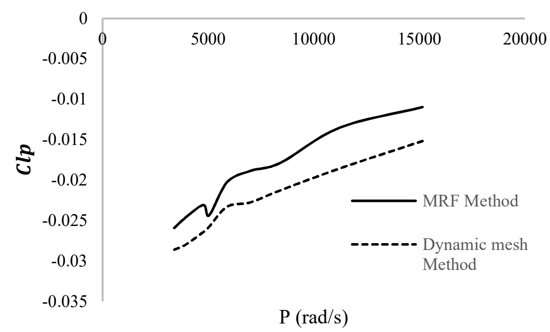

Fig. 11:The comparison between present methods and the method used in reference [2] using Kw-SSt model

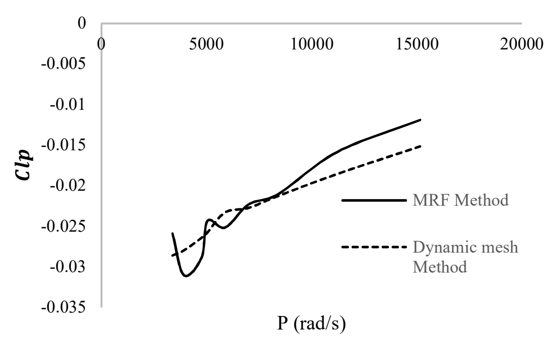

Fig. 12:The comparison between present methods and the method used in reference [2] using Spalart-Allmaras model

As it is shown in Fig. 11. and Fig. 12. the results of MRF method are slightly different compared to dynamic mesh method especially in Spalart-Allmaras turbulence model. Therefore, this error can be related to sound regimes characteristics and characteristics of turbulence models. Hence, MRF method is approved for use in the existing work.

Results and discussion

Now, by validating the MRF method, we will fully examine the existing work. For this purpose, we first place the geometry with the same rotational velocity at different angles of attack to examine the effect of angle of attack. Table 6 shows the effect of the angle of attack, in this case, turbulence method for this part is kw-SST.

Table 6: The effect of the angle of attack

Angle Of Attack (degree)	*V (m/s)*	*P (Rad/s)*	C_{lp}
0	15	3	-0.00225896
2	15	3	-0.00234297
4	15	3	-0.00276116
6	15	3	-0.00329797

Due to the changes in the angle of attack, it is clear that the amount of changes in the dumping roll coefficient from the angle of attack of 2 degrees onwards is different, and this can be due to the presence of the door block and the shape of the airfoil.
It is observed that there is not much difference between the angle of attack of 0 to 2 degrees, so the angle of attack of zero degree was selected for the existing study to simulate the ideal flight conditions.

Table 7: The results of roll dumping coefficient of airship

V(m/s)	C_l	*P(Rad/s)*	*D(m)*	C_{lp}
15	-0.0049928	3	22.1022	-0.00225896
20	-0.0041211	3	22.1022	-0.00248608
25	-0.0034543	3	22.1022	-0.00260479
30	-0.0030225	3	22.1022	-0.00273502
35	-0.0025429	3	22.1022	-0.00268454
40	-0.0021103	3	22.1022	-0.00254611
45	-0.0018747	3	22.1022	-0.00254458
50	-0.0016313	3	22.1022	-0.00246023
55	-0.0010866	3	22.1022	-0.00180262
60	-0.0009382	3	22.1022	-0.00169793

