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FUZZY LOGIC APPROACH FOR PREDICTION THE LIFT COEFFICIENT OF AN AIRCRAFT MODEL WITH AND WITHOUT WINGLET

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ABSTRACT

This paper describes the unique structure of an aircraft model with and without winglet tested at Aerodynamics Laboratory, Faculty of Engineering (University Putra Malaysia) using subsonic wind tunnel of 1000 mm × 1000 mm rectangular test section and 2500 mm long. Focusing on predicting the aerodynamic characteristics of the aircraft model, three main issues are studied in this paper. First, a six component wind tunnel external balance is used for measuring lift, drag and pitching moment. Secondly, Tests are conducted on the aircraft model with and without winglet. And thirdly, Artificial intelligence system such as fuzzy logic approach is used to predict the lift coefficient performance. Therefore, the primary purpose of this work was to investigate the relationship between lift coefficients, with free-stream velocities and angle of attacks, and to illustrate how fuzzy system might play an important role in prediction of lift coefficient with the addition of certain winglet configurations.

Keywords: Winglet, External Balance, Lift Coefficient, Fuzzy Logic.

1. INTRODUCTION

The aerodynamic efficiency of an aircraft can be improved through a wingtip device which diffuses the strong vortices produced at the tip and thereby optimize the span wise lift distribution, while maintaining the additional moments on the wing within certain limits. For a number of years many investigations have been carried out to prove the possible benefits of modifying wing tip flow. Modern interest in winglets spans the last 25 years. Small and nearly vertical fins were installed on a KC-135A and flight was tested in 1979 and 1980 [1-2]. Whitcomb showed that winglets could increase an aircraft's range by as much as 7% at cruise speeds. A NASA contract [3] in the 1980s assessed winglets and other drag reduction devices, and they found that wingtip devices could improve drag due to lift efficiency by 10 to 15% if they are designed as an integral part of the wing. The "spiroid" wingtip [4] produces a reduction in induced drag at the same time blended winglet reduces drag by eliminating the discontinuity between the wing tip and the winglet. Flight tests on the Boeing Business Jet 737-400 resulted in a 7% drag reduction. Theoretical predictions had indicated that the configuration would have only a 1-2% improvement, and wind tunnel tests had shown only 2% drag reduction [5]. The advantages of single winglets for small transports were investigated by Robert Jones [6], on which they can provide 10% reduction in induced drag compared with elliptical wings.

The Pennsylvania State University (PSU) 94-097 airfoil has been designed for use on winglets of high-performance sailplanes [7]. To validate the design tools, as well as the design itself, the airfoil was tested in the Penn State Low-Speed, Low-Turbulence Wind Tunnel from Reynolds numbers of 2.4×10^5 to 1.0×10^6. Another investigation was carried out on wing tip airfoils by J. J. Spillman at the Cranfield Institute of technology in England [8]. He investigated the use of one to four sails on the wingtip fuel tank of a Paris MS 760 Trainer Aircraft. Experiments on flight test confirmed the wind tunnel tests and demonstrated shorter takeoff rolls and reduced fuel consumption [9]. Spillman later investigated wingtip vortex reduction due to wing tip sails, and found lower vortex energy 400-700 m behind the aircraft, although the rate of decay beyond that was somewhat lower [10]. There has been limited investigation of multiple winglets for aircraft. The split-tip design [11] by Heinz Klug for an aircraft wing is considered a primitive multiple winglets which was created to exploit the non-planar wake geometry by reducing induced drag and wing stress. A biologist with an aerodynamic background has done extensive investigation of the split wingtips of soaring birds and he demonstrated that the tip slots of soaring birds reduce induced drag and increase the span factor of the wings [12]. He found remarkable improvements of slotted wingtips compared with conventional wing with a Clark Y airfoil and he investigated that with the same increase in angle of attack, the Clark Y tip increased the base wing drag by 25%, while the feathered tip actually reduced the drag by 6%.

To improve the performance of a wing, the multi-winglet [13] design was evaluated to demonstrate its advanced performance potential over the baseline wing and an equivalent single winglet. The results of their wind tunnel testing show that certain multi-winglet configurations reduced the wing induced drag and improved L/D by 15-30% compared with the baseline 0012 wing. In Europe, an extension to the wing tip airfoils has been developed called Wing-Grid [14]. But this concept is limited, since it is not able to change configuration in flight to optimize drag reduction.

