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A Methodology Based on Experimental Investigation of a DBD-Plasma Actuated Cylinder Wake for Flow Control

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1. Introduction

The main purpose of flow control is to improve the mission performance of air vehicles. Flow control can either be passive or active and active flow control is further characterized by open-loop or closed-loop techniques. Gad-el-Hak (1996) provides an insight into the advances in the field of flow control. Research of closed-loop flow control methods has increased over the past two decades. Cattafesta et al (2003) provide a useful classification of active flow control.

Before proceeding into the details of modeling and control, it is imperative to appreciate the reasons as to why closed-loop control is of importance and the main advantages associated with its application to flow control problems. It is advantageous to opt for closed-loop flow control for the following reasons:

1. It enables addressing problems that have over the years not been solved using passive means and /or open-loop techniques.
2. It provides performance augmentation of an open-loop flow control system.
3. It lowers the amount of energy required to manipulate the flow to induce the desired behavior. This aspect affects actuation requirements and may be a deciding factor for the feasibility of implementation.
4. It enables adaptability to a wider operating envelope, thereby limiting the drop in performance associated with multiple design working points.
5. It provides design flexibility and robustness.

Several applications of closed-loop control have been reported in literature, namely, specific areas of interest include flow-induced cavity resonance. (Cattafesta et al, 2003, Samimy et al, 2003), vectoring control of a turbulent jet (Rapoport et al, 2003), separation control of the NACA-4412 Airfoil (Glauser, 2004) and control of vortex shedding in circular cylinder wakes (Gerhard et al, 2003, Gillies, 1995). The ability to control the wake of a bluff body could be used to reduce drag, increase mixing and heat transfer, and vibration reduction.

We can consider the cylinder wake problem. In a two-dimensional cylinder wake, self-excited oscillations in the form of periodic shedding of vortices referred to as the von Kármán Vortex Street. Shedding of counter-rotating vortices is observed in the wake of a two-dimensional cylinder above a critical Reynolds number (Re ~ 47, non-dimensionalized with respect to free stream speed and cylinder diameter). An effective way of suppressing the self-excited flow oscillations, without making changes to the geometry or introducing vast amounts of energy, is by the incorporation of active closed-loop flow control (Gillies, 1995). A closed-loop flow control system is comprised of a controller that introduces a perturbation into the flow, via a set of actuators, to obtain desired performance. Furthermore, the controller acts upon information provided by a set of sensors. During the past years, the closed-loop flow control program research effort at the United States Air Force Academy (USAFA) focused on developing a suite of low-dimensional flow control tools based on the low Reynolds numbers (Re ~ 100-300) cylinder wake benchmark (Cohen et al, 2003, Cohen et al, 2004, Cohen et al, 2005, Cohen et al, 2006a, Siegel et al, 2003a) Several computations and experiments were also performed for the cylinder wake at high Reynolds numbers (Re=20000) (Aradag, 2009, Aradag et al, 2010)

Energy is introduced into the flow via actuators and the flow field in the wake of a cylinder may be influenced using several different forcing techniques with the wake response being similar for different types of forcing (Gillies, 1998) The following forcing methods have been employed: external acoustic excitation of the wake, longitudinal, lateral or rotational vibration of the cylinder, and alternate blowing and suction at the separation points (Gillies, 1998). Work at USAFA has shown that the Dielectric Barrier Discharge (DBD) plasma actuator (Munska and McLaughlin, 2005) is an effective means of forcing at higher frequencies without mechanical movement. This relatively simple actuation device is composed of two thin electrodes separated by a dielectric barrier. When an AC voltage is applied to the electrodes, a plasma discharge propagates from the edge of the exposed electrode over the insulated electrode. The emergence of this plasma is accompanied by a coupling of directed momentum into the surrounding air as the plasma propagates over the buried electrode during each oscillation forcing cycle (Enloe et al, 2004). This momentum can effectively alter a moving flow or generate flow in the direction of plasma propagation, as several application-based papers have shown (List et al, 2003, Asghar and Jumper, 2003, Bevan et al, 2003). The non-mechanical nature of the plasma actuator makes it ideal for high Re flow control applications. Its high fundamental operating frequency suggests it can be effective over a very wide bandwidth (by fluid time scale standards). This enables operation over a much broader range of frequencies than mechanical actuators. It has no moving parts, and has no resonant frequency. Munska and McLaughlin (2005) established that plasma actuators can achieve vortex shedding lock-in and span-wise coherence over a range of forcing conditions. They employed a cylinder arrangement similar to that of Asghar and Jumper (2003), with electrodes at ±90º and Re up to 88x10³, and used a similar amplitude-modulated forcing scheme.Low-dimensional modeling is a vital building block when it comes to realizing a structured model-based closed-loop flow control strategy. For control purposes, a practical procedure is needed to represent the velocity field, governed by the Navier Stokes partial differential equations, by separating space and time. A common method used to substantially reduce the order of the model is Proper Orthogonal Decomposition (POD). This method is an optimal approach in that it will capture a larger amount of the flow energy in the fewest modes of any decomposition of the flow. The two

dimensional POD method was used to identify the characteristic features, or modes, of a cylinder wake as demonstrated by Gillies (1998) and Gerhard et al (2003).

The major building blocks of the structured approach presented here are comprised of a reduced-order POD model, a state estimator and a controller. The desired POD model contains an adequate number of modes to enable accurate modeling of the temporal and spatial characteristics of the large scale coherent structures inherent in the flow in order to model the dynamics of the flow. A Galerkin projection may be used to derive a set of reduced order ordinary differential equations by projecting the Navier-Stokes equations on to the modes (Holmes et al, 1996). Further details of the POD method may be found in Holmes et al (1996). A common approach referred to as the method of "snapshots" introduced by Sirovich (1987) is employed to generate the basis functions of the POD spatial modes from flow-field information obtained using either experiments or numerical simulations. This approach to controlling the global wake behavior behind a circular cylinder was effectively employed by Gillies (1998) and Noack et al (2004) and is also the approach followed in the current research effort.

For practical applications, it is important to estimate the state of the flow, i.e. the relevant POD time coefficients, using body mounted sensors. The advantages of body mounted sensors are:

1. Simple, relatively inexpensive and reliable.
2. Essential for real-life, closed-loop flow control applications where the direct measurement of the separated wake flow field is cumbersome (if not impossible)
3. Enable collocation of sensors and actuators, which eliminates substantial phase delays effecting controller design.

Pressure sensors, mounted on the surface have been used on a back-ward facing ramp by Taylor and Glauser (2004) and by Glauser et al (2004) on a NACA 4412 airfoil. Recent efforts have successfully demonstrated estimation of the time coefficients of the POD model for a "D" shaped cylinder for laminar flow at low Reynolds numbers (Cohen et al, 2004, Stalnov et al, 2005). The body mounted sensors may measure skin friction or surface pressures, as is done in this effort. The intention of the proposed strategy is that the measurements, provided by a certain configuration of body mounted pressure sensors placed on the model surface, are processed by an estimator to provide the real-time estimates of the POD time coefficients that are used to close the feedback loop. The estimation scheme is to behave as a modal filter that "combs out" the higher modes. The main aim of this approach is to thereby circumvent the destabilizing effects of observation "spillover". The estimation scheme may be based on the linear stochastic estimation procedure introduced by Adrian et al (1977) or a quadratic stochastic estimation proposed by Murray and Ukeiley (2002) as well as by Ausseur et al (2006).

This chapter is organized as follows: The following section provides the main objective of this chapter. The basic approach to feedback flow control for turbulent wake flows is presented in Section III. A wind tunnel experiment of a plasma actuated cylinder wake, at a Reynolds number of 20,000, is described in Section IV. Preliminary experimental results using POD and a Neural Network based estimator and a subsequent discussion are presented in Section V. Finally, the conclusions of this research effort and recommendations for future work are summarized in Section VI.

2. Aims and concerns

Technological advances in sensors, actuators, on-board computational capability, modeling and control sciences have offered a possibility of seriously considering closed-loop flow control for practical applications. The main strategies to closed-loop control are a model-independent, full-order optimal control approach based on the Navier-Stokes equations and a reduced order model strategy. This effort emphasizes the methodology based on the low-dimensional, proper orthogonal decomposition method applied to the problem concerning the suppression of the von Kármán vortex-street in the wake of a circular cylinder. Focus is on the validity of the low-dimensional model, selection of the important modes that need representation, incorporation of ensembles of snapshots that reflect vital transient phenomena, selection of sensor placement and number, and linear stochastic estimation for mapping of sensor data onto modal information. Furthermore, additional issues surveyed include observability, controllability and stability of the closed-loop systems based on low-dimensional models. Case studies based on computational and experimental studies on the cylinder wake benchmark are presented to illuminate some of the important issues.

