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Simulation and Investigation of Geometrical Scaling Effects in the Prediction and Calculation of Aerodynamic Coefficients from Wind Tunnel to Real Scale

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Abstract
The effects Study of the model scale on wind tunnel tests of aerodynamic vehicles and their components to generalize it, to the real scale, is very important because of the direct impact on the performance of the flight system. The aim of the present research is to present a methodology for applying the geometrical scaling effects of NACA 0012 airfoil on airfoil aerodynamic performance. Sixteen scale scenarios include changing the Reynolds number and the angle of attack assuming the Mach number constant is 0.256. The rate of deviation of the validated results for the drag and lift coefficients are 11 and 1 percent, respectively. The results showed that at an angle of attack of 10 o, doubling the airfoil length (Reynolds growth from 3 to 6 million) leads to a decrease of 7.92% in the drag coefficient, an increase of 1.25% in the lift coefficient, and decrease of 18.30% in the pitching moment coefficient. The most important achievement of the present study is the presentation of a methodology for applying the geometrical scaling effects in the form of correlations for aerodynamic performance parameters of drag, lift, and pitch moment coefficients.

Keywords: Geometrical Scaling; Numerical simulation; Aerodynamic performance; Wind tunnel; Presentation of correlations.

1. Introduction

The design and construction of aerodynamic equipment and flight systems are carried out on a much smaller scale than the actual model (scale model) according to dimensional limitations and economic cost considerations. For this purpose, often, a small-scale model of the desired aerodynamic equipment is designed and placed in the manufacturing process to save the costs of the actual model design process and also take into account economic considerations.

The review of the conducted research [1-4] shows that most of the research conducted in the field of aerodynamic equipment scale model has been limited to scales laboratory studies in special conditions and also limited numerical studies, and there is a significant gap in complete studies and simulations that lead to the presentation of the model. There is scaling and prediction of aerodynamic performance parameters. It can also be seen that many researchers, despite extensive research on scale models, have not made a generalization of the results from the scale to the main dimensions. From this point of view, there is a significant gap in research on the method or methods of generalization and development of scale models to model in real dimensions. The basis of the definition of the subject of the current research is due to the lack of sufficient experimental results in this regard. The experimental data available for a particular model are often available at a particular scale. This is if the real problem is on a larger scale, but due to the possibility of measuring the problem, it has been scaled so that its model can be placed in the wind tunnel. After that, studies have been conducted on the desired phenomenon and conclusions have been drawn, but whether the existing scale difference between the wind tunnel scale and the actual scale affects the accuracy and quality of the obtained results to what extent, it has not been evaluated in any source. And at best it has been postponed to the proposal for future work. From this point of view and considering that the main desired parameter and the focus of this study is the changes in the geometrical scale and its effect on the results obtained in the base scale (for example wind tunnel scale), there are few articles that are experimentally based on a model has compared and evaluated its results at different scales in the wind tunnel, and this relative poverty of the source is the main reason for defining the topic of this article. The current research has done extensive and comprehensive studies and simulations in order to investigate the effects of scale on the operating parameters of aerodynamic equipment. Due to the necessity of a detailed analysis of the effect of the geometric scale on the performance of the aerodynamic device of the actual model and, accordingly, the performance of the system, a complete and comprehensive understanding of the methodology of generalizing flight test results is of particular importance. Examining aerodynamic performance parameters such as drag, lift, and pitch moment coefficients under the influence of a small scale compared to the real model is of special importance; Therefore, the importance of investigating and studying the effects of the model scale on the flight tests of aerodynamic equipment in order to generalize and expand it to the real scale, with regard to the direct effect on the performance of the flight system, becomes more clear. In general, the aim of this research is to study and numerically simulate different scenarios of scale effects on the performance parameters of NACA0012 airfoil and extract the outputs, and finally by using its results, the aim is to present and introduce correlations in different performance conditions (including Reynolds, Mach number and angles of attack).

