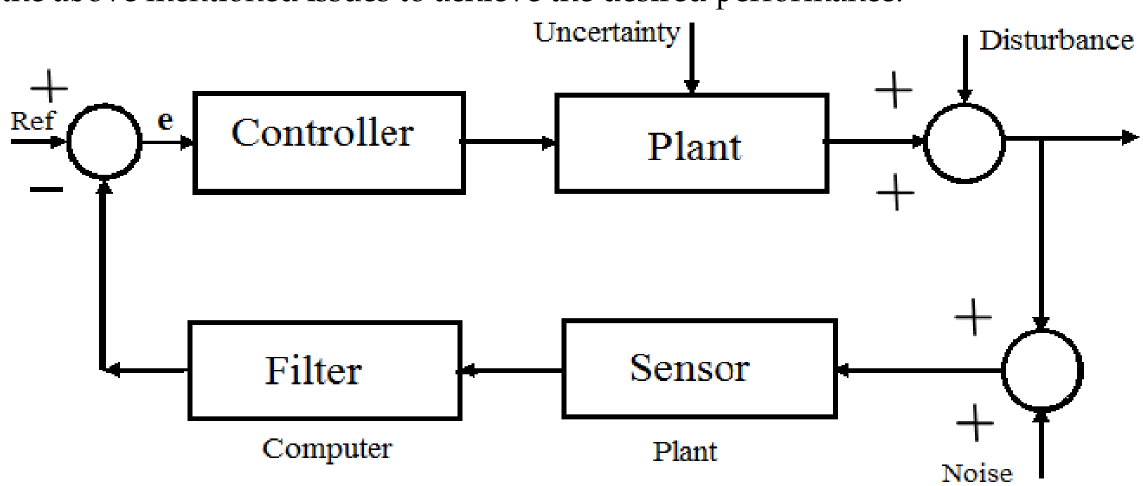
# *Control Synthesis and Analysis of unsteady airfoil at transitional Reynolds numbers with flow control*

**Research achievements:**

The research in qualitative theory of dynamical systems has remarkably well developed and its significance is well documented. The theory describes the behaviors of complex and nonlinear phenomena in mathematics and physics, but it also has a long and rich tradition of classifications in engineering, biology, economics, statistics, and so forth. The properties of dynamical systems play a central role in control systems. The research in this area is extremely important because of its wide range of applications in many areas of science and engineering such as aerospace, defense, robotics, pattern recognition, optimal computation, combinatorial optimization and so on. On the other side, mathematical modeling is an essential tool in studying a diverse range of dynamical systems. In particular, when modeling dynamical systems, kinematics of the actuators, reliability and security of communications, bandwidth allocation, and development of data communication protocols, real-time information collection and efficient processing of sensors data are the main issues. Moreover, the modeling errors and external noise are a concern; the main difficulty is finding suitable user defined controllers to deal the above issues. Moreover, the controllers designed to reduce the plant perturbations, are sometimes very sensitive, or fragile to their own controller coefficient fluctuations. That is, in practical implementation of the controller, due to the existence of the accuracy problem, parameter drift and other environmental factors, the gain parameters of the controller are possible to accumulate some parameter variations. So, in this case the designed controller can be implemented with infinite precision. More precisely, by designing a proper controller for a dynamical system we can overcome all the above mentioned issues to achieve the desired performance.




Robust control methods are designed to ensure the system works as properly provided that uncertain parameters or disturbances are found within some (typically compact) set. Fig. 1 describes the typical control plant, with uncertainty, disturbances and noise.

Also, Fig. 1 shows the separation of the computer control system with that of the plant. It is important to understand that the control system designer has little control of the uncertainty in the plant. The designer creates a control system that is based on a model of the plant. However, the implemented control system must interact with the actual plant, not the model of the plant

Motivated by this consideration, we focused on the mathematical modeling, analysis and control design for various types of air vehicle gust-response, wind-energy and high-speed rotorcraft, among other applications. Airfoils may be subject to simultaneous surge and pitch, where the flow can be attached, partially separated, or massively separated. Under these unsteady conditions, there is often a desire to control these flows with the objective, for example, of minimizing unsteady loads or maximizing net aerodynamic efficiency.

Present Work:- **Goman-Khrabrov(G-K) Model with Flow Control**

The G-K model is capable of reproducing the dynamic hysteresis effects on a pitching NACA 0018 airfoil for dimensionless frequencies and pitch amplitudes. Also, the G-K model works adequately well for a certain range of reduced frequencies and angles of attack. The model performance suffers at small reduced frequencies where static hysteresis is present or at large angles of attack where the path dependency of the static hysteresis plays a role in the unsteady lift forces. In the G-K model, derived by Goman and Khrabrov (1994), the lift or the momentum coefficients are related to the dynamics of the location of the separation point, denoted as $X \in [0,1]$, where this point corresponds to the distance from the leading edge, normalized by the chord length, where the flow is separated from the wing. Thus, picking $X = 0$ corresponds to a fully separated flow while $X = 1$ represents a fully attached flow.