3. Research methods

3.1 Closed loop control methodology

Based on the research effort at the USAF Academy over the past years, a methodology for approaching closed-loop flow control has been developed. This approach has been applied to control of laminar bluff body wakes at low Reynolds numbers (Re~50-180). In this work, this methodology is extended to higher Reynolds number turbulent wakes (Re~20,000). A schematic representation of the setup is presented in Figure 1.
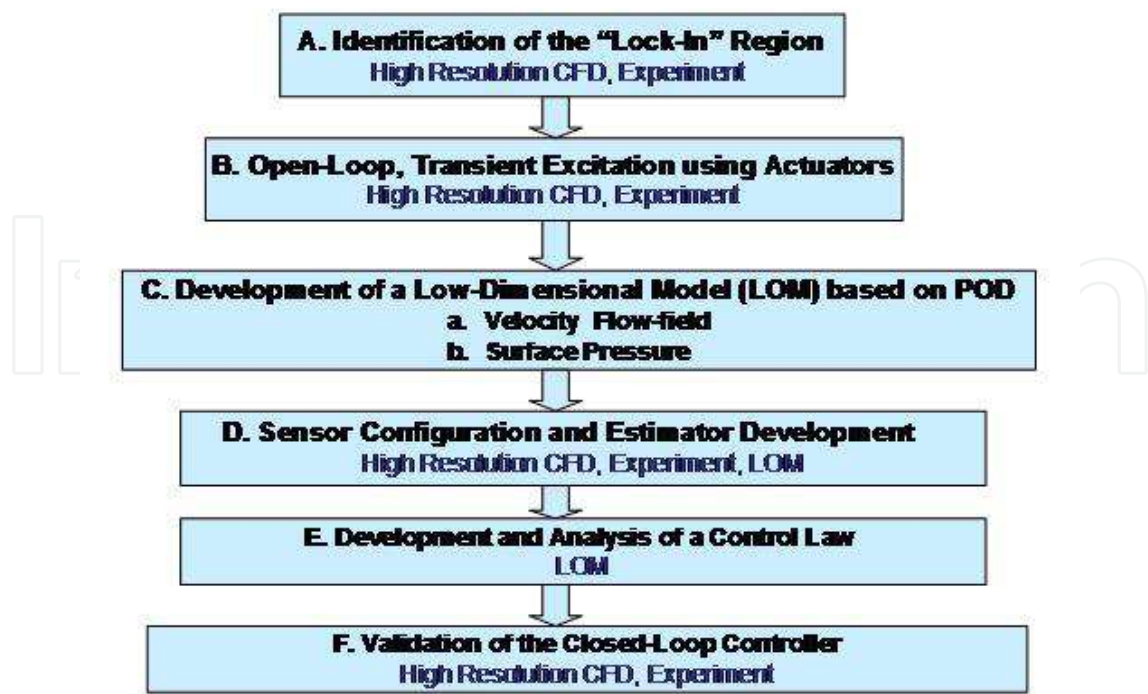

Fig. 1. Methodology for Closed-Loop Flow Control.

The following is a more detailed look into each of the six steps:

a.   Identification of the "Lock-In" Region

In order to obtain a meaningful low-order representation of the flow, it is imperative that the behavior of the flow be constrained so that it can be characterized using a relatively small number of parameters. A good example that illustrates this feature is the "lock-in" envelope of a cylinder wake. The cylinder wake flow can be forced in an open loop fashion using sinusoidal displacement of the cylinder with a given amplitude and frequency. Koopmann (1967) investigated the response of the flow to this type of forcing in a wind tunnel experiment. He found a region around the natural vortex shedding frequency where he could achieve "lock-in", which is characterized by the wake responding to the forcing by establishing a fixed phase relationship with respect to the forcing. The frequency band around the natural vortex shedding frequency for which lock-in may be achieved is amplitude dependent. In general, the larger the amplitude, the larger the frequency band for which lock-in is possible. However, there exists a minimum threshold amplitude below which the flow will not respond to the forcing any more. In Koopmann's experiment (1967), this amplitude was at 10% peak displacement of the cylinder. Siegel et al (2003a) show that for a circular cylinder, at Reynolds number of 100, a closed-loop controller operating within the "lock-in region" achieves a drag reduction of close to 90% of the vortex-induced drag, and lowers the unsteady lift force by the same amount.

Recently, the dielectric barrier discharge (DBD) plasma electrode has been developed as a flow control actuator, showing the ability to affect flow behavior in a range of applications. McLaughlin et al (2006) applied the DBD plasma actuator to a circular cylinder at Reynolds numbers of up to 3×10^5. Hot film measurements show that vortex shedding frequency can be driven to the actuator forcing frequency, within the lock-in range, at all Reynolds numbers investigated. The wake forced with plasma actuators exhibits "lock-in" behavior similar to that previously reported by Koopmann using cylinder displacement for forcing (Munska and McLaughlin, 2005).

b.   Open-Loop, Transient Excitation using Actuators

Since the intended use of the low dimensional model, based on POD, is feedback flow control, the low dimensional state of the flow field needs to be accurately estimated as input for a controller. This poses the problem of snapshot selection: For the state to which the feedback controller drives the flow, usually no snapshots are available beforehand. We investigated POD bases derived from steady state, transient startup and open loop forced data sets for the two dimensional circular cylinder wake at Re = 100. None of these bases by itself is able to represent all features of the feedback controlled flow field. However, a POD basis derived from a composite snapshot set consisting of both transient startup as well as open loop forced data accurately models the features of the feedback controlled flow. For similar numbers of modes, this POD basis, which can be derived *a* priori, represents the feedback controlled flow as well as a POD model developed from the feedback controlled data a posteriori. These findings have two important implications: Firstly, an accurate POD basis can be developed without iteration from unforced and open loop data. Secondly, it appears that the feedback controlled flow does not leave the subspace spanned by open loop and unforced startup data, which may have important implications for the performance limits of feedback flow control. Further details on this approach are presented by Siegel et al (2005a) and Seidel et al (2006).

An important aspect of the developed methodology is to obtain a low-dimensional model that can predict the modal behavior of the flow when subject to various forcing inputs within the lock-in region. The emphasis is on the robustness of the predictive capability of the model. The main aim here is to predict the time histories of the time coefficients of the truncated POD model under the influence of open-loop control within the lock-in region. For the low Reynolds number, circular cylinder wake problem, Cohen et al (2006b) used nine different data sets, as marked in Figure 2, for the open loop forced cases at 10, 15, 20, 25 and 30 percent cylinder displacement. Some of the cases use 5-10% lower or higher frequency at 30% displacement, which is still within the lock-in region. In this example, the 25 percent cylinder displacement sinusoidal forcing serves as design point for model development.
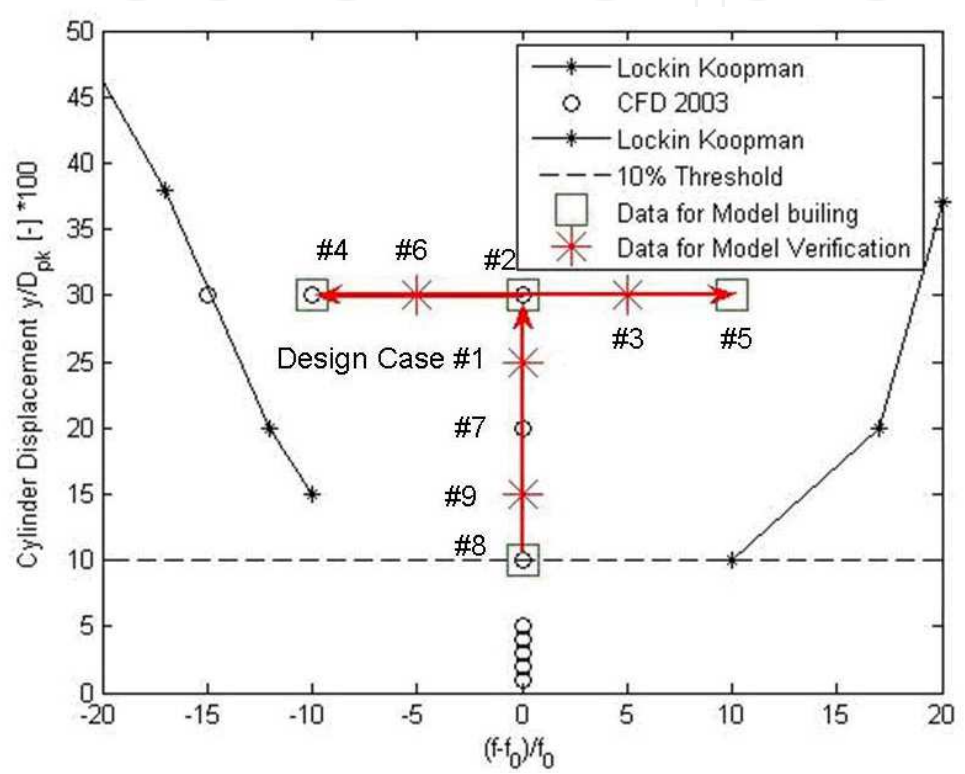
Fig. 2. Model Building within "Lock-In" Envelope for the Circular Cylinder Wake.

c.   Development of a Low-Dimensional Model (LOM) based on POD

In the developed approach, the main advantage of POD, namely its optimality and thus ability to capture the global behavior of a flow field with a minimum number of modes, is combined with established system identification techniques developed for the modeling of dynamical systems. Over the past decades, the controls community has developed methods to identify the dynamic properties of complex structures based on experimental measurements. These rely on the acquisition of transient measurements based on a known excitation input to the system. So called System Identification methods are then used to develop a dynamical mathematical model that can be used later for design and analysis of an effective control law as well as dynamic observer development. The main emphasis is then to develop an effective system identification technique that captures the dynamics of the time dependent coefficients of the POD modes with respect to transient actuation inputs within the lock-in region.

