CLOSED-LOOP FLOW CONTROL:

A BEGINING

Aeronautics Research Center – March 2002

MAIN PURPOSE & OUTLINE OF PRESENTATION

AIM

- To highlight the assets, effort required and the related risks concerning the modeling and control aspects of the closed-loop flow control activity at USAF Academy.

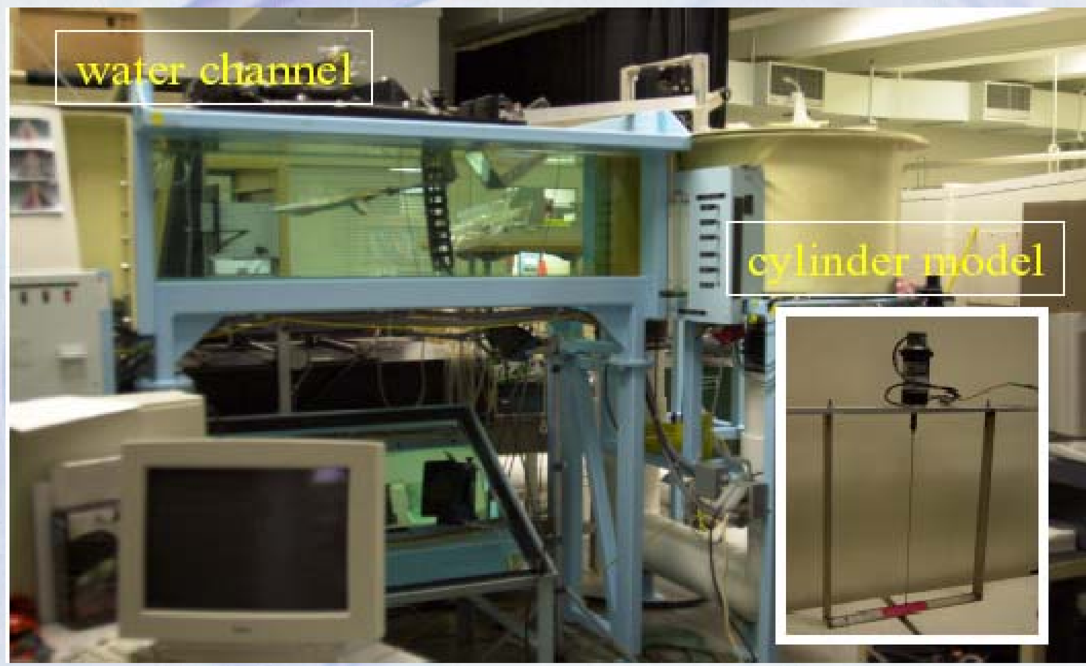
OUTLINE

- Introduction
- Modeling Issues
- Estimation Issues
- Control Issues
- Risk Areas
- Conclusions