2. Methodology

The simulation of the aerodynamic equipment is done in Ansys Fluent software. Numerous simulations corresponding to the objectives of the research have been carried out in the Workbench environment of Ansys Fluent software.

It should be noted that each of the performed simulations has gone through various processes, including choosing the right model, proper meshing, and other numerical and physical considerations which include the classification of different simulation scenarios. Several scenarios and scale models for the simulation process and the study of scale effects on the performance of aerodynamic parameters of NACA 0012 airfoil equipment should be applied and considered. According to Table 1, the scenarios of the scale model include performing multiple simulations at the studied angles of attack from 0 to 15 degrees and Reynolds numbers from 1.5 to 9 million at a Mach number of 0.256. The desired length scale is the airfoil cord length of 50 cm (base case) and the velocity used in the dimensionless numbers is the free flow velocity.

In Table 1, the coding of the scenarios has been done in order to facilitate an appropriate classification in the process of displaying the outputs and simulation results. It should be noted that the base case of the airfoil length is 50 cm, corresponding to the Reynolds number of 3 million, and the scale models compared to the base case have been simulated, examined, and studied.

3. Results and Discussion

Examining the simulation outputs of different scale models, including static pressure distribution, velocity, aerodynamic parameter values, including drag, lift, and pitch moment coefficients, as well as pressure coefficient changes relative to the length of the solution field for each of the simulation scenarios have been done and in the present section, it will be discussed in detail.

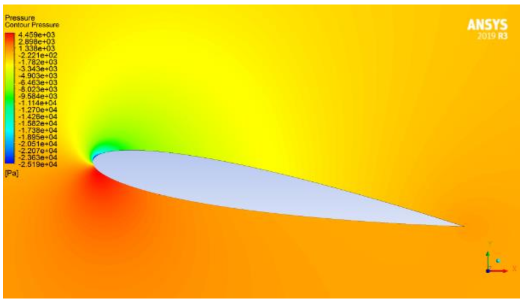
Table 1. The scenario of studied scale models

Scaling Case	Scaling Model	Cord (cm)	Reynolds Number (Million)	Angle of Attack (Case #)	Mach Number
01A	0.5	25	1.5	**0 (01)**	**0.256**
Base (01B)	1	50	3		
01C	2	100	6		
01D	3	150	9		
02A	0.5	25	1.5	**5 (02)**	
Base (02B)	1	50	3		
02C	2	100	6		
02D	3	150	9		
03A	0.5	25	1.5	**10 (03)**	
Base (03B)	1	50	3		
03C	2	100	6		
03D	3	150	9		
04A	0.5	25	1.5	**15 (04)**	
Base (04B)	1	50	3		
04C	2	100	6		
04D	3	150	9		

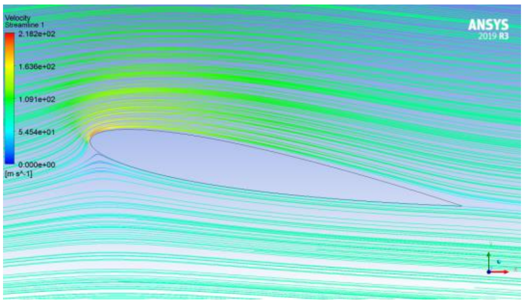
In order to validate and evaluate the simulation results, in the present research, the information and experimental data of the wind tunnel reported by Ladson [5] have been used. Also, in order to qualitatively compare the details of the flow distribution, the pressure coefficient distribution obtained from the simulation of the present study with the wind tunnel data [6], the validation of the simulation results with the experimental results has been done. The comparison of the results shows the appropriate and acceptable accuracy of the simulation of the present research.

The static pressure distribution contour, velocity parameter, and velocity streamline in the solution field in the base case model (at Mach number 0.256, angle of attack 10 degrees, and Reynolds number 3 million) are shown in Figure 1. In Figure 1-a, the stagnation point of the flow, which is very high pressure and in the lower regions of the front of the airfoil, is clearly defined. High-pressure areas on the lower surface of the airfoil and low-pressure areas on the upper surface of the airfoil as shown in the contour will eventually lead to lift force. Also, the formation of streamlines around the stagnation point as well as the upper and lower levels are clearly shown in Figure 1-b.

