Correction of Reynolds number effect for wind-tunnel model with flying wing

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Abstract. A method of Re (Reynolds number, Re) effect correction based on data of wind-tunnel test for flying wing is proposed in this paper. By investigating change laws for longitudinal aerodynamic and moment coefficient, corrective parameters, correction equations and acquisition of correction quantity are introduced. And at the same time, CFD simulations at different Re are carried out to obtain the evidence of what Re does to aerodynamic characteristics and corrective parameters. To reduce fitting error based on polynomial functions, fitting equations of power exponential function are adopted to obtain correction for all corrective parameters. According to the correction quantities and correction equations, the data for wind-tunnel model is corrected to full-scale model. To verify the present method, the results will be compared with result of supercharging wind-tunnel test.

1. Introduction
Although the influence of Re (Reynolds number, Re) for turbo-machinery and centrifugal compressor has received considerable attention in the literatures [1], more and more in-depth research has appeared as the repaid development of aircraft design [2]. In recent years, due to the continuous development of computer technology and CFD (Computational Fluid Dynamics, CFD), numerical simulation becomes very important method for optimization of aerodynamic base on aircraft [3]. However, there still exist some faults in term of turbulence, transition, high resolution scheme and computing resources for CFD technique. Therefore, tunnel-wind test is one of the primary methods to acquire aerodynamic characteristics and conduct optimum designs for the aircraft [4-5].

Limited by wind-tunnel scales, there are very large difference, even in orders of magnitude, between wind-tunnel test and actual flight test for Re, which could give rise to inaccuracy for the data for wind-tunnel test. In other words, that is caused by scale effect. Consequently, extrapolation of wind-tunnel data, namely correction of Re effect, has brought the widespread attention for designers since construction of wind tunnel.

In order to apply the method for correction of Re effect to the real aircraft, a variety of literatures have been studied by a large number of scholars. Saltzman et al [6] compared with wind-tunnel model and flight drag data for various configurations representing aircraft from the mid-1940s to the 1970s. Traub [7] reported a method to extrapolate the drag polar of an airfoil or wing to a higher Re. Zhang et al [8] presented a simple and effective method for drag correction of a transport aircraft from he lower Re to higher Re.
For the method of correction above, there is only drag rather than other aerodynamic forces and moment. That is because the lift and pitching moment don’t change a lot with Re for fighter and transport plane. However, influence on Re is highly complex, including laminar, transition, turbulence, shock wave and boundary layer thickness. For flying wing without tail, change of flow state on the wing surfaces not only affects the drag coefficient, but also influences the maximum lift coefficient and pitching moment coefficient, especially, could cause flight safety. Therefore, the correction of Re effect for the lift coefficient, the drag coefficient and the pitching moment coefficient based on flying wing must be carried out.

In present study, an accurate and efficient method of correction for the lift coefficient, the drag coefficient and the pitching moment coefficient is proposed. And at the same time, for the flying wing, CFD simulations for different Re are carried out to obtain the influence on aerodynamic characteristics for Re and relationships for the corrective coefficients with Re are analyzed. Based on the corrective method and the relationship between the corrective coefficients and Re, the data for wind-tunnel model is corrected to full-scale model. A great agreement is gained with the result of supercharging test.

2. Correction equations

In this section, a brief description of correction equations is provided. This corrective method could correct the lift coefficient $C_L$, the drag coefficient $C_D$ and the pitching coefficient $C_m$ by critical parameter. Meantime, any aircraft is applicable to this method.

2.1. Correction equation of the lift coefficient

The lift $L$ is component of aerodynamic force $R$ perpendicular to free stream velocity $V_\infty$ and dimensionless $L$ named as the lift coefficient $C_L$ is defined as follows:

$$C_L = \frac{1}{2} \rho V^2 S$$

Where $\rho$ is the density of free stream and $S$ is the platform area of wing. figure 1 shows that $C_L$ changes as the angle of attack $\alpha$. From seen this figure, $C_L$ is decided by four main parameters, including the lift curve slope $C_{La}$, the lift coefficient when $\alpha$ is $0^\circ$ $C_{L\alpha=0^\circ}$, the maximum lift coefficient $C_{Lmax}$ and corresponding angle of attack $\alpha$. Hence, $C_L$ is corrected through the subsection. In the linear regime, the corrected lift coefficient $\tilde{C}_L$ can be compute by the corrected lift curve slope $C_{La}$ and the corrected lift coefficient when $\alpha$ is $0^\circ$ $\tilde{C}_{L\alpha=0^\circ}$:

$$\tilde{C}_L = \tilde{C}_{La} \cdot \alpha + \tilde{C}_{L\alpha=0^\circ}$$

$\tilde{C}_{La}$, $\tilde{C}_{L\alpha=0^\circ}$, the corrected maximum lift coefficient $\tilde{C}_{Lmax}$ and corresponding angle of attack $\tilde{\alpha}$ can be deduced by the variation law of $C_{La}$, $C_{L\alpha=0^\circ}$, $C_{Lmax}$ and $\alpha$ related to the Re when the wind tunnel test with variable Re is carried out. However, numerical simulations for different Re are implemented to gain some practical and useful fitting equations, which can be referred at the shortage of test data. Under the circumstances, $\tilde{C}_{La}$, $\tilde{C}_{L\alpha=0^\circ}$, $\tilde{C}_{Lmax}$ and $\tilde{\alpha}$ can be calculated by the following expressions:

$$\tilde{C}_{La} = C_{La} + \Delta C_{La}, \quad \tilde{C}_{L\alpha=0^\circ} = C_{L\alpha=0^\circ} + \Delta C_{L\alpha=0^\circ}, \quad \tilde{C}_{Lmax} = C_{Lmax} + \Delta C_{Lmax}, \quad \tilde{\alpha} = \alpha + \Delta \alpha$$

Where $\Delta C_{La}$, $\Delta C_{L\alpha=0^\circ}$, $\Delta C_{Lmax}$ and $\Delta \alpha$ represent the difference between the corrected Re and the model test Re respectively. In the light of fitting equation for the results of numerical simulations at different Re, the the lift curve slope, the lift coefficient when $\alpha$ is $0^\circ$, the maximum lift coefficient and corresponding angle of attack at these two Re can be calculated.
To guarantee the consistency with the test for the lift coefficient curve, which the lift coefficient changes as the angle of attack, the equation for corrected lift coefficient $C_l$ in the nonlinear segments can be expressed as:

$$C_l = C_{L_0} + \Delta C_{L_{0\alpha}} \cdot \alpha + \Delta C_{L_{\alpha=0}} \cdot \Delta \alpha \cdot \alpha$$

Where $C_{L_0}$, $C_{L_{0\alpha}}$ and $C_{L_{\alpha=0}}$ are the lift coefficient, the lift curve slope and the lift coefficient when $\alpha$ is $0^\circ$ for the model-scale data of wind tunnel test.

Based on the previous results, the lift coefficient for the nonlinear range $C_l$ should be revised again by $C_{L_{\text{max}}}$.

The curve of $C_l$ changing as $\alpha$ is presented in figure 2. It shows that the slope of tangency decreases continuously in the nonlinear segment. Therefore, the slope can be expressed as:

$$k_n = k_1 \cdot \alpha + b_1$$

The formula for curve of lift coefficient in nonlinear range can be obtained by integrating equation (5):

$$C_l = \frac{1}{2} k_1 \cdot \alpha^2 + b_1 \cdot \alpha + c_1$$

The solution for parameters $k_1$, $b_1$ and $c_1$ can be solved by putting the point of intersection of the linear and nonlinear segments $(\alpha, C_{L_{\text{max}}})$ and point of maximum lift coefficient $(\alpha, C_{L_{\text{max}}})$ into the equation (6), and $(\alpha, C_{L_{\text{l}}})$ into equation (5).

Figure 1. The lift coefficient changes as the angle of attack

Figure 2. The curve of $C_l$ changing as $\alpha$

Figure 3. The drag coefficient changes as the angle of attack

2.2. Correction equation of the drag coefficient

The drag $D$ is component of aerodynamic force $R$ parallel to free stream velocity $V_\infty$ and dimensionless $D$ named as the drag coefficient $C_D$ is defined as follows:

$$C_D = \frac{D}{\frac{1}{2} \rho V^2 S}$$

Figure 3 gives the curve of $C_D$ changing as $\alpha$. In this figure, $C_D$ can be expressed by quadratic polynomial $C_D = A \cdot \alpha^2 + B \cdot \alpha + C$, so three parameters affecting $C_D$ are $A$, $B$ and $C$ respectively. Therefore, the corrected drag coefficient $C_{D_{\text{corr}}}$ can be computed by the corrected parameters $A$, $B$ and $C$.