An important question that needs to be answered is: "What are the desired characteristics most sought after in a low-order, POD based model?" It is imperative to understand that given the complexity of the problem at hand, it may not be possible to address this problem with off-the-shelf methods but instead we propose a unique synthesis of software tools that appear to be promising. The important features are:

1. **Structured scalable methodology:** Developing an ad-hoc approach as demonstrated by Gillies (1995) using the least squares technique may address a particular problem for a given design point under certain conditions but is not generic enough. An approach which may be applied to a wide range of flow conditions (Reynolds numbers) is preferable. Another important principle is to let the data determine the dynamic complexity, i.e. the number of POD modes, of the reduced order model using the amount of truncated energy as a criterion. This approach differs from that of Noack et al (2003) that uses first principles to make an a priori decision on the number and nature of the modes.

2. **Numerical issues and model stability**: The non-linearity and scaling characteristics of the temporal coefficients lead to numerical stability issues which undermine the development and analysis of effective estimation/control laws. A major numerical problem which emerges using the Galerkin projection is the effect of noisy data on higher order derivatives required for model development. In order to assure model stability, the system identification community very widely uses the ARX dynamic model structure. A salient feature of the ARX model is that it is inherently stable even if the dynamic system to be modeled is unstable. This characteristic of ARX models often lends itself to successful modeling of unstable processes as described by Nelles (2001).

3. **Model validity and robustness**: An important task of model building is the determination of the dynamic envelope within which the model is valid. Then, after deriving a model, one needs to ensure that the model is capable of providing relatively accurate predictions within the region of validity. Validity and robustness are necessary conditions to design a model based observer/controller. For this reason, we validate the model by comparing it to a high resolution, closed-loop, CFD simulation.

4. **Universal approximation of non-linear mappings**: The decision was to look into universal approximators, such as artificial neural networks (ANN), for their inherent robustness and capability to approximate any non-linear function to any arbitrary degree of accuracy (Cybenko, 1989). The ANN, employed in this effort, in conjunction with the ARX model is the mechanism with which the dynamic model is developed using the POD time-coefficients extracted from the high resolution CFD simulation. Non-linear optimization techniques, based on the back propagation method, are used to minimize the difference between the exact POD time coefficients and the ANN based estimate while adjusting the weights of the model (Haykin, 1999).

The ARX-ANN algorithms used in this effort are a modification of the toolbox developed by Nørgaard et al (2000). After the POD time coefficients were extracted, a basic single hidden layer ANN-ARX architecture was selected. The training set was then developed using Input-Output data obtained from CFD simulations. The model was validated for off-design cases and if the estimation error was unacceptable, then the ANN architecture was modified. This cycle repeated until estimation errors were acceptable for all off-design cases. Cohen et al (2006b) successfully demonstrated this approach for modeling of a cylinder wake at Reynolds numbers of 100.

Most of the modeling effort has been based on the velocity field. The low Reynolds number cylinder wake flow is two dimensional in nature, simplifying the spatial characteristics of the POD modes. However, as the Reynolds number is increased to turbulent regimes or as the geometry of the model becomes more complex, the flow field becomes three dimensional in nature.

a.   Sensor Configuration and Estimator Development

A major design challenge lies in finding an appropriate number of sensors and their locations that will best enable the flow estimation. For low-dimensional control schemes to be implemented, a real-time *estimation* of the modes present in the wake is necessary, since it is not possible to measure them directly. Velocity field (Cohen et al, 2006a), surface pressure (Cohen et al, 2004), or surface skin friction (Stalnov et al, 2005) measurements, provided from either simulation or experiment, are used for estimation. This process leads to the state and measurement equations, required for design of the control system. For practical applications it is desirable to reduce the information required for estimation to the minimum. The spatial modes obtained from the POD procedure provide information that can be used to place sensor in locations where modal activity is at its highest. These areas would be the maxima and minima of the spatial modes (Cohen et al, 2006a). Placing sensors at the energetic maxima and minima of each mode is the basic hypothesis of the developed approach and the purpose of the CFD simulation is to design a sensor configuration which is later validated using experiments (Cohen et al, 2004).

The estimation scheme may be based on the linear stochastic estimation procedure introduced by Adrian (1977) a quadratic stochastic estimation (Ausseur et al, 2006) or in the form of an artificial neural network estimator, ANNE (Cohen et al, 2006c). Cohen et al (2006c) compare the effectiveness of the conventional LSE versus the newly proposed ANNE. The development of the procedure was based on CFD simulations of a cylinder at a Reynolds number of 100. Results show that for the estimation of the first four modes, it is seen that for the design condition (no noise) 4 sensors using ANNE provide significantly better results than 4 sensors using LSE. For the estimation of the first four modes, we show that a considerably smaller number of sensors using ANNE estimation provide better results than more sensors using LSE estimation. Furthermore, ANNE displays robust behavior when the signal to noise ratio of the sensors is artificially degraded.

b.   Development and Analysis of a Control Law

A simple approach to control the von Kármán Vortex Street behind a two dimensional circular cylinder, based on the proportional feedback of the estimate of *just* the first POD mode was presented by Cohen et al (2003). A stability analysis of this control law was conducted after linearization about the desired equilibrium point and conditions for controllability and asymptotic stability were developed. The control approach, applied to the 4 mode cylinder wake POD model at a Reynolds number of 100 stabilizes the POD based low-dimensional wake model. While the controller uses only the estimated amplitude of the first mode, all four modes are stabilized. This suggests that the higher order modes are caused by a secondary instability. Thus they are suppressed once the primary instability is controlled. This simple control approach was later modified by Siegel et al (2003a) when applying it to a high resolution CFD simulation. An adaptive gain strategy, based on the estimation of the "mean-flow" mode incorporated to tune the phase of a Proportional-

Differential (PD) controller was used (Siegel et al, 2003a). The closed loop feedback simulations explore the effect of both fixed phase and variable phase feedback on the wake. While fixed phase feedback is effective in reducing drag and unsteady lift, it fails to stabilize this state once the low drag state has been reached. Variable phase feedback, however, achieves the same drag and unsteady lift reductions while being able to stabilize the flow in the low drag state. In the low drag state, the near wake is entirely steady, while the far wake exhibits vortex shedding at a reduced intensity. We achieved a drag reduction of close to 90% of the vortex-induced drag, and lowered the unsteady lift force by the same amount.

c.   Validation of the Closed-Loop Controller

A low-dimensional model allows for controller development and if a more accurate non-linear model, having more modes that those used for controller development, is employed then the controller features may be analyzed as well. However, as the common saying goes "the taste of the pudding is in the eating", we need to validate the controller effectiveness in experiment. Nevertheless, a high resolution, CFD based truth simulation can provide very important insight into the complexities of feedback flow control. Both of these comprehensive approaches have been used by the USAFA team and the following are some highlights of these studies (Seidel et al, 2006, Siegel et al, 2004).

1.   Siegel et al (2004) investigated the effect of feedback flow control on the wake of a circular cylinder at a Reynolds number of 100 in a water tunnel experiment. Our control approach uses a low dimensional model based on proper orthogonal decomposition (POD). The mode amplitudes are estimated in real time using Linear Stochastic Estimation (LSE) and an array of 35 sensors distributed in a stream-wise plane in the near wake. The controller applies linear proportional and differential (PD) feedback to the estimate of the first POD mode. We find the Kármán Vortex Street to be either weakened or strengthened depending on the phase shift applied by the PD controller. For all cases with a strengthening in vortex shedding, the flow becomes two-dimensional and phase locked across the entire span of the model. For all cases with a reduction in vortex shedding strength, a strong span-wise phase variation develops which ultimately leads to a loss of control even at the sensor plane location. This suggests that for reduction of vortex shedding a three-dimensional sensing and / or actuation approach is needed.

2.   Siegel et al (2005b) conduct two dimensional feedback control simulations of the wake behind a D-shaped Cylinder and compare results to those obtained for the feedback controlled circular cylinder case. A POD based low dimensional model in conjunction with real time LSE is used to estimate the flow state. At laminar Reynolds numbers of up to 300, the von Kármán Vortex Street can be strengthened or weakened depending on the phase shift applied in the controller. As opposed to the circular cylinder simulations, where actuation was implemented by translating the cylinder normal to the flow, the D shaped cylinder wake is controlled using two blowing and suction slots near the base of the model. Since the D shaped cylinder features a fixed separation point, this investigation truly demonstrates that our control approach controls the wake instability and not the separation location. Results of the high resolution simulations of the feedback controlled truth model show a reduction in unsteady lift force of 40%, and a reduction in drag of 10% of the unforced flow field, using linear proportional fixed gain feedback of the first POD mode.

3. Seidel et al (2006) conduct high resolution, three-dimensional feedback controlled simulations of the wake behind a circular cylinder. In the current simulations, a three-dimensional sensor array was placed in the wake to estimate the flow state based on two dimensional POD Modes, which were applied at multiple span-wise locations. An LSE algorithm was used to map sensor readings to the temporal coefficients of the POD modes. The simulations were aimed at investigating the efficacy of three dimensional flow sensing to improve feedback control. Because the control input had only one degree of freedom (1 DOF), the mode amplitudes had to be combined into one actuator signal. Starting from an idealized, highly two-dimensional open loop case, the three-dimensional feedback controlled simulations show that, independent of the number and location of the sensor planes, control is initially successful for the whole span-wise extent. For approximately two seconds or ten vortex shedding cycles, the controller is able to significantly reduce the vortex shedding, resulting in a reduction of the drag coefficient of more than ten percent.