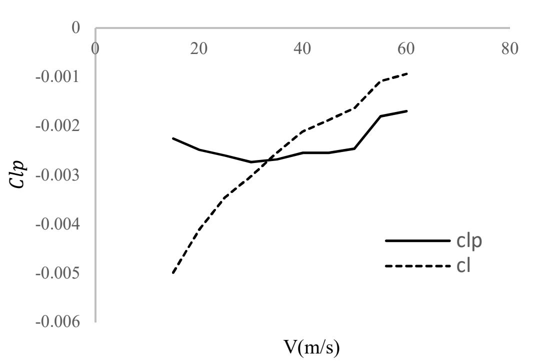

Fig. 13:Results of roll dumping coefficient for airship

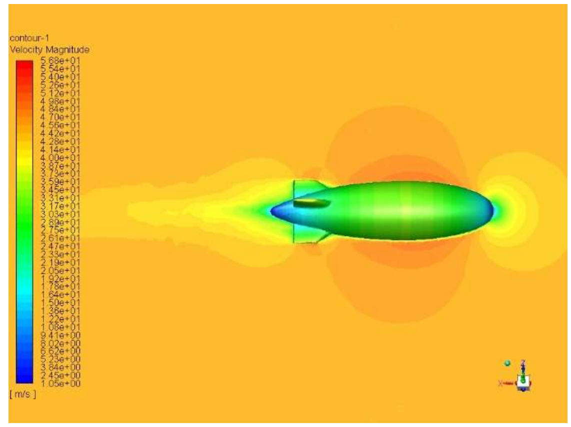

Fig. 14:Velocity contour of airship at 45 (m/s)

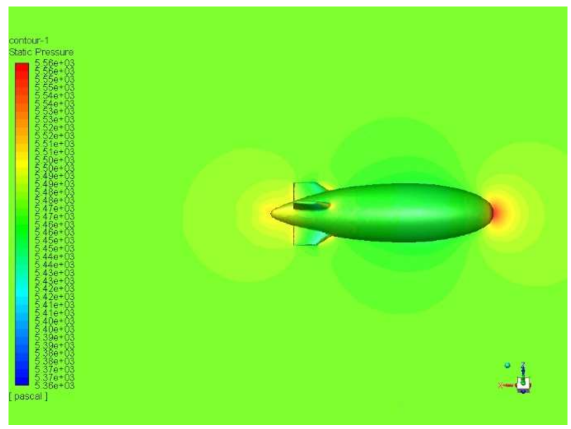

Fig. 15:Pressure contour of airship at 45 (m/s)

According to the obtained values in Fig. 13, it can be concluded that for this model of airship and by keeping the rotational speed constant at 3(*Rad/s)*, with increasing linear velocity up to 35(m/s), the stability rate increases and then decreases. As it is shown, at a linear speed of 55(m/s), a jump occurs in the value of the number C_{lp} occurs, which will affect the stability.
We know that in order to have the stability, damping roll sign must be negative and the larger this negative number, the better the stability of the roll. It means that the desired Airborne objects have the ability to return to their original state after rotating around the X axis. Of course, this stability must be applied to the geometry to the appropriate extent, because high stability imposes many movement restrictions on the geometry and clearly affects and reduces the geometry's good handling.
The amount of roll stability, which also keeps the Airborne objects in good handling, varies for different Airborne objects and depends on many parameters, including linear speed and rotational speed. Today, due to human advances in technology and the development

of supercomputers very small supercomputers, the field of control has become much broader and more complex.

Conclusion

In this paper, an attempt is made to provide a general procedure for calculating the dynamic coefficients of roll dumping numerically for some type of flying objects. To validate this procedure, a projectile with a known geometry was considered. By comparing the results of present work with another article, the static coefficients for airship was evaluated and using another reference, the efficiency of the MRF method was proved by calculating these coefficients for that projectile. Comparing the results of this process with the results of the references proved/showed the accuracy of the process in the present work. In the discussion of the turbulence model, according to a study performed on different turbulence models, it was found that to calculate the roll dumping coefficient for this geometry, the best turbulence model is the Spalart-Allmaras. It was also found that the airship towards instability by increasing the linear velocity at a constant rotational speed.

Nomenclature

α	(Rad) Angle of attack
$\dot{\alpha}$	$(Rad.s^{-1})$ Pitch rate
p	(pa) pressure
u	x velocity$(m \cdot s^{-1})$
v	y velocity$(m \cdot s^{-1})$
w	z velocity $(m \cdot s^{-1})$
ρ	Density $(kg \cdot m^{-1})$
g	Gravity
μ	Viscosity $(kg.m^{-1}s^{-1})$
c_D	Drag coefficient
c_L	Lift coefficient
c_M	Pitch moment coefficient
s	Area(m^2)
C_l	Roll moment coefficient
C_{lp}	Roll damping coefficient
p'	Roll rate
φ	Roll angle (Rad)
V	Velocity (m/s)
Re	Reynolds
L_{ft}	length from the apex of the airship to the leading of the root fin

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