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Analysis of Aerodynamic Characteristics Using the Vortex Lattice Method on Twin Tail Boom Unmanned Aircraft

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Abstract. This study focuses on analysis the aerodynamic characteristics of the LSU 05-NG aircraft in a relatively shorter time with sufficient results to provide an overview of aircraft characteristics. The method used is the Vortex Lattice Method (VLM) on XFLR5 software. VLM models an aircraft surface into infinite number of vortices to calculate lift curve slope, induced drag and force distribution. In this study, VLM was used to calculate aerodynamic parameters which include CL, CD, CM, CL with respect to CD, and L/D. The results showed that VLM can provide good results for the prediction of the lift coefficient. As for the drag coefficient, VLM used the assumption that fluid flow is inviscid so only induced drag is calculated. This also impacted the results of L/D analysis using VLM. Simulation results for the value of L/D results showed that the VLM simulation on XFLR5 has a higher magnitude than the results of the simulation with CFX.

INTRODUCTION

The need for unmanned aircraft increases the interest of various parties to develop unmanned aircraft. In Indonesia, developments of UAV are still in the early stage, so there is plenty of room to develop. Several produced UAVs in Indonesia still have some significant limitations in flight range, endurance, or payload capability. These limitations have made the demands on UAV in Indonesia still low, be it for civil or military purposes.

The needs for Unmanned Light Airplane stated before are including aerial research and observation, aerial patrol and surveillance, and Search and Rescue (SAR) missions. As an institution for aerospace technology development, Aeronautics Technology Center of National Institute of Aeronautics and Space of Indonesia (Pustekbang LAPAN) has been developing a Large Scale Heavy Payload UAV named LAPAN Surveillance UAV-05 New Generation (LSU-05NG). LSU-05NG is developed from its predecessor, LSU-05 as an attempt to improve the performance of LSU-05.

The development of LSU-05NG was started with Design Requirement and Development (DRO) study to determine the parameters and criteria that must be fulfilled and targets in the process of development.[1] This research focused on analytical and theoretical calculation of aerodynamic characteristics such as lift coefficient (CL), drag coefficient (CD), moment coefficient (CM), and lift-to-drag ratio (L/D). Early prediction for the value of aerodynamic characteristics can be done with tools such as DATCOM, CFD, XFLR5, LSAERO, AVL, and PMARC.[2]

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Research on aerodynamic characteristics has been done by various researchers. Kuitche and Botez have estimated aerodynamic coefficient for UAS-S4 Ethical aircraft with DATCOM and VLM. The result of this research shows that DATCOM can be used as a tool to estimate the value of the aerodynamic coefficient at various flight conditions in relatively short computation time. The result is validated with ANSYS Fluent's CFD and TORNADO's VLM.[3] In another research, Budziak has analyzed the aerodynamic characteristics in wing structure with various configurations using Athena Vortex Lattice (AVL).[4] Tomas Melin has researched the implementation of Vortex Lattice Method with Matlab on wing's aerodynamics linear analysis. The results of Melin's research shows that results from TORNADO are more accurate to experimental results and yields better results than any other software.[5]

From some of the studies above, making it a challenge to conduct research into the analysis of aerodynamic characteristics at LSU-05NG using the Vortex Lattice Method (VLM) on XFLR5. The objective of this research to evaluate flight performance of LSU-05NG.

THEORY

Vortex Lattice Method

The Vortex Lattice Method is a numerical method to analyze the dynamics of fluids. VLM models a surface on aircraft as infinite vortices to estimate the lift curve slope, induced drag, and force distribution.[4] It has been applied to the estimation of aerodynamic properties of lifting surfaces and even full airplanes.[6] The VLM is an extension of Prandtl's lifting line theory that is applicable to a broader range of lifting surfaces including swept and low aspect ratio wings.[7] In this research, VLM used to estimate the value of aerodynamic parameters such as CL, CD, CM, and lift-to-drag ratio. It is assumed that the fluid flows as an incompressible and inviscid fluid, and the thickness effect and viscosity are neglected.