3.2 Experimental set-up

All tests were conducted in the USAFA Low Speed Wind Tunnel (LSWT). This tunnel has a 3 ft x 3 ft test section with a usable velocity range from 16 ft/s to 115 ft/s. A 3.5 in diameter, D, PVC cylinder spanned the entire height of the test section. Plasma actuators were placed along the span at the ±90° marks based on previous work done by List et al (2003) indicating this as the best position. The actuators consisted of two strips of copper tape, one buried beneath the dialectic barrier and one on top. Computer controlled voltage was amplified and transformers were used to significantly increase the magnitude to 11kV. The plasma formed atop the Teflon tape over the area of the buried electrode. Five layers of Teflon dielectric tape were used, as shown effective through McLaughlin et al (2006). In this case however, the Teflon tape was only used on the front side of the cylinder to make room for the sensors on the back half (Figure 3).
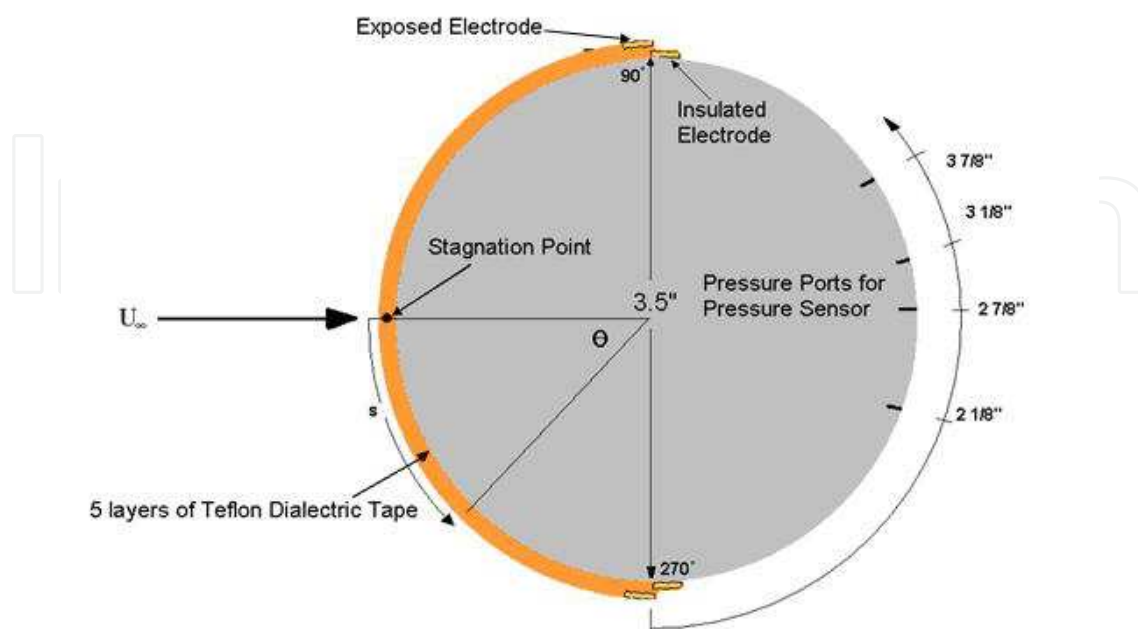

Fig. 3. Top view of cylinder set-up.

A panel was cut from the downstream side of the cylinder for sensor placement. Sixteen pressure ports consisting of four rows of four ports were placed into this panel and a Scanivalve pressure multiplexer was fixed inside the cylinder with tubing connected to each of the sixteen ports (Figure 4).
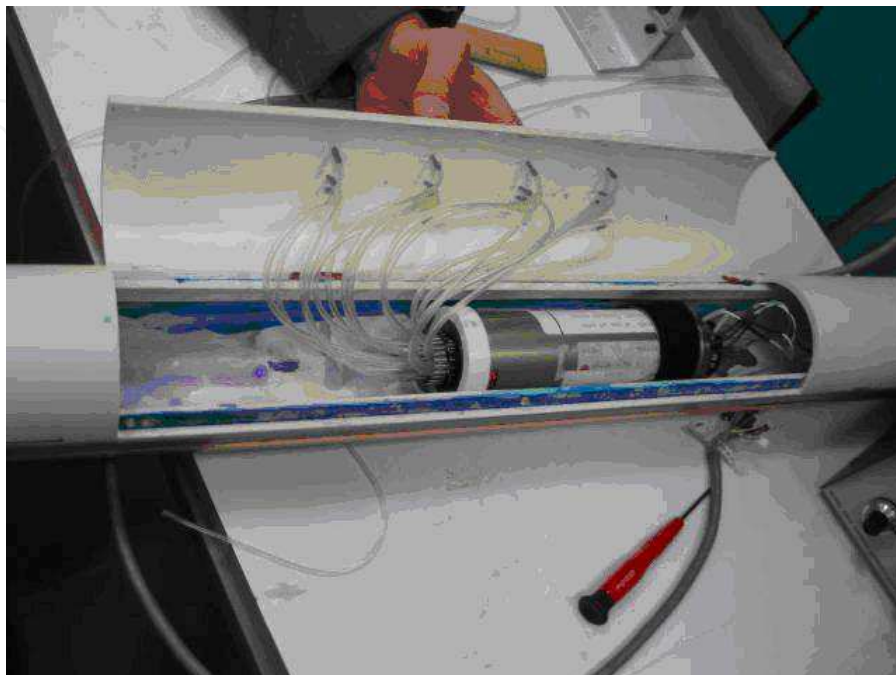

Fig. 4. Scanivalve pressure multiplexer and pressure ports in cylinder.

The location of the pressure ports was determined by doing hot film testing across the back side cylinder 1/8" behind the cylinder wall. The plasma actuators were operated at the natural shedding frequency to ensure lock-in and provide adequate flow control. Before data was collected, flow visualization was conducted to see the flow characteristics and ensure the plasma was effective in forcing the flow. Hot film anemometers were also used to validate the theoretical values for frequency downstream of the cylinder. The hot film anemometers were used to gather preliminary data very near the surface of the cylinder. The data collected was used to enable a preliminary guess in choosing pressure port locations for identifying certain flow characteristics. Figure 5 shows the tunnel set-up of the cylinder with pressure ports and the hot films positioned in the wake.

The Validyne pressure sensor was used in conjunction with a Scanivalve pressure multiplexer unit to cycle through the 16 different pressure ports. These ports were drilled into the removable rear section of the cylinder. The locations of the ports can be found in Figures 3-4. The pressure sensor has a pressure range of ±0.03 psid, an analog output of ±10Vdc, and accuracy of 0.25%. To use both the Scanivalve pressure multiplexer and Validyne sensor together, the central transducer of the Scanivalve pressure multiplexer was removed and replaced with a "dummy" plug which simply makes the Scanivalve pressure multiplexer a switching mechanism for the separate pressure ports. A period of 60 seconds was required between each pressure reading in order to ensure that the flow had "settled" after each Scanivalve pressure multiplexer switch. The remote placement of the sensor eliminated EMI issues because it was physically separated from the plasma actuators so that
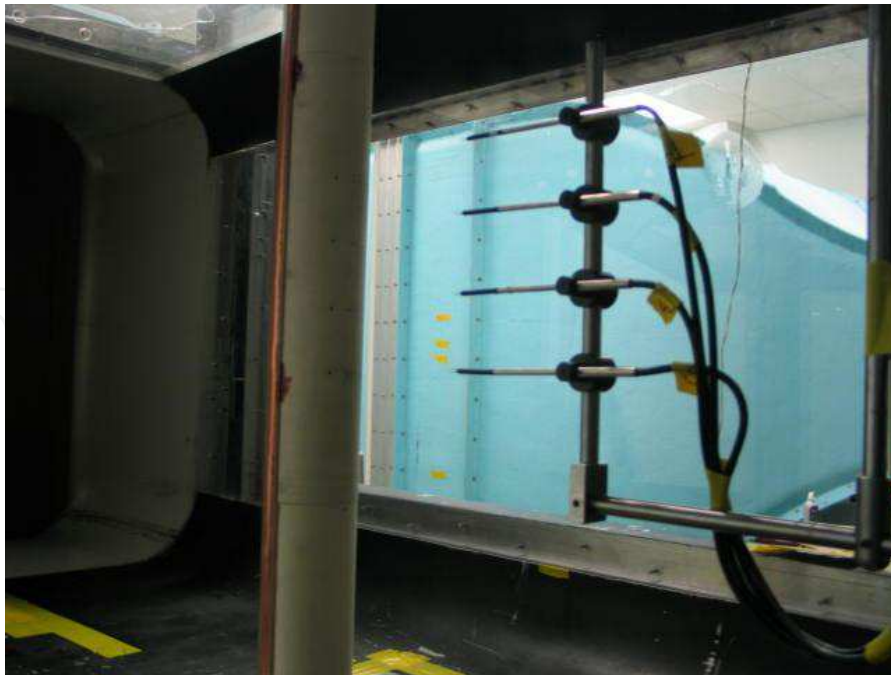
Fig. 5. Hot film anemometers and pressure ports.

id was not subject to any interference. To ensure the data acquired was not contaminated by the remote set-up, the characteristics of the plumbing were examined. For the sensor to output reliable data, the natural frequency of the plumbing system must be at least five times that of the largest frequency to be measured according to the documentation included with the sensor. The natural frequency of the system was found using the equation

$$\omega_n = \frac{c}{L\sqrt{\frac{1}{2} + \frac{Q}{aL}}} \, , \tag{1}$$

where ω_n is the natural frequency, c is the speed of sound (1089.2 ft/s), L is the length of tubing (2.5 ft), Q is the transducer cavity volume (2.03E-5 ft^3), and a is the cross sectional area of the tubing (2.13053E-5 ft^2). This yielded ω_n=73.87 Hz, which was well within the specified range since the maximum frequency measured was 9.1 Hz at Reynolds number of 20,000. This gave around 2-3% amplification of pressure waveform.

