term has been calculated. A comparison of effective pressure gradients over pitching and plunging thin airfoils has been made. The results show that the similarity between the two oscillatory motions, often assumed in the dynamic stall analyses, is not correct because of different leading-edge separation.

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Aerodynamic Suppression of Wing Rock Using Fuzzy Logic Control

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I. Introduction

WING rock is a limit-cycle roll oscillation experienced by aircraft with sweptback wings at high angles of attack. The amplitude and frequency of wing rock is a nonlinear function of many parameters such as angle of attack, side slip, etc. Nayfeh et al.[1] have suggested an approximate nonlinear mathematical model to describe the wing rock phenomenon.

Several theories have been put forward over the years to explain the wing rock phenomenon. Some of the factors, which emerge out of these, are as follows. 1) Wing rock is initiated because of vortex asymmetry.[2] 2) Vortex bursting does not initiate wing rock, but plays an active part in limiting the amplitude of the limit cycle.[3] 3) There is negative roll damping at small angles of bank and positive roll damping at higher angles of bank.[4] 4) Wing rock is caused by the relative time lag between the static and dynamic position of vortex normal to the wing surface.[5]

These studies indicate that the vortex formation plays an important role during wing rock. Hence, one can manipulate these vortices suitably for achieving wing rock suppression. Various techniques have been used for aerodynamic suppression of wing rock with this vortex manipulation. Some of them are 1) steady and pulsed blowing,[6] 2) tangential leading-edge blowing,[7] 3) spanwise blowing,[8] and 4) recessed angle spanwise blowing (RASB).[9] In addition to these blowing techniques, efforts have been made to alter the behavior of the vortices using sharp-edged deflectors[10] and apex flaps.[11]

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Paralleling these experimental efforts to study and suppress the wing rock phenomenon, various control techniques have been tried employing the approximate mathematical model. Some of the prominent ones are 1) optimal control-based techniques,[12,13] 2) use of fuzzy logic control (FLC) for suppression,[14] and 3) suppression using neural networks.[15,16] These methods have shown to be very successful in suppressing the wing rock numerically.

For most engineering systems, there are two important information sources. The sensors that provide numerical measurement of the variable of interest are the first source and another is the human expert who provides linguistic information about the system. Conventional engineering approaches have difficulty in incorporating this linguistic information. This results in a lot of valuable information being lost. A knowledge-based system[17] can be defined as a system in which the performance, reliability, and robustness of the system is improved by incorporating knowledge that cannot be accommodated in the analytical model and that is normally taken care of by the manual modes of the operator or by other safety and ancillary logic mechanisms. FLC[18] belongs to this class of knowledge-based systems, places more emphasis on the linguistic information, and is primarily concerned with the input output behavior of the plant. Hence, FLCs are robust and can be used to control processes whose mathematical models are not well defined or are nonlinear. The present work aims at suppressing the wing rock by the RASB technique. To control the amount of blowing and the direction of blowing, a simple FLC is derived. The FLC is developed without assuming a mathematical model of the system. For constructing the rule base, experience is gained by carrying out some initial experiments in the wind tunnel. A brief description of the FLC is provided in Sec. II. The development of the FLC based on the experimentation is outlined in Sec. III. Section IV discusses the experimental results with the FLC. The paper is concluded in Sec. V, outlining some future work.

II. FLC[17]

The FLC is based on the fuzzy set and fuzzy logic that is closer in spirit to human thinking and natural language than traditional logic systems. Figure 1 shows the block diagram of an FLC. The FLC consists of fuzzification, decision making, knowledge base, and defuzzification blocks. For the sake of completeness, the various blocks are discussed very briefly in the following paragraphs.

Fuzzification maps the crisp input variables into fuzzy variables with their associated degrees of membership. Thus, each value of the input variable is transformed into fuzzy term sets with associated degrees of memberships. Once the degrees of memberships of the crisp inputs are known, they are passed onto the decision making logic (DML) block. DML refers to the knowledge base for processing the data.