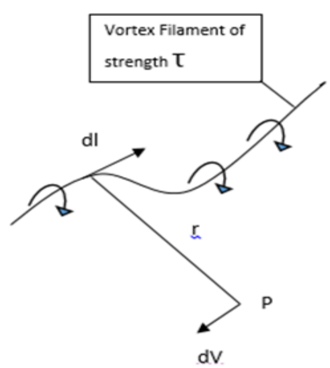

FIGURE 1.Curved three dimensional vortex filament of strength Γ

Irrotational and incompressible fluid flow is a complicated flow pattern. It can be synthesized by the addition of a vortex line flow.[8] This synthesis will change the incompressible and irrotational flow to vortex filaments. The infinite vortex lines will induce flow field below the line where the induced flows are perpendicular to the radius r. The flow field will have an opposite direction to the direction of radius strength. The description above can be seen in Fig. 1. The mathematical model by Biot-Savart Law is shown below.

$$dV = \frac{\tau_n}{4\pi}\frac{(dl\ \times r)}{|r|^3} \quad (1)$$

or

$$V = \frac{\tau_n}{4\pi}\int\frac{(dl\ \times r)}{|r|^3} \quad (2)$$

where

dl : the infinite small partition of the filament,
r : distance from P to a certain point in the filament,
τ : strength of the vortex, and
V : induced speed.

The solution of the integral equation above has been solved by Bertin and Cummings[9] to a simpler equation. Where is the integral of the equation above to describe the induced velocity for a vortex segment of arbitrary length, as follows

$$V = \frac{\tau_n}{4\pi} \frac{\overrightarrow{r_1} \times \overrightarrow{r_2}}{|\overrightarrow{r_1} \times \overrightarrow{r_2}|^2} \left[\overrightarrow{r_0} \cdot \left(\frac{\overrightarrow{r_1}}{|r_1|} - \frac{\overrightarrow{r_2}}{|r_2|} \right) \right] \tag{3}$$

In Eq. (3), V is the induced velocity, τ the vortex intensity, r_1 the position vector from the beginning of the vortex line to arbitrary point in space, r_2 the position vector from the end of the vortex line to an arbitrary point in space, r_0 the vector from the beginning to the end of the vortex line and r_1 and r_2 are the magnitudes of the vector.[10] The explanations for equation above are illustrated on Fig. 2.

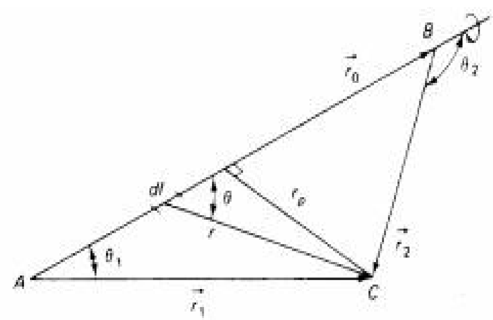

FIGURE 2. New nomenclature for the bound vortex filament[11]

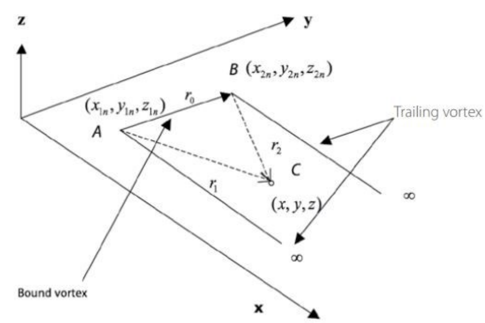

FIGURE 3. The horseshoe vortex implementation[11]

Equation (3) above is a general equation to estimate the value of induced velocity at a segment with finite length. From Fig. 3. a horseshoe vortex at XYZ plane will be made, as shown in illustration on Fig. 3. Based on Eq. (3), it can be defined the speed induced by bound vortex and the two trailing vortices at point C, which is defined in the equation below.

$$V_{AB} = \frac{\tau_n}{4\pi} (\gamma_{AB})(\phi_{AB}) \tag{4}$$

$$V_{A\infty} = \frac{\tau_n}{4\pi} (\gamma_{A\infty})(\phi_{A\infty}) \tag{5}$$

$$V_{B\infty} = -\frac{\tau_n}{4\pi} (\gamma_{B\infty})(\phi_{B\infty}) \tag{6}$$

The total speed induced by horseshoe vortex in the XYZ plane with the vortex boundary and two trailing vortices is the sum of Eqs (4)-(6), or in other words generally can be written in the mathematical model as follows.