4. Results

The Validyne sensor that was connected through the Scanivalve pressure multiplexer to the pressure ports provided the surface mounted measurements required for flow state estimation. The collection of wake mounted hot film measurements and the pressure readings at each port was acquired at a sampling rate of 1 kHz. This ensured that the comparative studies could be adequately analyzed. The fundamental frequency, associated with the von Kármán vortex shedding frequency is very distinctly identified. The frequency content of the data, pertaining to the von Kármán vortex shedding frequency, from the surface mounted pressure measurements perfectly correlates with that of the hot film anemometers. For the unforced flow, it can be seen that both sensors are picking up the

exact same shedding frequency of 9.1 Hz. Again, with plasma forcing within the lock-in regime, the same data are taken and using a fast Fourier transformation, the fundamental frequency is found to be very distinct. During the DBD plasma forcing, the flow's shedding frequency gets locked into the plasma actuation, which was set to a frequency of 8.8 Hz. The velocity measured by the hot films in the wake at 1.5-2.5 diameters downstream was 3-5% greater than the velocity set for the tunnel which was expected and within the range of the calculated blockage error. Since the area of the test section is reduced by the relatively large model (blockage ratio of 9.7%), the flow's velocity was increased while the resulting natural shedding frequency was also increased. Furthermore, the shedding frequency of the Re=20k flow was increased from 8.7 Hz to 9.1 Hz.

Feasible real time estimation and control of the cylinder wake may be effectively realized by reducing the model complexity of the cylinder wake using POD techniques. POD, a non-linear model reduction approach is also referred to in the literature as the Karhunen-Loeve expansion (Holmes et al, 1996). The truncated POD model will contain an adequate number of modes to enable modeling of the temporal and spatial characteristics of the large-scale coherent structures inherent in the flow. Since a pressure multiplexer is used to collect data from the 16 pressure ports, it is imperative to synchronize the time histories of the pressure measurements before any meaningful analysis of the results can be made. For this purpose, the hot film velocity measurements are used to initiate all pressure signals based on the very distinctive fundamental frequency. While this approach is inaccurate, it does provide some interesting insight into the applicability of surface mounted pressure sensors for low-order modeling of the cylinder wake at Re~20,000. In order to examine the robustness of this procedure, the POD procedure was applied to 4 snapshot sets each containing 1601, 2601, 3601 and 4601 snapshots for both plasma off and plasma on cases. The resulting Eigen-values, without and with the mean flow mode, are presented in Tables 1 and 2 respectively. It can be seen that the Eigen-value distribution is relatively insensitive to the number of snap-shots. Also, the spatial modes for plasma-off, as shown in Figure 6 (1601 snap-shots), and for plasma off (4601 snapshots), as shown in Figure 7, are fairly similar. The temporal coefficients were also found to be of a similar nature as will be discussed later. Additionally, it can be seen in Tables 1-2 that as the plasma is turned on, the intensity of the Eigen-values of modes one and two (von Kármán modes) is increased while the mean mode as well as the higher mode amplitudes are reduced.

Mode	1601 Snapshots		2601 Snapshots		3601 Snapshots		4601 Snapshots	
	Plasma Off [%]	Plasma On [%]	Plasma Off [%]	Plasma On [%]	Plasma Off [%]	Plasma On [%]	Plasma Off [%]	Plasma On [%]
1	37.99	45.97	29.04	46.01	24.00	44.88	21.25	44.27
2	17.88	31.95	20.70	31.70	21.35	32.78	17.82	33.40
3	10.58	3.38	9.82	2.93	11.51	2.68	13.12	2.45
4	6.41	3.06	7.70	2.67	7.23	2.35	7.11	2.34
5	4.12	2.50	4.76	2.28	6.09	2.09	6.65	2.09
6	3.66	2.13	4.16	2.03	4.74	1.96	5.59	1.99
7	3.31	1.92	3.83	1.92	3.67	1.92	4.64	1.85
8	2.97	1.67	3.22	1.66	3.52	1.78	3.88	1.68

Table 1. POD – Eigen-values of Surface Pressure @ Re~20K (after extraction of the mean).

Mode	1601 Snapshots		2601 Snapshots		3601 Snapshots		4601 Snapshots	
	Plasma Off [%]	Plasma On [%]	Plasma Off [%]	Plasma On [%]	Plasma Off [%]	Plasma On [%]	Plasma Off [%]	Plasma On [%]
Mean	97.38	96.74	97.25	96.73	97.36	96.74	97.37	96.76
1	0.94	1.51	0.78	1.52	0.69	1.47	0.60	1.44
2	0.51	1.06	0.56	1.05	0.48	1.09	0.41	1.11
3	0.28	0.11	0.28	0.10	0.31	0.09	0.34	0.08
4	0.17	0.10	0.23	0.09	0.21	0.08	0.20	0.08
5	0.11	0.08	0.14	0.07	0.17	0.07	0.18	0.07
6	0.10	0.07	0.12	0.07	0.13	0.07	0.16	0.06
7	0.09	0.06	0.11	0.06	0.11	0.06	0.13	0.06
8	0.08	0.05	0.09	0.05	0.10	0.06	0.10	0.05

Table 2. POD – Eigen-values of Surface Pressure @ Re~20K (after inclusion of the mean).
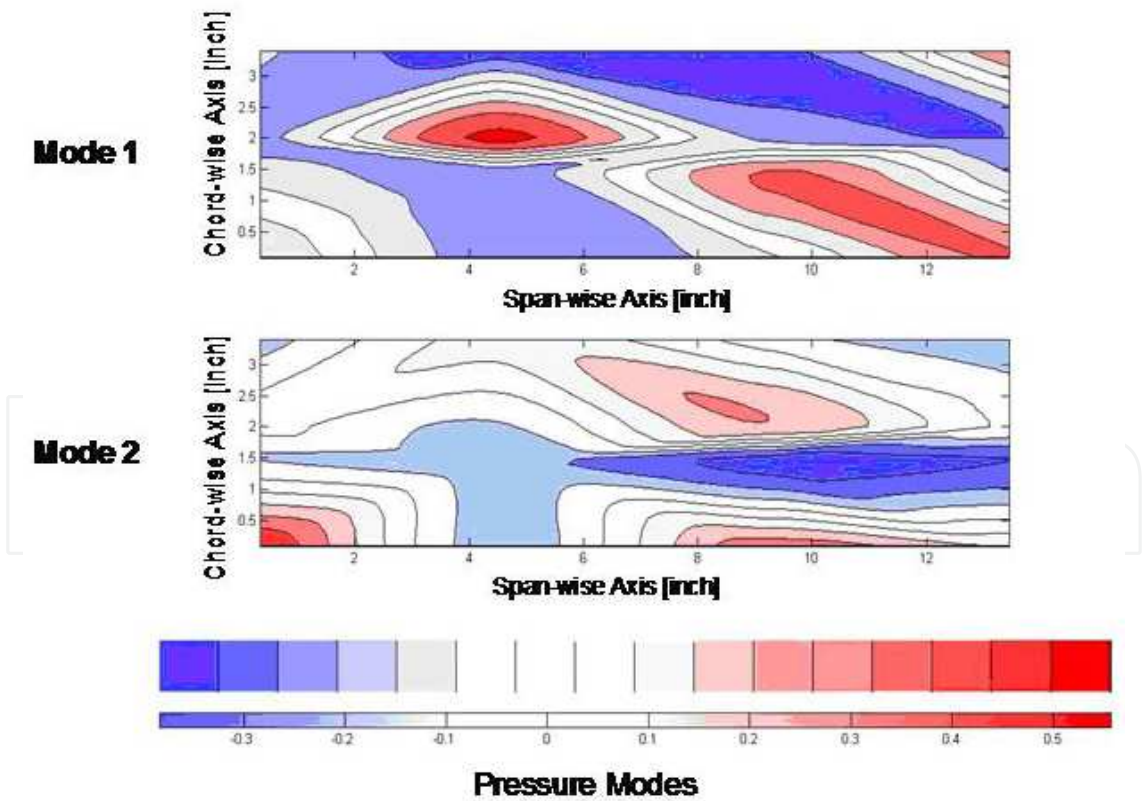
Fig. 6. First two POD Spatial Periodic Modes (1601 Snap-Shots) – Plasma Off.
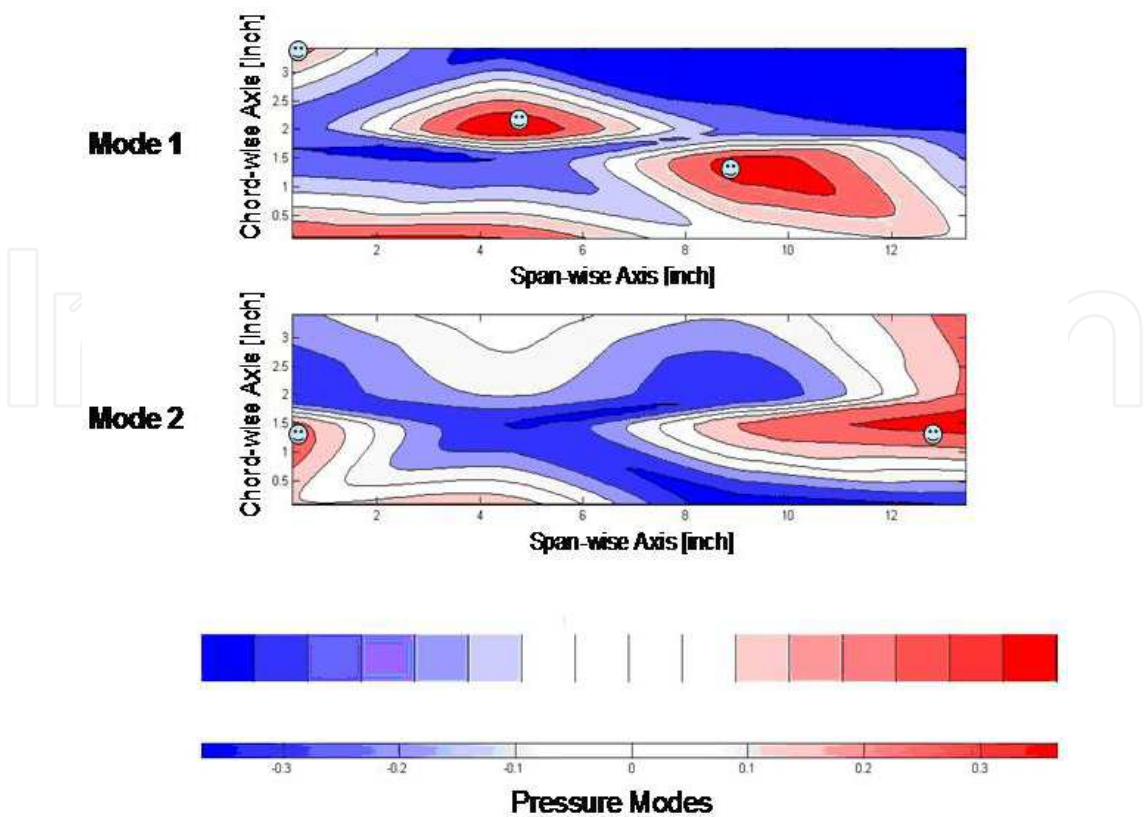
Fig. 7. First two POD Spatial Periodic Modes (4601 Snap-Shots) – Plasma On at 8.8 Hz, 11 KVolt, Position of Sensor is marked with ☺ .

