Effect of fuselage diameter on aerodynamic characteristics for straight wing at low and high aspect ratio

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\textbf{Abstract.} A computational code has been developed to investigate the effect of fuselage diameter with a combination of a straight wing on the aerodynamic characteristics. The case studies were performed on both wing-body combination at high wing aspect ratio (AR>4) and low wing aspect ratio (AR<4). The Prandtl’s Lifting Line Theory (LLT) and Helmbold’s Panel Method (HPM) were used to determine the wing lift and drag characteristics while Roskam’s Drag Prediction Method (RDPM) was used to compute the fuselage drag. The computed lift and drag coefficients obtained were then compared to verify the reliability of the computational results. It is found that a larger fuselage diameter contributes to the increment of the total drag of the wing-body combination without significant effect on the lift. The lift is mainly contributed by the wing for both low and high aspect ratio straight wing for low subsonic case.

1. Introduction

In an aircraft design process, each component of the aircraft must be optimized to achieve maximum performance. The most ideal condition in the design process in terms of aerodynamic is the aircraft should have a maximum production of lift and minimum production of drag to improve the efficiency. Hence, it is important to take into account of every surfaces, parts or components of the aircraft that contributes to the aerodynamic performance. The importance of lift and drag for an aircraft are significant to the overall flight performance. The wing generally contributes the most in terms of lift of the aircraft. However, every single part of the aircraft such as fuselage also contributes to the overall lift, albeit small. Fuselage is the main body structure of an aircraft which holds all the smaller parts such as wings, canards, empennage and landing gears together. It also consists of the cockpit, passenger compartment (cabin) and cargo compartment. Thus, designing a fuselage is neither easy nor simple task, especially for a civil aircraft as the passengers comfort must also be taken into account while sizing it and the fuselage covers a large area of an aircraft which most likely contributes to most of the drag. To minimize the effect of this problem, fuselage is usually designed to be streamlined shape to minimize the pressure drag.

In this article, the effect of wing-body combination on aerodynamic characteristics is studied and discussed, where the wing-body combination is the combination of fuselage and wing. The lift of the wing-body combination is not simply the addition of the lift of wing and lift of body alone, but the flow field across the whole wing-body has to be taken into consideration. The main objective of this
project is to investigate the effect of fuselage diameter for both straight wing for high AR and low AR on the aerodynamic characteristics. A MATLAB program is constructed to aid the study performed. The program is capable to compute the lift and drag for the wing-body combination and provides the comparison for different fuselage diameter. The program is also capable to assist an aircraft designer to perform the sensitivity analysis on aerodynamics characteristics for a wing-body combination when sizing a fuselage.

2. Literature Review
As the fuselage is a very important component in an aircraft and it poses a huge effect on the overall aircraft aerodynamic characteristics, many studies and researches are performed to study the fuselage design and also the wing-body combination of the aircraft on its aerodynamics characteristics. Some of the studies are carried out on the in-service aircraft in order to predict and improve its aerodynamic performance. These researches are essential as any findings will help in the overall aircraft aerodynamics characteristics and its performance.

The Commercial Aeronautics Sector is well aware that there is a need in fulfilling the society’s needs meanwhile reducing the environmental impact and global warming. A balancing between the public’s requirement of cheaper fares and the competition of economic infrastructure is hard to achieve without any significant improvements. Abbas and colleagues [1] had developed new aircraft combinations with laminar and turbulent drag reduction technologies and flow control devices to improve the aircraft performance under separated flow conditions of unsteady nature, also to reduce the complexity of the high-lift devices. The main objective of his research is to reduce the induced drag and noise.

The two basic parameters, namely lift and drag are crucial for the structural design of an aircraft. Before building a real aircraft, it is desirable to know the approximation of the aircraft’s aerodynamics properties. There are many software that are available in the market to perform simulation on the designed aircraft. However, to achieve a more reliable results, wind tunnel test is usually recommended. Ramon Lopez Pereira [2] from Linköpings University, Sweden had conducted the validation of four different aerodynamic modelling software (Tornado, AVL, PANAIR and a handbook-type preliminary method) by comparing the results obtained with experimental results using wind tunnel. He found that the shape of the wing will caused some of the methods to have difficulties in converging to valid results.