$$V = V_{AB} + V_{A_\infty} + V_{B_\infty} \tag{7}$$

Because $\tau_n$is contained in a linear filament, it can be synthesized into a simpler form by assuming point C to be a collocation point or control point on the i-th panel formed by coordinates (x_i, y_i, z_i) so that the equation can be rewritten as

$$V_{i,n} = C_{i,n} \tau_n \tag{8}$$

where $V_{i,n}$ and $C_{i,n}$ each of them is velocity induced which is located the i-th control point and vortex which is on the n-th panel and the coefficient is dependent on the horseshoe vortex geometry and depends on the distance from the i-th panel control point. Because the governing equation above is a linear equation, then $V_{i,n}$ can be written as

$$V_i = \sum_{n=1}^{2N} C_{i,n}\tau_n \tag{9}$$

According to Ref. 9, the control point of each panel is centered span-wise on the three-quarter chord line midway between trailing vortex legs. Figure illustrates the placement of the control point and bound vortex.

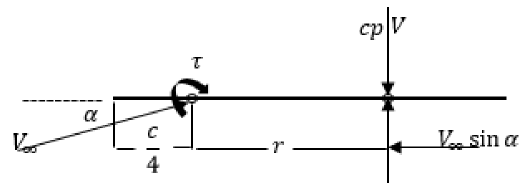

FIGURE 4. The position of control point at chord line

The strength of vortex τ is positioned at quarter chord location. Induces velocity at point C which has distance r from quarter chord location formulated become

$$V = \frac{\tau_n}{2\pi r} \tag{10}$$

According to Ref. 9., if the flow is to be parallel to the surface at the control point, the incidence of the surface relative to the free stream is given by

$$\alpha \approx \sin\alpha = \frac{V}{V_\infty} = \frac{\tau_n}{2\pi r V_\infty} \tag{11}$$

According to the Kutta-Joukovsky theorem a certain moving vortex with the strength of the velocity which is bound in the velocity flow V_∞ will produce an elevator, in other words

$$L = \frac{1}{2}\rho_\infty V_\infty^2 c 2\pi\alpha = \rho_\infty V_\infty \tau_n \tag{12}$$

Then Eq. (14) is substituted into Eq. (15) with the value of r, ie

$$r = \frac{c}{2} \tag{13}$$

So the location of the control point is at 0.75 chord location and bound vortex is at 0.25 chord location.

Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is a numerical simulation tool for analyzing and designing fluid flow systems, heat transfer, and other fluid phenomena. The numerical simulation was performed using ANSYS Software with CFX solver.[12] ANSYS CFX software supports arbitrary mesh topologies, including hexahedral, tetrahedral, wedge and pyramid elements.[13] General equation commonly used to represent fluid flow behavior is Navier-Stokes equation.[14] For incompressible flow assumption, the Navier-Stokes equation is expressed as

$$\rho\left(\frac{\partial v}{\partial t}+(v\nabla)v\right)=-\nabla p+\mu\nabla^2 v+\rho F \tag{14}$$

This study was performed to analyze aerodynamic characteristics of LSU-05NG. There are three main procedures using CFD, which are preprocessing, solving, and post-processing.[12] In pre-processing procedure, geometry, mesh generation, boundary condition and physical model definition are performed. In this research to solve this problem use Shear Stress Transport model provided by ANSYS-CFX solver. The Shear Stress Transport model works by solving a turbulence/frequency-based model (k–ω) at the wall and k-ε in the bulk flow.[15]

METHODOLOGY

Aerodynamic analysis using VLM is simulated in cruise conditions with XFLR5 software. XFLR5 software is a tool used to analyze airfoil, wings and aircraft.[16] This analysis is done as an initial prediction of the characteristics of the CL, CD, L / D, CM and CL versus CD values. The first aircraft modeling using XFLR5 is an airfoil geometry input which will be used for VTP, HTP and wings. In this research the airfoil used for HTP and VTP is NACA 0012 while for the aircraft wing it uses the FX 76-MP 160 airfoil. The parameters that need to be considered before starting the simulation in terms of air velocity and air material characteristics can be seen in Table 1.

TABLE 1. Simulations with parameter of cruise condition.

Parameter	Symbol	Value
Velocity	V	30 m/s
Height	h	300 m
Density	ρ	1.185 kg/m^3
Pressure	P	1 atm

Wing Geometry

LSU-05NG has wings that are connected to fuselage with high wing configuration. The wing has a tapered platform and is connected to fuselage. The LSU-05NG wing uses one type of airfoil, the FX 76-MP-160 airfoil from the root chord to the tip chord. The wing geometry of LSU-05 NG is given in the TABLE 2.

TABLE 2. Wing geometry of LSU-05NG.