The knowledge base primarily consists of a rule base and a database. The rule base consists of fuzzy IF–THEN statements; the IF part is the rule antecedent, and the THEN part is the rule consequent. The rule base is used to represent in a structured way the control policy of an experienced process operator and/or the control engineer. The rule base characterizes the control goals and the control policies of the domain experts by means of linguistic rules such as the following: If error e is negative big (NB) then control input u is positive big (PB). The defuzzification block is used to convert fuzzy outputs of the DML to crisp outputs to be given to the real world. This is the inverse of fuzzification.

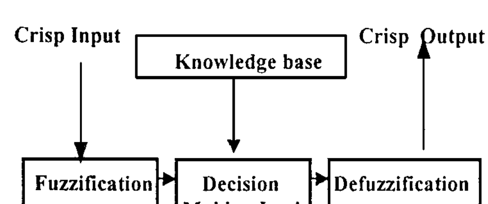

Fig. 1 Block diagram of FLC.

III. Development of FLC

The experiments are conducted in the low-speed stability wind tunnel of the Aerospace Engineering Department at the Indian Institute of Technology, Mumbai. The model is a free to roll stringed 80-deg delta wing with a sharp leading edge. The blowing is accomplished through two sealed copper tubes running along the leading edge. The blowing ports are drilled at an angle of 30 deg to the wing surface, at fixed distances. A commercial compressor is used for generating the required pressurized air supply for blowing. The outlet of the compressor is connected to a pressure regulator, and from the regulator it is given to the solenoid valves. The solenoid valves are of on/off type only. The switching of the solenoid valves is controlled by the FLC incorporated in a personal computer. The

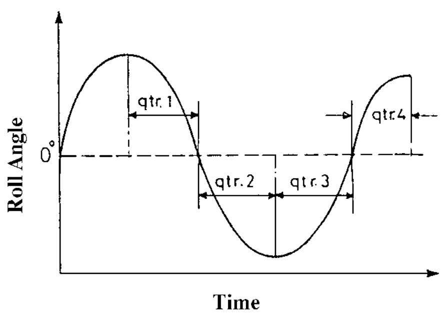

Fig. 2 Different quarters for blowing.

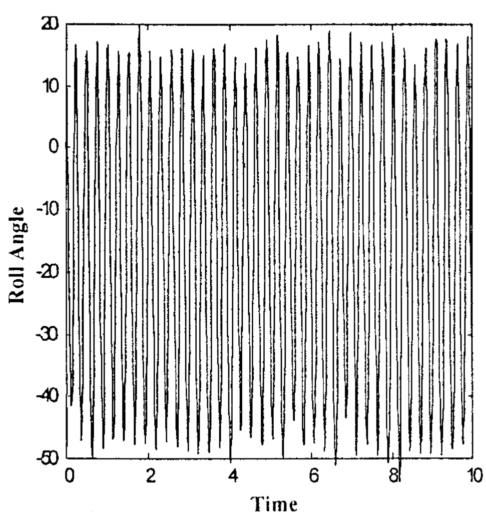

Fig. 3 Blowing during upward motion.

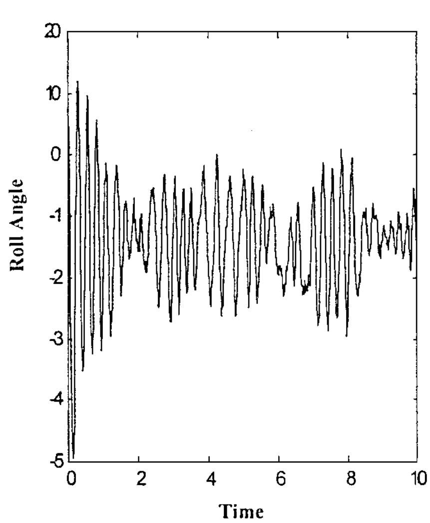

Fig. 4 Blowing during entire downward motion.