F. Nicolosi et.al. [3] had also performed a study on fuselage aerodynamics prediction methods. The study is performed to develop a CFD-based method to predict longitudinal and lateral-directional aerodynamic coefficients (drag, pitch and yaw) of and aircraft. This study carried out shows that about 30% of and aircraft zero lift drag source is attained to the fuselage. As aerodynamics characteristics are strictly related and will affect the stability of the aircraft, it is vital to obtain a reliable aerodynamic characteristic estimation to carry out a well-designed aircraft. The other group of researchers led by Welstead [4] suggest that using vortex lattice method in aerodynamic characteristics prediction as it produce a reasonably accurate estimation for the lift distribution, induced drag, and the moments for a given planform.

As mentioned above, aerodynamics characteristics will have a direct impact on the aircraft stability, thus, there are researches that are conducted in order to understand the effect of the aerodynamics characteristics on the aircraft’s stability behavior. Walter and David [5] had performed the study on the static longitudinal and lateral stability characteristics at low speed of unsweep mid-wing with models of different AR. The research is done by conducting experiments in the Langley stability wind tunnel where both aerodynamics and stability characteristics can be studied on the same time.

In addition to that, Charles F. Hall [6] has also presented the results obtained from a wind tunnel test experimenting on the thin, low aspect ratio wings in combination with a body at subsonic and supersonic speed. The data obtained are lift, drag and pitching moment coefficients for varies Mach number range from 0.25 to 1.9. Furthermore, a series of wing with different planform, aspect ratio,
thickness, thickness distribution, wing camber and twist in combination with the fuselage to perform study on the wing-body combination. His research shows that wings with a sharp leading edge had a lower value of minimum drag at supersonic speed.

3. Theory

To determine the lift curve slope for a straight finite wing, lifting line theory (LLT) is the most common method, where lift curve slope of the finite wing, $a$ is given as:

$$a = \frac{a_0}{1 + (a_0/\pi eAR)}$$  \hspace{1cm} (1)

Where $a_0$ is the lift curve slope of the airfoil used for the finite wing while $e$ refers to the Oswald efficiency factor which is a correction factor that is proportional to the square of wing lift, $C_L^2$, taking into account the non-elliptical lift distribution on wings general shape [7, 8]. According to McCormick [9],

$$e = \frac{1}{1 + \delta}$$  \hspace{1cm} (2)

The induced drag factor, $\delta$ is a function of aspect ratio (AR) and taper ratio (TR) which can be obtained graphically. However, the value of $\delta$ available is limited up to AR of 10 only. TR is the ratio of the tip chord to the root chord. It will affect the lift distribution and structural weight of the wing [10]. A tapered wing helps to create lift distribution that is more similar to an elliptical lift distribution.

However, LLT is not capable to determine the lift curve slope for the wing in some cases where $AR < 4$. Hence, modification is done on equation (1), making it into the Helmbold equation which is applicable to low AR straight wing as shown below: [11]

$$a = \frac{a_0}{1 + (a_0/\pi eAR)^{1/2} + a_0/\pi eAR}$$  \hspace{1cm} (3)

Induced drag coefficient, $C_D0$ for the wing can be determined directly using lift curve slope because $C_D0$s directly proportional to the $CL^2$.

When the wing is attached to the fuselage, the fuselage contributes a large amount of drag to the entire wing-body combination. Flow separation due the geometry of the fuselage is one of the source of drag. Fuselage will contribute few types of drag which includes friction drag, interference drag, form drag, base drag and induced drag [12].

There are several methods that are capable to compute the drag of the fuselage. The most common method used is the Roskam’s Drag Prediction method where it suggest that the fuselage drag coefficient is the summation of the fuselage zero-lift drag and drag due to lift. It can be represented using the following equation [13]:

$$C_{Df} = C_{D_{0f}} + C_{D_{Lf}}$$  \hspace{1cm} (4)

where:

$C_{D_{0f}}$ = zero-lift drag coefficient of the fuselage

$C_{D_{Lf}}$ = fuselage drag coefficient due to lift

As the fuselage drag is highly dependent on the fuselage geometry, its diameter and length will be the main parameters that influence the fuselage drag. Hence, the equation below shows the equation that used to model the zero-lift drag which is also the function of the fuselage geometry.

$$C_{D_{0f}} = R_{wf} C_f \left[ 1 + \frac{60}{(l_f/d_f)^2} + 0.0025 \left( \frac{l_f}{d_f} \right) \frac{S_{wea}}{S} + C_{D_{bf}} \right]$$  \hspace{1cm} (5)

where:

$R_{wf}$ : Wing-fuselage interference factor
\( C_{f} \): Turbulent flat plate skin-friction factor as a function of Mach number and the Re.