Parameter	Symbol	Value
Wing Area	S	3.22 m^2
Aspect Ratio	AR	9.4
Wing span	b	5.5 m
Taper Ratio	λ	0.6
Swept Angle	Λ	0°
Hedral Angle	Γ	0°
Incidence Angle	i	0°
Twist Angle	τ	0°
Root Chord	C_r	0.73 m
Tip Chord	C_t	0.44 m
Mean Aerodynamic Chord	c	0.597 m
Airfoil	-	FX 76-MP-160
HLD	-	Single Slotted Flap

Tail Geometry

LSU-05NG unmanned aircraft use tails where twin tail rods are attached to the wing or so-called twin tail boom. The concept used is suitable for this aircraft because it can position the heavy engine closer to the Center of Gravity (CG), so that it can provide good CG settings. The HTP and VTP tail geometry are presented in Table 3.

TABLE 3. HTP and VTP geometry.

Parameter	Symbol	HTP	VTP
HTP and VT Area	S	0.6603 m^2	0.1610 m^2
Aspect Ratio	AR	3.4	1.6
HTP and VTP Span	b	1.5 m	0.5 m
Taper Ratio	λ	1	0.46
Swept Angle 0.25c	Λ0.25c	0°	40°
Swept Angle LE	ΛLE	0°	37°
Root Chord	C_r	0.440 m	0.44 m
Tip Chord	C_t	0.440 m	0.204 m
Airfoil	-	Naca 0012	Naca 0012

Fuselage Sizing

The fuselage design has a total length of 2.21 meters with details of 60 cm long, pointed nose, 80 cm which is the center with a fixed width and 81 cm to the rear end. From the side of the fuselage design has a maximum height of 41.5 cm and width of 45 cm

Flow Chart on XFLR5

Before conducting the analysis process to determine the aerodynamic characteristics of the LSU 05-NG aircraft using XFLR5 software based on input parameters from Wing Geometry, HTP and VTP Geometry, and fuselage sizing obtained the LSU 05-NG image in Fig. 5.

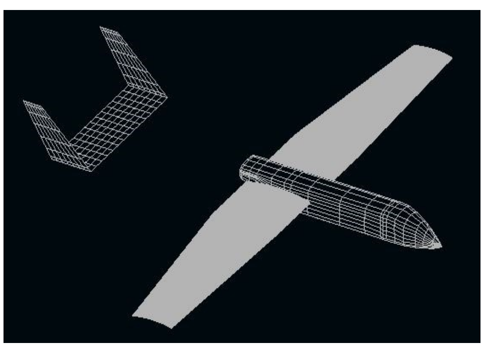

FIGURE 5. Airplane modeling with XFLR5

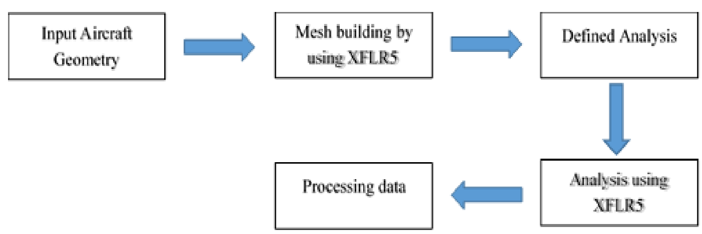

FIGURE 6. Flow chart of XFLR5

Then, an analysis using VLM on XFLR5 software was performed. In general, the simulation process of aerodynamic analysis using XFLR5 software is presented in the flow chart on Fig. 6. This analysis process was carried out with a total of 27114 panels with 125 bound vortex X-axis direction and 106 Y-axis direction at wing. This simulation is to analyze the aerodynamic forces which include lift coefficient, drag coefficient, moment coefficient, CL versus CD and efficiency (L/D). As discussed in the previous section that in analysis using VLM on XFLR5 cannot analyze using viscous conditions. This is because the code in XFLR5 is derived from non-viscous assumptions for the fluid.

CFD Concept

This CFD simulation discusses aerodynamic analysis for the state of a whole aircraft in cruise conditions. The parameters that need to be considered before starting the simulation in terms of air velocity and air material characteristics can be seen in. Simulations performed varied from Alpha attack angles from a range of -15° to 24° with intervals of 2° using ANSYS CFX software. The CFX solver needed a discrete model to do the calculation, therefore the model was discretized using unstructured grid generation using ICEM CFD software.[17]

CFD simulation begins with meshing (division of elements) of the geometry that has been made. The simulated flow is external air, so a Boolean subtraction is carried out to form the air flow. As the domain, the simulation is made with symmetry conditions to make the simulation time efficient. Forms of CFD simulation models that have been made can be seen in Fig. 7. The number of mesh used in the analysis process using CFD is 2804124. The meshing results obtained are as shown in Fig. 8.