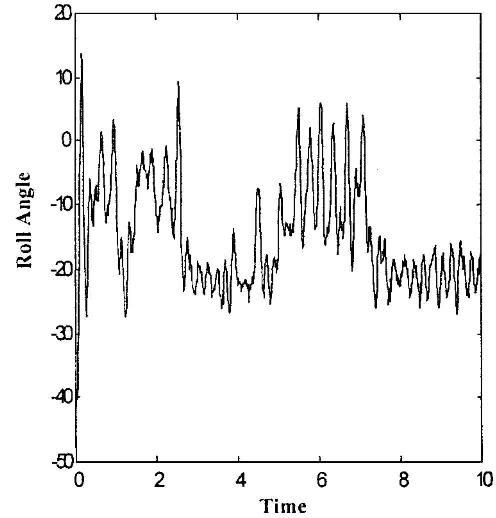

Fig. 5 Blowing during second-half of downward motion.

Fig. 6 Rule base.

e \ $\dot{e}$	PB	Z	NB
PB	NB	Z	Z
Z	Z	Z	Z
NB	Z	Z	PB

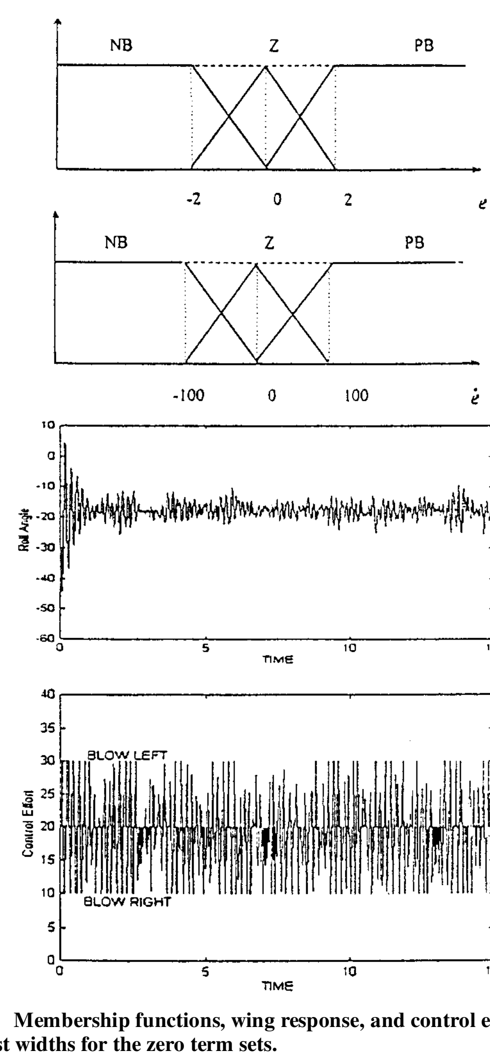

Fig. 7 Membership functions, wing response, and control effort with the best widths for the zero term sets.

roll angle is measured using a potentiometer, and the roll rate is calculated through a finite difference method. The rule base is constructed by experimenting with the system using a simple controller. The controller switches on the blowing during different phases of the wing motion, and the effect of blowing is studied. Figure 2 shows the motion of the right wing (right side of the wing) with different quarters considered for blowing.

1) Blowing during upward motion occurs in quarter numbers 3 and 4. The blowing strategy involved the blowing of air alternatively between the left side and right side of the wing that is undergoing upward motion. Figure 3 shows that the amplitude of wing rock has increased. This eliminates the possibility of reaction force from the jets contributing to the suppression of wing rock.

2) Blowing during the downward motion occurs in quarter numbers 1 and 2. This involved the blowing of air alternatively between the left side and right side of the wing that is undergoing downward motion. The reduction in the wing rock amplitude is clearly seen in Fig. 4.

3) Blowing occurs during the different halves of the downward motion. This experiment is conducted to isolate the half in which there is effective suppression. It is seen that the blowing during the second-half of the downward motion (quarter 2) is effective in suppressing the wing rock (Fig. 5).

Based on the results of the experiment, a simple nine rule set is constructed (Fig. 6) for a fuzzy proportional and derivative (PD) type of controller. The FLC employs both the roll angle and the roll rate (hence, PD type). The roll rate is obtained by numerically differentiating the roll angle measurements from the potentiometer. The on–off nature of the solenoid valves (the control effort) is reflected in the rule base. The FLC is incorporated in the personal computer by programming in Borland Turbo C++.