With the help of wind tunnel test for variable Re, $A$, $B$ and $C$ can be deduced by the change law of $A$, $B$ and $C$ over Re. Under the condition of lacking test data, numerical simulations for different Re are carried out to get fitting equation related to Re for the parameters $A$, $B$ and $C$, and $A$, $B$ and $C$ can be calculated by the following expressions:
Where $\Delta A$, $\Delta B$ and $\Delta C$ are the difference between the corrected Re and the test Re for CFD calculation. In the light of fitting equation for the results of numerical simulations at different Re, the corresponding parameters $A$, $B$ and $C$ can be calculated. Therefore, $\Delta A$, $\Delta B$ and $\Delta C$ can be obtained by solving difference.

\begin{equation}
\dot{A} = A + \Delta A, \quad \dot{B} = B + \Delta B, \quad \dot{C} = C + \Delta C
\end{equation}

Figure 4. The pitching coefficient changes as the lift coefficient

Figure 5. The curves of $\dot{C}_\alpha$ changing as the lift coefficient

Figure 6. The present model of numerical simulation or flying wing

2.3. Correction equation of the pitching moment coefficient

The aerodynamic moment $M$ exerted on the body depends on the point about which moments are taken. The dimensional pitching moment coefficient $C_m$ is defined as follows:

\begin{equation}
C_m = \frac{M}{\frac{1}{2} \rho V^2 Sb_d}
\end{equation}

Where $b_d$ is the length of average aerodynamic chord. From this figure it can be seen that $C_m$ is indicated by four major parameters, including the aerodynamic center $C_{m_C}$, the zero-lift pitching moment coefficient $C_{w0}$, maximum available lift coefficient $C_{L_{max}}$ and corresponding pitching moment coefficient $C_{m1}$. According to the relationship between the pitching moment coefficient and the lift coefficient for the result of wind tunnel test, the corresponding pitching moment coefficient $C_m'$ based on the corrected lift coefficient $\dot{C}_\alpha$ is interpolated. In figure 4, $C_m'$ can be corrected by segmentation. In the
In the linear regime, the corrected pitching moment coefficient $\tilde{C}_m$ can be calculated by the corrected aerodynamic center $\tilde{C}_{mcL}$ and the corrected zero-lift pitching moment coefficient $\tilde{C}_{n0}$:

$$\tilde{C}_m = \tilde{C}_{mcL} \ast \tilde{C}_L + \tilde{C}_{n0}$$

(10)

$\tilde{C}_{mcL}$, $\tilde{C}_{n0}$, the corrected maximum available lift coefficient $\tilde{C}_{L_{max1}}$ and corresponding pitching moment coefficient $\tilde{C}_{n1}$ can be deduced by the variation law of $C_{mcL}$, $C_{n0}$, $C_{L_{max1}}$ and $C_{n1}$ related to the Re when the wind tunnel test with variable Re is carried out. But the data of wind tunnel test with variable Re is absent, numerical simulations for different Re are adopted to get some practical and useful fitting equations. Therefore, $\tilde{C}_{mcL}$, $\tilde{C}_{n0}$, $\tilde{C}_{L_{max1}}$ and $\tilde{C}_{n1}$ can be calculated by the following expressions:

$$\tilde{C}_{mcL} = C_{mcL} + \Delta C_{mcL}, \quad \tilde{C}_{n0} = C_{n0} + \Delta C_{n0}, \quad \tilde{C}_{L_{max1}} = C_{L_{max1}} + \Delta C_{L_{max1}}, \quad \tilde{C}_{n1} = C_{n1} + \Delta C_{n1}$$

(11)

Where $\Delta C_{mcL}$, $\Delta C_{n0}$, $\Delta C_{L_{max1}}$ and $\Delta C_{n1}$ represent the difference between the corrected Re and the model test Re respectively. In the light of fitting equation for the results of at different Re, the aerodynamic center, the zero-lift pitching moment coefficient, the maximum available lift coefficient and corresponding pitching moment coefficient at these two Re can be calculated.