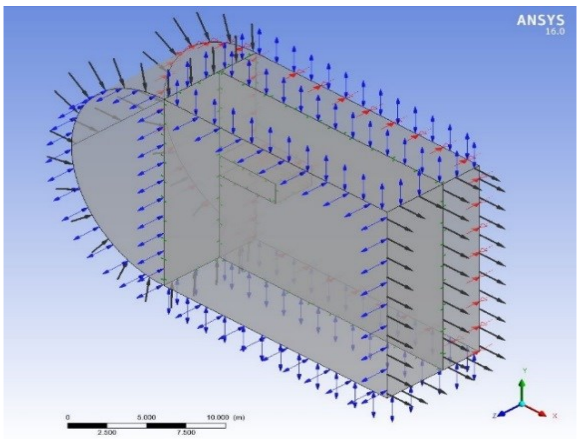

FIGURE 7. Simulation domain in CFD plane

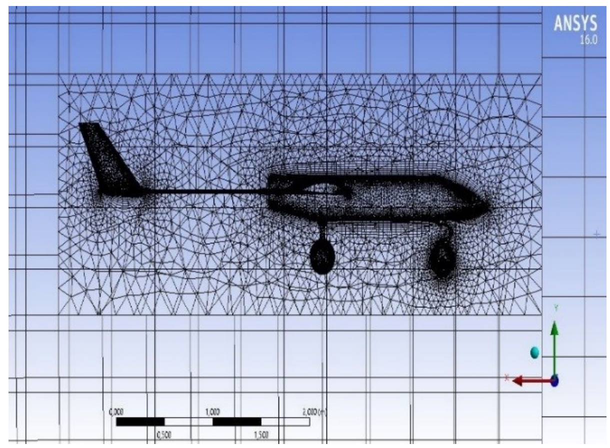

FIGURE 8. The meshing result using relevance 25

RESULTS AND DISCUSSION

Making panels with XFLR5 consists of making panels on VTP, HTP, wings and body. Analysis of aerodynamic forces using VLM on XFLR5 was simulated on the number of panels 27114 panels. Simulation at an angle of attack -15° to 24°. The simulation results for analyzing the lift coefficient with VLM are presented in the Fig. 9.

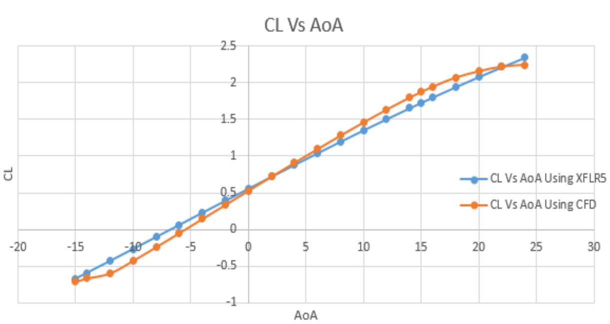

FIGURE 9. Graph of CL versus AoA

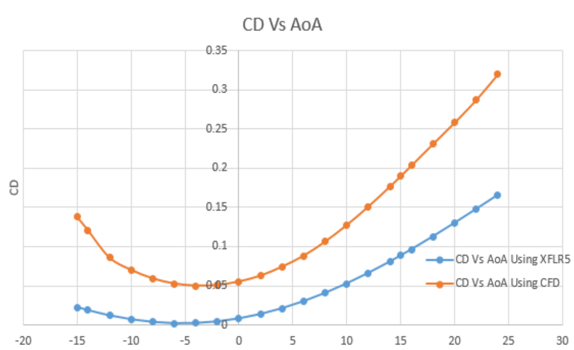

FIGURE 10. Graph of CD versus AoA

Based on the graph above, it shows that the value of C_L using VLM when α = 0 is 0.556816. While the results of the simulation using CFD results from the value of C_L when α = 0 is 0.530098581. Referring to Fig. 9, there is no significant difference in the C_L value at each angle of attack using either VLM or CFD. VLM shows the value of C_L which is linear, whereas CFD is not linear. This difference is due to the velocity induced matrix VLM method which is a matrix whose elements are linear equations. In addition, based on Fig. 9, analysis using XFLR5 cannot evaluate the stall point on the lift coefficient curve. While the result from CFX simulation shows stall phenomenon. Stall is the phenomenon of flow separation at surface of wing due to exceeding limit of wing angle (angle of attack) and resulting on decreasing lift force.[18]