\( l_f \): Fuselage length

\( d_f \): Maximum fuselage diameter

\( S_{wet} \): Wetted area of the fuselage

\( C_{D_{bf}} \): Fuselage base drag coefficient

Based on equation (5), in order to obtain a minimal fuselage zero-lift drag coefficient, its wetted area should be minimized and fuselage fineness ratio should be maximized. Another term that will affect the fuselage zero-lift drag coefficient is the base drag which is produce due to the presence of base area of the fuselage. Figure 1 show the fuselage without base area and with base area. The presence of base will leads to flow separation, where the larger the base area, the greater the base drag.

![Figure 1. Example of fuselage without and with base area.](image)

The base drag coefficient of the fuselage can be determined by using the equation below [13]:

\[
C_{D_{bf}} = \left( \frac{0.029(d_b/d_f)^3}{C_{D_{fus-base}}(S/S_{fus})^{1/2}} \right) \left\{ S_{fus}/S \right\}
\]

where,

\( d_b \): Fuselage-base diameter

\( C_{D_{fus-base}} \): Zero-lift drag coefficient of fuselage exclusive of the base from equation (5)

\( S_{fus} \): Fuselage maximum frontal area

From equation (6), the higher base diameter will leads to a greater base drag coefficient as it yields a higher base area.

Similar to the wing, a fuselage will also experience drag that are due to lift. The drag due to lift can be computed using the following equation:

\[
C_{D_{Lf}} = \left( \frac{2a^2S_b}{S} \right) + \left( \frac{\eta C_{d_c}a^3S_{plf_{fus}}}{S} \right)
\]

where,

\( a \): Fuselage angle of attack in radian

\( S_{plf_{fus}} \): Fuselage planform area

\( C_{d_c} \): Experimental steady state cross-flow drag coefficient of a circular cylinder

\( \eta \): Ratio of the drag of a finite cylinder to the drag of an infinite cylinder

Fuselage drag due to lift coefficient is relatively very small compare to the fuselage zero-lift drag. Thus, in some cases, it is neglected as its value is not significant to the total drag of the fuselage. However, it is taken into account for this project to achieve a more accurate computational result.

Although the individual lift of the fuselage is not calculated as its value is very small, the lift generated by the entire wing-body is still been calculated. The lift curve slope of the wing-body combination can be obtained by the equation below:
where,
\[ C_{L_{awf}}: \text{Wing-fuselage (wing-body) lift curve} \]
\[ C_{L_{aw}}: \text{Wing lift curve slope} \]
\[ K_{wf}: \text{Wing-fuselage interference factor} \]

Lift curve slope of the wing-fuselage is the function of the lift curve slope of wing with the wing-fuselage interference factor. This is because the flow across the wing and fuselage will interfere at the position where wing is attached to the fuselage. The wing-fuselage interference factor can be obtained by the equation:

\[
K_{wf} = 1 + 0.025 \left( \frac{d_f}{b} \right) - 0.25 \left( \frac{d_f}{b} \right)^2
\]

From equation 9, it can be agreed that diameter of fuselage and wingspan are the parameters that will directly affects the lift-curve slope of wing-body.

4. Methodology
This article focuses on the effect of fuselage diameter on aerodynamic characteristics for straight wing at both low and high AR. The chosen airfoil, NACA 65209 is analyzed for both low and high AR in order to establish a consistent comparison. The AR that is used to perform the computation is 2 for low AR case and 6 for high AR case while the Reynolds number (Re) are 100000 and 590000 respectively. Vary in Re is due to different chord length of the model for both cases. Other parameters such as TR, wing span, Mach number, fuselage diameter, fuselage base diameter and fuselage length are consistent for both cases, which are 0.6, 1.1025m, 0.13, 0.15m, 0.075m and 1.125m respectively.