The spatial modes obtained from the POD procedure provide information concerning the location of areas where modal activity is at its highest. These energetic areas are the maxima and minima of the spatial modes (Cohen et al, 2006a). In this effort, 5 of the surface mounted pressure sensors, which are positioned at the energetic maxima and minima of each of the von Kármán modes, are used to provide an estimate of the POD time coefficients.

Now that the sensor configuration is determined an Artificial Neural Network Estimator (ANNE) is developed for the real-time mapping of pressure measurements onto POD time coefficients. The main features of ANNE, as described in a flow-chart and schematically in Figures 8-9, are as follows:

- **Input Layer**
- Five body mounted pressure sensor signals
- # inputs to ANN = (# past inputs per sensor) * (# sensors)*(# Time Delay) + bias
  # inputs to ANN = 4*5*4+1 = 81
- **Hidden Layer**
- 6 neurons in single hidden layer
- Activation function is based on the *tanh* function.
- A single bias input has been added
- **Output Layer**
- Three outputs, namely, the 3 POD states (A "mean flow" aperiodic mode and the two von Kármán periodic modes)
- A linear activation function.
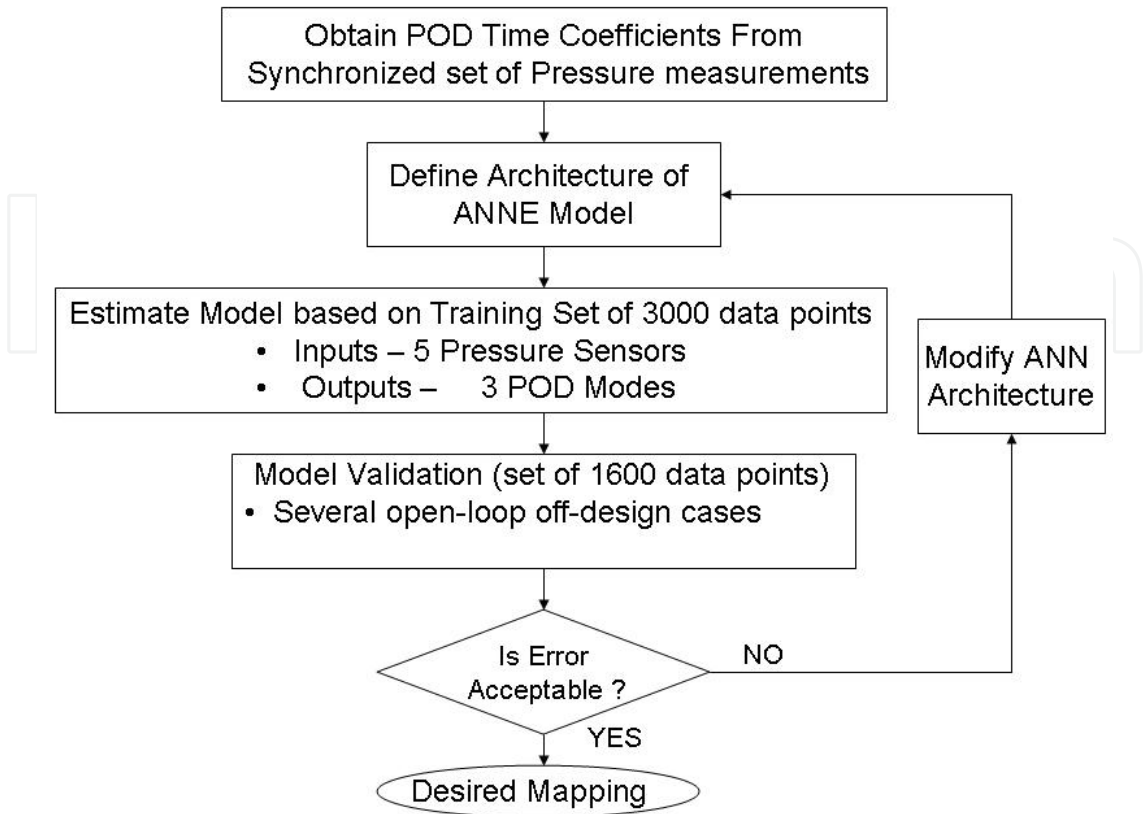
Fig. 8. Mapping of Body Mounted Pressure Measurements to POD time coefficients.
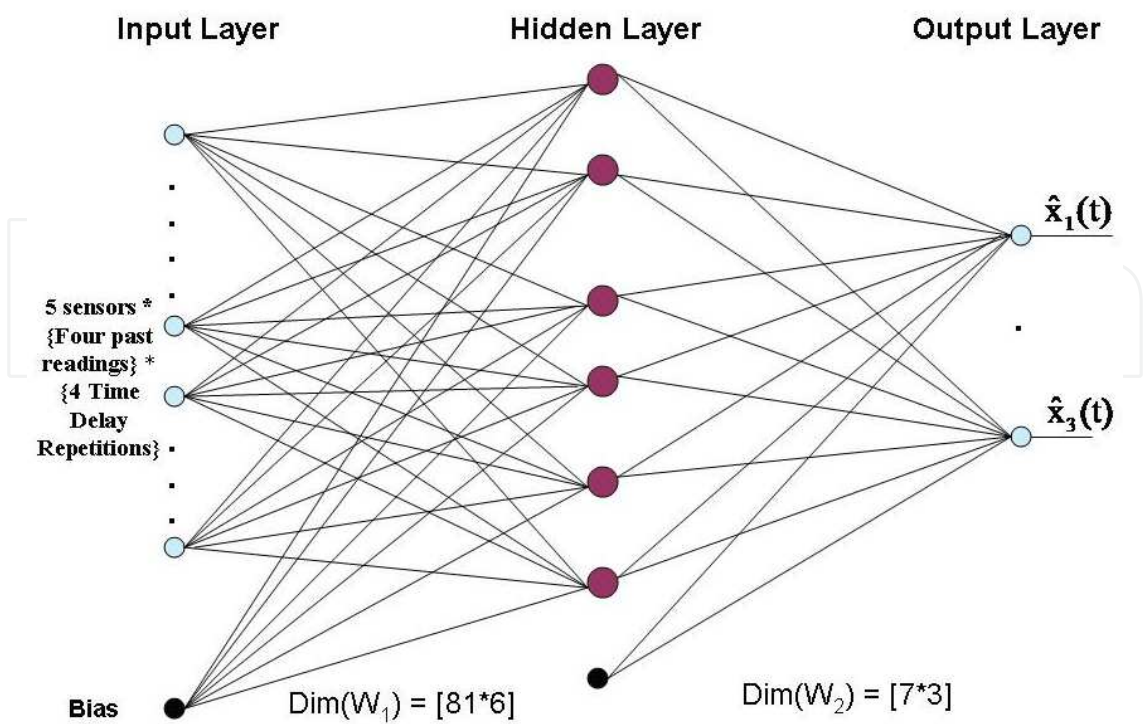
Fig. 9. Basic Architecture of ANNE.