Generally for flight on cruise conditions, the lift coefficient is 0.55 which has a lift force 1022 N, where this value is enough to carry an aircraft load of about 102 kg. Based on the Design Requirement and Development, the LSU 05-NG aircraft with a maximum payload has weight 85kg. This means that with the current configuration, it is fulfilling to fly on cruise conditions.

It also analyzes the drag coefficient values at each angle of attack. Figure 10 shows the simulation results for calculating the value of the drag coefficient at each angle of attack. Figure 10 shows that for the analysis of the drag coefficient using VLM gives a fairly far value compared to CFD. As for the angle of attack -12° to 0° the value of the CD goes to zero, this is because the assumption used is inviscid condition. In addition, from Fig. 10, it can be seen that the aircraft has a low drag at a small angle of attack, therefore when the cruise conditions are carried out at a low angle of attack to get high efficiency.

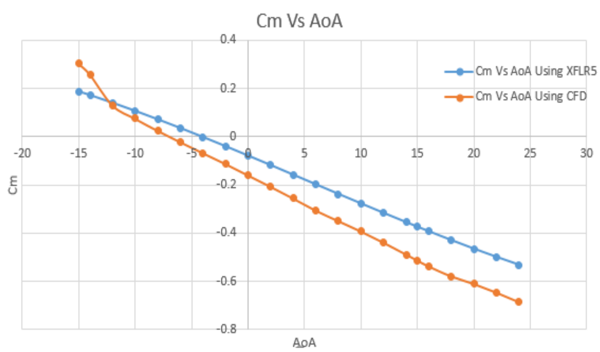

FIGURE 11.Graph of CM Vs AoA

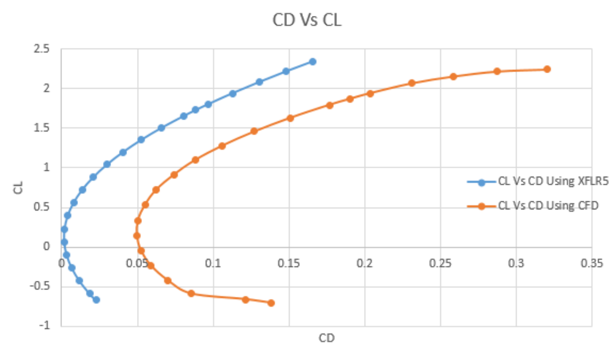

FIGURE 12. Graph of CD vs CL

In the Fig. 11, the results of the analysis of pitching moments with CFD and VLM show that the plane has a tendency of negative pitching moments, meaning that the aircraft has enough stability in operation. So that if there is interference will be able to produce a force to return to a neutral or original position.

In the Fig. 12, the simulation results of the analysis of aerodynamic characteristics for the polar drag curve with a clean configuration. The results show that the VLM simulation on XFLR5 has a higher magnitude than the results of the simulation with CFX. VLM simulation results on XFLR5 have L / D result of 34.71944 and a simulation using CFX of 12.45777 at an angle of attack of 6 degrees. This difference is due to the simulation of VLM on XFLR5 using the ideal method because it is unable to model the effect of air viscosity and to predict the occurrence of flow separation and boundary layer thickness. Therefore it can lead to optimistic results rather than the results of CFX simulations

CONCLUSION

The VLM method is a numerical method that can be used to analyze aerodynamic characteristics on aircraft. In simulations using VLM on XFLR5 it is assumed that the flow is inviscid. Based on the simulation results, VLM gives a pretty good result to find out the aerodynamic characteristics. It can be seen on the CL graph with respect to the angle of attack that the VLM shows good performance. However, for the drag coefficient, the simulation results with VLM do not give good results, this has an impact on CL respect to CD and L / D. Therefore, VLM needs to be developed to be able to provide a good picture related to the characteristics of aerodynamics in aircraft. Based on the results of the analysis of aerodynamic characteristics using VLM on XFLR5 on the LSU-05NG aircraft model, the flight performance of LSU-05NG can flight well under cruising conditions.

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