To guarantee the consistency with the wind tunnel test for the pitching moment coefficient curve, which the pitching moment coefficient changes as the lift coefficient, the equation for the corrected pitching moment coefficient $\tilde{C}_m$ in the nonlinear segments can be expressed as:

$$\tilde{C}_m = C_m + \Delta C_{mcL} \ast \tilde{C}_L + \Delta C_{n0}, \quad \Delta C_{mcL} = \tilde{C}_{mcL} - C_{mcL}, \quad \Delta C_{n0} = \tilde{C}_{n0} - C_{n0}$$

(12)

Where $C_{mcL}$ and $C_{n0}$ are the aerodynamic center and the zero-lift pitching moment coefficient for the model-scale data of wind tunnel test respectively.

Based on the previous results, the pitching moment coefficient for the nonlinear range $\tilde{C}_m$ should be revised again by $\tilde{C}_{L_{max1}}$ and $\tilde{C}_{n1}$. The curve of $\tilde{C}_m$ changing as $\tilde{C}_L$ is presented in figure 5. It presents that the slope of tangency decreases continuously in the nonlinear segment. Therefore, the slope can be expressed as:

$$C_{mcL} = k_1 \ast \tilde{C}_L + b_1$$

(13)

The formula for curve of pitching moment coefficient in the nonlinear range can be obtained by integrating equation (13):

$$\tilde{C}_m = \frac{1}{2} k_1 \ast \tilde{C}_L^2 + b_1 \ast \tilde{C}_L + c_1$$

(14)

The solution for parameters $k_1$, $b_1$ and $c_1$ can be solved by putting the point of intersection of the linear and nonlinear segments $(\tilde{C}_{L2}, \tilde{C}_{n2})$ and point of available maximum lift coefficient $(\tilde{C}_{L_{max1}}, \tilde{C}_{n1})$ into the equation (14), and $(\tilde{C}_{L2}, \tilde{C}_{mcL})$ into the equation (13).

3. Results

Based on the flying wing in this paper, the Re is $3.2 \times 10^6$ and $1.5 \times 10^7$ for the wind tunnel test and the actual flight test respectively. In order to reduce the cost of the higher Re test, numerical simulations must be carried out at different Re to gain influence on aerodynamic characteristics for the Re.

In this section, Section 3.1 first presents the illustration and results of numerical simulations at different Re. Then the law of all the corrected parameters changing as Re and comparison for every
corrected parameter are proposed in Section 3.2. Finally, the corrected results for $C_L$, $C_D$ and $C_m$ are listed in Section 3.3.

3.1. Correction equation of the pitching moment coefficient
In present paper, flying wing shown in figure 6 is simulated with the application of commercial software CFX while Re is $3.2 \times 10^6$, $5.0 \times 10^6$, $8.0 \times 10^6$, $1.2 \times 10^7$ and $1.6 \times 10^7$, computational Ma (Mach number, Ma) is 0.6 at the altitude of 10km. And at the same time, SST turbulent model that is based on couple equations for $k$-$\omega$ and $k$-$\varepsilon$ and $\gamma$-$Re_\theta$ transition model are adopt to obtain more precise. The curves for lift coefficient, drag coefficient and pitching moment coefficient are indicated in figure 7, figure 8 and figure 9. The results indicate as follows:

1) The Re has little effect on the lift curve slope and the maximum lift coefficient increases with increase of Re;
2) The Re has obvious influence on $C_D$ and minimum drag coefficient increases with the increase of Re;
3) The Re has some effects on $mC_L$ and $mC_m$, and at the same time, the lift coefficient beginning to present nonlinear for the curve of pitching moment coefficient decreases gradually as the increase of Re.