- **Weighting Matrices**
- The weighting matrices (W1 and W2) are initialized randomly.
- W1 between the input layer and the hidden layer is of the order of [81*6].
- W2 between the hidden layer and the output layer is of the order of [7*6].
- **Training ANNE**
- ANNE model based on Nørgaard et al's [33] toolbox.
- Back propagation was based on the Levenberg-Marquardt algorithm.
- The training data has 3000 time steps taken at a sampling rate of 1 KHz (~26 shedding cycles)
- The training procedure converged after 250 iterations.
- **Validating ANNE**
- Comprised of 1600 time steps taken at a sampling rate of 1 kHz (~14 shedding cycles).
- The RMS error in [%], for the 6 modes for each case was then calculated.

The estimations provided by ANNE for the 3 mode model is given in Figure 10 for the training data and in Figure 11 for the validation data. These preliminary results appear to be promising. However, one must be reminded that the main aim in this exercise is to obtain an insight for the application of the d low-dimensional suite of tools, which were primarily developed for low Reynolds laminar bluff body wakes, to higher Reynolds number turbulent wakes.
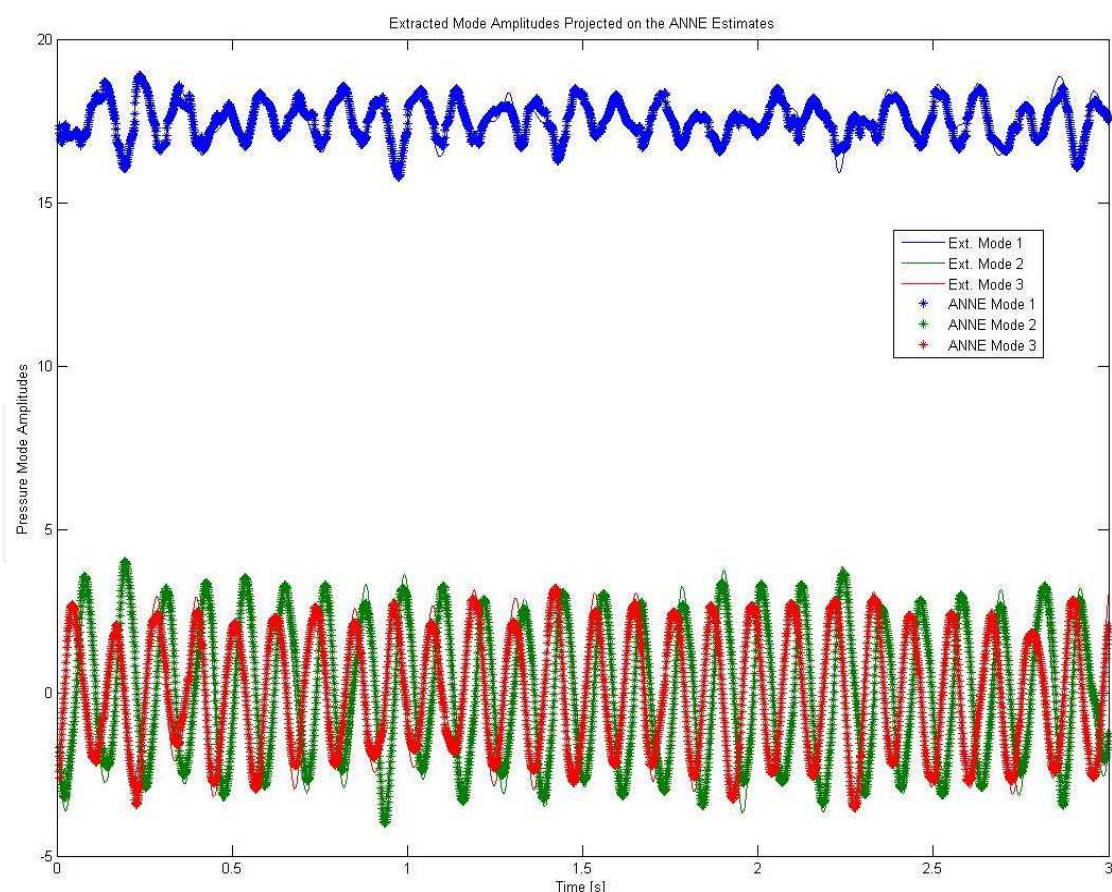
Fig. 10. Predictions based on ANNE (Training Data).
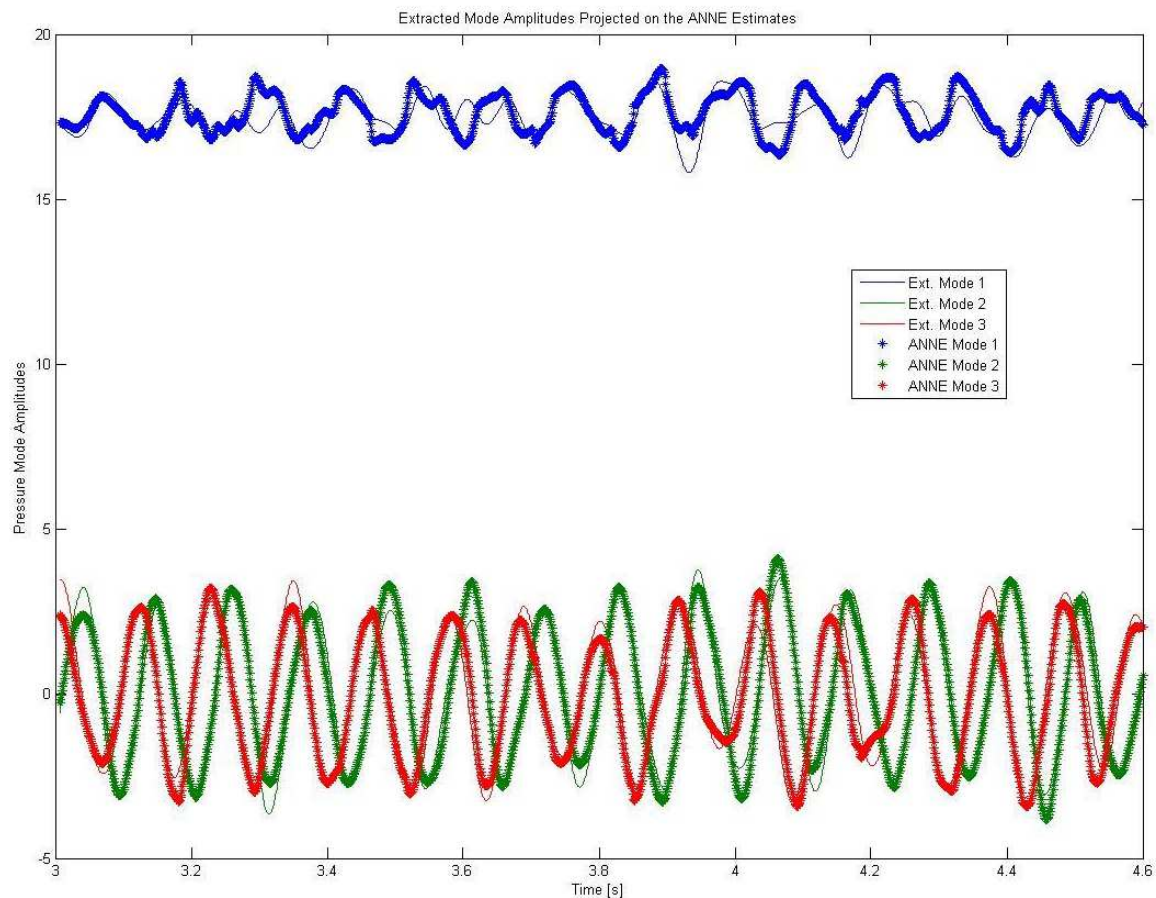
Fig. 11. Predictions based on ANNE (Validation Data).

5. Conclusions

In this chapter, we present a potentially promising approach for closed-loop flow control of a turbulent wake behind a circular cylinder at higher Reynolds numbers (Re ~ 20,000), with the ultimate goal being closed-loop flow control of the cylinder wake using DBD plasma actuators. The proposed methodology for approaching closed-loop flow control is based on the research effort at the USAF Academy over the past five years. This approach has been developed with a focus on control of laminar bluff body wakes at low Reynolds numbers (Re~50-180). The approach consists of six steps, namely: Identification of the "lock-in" region; open-loop, transient excitation using actuators; development of a low-dimensional model based on POD; sensor configuration and estimator development; development and analysis of a control law; and finally validation of the closed-loop controller.

Experimental results using plasma actuation and surface mounted pressure sensors for a circular cylinder at Reynolds number of 20,000 show that the fundamental frequency,

which is paramount for feedback, is distinctly and accurately picked up by the surface mounted pressure measurements. Surface mounted pressure measurements seem to be useful for feedback of plasma forced cylinder wake at Reynolds number of 20000. Based on these experimental results, it appears that the low dimensional approach and tools developed by USAFA/DFAN for low Reynolds number (Re~100) (Sensor placement and number strategy; and ANNE estimation of the POD temporal coefficients based on surface mounted pressure sensors) feedback flow control is applicable to much higher Reynolds number (Re~20,000).

6. Acknowledgments

7. References

Adrian, R.J. (1977). On the Role of Conditional Averages in Turbulence Theory, Proceedings of the Fourth Biennial Symposium on Turbulence in Liquids, Science Press, Princeton.