Aerodynamic characteristics for the aircraft model with and without winglet having NACA wing No. 65-3-218 has been explained [15]. An interaction matrix method has also been presented to revalidate the calibration matrix data provided by the manufacturer of the six-component external balance. The calibration of free stream velocity and flow quality in the test section has been established and documented [16].

At present, various techniques exist in soft computing method such as neural network, simulated annealing (SA), genetic algorithms, and fuzzy data analysis. Based on the studies on characteristics of the aircraft, an intelligent system using Fuzzy Logic was proposed to predict the aerodynamic characteristics of the aircraft model. Fuzzy Logic has been applied successfully to a large number of expert applications. Fuzzy [17-18]. This work presents the model of fuzzy system, comprising the control rules to express vague human concepts using fuzzy sets and also describe the corresponding inference systems based on fuzzy rules [19]. The aim of this study was the construction of fuzzy knowledge-based models for the prediction of aerodynamic characteristics of the aircraft model by controlling free stream velocities and angle of attack based on the Mamdani approach. A comparative performance analysis of this approach, by sampling data collected from the operation, was used to validate the fuzzy models.

2. METHODOLOGY

Experiments were conducted in the Aerodynamics Laboratory Faculty of Engineering (University Putra Malaysia) with subsonic wind tunnel of 1000 mm ×1000 mm rectangular test section and 2500 mm long. The wind tunnel can be operated at a maximum air speed of 50 m/s and the turntable has a capacity for setting an angle of attack of 14 degree. Fig. 1 shows a photograph of the aircraft model with elliptical shaped winglet, which is mounted horizontally in the test section of the wind tunnel.

2.1 Calibration of the Balance

Calibration of the six-component balance has been done to check the calibration matrix data provided by the manufacturer Fig. 2 shows a photograph of the calibration rig used for the validation of calibration matrix, which is mounted on the upper platform of the balance in place of model. The relationship between signal readings, L_i and the loads, F_i applied on the calibration rig are given by the following matrix equation, the detailed procedure of calibration using Matlab software is explained elsewhere [16].

$$\{L_i\} = \lfloor K_{ij} \rfloor \{F_i\} \tag{1}$$

Where, $[K_{ij}]$ is the coefficient matrix, $\{L_i\}$ is the signal matrix, and $\{F_i\}$ is the load matrix. The calibration matrix is obtained and it compares well with the calibration matrix data supplied by the manufacturer with six component external balance.

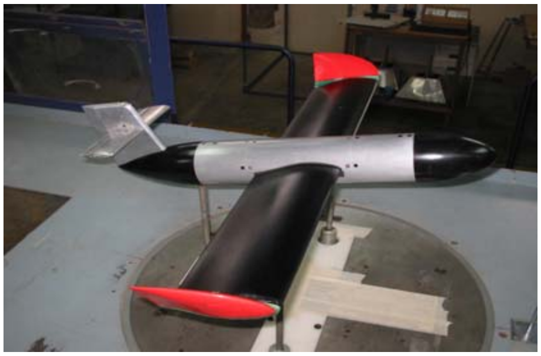

Fig 1. Aircraft Model with Elliptical shaped Winglet

Fig. 2. Calibration rig mounted on the floor of the wind tunnel test section

2.2 Lift coefficient model and Analyses

Coefficient of lift is defined as [20]

$$C_L = \frac{L}{\frac{1}{2}\rho_\infty V_\infty{}^2 S} \tag{2}$$

where L is the lift force in N, ρ_∞ is the air density in kg/m^3, V_∞ is the free stream velocity in m/s, c is the chord length in m, and S is reference area in m^2.

Using equations of state for perfect gas the air density, ρ_∞ in kg/m^3 is defined as

$$\rho_\infty = \frac{p}{RT} \tag{3}$$

Where, p is the absolute pressure in N/m^2, T is the temperature in K, and R is the gas constant of air in Nm/(kg) (K).

Reynolds number based on the chord length is defined

$$\mathrm{Re} = \frac{\rho_\infty v_\infty c}{\mu_\infty} \tag{4}$$

Where, v_∞ is the free stream velocity in m/s; μ_∞ is the dynamic viscosity in kg/(m)(s) and c is the chord length in m.

The air viscosity, μ_∞ is determined using the Sutherland's equation [21] described below

$$\mu_\infty = 1.458 \times 10^{-6} \frac{T^{1.5}}{T + 110.4} \tag{5}$$

Where, T is the temperature in K.