3.2. The investigation on aerodynamic characteristics along with Re
The curves of maximum lift coefficient and drag coefficient changing as logarithm of Re are given, respectively, in figure 10 and figure 11. The results appear as shown below:

1) The maximum lift coefficient increases linearly with the logarithm of Re, but this is unchanged basically when Re increases to a certain value;
2) With the logarithm of Re, the drag coefficient increases monotonously. In order to explain this problem, intermittent factor $\gamma$, which suddenly changes from zero standing for laminar flow to one standing for turbulent flow, is applied to measure transition location on the wing surface that is plotted in figure 12. Figure 13 shows intermittent factor distribution for different Re and figure 14 gives the corresponding shear stress curves at the middle section along wing span for contrast. According to the figure 13, breakpoint of intermittent factor become forward with increase of Re, which demonstrates that the transition position gradually moves forward, laminar flow range decreases and turbulent flow range increases with increasing Re. Therefore, friction resistance should increase when Re increases. This conclusion has been certified in figure 14.

3.3. The correction of Re effect
Taking Ma=0.6 for example, in wind-tunnel test, the Re for normal pressure and boost pressure are $3.21 \times 10^6$ and $7.92 \times 10^6$ respectively. By the corrected method in this paper, based on data of test at normal pressure, corrected data can be obtained at Re=$7.92 \times 10^6$ and is used for comparison with the results of pressurized test to be proved the present method.
3.3.1. The correction of lift coefficient. The curve of lift curve slope changing with logarithm of Re is given in figure 15, which shows that this relationship is approximately linear. Accordingly, polynomial fitting method can be adopted as follows:

\[ C_{\alpha} = 0.001 \cdot (\lg(Re))^2 - 0.012 \cdot (\lg(Re)) + 0.1205 \]  \hspace{1cm} (15)\]

But higher order terms in polynomial may be produce a large deviation, power-exponent function fitting is used to reduce the correction error. The correction formula for lift curve slope is following:

\[ C_{\alpha} = 0.0642 \cdot (\lg(Re))^{0.1521} \]  \hspace{1cm} (16)\]

According to equation (16), the correction of lift curve slope \( C_{mCL} \) which is about 0.000763 can be obtained.

The lift coefficient when \( \alpha = 0^\circ \) \( C_{\alpha=0} \) is presented in figure 16 for fitting curve with logarithm of Re. Therefore, the correction formula of \( C_{\alpha=0} \) is as follows:

\[ C_{\alpha=0} = 0.1224 \cdot (\lg(Re))^{0.6904} \]  \hspace{1cm} (17)\]

The correction formula of lift curve slope changing with logarithm of Re is given in figure 15.
\[ C_{\alpha=0} = 0.03371 \times (\log(Re))^{0.0719} \] (17)

By this formula, the correction of lift coefficient when \( \alpha = 0^\circ \) \( \Delta C_{\alpha=0} = 0.000163 \) can be calculated.

The curve of maximum lift coefficient with logarithm of Re is plotted in figure 17. The fitting formula is proposed as follows:

\[ C_{\alpha=0} = 0.2224 \times (\log(Re))^{0.6904} \] (18)

Accordingly, the correction of maximum lift coefficient \( \Delta C_{\text{max}} = 0.033418 \) is available to be acquired.

Because the angle of attack simulated in present example is less than stall angle of attack, angle of attack associated with maximum lift coefficient \( \alpha' \) should keep maximum calculated angle of attack.

Based on the results of wind-tunnel test at 3.21\( \times \)10^6 and the corrections for lift curve slope, lift coefficient when \( \alpha = 0^\circ \) \( C_{\alpha=0} \) and maximum lift coefficient, the revised results of lift coefficient at Re=7.92\( \times \)10^6 can be obtained by formula (2)–(6). The contrast curves for lift coefficient with angle of attack are drawn in figure 18. This result is consistent with data of wind-tunnel test, and demonstrates the rationality and credibility of our method.

**Figure 18.** The contrast curves for lift coefficient with angle of attack

**Figure 19.** The corrected parameter \( A \) with logarithm of Re

**Figure 20.** The curve for corrected parameter \( B \) with logarithm of Re

3.3.2. The correction of drag coefficient. The corrected parameter \( A \) with logarithm of Re is presented in figure 19. From this figure, it can be seen that parameter \( A \) is kept constant, which indicates that higher order term in the expression for drag coefficient will not be affected by Re.