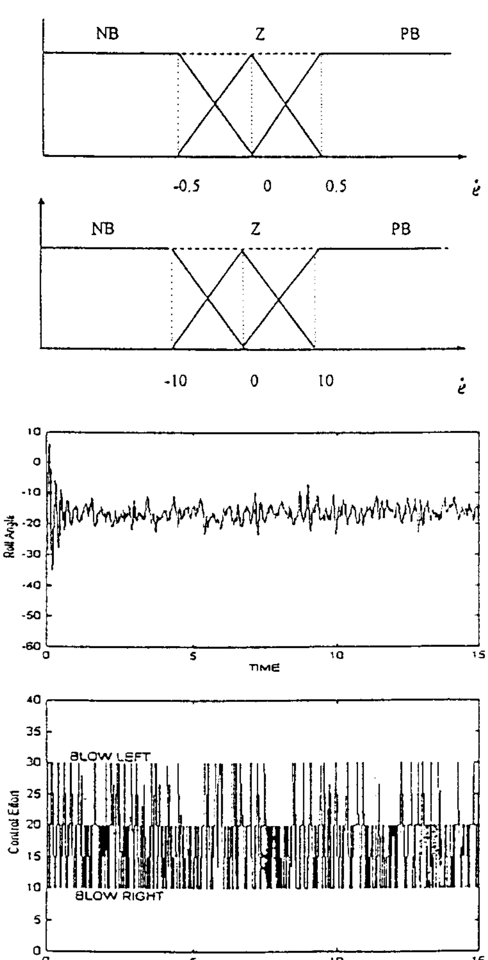

Fig. 8 Membership functions, wing response, and control effort with smaller widths for the zero term sets.

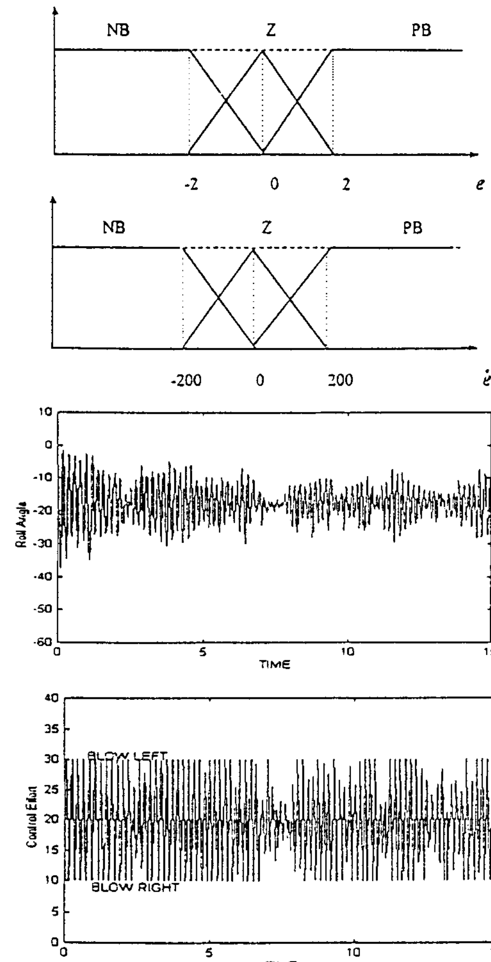

Fig. 9 Membership functions, wing response, and control effort with larger term set for the error rate.

The term sets for obtaining the fuzzification are adjusted to increase the effectiveness of the controller. It is seen that the best suppression is obtained by keeping the zero error rate term set base width to from +100 to −100 and narrowing the zero error term set base width to from +2 to −2 (Fig. 7). If the error rate or error term set is decreased it results in more control effort to achieve the same degree of suppression (Fig. 8). If the error rate or the error term set is increased, then the suppression is ineffective (Fig. 9).

IV. Discussion of Experimental Results

The experimental results indicate that the RASB using a proper FLC can be very effective in suppressing the wing rock. The tuning of the FLC is done based on the expertise gained during the experiments. This circumvents the necessity for a proper mathematical model to get good results, a major drawback of conventional controllers.