The tests were carried out with free-stream velocity of 21.36 m/s, 26.76 m/s, and 32.15 m/s respectively with and without winglet of different configurations. The coefficient of lift (Table 1) is obtained from the experimental results as per the procedure explained in [16]. The simulations on the parameters are conducted by using the MATLAB/Simulink.

Table 1: Lift coefficients from experimental data

S. No.	Winglet Config-uration	Reynolds Number 10^6	Lift coefficient, C_L		
			Initial Angle of Attack 0^0	Stall Angle of Attack 8^0	Final Angle of Attack 14^0
1	WW	0.17	0.237	0.805	0.657
		0.21	0.259	0.817	0.584
		0.25	0.306	0.879	0.733
2	EWC1	0.17	0.299	0.829	0.641
		0.21	0.327	0.889	0.700
		0.25	0.359	0.934	0.713
3	EWC2	0.17	0.386	0.930	0.729
		0.21	0.394	0.934	0.815
		0.25	0.416	1.018	0.885

Notifications: WW-Without Winglet; EWC1-Elliptical Winglet, Configuration 1 (0^0 angle); EWC2-Elliptical Winglet, Configuration 2 (60^0 angle)

3. FUZZY LOGIC SYSTEM

There are a number of different techniques that would work here. Some of the techniques require a relatively accurate model of the system in order to develop a satisfactory system. Fuzzy expert system, on the other hand, does not require a model of the system. Instead, they rely on the knowledge of an expert for the particular system. Therefore, a Fuzzy Logic expert system is introduced for the prediction of aerodynamic characteristics of the aircraft model. The general configuration of the fuzzy expert system, which is divided into four main parts, is shown in Fig. 3. For implementation of fuzzy values into the model by using Fuzzy expert system (FES), free stream velocity (FV) and angle of attack (AA) were used as input parameters and lift coefficient (CL) was used as output. The linguistic variables very low (VL), low (L), medium (M), high (H), and very high (VH) were used for the inputs and output. In this study, the center of gravity (Centroid) method for defuzzification was used.

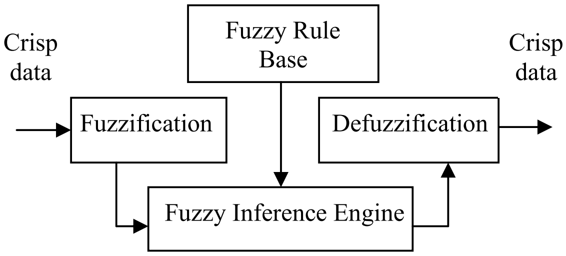

Fig 3. The diagram of the fuzzy system.

The units of the used factors were: FV (m/s), AA (degree), and CL is dimensionless. For the two inputs and one output, a fuzzy rule table is developed as shown in Table 2. Total of 25 rules were formed.

Table 2: Rule base of fuzzy expert system.

Rules	Input variables		Output variable
	FV	AA	CL
Rule1	VL	VL	VL
……	….	….	….
Rule5	VL	VH	VH
Rule 9	L	H	H
……	….	….	….
Rule 14	M	H	H
……	….	….	….
Rule 19	H	H	H
……	….	….	….
Rule 25	VH	VH	VH

3.1 Fuzzification

The first block inside the fuzzy expert system (FES) is fuzzification, which converts each piece of input data to degrees of membership by a lookup in one or several membership functions. There is a degree of membership for each linguistic term that applies to that input variable. Using MATLAB FUZZY Toolbox, prototype triangular fuzzy sets for the fuzzy variables, namely, free stream velocity (FV), angle of attack (AA), and coefficient of lift

(CL) is set up. The term of parameters (membership functions) are presented in the Fig. 4 (a), (b), and (c)).

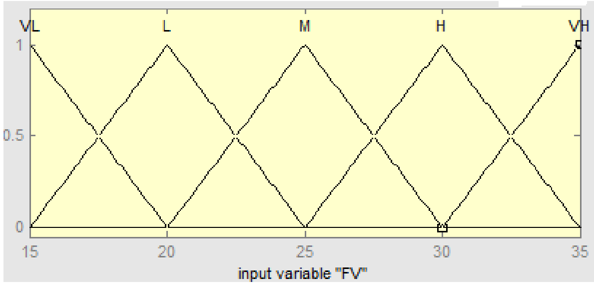

Fig 4 (a). Prototype membership functions for free stream velocity (FV).