The computation of wing-body combination’s aerodynamics characteristics are performed using MATLAB, by constructing relevant coding to perform the simulation. LLT is applied to determine the aerodynamic characteristics of the wing. Meanwhile, fuselage drag is computed by using Roskam’s Drag Polar Prediction Method. The general idea of this method is basically summing up the aircraft components that contributes to the drag. Wing-body lift is also calculated by using Roskam’s Lift Prediction Method and is compare with lift produced by wing alone.

After obtaining all the results, it is compared with established journal results to verify the accuracy of computed result. Similar to all the values of coefficients that are graphically presented, the established journal result data was extracted by using WebPlotDigitizer and plotted in the same graph with analytical result to the ease of comparison.

5. Results
In this article, two case study are performed. The first case study is performed on low AR NACA 65209 wing (AR=2) and wing-body combination at Re=10^6. The outcome of the program is as shown as below.

Referring to figure 2, it shows that lift coefficient for wing and wing-body combination have almost the same lift slope. However, zooming into the graph, it can be seen that the wing body lift curve slope is slightly lower than the wing. This is because the lift of the wing is calculated separately using LLT which considering only the wing itself. Thus, in the wing-body combination where part of the wing is embedded in the fuselage as attachment, the area of the lifting surfaces decrease leading to the decrease in lift produced by the wing, and the fuselage does not produced any lift in this case, causing the lift generated by the wing-body combination is less than the wing. It can be agreed that the lift of wing-body combination is simply from the wing.

Fuselage contributes significant amount of zero-lift drag as it consists of skin friction drag and pressure drag which due to flow separation. Hence, it can be clearly seen in figure 3 that wing body
combination has a higher drag coefficient compared to the wing alone. The difference of drag coefficient of the wing-body combination and the wing indicates the amount of drag produced by the fuselage.

Since the effect of fuselage diameter on lift and drag coefficients is the main objective, the results are clearly presented in Figure 4 and Figure 5. Figure 4 shows that the lift produced by wing-body combination with different fuselage diameter is essentially constant. This is because the fuselage does not produce any lift in this case, thus changing the fuselage diameter does not affect the amount of lift generated. Besides, the varying value is only the fuselage diameter while the wing parameter are kept constant, thus the amount of lift generated by the wing at each wing-body combination is the same, yielding the same results.

The effect of fuselage diameter toward the drag coefficient can be seen in Figure 5, where it shows that the larger fuselage diameter experience higher drag coefficient. This is due to larger fuselage diameter will have a greater surface and cross-sectional area, resulting in greater skin friction and pressure drag. According to equation (5) and (6), fuselage drag coefficient is the function of fineness ratio which is inversely proportional to the fuselage diameter. Fuselage drag coefficient will increase as fineness ratio decreases. This indicates that the fuselage drag coefficient increases with fuselage diameter.

In order to verify the results obtained from the program, comparison between the computational results and published technical journal are done. The published journal results were experimental data obtained by Walter D. W and David F. T., Jr. [5] are plotted together with the theoretical data and presented in Figure 6 and 7 for low AR case. However, the available data obtained from the journal is only started from angle of attack at -4°.
Figure 6. Comparison of theoretical results with journal for lift coefficient against angle of attack with low aspect ratio.

Figure 7. Comparison of theoretical results with journal for drag coefficient against angle of attack with low aspect ratio.

Referring to figure 6, the percentage difference of the experimental data with the computational result is approximately 38.75%. The experimental data has a higher lift curve slope. One of the reasons might be due to the airfoil data used in this study is NACA 65209 while the airfoil used in the experiment is NACA 65A008 as there is no available data for the latter in the airfoil database. The difference in thickness might influence the flow across the airfoil might delay the flow separation. The other reason might due to the difference in Re. The Re used in the experiment is $1.02 \times 10^6$ while due the limitations of available airfoil data, the Re used to perform the computation is $1.0 \times 10^6$. This might cause the computational results to lose some accuracy.