The blowing technique using RASB increases the swirl angle of the vortex by inducing a higher rotational velocity in the core.[9] As the swirl angle increases beyond a critical value, bursting occurs. Additionally, the induced velocities will tend to reduce the pressure gradient resulting in the vortex breakdown. Hence, if the blowing is switched on during the downward motion of the wing, it creates local maxima in the circulation profile and makes the vortex structure unstable, preventing the building up of the lift that is essential for sustaining wing rock.

There will be a time lag between the controller giving the command for blowing and the wing response to opening the port. The time lag, if large, will significantly alter the wing behavior to the control inputs. The time lag is measured by recording the time history of the wing response and the control input. This time lag is found to be of the order of 30 ms, which is small when compared to

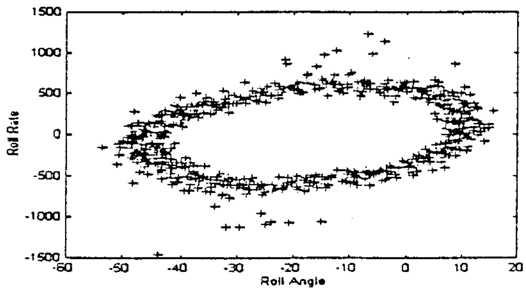

Fig. 10 Phase plane plot.

the wing rock time period of 250 ms. Hence, the time lag has been ignored.

The phase plane plot of the wing rock should ideally be a closed figure, but as seen from the data acquired during the experiments (Fig. 10), it is not so. This could be attributed to the presence of noise. Noise from the potentiometer would be due to the vibration of the sensor, due to the vibration of the tunnel itself. No effort has been made in the present exercise to eliminate the noise. The FLC is seen to be effective even in the presence of this noise.

An approximate estimate of the blowing coefficient C_μ indicated a value of 0.033. In spite of the restriction in terms of limited control available and the noisy input, the wing rock amplitude that used to be of the order of 60-deg amplitude is seen to be suppressed to the order of $\frac{1}{4}$ of the original amplitude. Further fine tuning and reduction in noise may lead to better suppression.

V. Conclusion

An FLC is presented to suppress the nonlinear wing rock phenomenon. RASB is employed for the vortex manipulation. The rules for the FLC are developed by the experience acquired during the experiments. The hardware in the loop simulation (with a delta wing in the tunnel and the controller in the personal computer) has shown encouraging results. Further experiments are being planned with improved fine tuning of the controller, proper filtering to reduce the noise, a possible increase in the blowing coefficient, and a better control over the airflow using servovalves rather than on–off valves. Vortex mapping is also planned to reason out the possible mechanism for the suppression of wing rock with the controlled blowing.

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Origin of Vortex Wandering over Delta Wings

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Introduction

VORTEX wandering is defined as the random displacement of the vortex core. It has been observed over delta wings[1] as well as in tip vortices trailing from rectangular wings.[2–4] Several possibilities for the origin of vortex wandering were suggested previously. However, there has been no convincing explanation regarding the source of this random motion. The purpose of this Note is to present new evidence that suggests that vortex wandering may be due to the Kelvin–Helmholtz instability of the shear layer separated from the leading edge of a delta wing.

Very large swirl velocity fluctuations due to vortex wandering were observed in the vortex subcore over a delta wing[1] (in the absence of vortex breakdown) as shown in Fig. 1. The maximum rms swirl velocity, which occurs at the axis of the time-averaged vortex, increases with angle of attack and can exceed the freestream velocity. Other investigators[5–9] also observed large velocity fluctuations in the vortex cores over delta wings, model aircraft and ogive-cylinders over a wide range of Reynolds numbers. These observations are summarized in Table 1. It is seen that large velocity fluctuations in the vortex cores are common regardless of geometry and Reynolds number. Note that the amplitude of the velocity fluctuations depends on the time-averaged velocity, which is a function of particular geometry and angle of attack. Also, Gursul and Xie[10] suggested that the vortex wandering is responsible for the delta wing and fin buffeting at low angles of attack, where vortex breakdown is not observed.

It is suggested in Refs. 2 and 4 that the vortex wandering in tip vortices is due to the freestream turbulence. In Ref. 1, several possibilities including the Kelvin–Helmholtz instability in the shear layer and the unsteady turbulent flow in the wake of the wing were discussed as potential sources of vortex wandering over delta wings. It is known

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