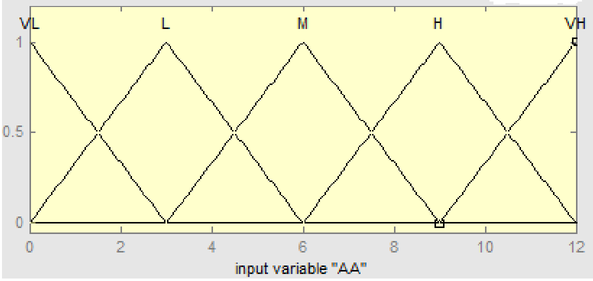

Fig 4(b). Prototype membership functions for angle of attack (AA).

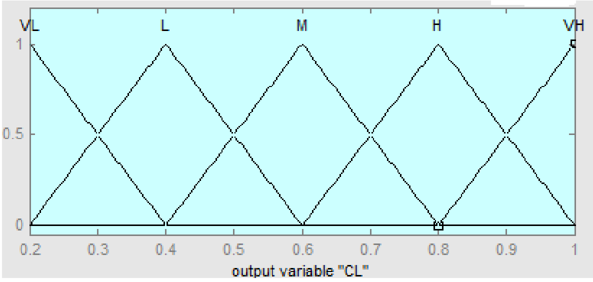

Fig 4 (c). Prototype membership functions for coefficient of lift (CL).

The membership values used for the FES were obtained from the formulas presented analytically in Eqns. (6-8). These membership functions helped in converting numeric variables into linguistic terms.

3.2 Inference step

The determination of conclusion is taken when the rules that are applied to deciding what the output to the plant (aircraft model) should be. In defuzzification stage, truth degrees (μ) of the rules were determined for the each rule by aid of the min and then by taking max between working rules. For example, for FV = 27 m/s and AA = 8^0, the rules 13, 14, 18 and 19 will be fired.

The strength (truth values) of the four rules are obtained as

$$\alpha_{13}=\min\{\mu_M(FV),\mu_M(Aa)\}=\min(0.6,0.33)=0.33$$

$$\alpha_{14}=\min\{\mu_M(FV),\mu_H(AA)\}=\min(0.6,0.67)=0.6$$

$$\alpha_{18}=\min\{\mu_H(FV),\mu_M(AA)\}=\min(0.4,0.33)=0.33$$

$$\alpha_{19}=\min\{\mu_H(FV),\mu_H(AA)\}=\min(0.4,0.67)=0.4$$

For rule (13) the consequent is “coefficient of lift (CL) is medium”. The membership function for the conclusion reached by rule (13), which is denoted as μ_{13}, is given by

$$\alpha_{13}(CL)=\min\{0.33,\mu_M(CL)\}$$

Similarly, the membership functions for the conclusion reached by rule (14), (18) and (19), are

$$\alpha_{14}(CL)=\min\{0.6,\mu_H(CL)\},$$

$$\alpha_{18}(CL)=\min\{0.33,\mu_M(CL)\}$$

$$\alpha_{19}(CL)=\min\{0.4,\mu_H(CL)\}$$

$$\mu_{FV}(i_1)=\left\{\begin{array}{l}\mu_{VL}(i_1)=\dfrac{20-i_1}{5};15\le i_1\le 20\\ \mu_L(i_1)=\begin{Bmatrix}\dfrac{i_1-15}{5};15\le i_1\le 20\\ \dfrac{25-i_1}{5};20\le i_1\le 25\end{Bmatrix}\\ \mu_M(i_1)=\begin{Bmatrix}\dfrac{i_1-20}{5};20\le i_1\le 25\\ \dfrac{30-i_1}{5};25\le i_1\le 30\end{Bmatrix}\\ \mu_H(i_1)=\begin{Bmatrix}\dfrac{i_1-25}{5};25\le i_1\le 30\\ \dfrac{35-i_1}{5};30\le i_1\le 35\end{Bmatrix}\\ \mu_{VH}(i_1)=\dfrac{i_1-30}{5};30\le i_1\le 35\end{array}\right\} \tag{6}$$

$$\mu_{AA}(i_2)=\left\{\begin{array}{l}\mu_{VL}(i_2)=\dfrac{3-i_2}{3};0\le i_2\le 3\\ \mu_L(i_2)=\begin{Bmatrix}\dfrac{i_2}{3};0\le i_2\le 3\\ \dfrac{6-i_2}{3};3\le i_2\le 6\end{Bmatrix}\\ \mu_M(i_2)=\begin{Bmatrix}\dfrac{i_2-3}{3};3\le i_2\le 6\\ \dfrac{9-i_2}{3};6\le i_2\le 9\end{Bmatrix}\\ \mu_H(i_2)=\begin{Bmatrix}\dfrac{i_2-6}{3};6\le i_2\le 9\\ \dfrac{12-i_2}{3};9\le i_2\le 12\end{Bmatrix}\\ \mu_{VH}(i_2)=\dfrac{i_2-9}{3};9\le i_2\le 12\end{array}\right\} \tag{7}$$