**Objective and Contribution:** On the other hand, the G-K model can be capable of modeling the controller where predominantly trailing-edge separation is present. The combined effect of trailing-edge separation and the formation and shedding of the leading-edge dynamic stall vortex is a particularly challenging problem to model. The G-K model can clearly predict the dynamic effects associated with trailing-edge separation, but modification would need to be introduced in order to predict the effect of the generation and advection of the dynamic stall vortex as well as its shedding into the wake.

This work is to introduce a modification to the G-K model that can compensate the presence of disturbance models for the lift response to pitching at different steady-state blowing amplitudes. A plant model for the lift response to sinusoidal blowing amplitude is designed as a time delay model and used to design a feed-forward controller. Active flow control techniques can be used to mitigate the effects of the flow separation, by delaying the onset of stall. The main contribution of this work is the ability of time-delay models to predict the lift coefficient history during pitching of the

NACA 0018 airfoil when subjected to slot-blowing flow control. The model of the aerodynamic moment produced by the wing without actuation is presented in this work.

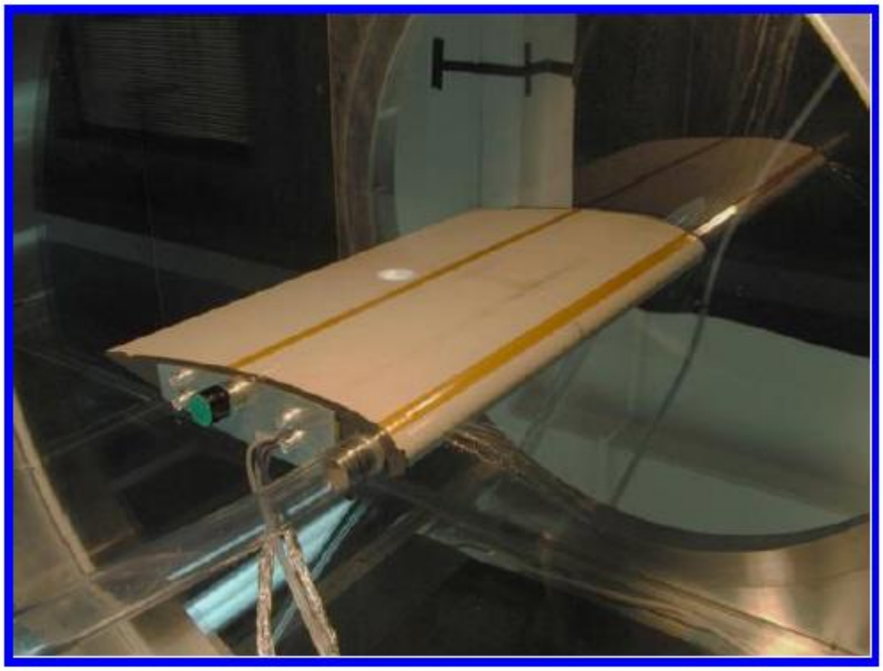


Fig. 2. Photograph of the NACA 0018 airfoil mounted in the wind tunnel between two transparent Plexiglas endwalls, also showing the tubing that supplied the leading-edge blowing slot.

**Results:** The G-K model for the effect of dynamic actuation is a time-delay dynamical system. The model for pitching represented the effect of a disturbance to the system in a feed-forward controller design. Moreover, all the design criteria's developed in this work have been formulated in terms of simulation with the help of experimental data set, which can be solved efficiently by using the available solvers. A photograph of the airfoil mounted in the wind tunnel is shown in Fig. 2. The airfoil has a chord length c=348mm and spans the width of the tunnel, s = 610mm. The freestream speed of the wind tunnel was 12.9 m/s for the data presented in this paper, which produced a chord based Reynolds number Re = 300,000. The simulations show a large reduction in the lift coefficient fluctuation amplitude when dynamic flow control is activated.

**Future work:** When models of the airfoil's response to external disturbances are available, the controller becomes more effective in achieving the desired state. It is important to design a controller to eliminate the effect of modeling errors and external disturbances to achieve desired performance. To achieve additional improvements in performance will require the use of controllers that can adapt to changing flow conditions. More precisely, by designing a feedback controller for a dynamic still, we can overcome all the above mentioned issues to achieve the desired performance, which is a topic for future investigations.