Aradag, S. (2009). Unsteady Vortex Structure Behind a Three Dimensional Turbulent Cylinder Wake, Journal of Thermal Science and Technology, vol 29 (1), pp 91-98.

Aradag, S., Cohen, K, Seaver, C. and Mclaughlin, T. (2010). Integrating CFD and Experiments for Undergraduate Research, Computer Applications in Engineering Education, Vol. 18, No.4, pp 727-735.

Asghar, A., and Jumper, E.J. (2003). Phase Synchronization of Vortex Shedding from Multiple Cylinders using Plasma Actuators, AIAA Paper 2003-1028.

Ausseur, J. M., Pinier J., T., Glauser, M.N., Higuchi H., and Carlson, H. (2006). Experimental Development of a Reduced-Order Model for Flow Separation Control, AIAA Paper 2006-1251.

Bevan, B., Locke, E., Siegel, S., Mclaughlin, T.E., and Cohen, K. (2003). Flow Visualization of Three Dimensional Effects in a Cylinder Wake Flow, APS / DFD Meeting East Rutherford, NJ.

Cattafesta Iii, L.N., Williams, D.R., Rowley, C.W., and Alvi, F.S. (2003). Review of Active Control of Flow-Induced Cavity Resonance, AIAA Paper 2003-3567, 2003.

Cohen K., Siegel S., Mclaughlin T., and Gillies E. (2003). Feedback Control of a Cylinder Wake Low-Dimensional Model, AIAA Journal, 41 (8).

Cohen, K., Siegel, S., Wetlesen, D., Cameron, J., and Sick, A. (2004). Effective Sensor Placements for the Estimation of Proper Orthogonal Decomposition Mode Coefficients in von Kármán Vortex Stree, Journal of Vibration and Control, 10 (12), 1857-1880.

Cohen, K., D., Siegel, S., Luchtenburg, M., and Mclaughlin, T., And Seifert, A. (2004). Sensor Placement for Closed-loop Flow control of a 'D' Shaped Cylinder Wake, AIAA-2004-2523.

Cohen, K., Siegel S., Mclaughlin T., Gillies E., and Myatt, J. (2005). Closed-loop approaches to control of a wake flow modeled by the Ginzburg-Landau equation, Computers and Fluids, 34 (8) , 927-949.

Cohen, K., Siegel S., and Mclaughlin T. (2006a). A Heuristic Approach to Effective Sensor Placement for Modeling of a Cylinder Wake, Computers and Fluids, 35 (1), 103-120, 2006.

Cohen, K., Siegel, S., Seidel, J., and Mclaughlin, T. (2006b). System Identification of a Low Dimensional Model of a Cylinder Wake, AIAA-2006-1411.

Cohen, K., Siegel, S., Seidel, J., and Mclaughlin, T. (2006c). Neural Network Estimator for Low-Dimensional Modeling of a Cylinder Wake, AIAA-2006-3491.

Cybenko, G.V. (1989). Approximation by Superpositions of a Sigmoidal function, Mathematics of Control, Signals and Systems, 2, 303-314.

Enloe, C.L., Mclaughlin, T.E., Vandyken, R.D., Kachner, K.D., Jumper, E.J., and Corke, T.C. (2004). Mechanisms and Responses of a Single Dielectric Barrier Plasma Actuator: Plasma Morphology, AIAA Journal, 42 (3).

Gad-El-Hak, M. (1996). Modern Developments in Flow Control", Applied Mechanics Reviews, 49, 365–379.

Gerhard, J., Pastoor, M., King, R., Noack, B.R., Dillmann, A., Morzynski, M. and Tadmor, G. (2003). Model-based Control of Vortex Shedding using Low-dimensional Galerkin Models, AIAA Paper2003-4262.

Gillies, E. A. (1995). Low-Dimensional Characterization and Control of Non-Linear Wake Flows, Ph.D. Dissertation, Faculty of Engineering, Univ. Of Glasgow, Glasgow, Scotland, U.K.

Gillies, E. A. (1998). Low-dimensional Control of the Circular Cylinder Wake, Journal of Fluid Mechanics, 371, 157-178.

Glauser, M., Young, M., Higuchi, H., Tinney, C.E., and Carlson, H. (2004). POD Based Experimental Flow Control on a NACA-4412 Airfoil (Invited), AIAA Paper 2004-0574.

Haykin, S. (1999). Neural Networks – A comprehensive foundation, Second Edition, Prentice Hall, New Jersey, USA.

Holmes, P., Lumley, J.L., and Berkooz, G. (1996). Turbulence, Coherent Structures, Dynamical Systems and Symmetry, Cambridge University and Press, Cambridge.

Koopmann, G. (1967). The Vortex Wakes of Vibrating Cylinders at Low Reynolds Numbers, Journal of Fluid Mechanics, 28 (3), 501-512.

List, J., Mclaughlin, T.E., Byerley, A.R., and Van Dyken, R.D. (2003). Using Plasma to Control Separation on a Linear Cascade Turbine Blade, AIAA Paper 2003-1026.

Mclaughlin, T., Felker, B., Avery, J. and Enloe, C. (2006). Further Experiments in Cylinder Wake Modification With Dielectric Barrier Discharge Forcing, AIAA-2006-1409.

Munska, M. And Mclaughlin, T.E. (2005) Circular Cylinder Flow Control using Plasma Actuators, AIAA Paper 2005-0141.

Murray, N.E., and Ukeiley, L.S. (2002). Estimating the Shear Layer Velocity Field Above an Open Cavity from Surface Pressure Measurements, AIAA Paper 2002-2866.

Nelles, O. (2001). Nonlinear System Identification, Springer-Verlag, Berlin, Germany.

Noack, B.R., Afanasiev, K., Morzynski, M. And Thiele, F. (2003). A hierarchy of low-dimensional models for the transient and post-transient cylinder wake, J. Fluid Mechanics, 497, 335–363.

Noack, B.R., Tadmor, G., and Morzynski, M. (2004). Low-dimensional models for feedback flow control. Part I: Empirical Galerkin models, AIAA-2004-2408.

Nørgaard, M., Ravn, O., Poulsen, N. K., and Hansen, L. K. (2000). Neural Networks for Modeling and Control of Dynamic Systems, Springer-Verlag, London, UK.

Rapoport, D., Fono, I., Cohen, K., and Seifert, A. (2003). Closed-loop Vectoring Control of a Turbulent Jet Using Periodic Excitation, Journal of Propulsion and Power, 19 (4), 646-654.

Samimy, M., Debiasi, M., Caraballo, E., E.C., Ozbay, H., Efe, M.O., Yuan, X., Debonis, J., and Myatt, J.H. (2003). Development of Closed-loop Control for Cavity Flows, AIAA Paper 2003-425.

Seidel, J., Siegel, S., Cohen, K., and Mclaughlin, T. (2006a). Simulations of Flow Control of the Wake behind an Axisymmetric Bluff Body, AIAA-2006-3490.

Siegel S., Cohen, K. and Mclaughlin T. (2003a). Feedback Control of a Circular Cylinder Wake in Experiment and Simulation, AIAA Paper 2003-3569.

Siegel, S., Cohen, K., and Mclaughlin, T. (2004). Experimental Variable Gain Feedback Control of a Circular Cylinder Wake, AIAA-2004-2611.

Siegel S., Cohen K., Seidel, J., and Mclaughlin T. (2005a). Short Time Proper Orthogonal Decomposition for State Estimation of Transient Flow Fields, AIAA-2005-0296.

Siegel S., Cohen K., Seidel, J., and Mclaughlin T. (2005b). Two Dimensional Simulations of a Feedback Controlled D-Cylinder Wake, AIAA-2005-5019.

Sirovich, L. (1987). Turbulence and the Dynamics of Coherent Structures Part I: Coherent Structures, Quarterly of Applied Mathematics, 45 (3), 561-571.

Stalnov, O., Palei, V., Fono, I., Cohen, K., and Seifert, A. (2005). Experimental Validation of Sensor Placement for Control of a "D" Shaped Cylinder Wake, AIAA 2005-5260.

Taylor, J.A. and Glauser, M.N. (2004). Towards Practical Flow Sensing and Control via POD and LSE Based Low-Dimensional Tools, Journal of Fluids Engineering, 126, 337-345.
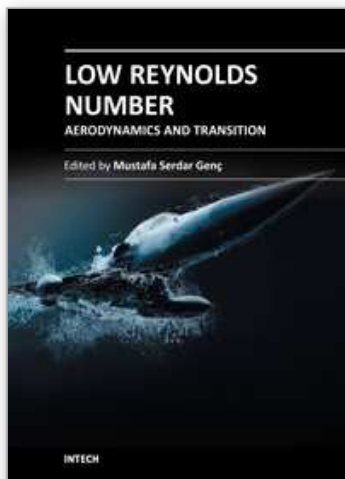
Low Reynolds Number Aerodynamics and Transition

Edited by Dr. Mustafa Serdar Genc

This book reports the latest development and trends in the low Re number aerodynamics, transition from laminar to turbulence, unsteady low Reynolds number flows, experimental studies, numerical transition modelling, control of low Re number flows, and MAV wing aerodynamics. The contributors to each chapter are fluid mechanics and aerodynamics scientists and engineers with strong expertise in their respective fields. As a whole, the studies presented here reveal important new directions toward the realization of applications of MAV and wind turbine blades.

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