$$\mu_{CL}(o_1)=\begin{cases}\mu_{VL}(o_1)=\dfrac{0.4-o_1}{0.2};0.2\le o_1\le 0.4\\ \mu_L(o_1)=\begin{cases}\dfrac{o_1-0.2}{0.2};0.2\le o_1\le 0.4\\ \dfrac{0.6-o_1}{0.2};0.4\le o_1\le 0.6\end{cases}\\ \mu_M(o_1)=\begin{cases}\dfrac{o_1-0.4}{0.2};0.4\le o_1\le 0.6\\ \dfrac{0.8-o_1}{0.2};0.6\le o_1\le 0.8\end{cases}\\ \mu_H(o_1)=\begin{cases}\dfrac{o_1-0.6}{0.2};0.6\le o_1\le 0.8\\ \dfrac{1-o_1}{0.2};0.8\le o_1\le 1.0\end{cases}\\ \mu_{VH}(o_1)=\dfrac{o_1-0.8}{0.2};0.8\le o_1\le 1.0\end{cases}\qquad (8)$$

3.3 Defuzzification Module

In this stage defuzzification operation is considered that is the final component of the fuzzy controller. Defuzzification operates on the implied fuzzy sets produced by the inference mechanism and combines their effects to provide the "most certain" controller output (plant input). Due to its popularity, the "center of gravity" (COG) defuzzification method is used for combing the recommendations represented by the implied fuzzy sets from all the rules [19].

The output membership values are multiplied by their corresponding singleton values and then are divided by the sum of membership values.

$$CL^{crisp}=\frac{\sum b_i\mu_i}{\sum \mu_i}\qquad (9)$$

Where b_i is the position of the singleton in *i* the universe, and $\mu_{(i)}$ is equal to the firing strength of truth values of rule *i*. Using the above mentioned rules in Fig. 4(c), the following values are obtained as

$$b_{13}=0.6\,,b_{14}=0.8\,,b_{18}=0.6\,,b_{19}=0.8$$

Using equation (9) with membership values obtained from the rules, the coefficient of lift (CL) could be obtained as the crisp output of 0.72.

In addition, the predictive ability of developed system was investigated according to mathematical and statistical methods. In order to determine the relative error (ε) of system, the following equation was used:

$$\varepsilon=\sum_{i=1}^{n}\left|\frac{y-\hat{y}}{y}\right|\frac{100\%}{n}\qquad (10)$$

Where n is the number of observations, y is the actual value, and $\hat{y}$ is the predicted value. The relative error gives the deviation between the predicted and experimental values and it is required to reach zero. In addition, goodness of fit (η) of predicted system was calculated by following equation:

$$\eta=\sqrt{1-\frac{\sum_{i=1}^{n}\left(y-\hat{y}\right)^2}{\sum_{i=1}^{n}\left(y-\bar{y}\right)^2}}\qquad (11)$$

Where $\bar{y}$ is the mean of actual values. The goodness of fit also gives the ability of the developed system and its highest value is 1.

4. RESULTS AND DISCUSSIONS

4.1 Simulation Condition

The lift coefficient characteristics of the aircraft model without winglet under test are shown in Fig. 5 for all Reynolds numbers. The lift increases with increase in angle of attack to a maximum value and thereby decreases with further increase in angle of attack. At the maximum value of the angle of attack the lift coefficient characteristic has a mixed behavior e.g. the value of the lift coefficient first decreases with increase in Reynolds number and then increases with further increase in Reynolds number. At the maximum angle of attack of 14 degree the lift coefficients are 0.657, 0.584, and 0.733 respectively for the Reynolds numbers of 1.7×10^5, 2.1×10^5, and 2.5×10^5.

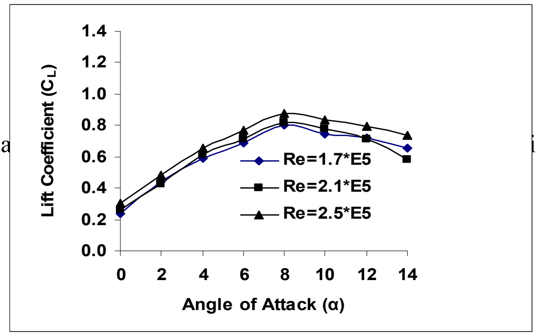

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Fig 5. Lift Coefficients for the Aircraft Model without Winglet.