Figure 20 gives the curve for corrected parameter \( B \) with logarithm of Re, which the ordinate takes as \(-B\) to meet requirement of positive value for the number of power-exponent function. This parameter is expressed as following:

\[ B = -84.5831 \times (\log(Re))^{-6.164} \] (19)

In the light of above formula, the correction of parameter \( B \) \( \Delta B = 0.000248 \) can be calculated. The parameter \( C \) with logarithm of Re is shown in figure 21. The fitting formula is as follows:

\[ C = 0.00006 \times (\log(Re))^{2.5534} \] (20)

Therefore, the correction of parameter \( C \) \( \Delta C = 0.001154 \) can be obtained.

Based on the above analysis and studies, Re does not play an important role to high-order terms for drag coefficient. However, Re has a very significant effect on zero-order term of drag coefficient, namely, frictional resistance coefficient is sensitive to the change of Re. Therefore, under the conditions of low precision requirements, the correction of Re effect for drag coefficient may correct minimum drag coefficient only.

According to the results of wind-tunnel test at 3.21\( \times \)10^6 and the corrections for parameters \( A \), \( B \) and \( C \), the corrected data for drag coefficient at Re=7.92\( \times \)10^6 can be got by formula (8). The contrast
curves for drag coefficient with angle of attack are plotted in figure 22. The results show that the present method has a good agreement with the test.

3.3.3. The correction of pitching moment coefficient. The curve of aerodynamic center \( C_{mCL} \) changing with logarithm of Re is given in figure 23, and the correction formula is following:

\[
C_{mCL} = -0.04281 \cdot \left( \log(Re) \right)^{0.288}
\]  

(21)

According to equation (21), the correction of aerodynamic center \( \Delta C_{mCL} \) which is about -0.00125 can be obtained.

The zero-lift pitching moment coefficient \( C_{m0} \) is presented in figure 24 for fitting curve with logarithm of Re. Therefore, the correction formula of \( C_{m0} \) is as follows:

\[
C_{m0} = 0.0011 \cdot \left( \log(Re) \right)^{1.1334}
\]  

(22)

By this formula, the correction of zero-lift pitching moment coefficient \( \Delta C_{m0} = 0.00063 \) can be calculated.

The curve of the maximum available lift coefficient \( C_{Lmax1} \) with logarithm of Re is plotted in figure 25. The fitting formula is proposed as follows:

\[
C_{Lmax} = 0.4898 \cdot \left( \log(Re) \right)^{0.1971}
\]  

(23)

Accordingly, the correction of maximum available lift coefficient \( \Delta C_{Lmax1} = 0.033418 \) is available to be acquired.

Figure 26 gives the curve for pitching moment coefficient \( C_{m1} \) associated with maximum available lift coefficient changing with logarithm of Re. This parameter is expressed as following:
In the light of above formula, the correction of $C_{nl} \Delta C_{nl} = -0.00441$ can be calculated.

Upon the results of wind-tunnel test at $3.21 \times 10^6$ and the corrections for aerodynamic center, zero-lift pitching moment coefficient, maximum available lift coefficient and corresponding pitching moment coefficient, the correction of pitching moment coefficient at $Re=7.92 \times 10^6$ can be gained by formula (10~(14). The contrast curves for pitching moment coefficient with angle of attack are drawn in figure 27. The result shows that the proposed method is well consistent with wind-tunnel test within the scope of available lift coefficient. However, the error in the scope of non-available lift coefficient has no influence on use of aerodynamic data.

4. Conclusion
A method of Re effect correction for wind-tunnel model with flying wing is introduced in present work. With the help of theoretical analysis for longitudinal aerodynamic curves, corrective parameters, correction equations and acquisition of correction quantity are proposed. To obtain the laws of aerodynamic characteristics and corrective parameters changing with Re, numerical simulations at different Re are carried out. The corrections for corrective parameters are obtained by fitting equations of power exponential function instead of polynomial function to reduce fitting errors.

The validation of the present method for Re effect is achieved by successfully contrasting the corrective results and supercharging wind-tunnel test. It is believed that the present method is an efficient approach for the correction of Re effect with flying wing. It can be extended to aircraft for any other layouts, such as, normal configuration and tail flying wing.

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