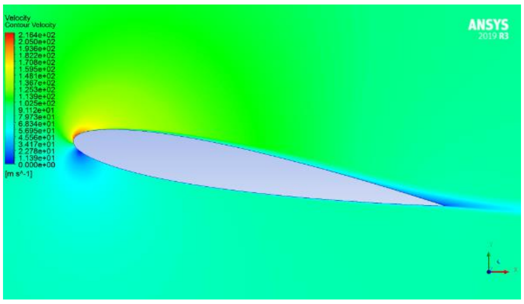
Correlations for aerodynamic coefficients of drag, lift, and pitch moment in scale scenarios are extracted and introduced in the form of correlations 1 to 3, according to the changes of drag, lift, and pitch moment aerodynamic coefficients in relation to Reynolds number.



a



b



c

Figure 1. Distribution (contour) of (a) static pressure (b) streamline (c) velocity in the solution field based on the base scale

$$C_D = a\,Re^b \tag{1}$$

$$C_L = c\,Re^d \tag{2}$$

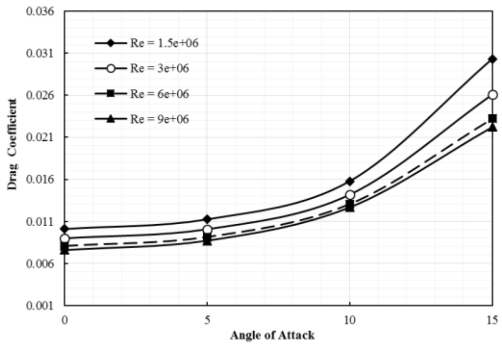
$$C_M = f\,Ln(Re) + h \tag{3}$$

The diagram of changes in drag, lift, and pitch moment coefficients in different Reynolds numbers (scales) according to the angle of attack in all modes of the studied scale (Mach number 0.256) is shown in Figure 2. The diagram in Figure 2a shows that, as expected, the drag coefficient increases with the increase of the attack angle in all Reynolds numbers. Also, at any specific angle of attack, the value of the drag coefficient will decrease with the increase of the Reynolds number. What is interesting is that the amount of changes in the drag coefficient increases with the increase in the angle of attack, as the scale of the model increases. In other words, for a model in the wind tunnel scale, the obtained values of the drag coefficient in all angles of attack are estimated to be lower than the value of the drag coefficient in the real scale, and what is more interesting is that with the increase of the attack angle, this amount of difference in the estimation of the drag coefficient in the wind tunnel and the actual scale has a significant increase. In such a way that at zero-degree angle, this difference is about 20.04 percent, and at 15-degree angle this difference is about 23.47 percent. It should be noted that these differences seriously need to be considered when a model with a specific scale is tested in the wind tunnel, but its results are supposed to be generalized to the real scale, and after obtaining the results with the methodology presented in this article should be applied as correction coefficients to the obtained results. The amount of these differences can be calculated using the correlations presented in this article in each scenario (each angle of attack) and then applied.

Table 2. Correlations presented for aerodynamic coefficient according to scale scenarios

Case / Values	Case 01	Case 02	Case 03	Case 04
Coeff. a	0.097	0.0857	0.0912	0.3630
Coeff. b	−0.1593	−0.1431	−0.1240	−0.1754
C_D R^2 Index	99.95	99.70	98.56	98.62
Coeff. c	*	0.4406	0.7842	0.7620
Coeff. d	*	0.0134	0.0193	0.0424
C_L R^2 Index	*	97.98	98.96	99.13
Coeff. f	*	0.0012	0.0027	0.0035
Coeff. h	*	−0.0219	−0.0503	−0.0751
C_M R^2 Index	*	99.35	99.84	99.62