From figure 7, experimental result for wing-body drag coefficient is almost the same with the computational result when the angle of attack is greater than 4°. It both results has a mean percentage difference of 29.4%. This indicates the program is capable to compute drag for the wing-body combination for low AR case. The difference of both results might due to the experiment is carried out in the wind tunnel to simulate the real case of the flow. However, a lot of undesired disturbance that is unpredictable might occur which has the tendency to affect the accuracy of the result. Besides, the surface roughness of the prototype might contribute more skin friction drag as estimated.

The second case study is performed on high AR (AR = 6) of NACA 65209 wing and wing body combination at $Re=5.9 \times 10^5$. Similarly, the lift slope for wing-body combination is almost the same lift slope for wing as shown in figure 8. The zoom in view of the graphs shows that the wing-body lift curve slope is lower than the wing lift. The reason of this phenomenon is discussed had been discussed in previous case.

Comparing figure 8 to figure 2 which is the low AR case, the lift curve slope for the high AR case is higher. Based on LLT, high AR wing contributes to a higher finite wing lift slope. The physics behind this phenomena is a longer wing span (higher AR) will generate more lift with larger span-wise lifting surface. Although the wing lift slope varies with AR, angle of attack at zero lift will remains, which is equal to the airfoil zero lift angle of attack. This can be observed from figure 2, 4, 6 and 8.

As the same theory applies for both case, the drag coefficient of wing-body combination in figure 9 is higher than the wing alone. However, comparing figure 3 and figure 9, it is shown that the fuselage drag in high AR is more significant. The fuselage contribute an average of 31% and 12.5% of drag to the wing-body combination for high AR and low AR respectively. This is due to the reference area, $S$ for high AR is smaller, which contributes to higher fuselage base drag coefficient, fuselage zero lift drag coefficient and fuselage drag due to lift coefficient. Thus, it results in higher total drag coefficient.
Likewise, the graphs in figure 10 has the same pattern with the low AR case. The difference in fuselage diameter for high AR wing does not affect the lift curve slope, i.e. the three fuselage with different diameter share the same lift curve slope. The only difference between both high AR and low AR case is the lift curve slope which depends on the AR.

Observing figure 5 and 11, drag coefficient increases with fuselage diameter. The increment of drag coefficient with increment of 15% fuselage diameter is compared and the increment are 8% and 14% for low AR and high AR respectively. The reason of more increment in high AR case is basically the same concept as discussed while comparing figure 3 and 9. Ratio of fuselage wetted area to reference area is the main reason on contributing different increment in drag coefficient between different AR.

In order to verify the computational results obtained for high AR wing case, comparison with published journal results is crucial. Figure 12 shows the comparison of result from both computational and journal by by Walter D. W and David F. T., Jr. [5]. Both results shows a percentage difference of approximately 13.85%. This difference might due to theoretical results are always obtained base on the ideal case such as the surrounding temperature and pressure are set to remain constant for the entire simulation performed. However, in reality, temperature and pressure might fluctuates during the experiment. At the same time, some assumptions are also made to simplify the mathematic equation and also to apply some principle or theory in some cases.

Figure 13 shows the comparison of journal results with the computational results of the drag coefficient for wing-body combination. Both results are about the same visually, but it has a difference of approximately 12%. This indicates that the program is capable and reliable to compute drag of the wing-body combination for high AR.
Figure 12. Comparison of theoretical results with journal for lift coefficient against angle of attack with high aspect ratio.

Figure 13. Comparison of theoretical results with journal for drag coefficient against angle of attack with high aspect ratio.

6. Conclusion
The fuselage diameter does not contribute to the increment of the lift coefficient of the wing-body combination. The main contribution of the lift in a wing-body combination is mainly from the wing. Fuselage drag is found to be significant in the combination and highly affected by the diameter with larger drag produced by a larger fuselage diameter. The Prandtl’s Lifting Line Theory and Helmbold’s Panel Method have managed to successfully compute the lift and drag for the wing while Roskam’s Drag Prediction Method only capable to compute the drag of the fuselage the wing-body combination. The computational results agree well with the experimental results based on the trend and this suggests that the program is reliable in computing the lift and drag for a wing-body combination for low and high aspect ratio case.

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