The reason for a drop in lift coefficient beyond a certain angle of attack e.g. 8^0 is probably due to the flow separation, which occurs over the wing surface instead of having a streamlined laminar flow there. This condition is called stalling condition and the corresponding angle of attack is called stalling angle. The stalling angle happens to be approximately 8^0 for all the Reynolds numbers under the present study. The lift coefficient data for elliptical winglet of two configurations i.e. configuration 1 (winglet inclination 0^0), and configuration 2 (winglet inclination 60^0) is given in Fig. 6 and 7 respectively.

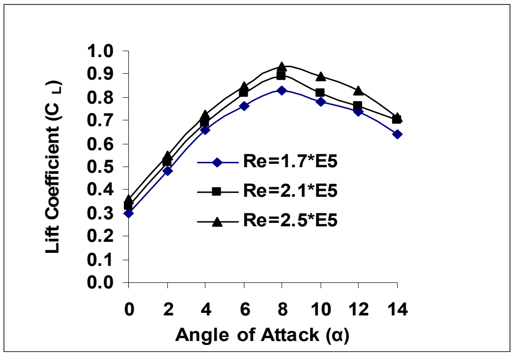

Fig 6. Lift Coefficients for the Aircraft Model with Elliptical Winglet at 0^0 (Configuration 1).

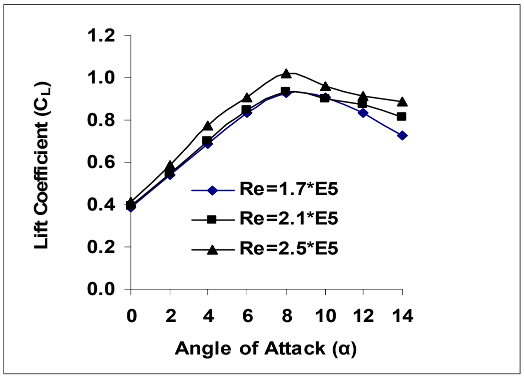

Fig 7. Lift Coefficients for the Aircraft Model with Elliptical Winglet at 60^0 (Configuration 2).

In case of the winglet for both configurations 1 and 2 a similar pattern is observed. For maximum Reynolds number of $2.5x10^5$ lift coefficients for config.- 1 (Fig. 6) and for config.-2 (Fig. 7) are 0.934 and 1.018 respectively corresponding to an angle of attack of 8^0.

The results of the developed fuzzy expert system (FES) were compared with the experimental results. For lift coefficient analysis, the mean of actual and predicted values were 0.62 and 0.60 respectively. The coreelation between actual and predicted values (from FES model) of lift coefficient in different angle of attack was given in Fig. 8. The relationship was significant for all parameters. The correlation coefficient of reltionship was found as 0.99. The mean relative error of actual and predicted valus (from FES model) was found as 5.18% for the velocity of 26.36 m/s which was found to be less than the acceptable limits (10%). The goodness of fit of prediction (from FES model) value was found as 0.95 which was found to be close to 1.0. The above indices indicate that the system is qualified to replace the work of an operator.

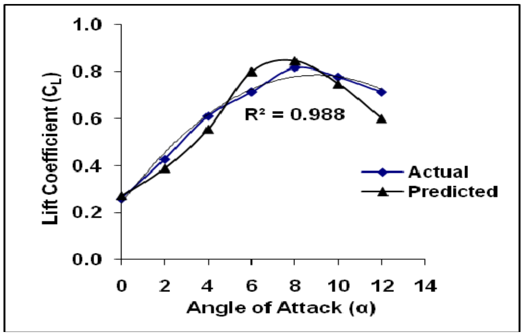

Fig 8. Correlation between actual and predicted values of lift coefficient.

5. CONCLUSION

Prediction of aerodynamic characteristics for an aircraft model is necessary for aerospace industry. In comparison to other predictive modeling techniques, fuzzy models have the advantage of being simple (rule base and membership functions) and robust. In this study, according to evaluation criteria of predicted performances of developed fuzzy knowledge-based model was found to be valid. However, the conclusions drawn from this investigation are as follows:

(a) The developed model can be used as a reference for the full scale aircraft.
(b) This system can be developed further by increasing the knowledge rules and by the addition of neural network to the system.

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