Similarly, with the increase of the angle of attack, the values of the lift coefficient and the absolute value of the pitch moment coefficient will increase, and also the amount of this increase, decreases with the increase of Reynolds. In summary, according to Figures 2b and 2c, it is concluded that the values of the coefficients of lift and the pitch moment obtained at each angle for the scale model in the wind tunnel are estimated to be higher than the values of these parameters in the real scale, and therefore, if necessary, the results obtained in the wind tunnel to be generalized to the real scale, these changes are necessary to be applied as correction coefficients in the results obtained from the wind tunnel. The most important achievement of this study is that by using the presented methodology, these correction coefficients can be easily calculated and applied to the results of the measured scale model and used with good accuracy for the real model results.



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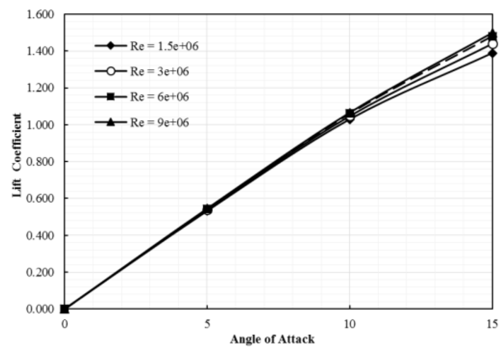

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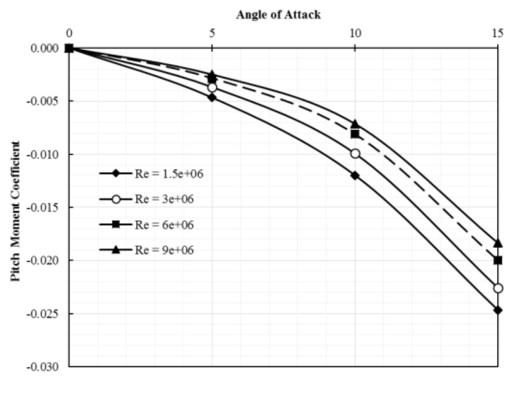

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Figure 2. Changes of (a) drag (b) lift (c) pitch moment aerodynamic coefficients according to attack angles in different Reynolds numbers

4. Conclusions

Investigating the operating parameters of aerodynamic equipment, including drag, lift, pitch moment coefficients, and pressure distribution under the influence of small scale compared to the real model, considering the need for a detailed analysis of the effect of geometric scale on the performance of the aerodynamic equipment of the real model and, accordingly, the system performance, a complete and comprehensive understanding of the methodology of generalizing flight test results is of particular importance. Investigation and numerical simulation of different scenarios of scale effects on the operating parameters of NACA0012 airfoil aerodynamic equipment and extracting the outputs in the present research have been done in multiple scale scenarios.

The results of the simulation are summarized as follows:

• At a Mach number of 0.256 and an angle of attack of 15 degrees, increasing the length of the airfoil by 2 times from 50 cm to 100 cm (the increase in the Reynolds number from 3 to 6 million) leads to an 11% decrease in the drag coefficient, an increase of 2.79% in the lift coefficient and a reduction of 11.59% in the coefficient of pitch moment.

• Increasing the scale by 2 times the length of the airfoil compared to the base case (increasing the Reynolds number from 3 to 6 million) leads to a 10.17% decrease in the value of the drag coefficient.

• With the tripling of the angle of attack from 5 degrees to 15 degrees (in the case of 2 times the Reynolds number growth from 3 million to 6 million), the lift coefficient increases to a greater extent and the increase is 320.84% in the case of 5º.

• The behavior of decreasing the drag coefficient, increasing the lift coefficient, and decreasing the pitching moment coefficient is not linear and in higher scales (high Reynolds) it will follow a smaller amount.

One of the important achievements of the present research is to introduce and present correlations for aerodynamic performance parameters including drag, lift, and pitching moment coefficients for each of the scenarios to be simulated according to the results of numerical simulations of scale scenarios.

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