RESEARCH OBJECTIVE

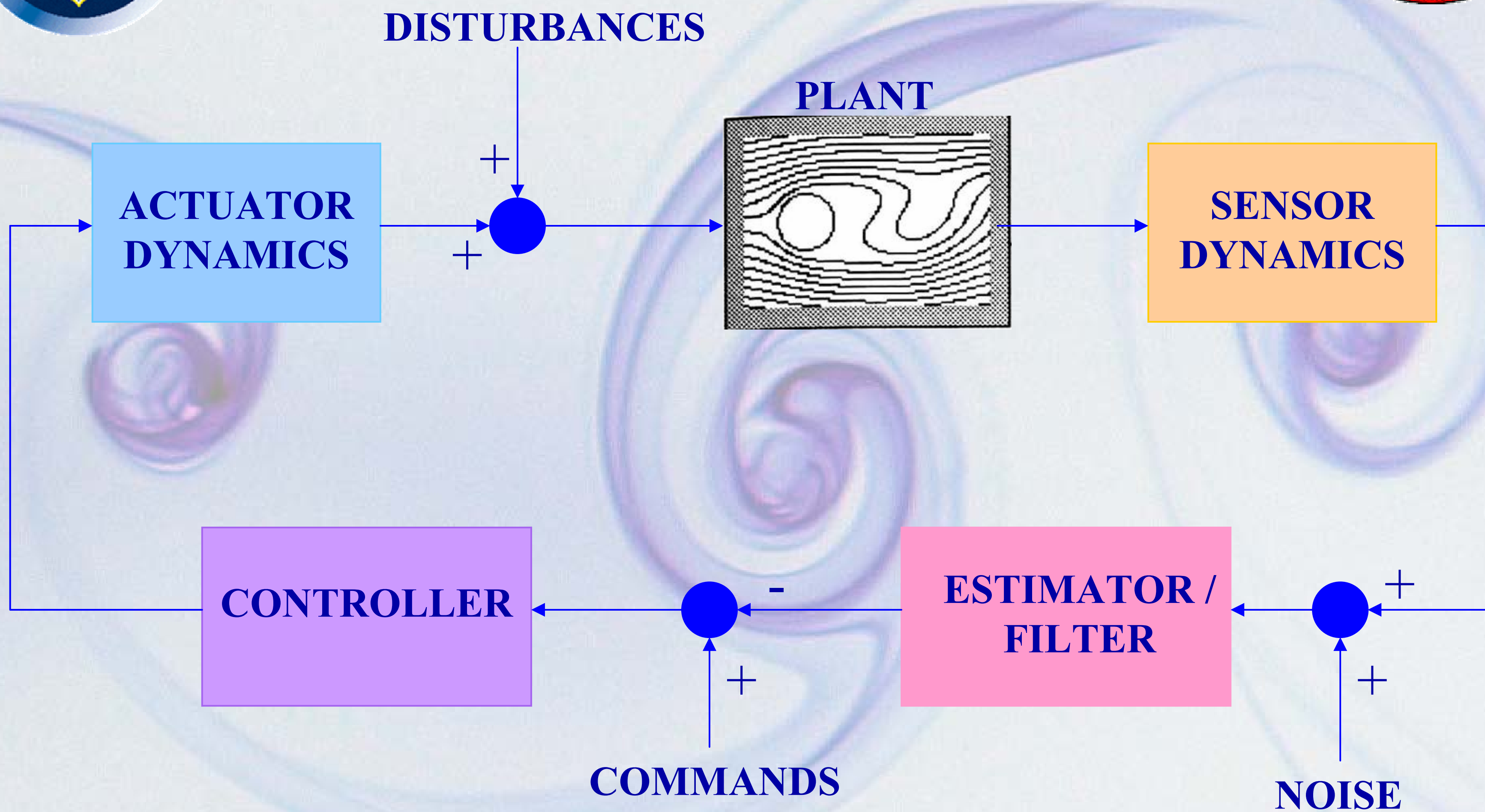
- Better understand the physical mechanisms involved in the closed-loop control of fluid instability, with the ultimate goal of enhancing air vehicle performance.

- Develop a closed-loop robust strategy to suppress the Von-Karman vortex street of a bluff body, thereby decreasing drag and flow-induced vibration.



Circular Cylinder in water tunnel at USAFA

TYPICAL CONTROL SYSTEM ARCHITECTURE



CONTROL – LIFE CYCLE

CONTROL PROBLEM
Vortex Suppression in Cylinder Wake
(Governed by Non-Linear Navier Stokes P.D.E.)

MODELING THE CONTROLLED FLOW
- Truth Model – CFD (Cobalt)
- Evaluation Model – Low-dimensional POD

ESTIMATOR
Real-time mapping of PIV Measurements onto POD states

CONTROLLER
Real-Time Mapping of POD States to Actuator Commands

CONTROL STRATEGY VERIFICATION
- Truth Model – CFD (Cobalt)
- Water Tunnel Test & Evaluation

MODELING THE CONTROLLED FLOW

- Cylinder wake flows are dominated by the dynamics of a relatively small number of characteristic large-scale spatial structures, as observed in experimental periodically forced vortex sheets.

- A desirable controller will on the one hand simply measure and control a *finite number of large-scale spatial structures*. On the other hand, it will keep the wake flow *low dimensional* by not exciting it into a higher dimension state.

- If the complex spatio-temporal information is characterized by a relatively small number of quantities, then feedback can be computationally feasible.

- Therefore, to obtain a controller that can be implemented, a reduced-order-model) is sought which may be constructed using POD (Proper Orthogonal Decomposition) and modal truncation techniques.

THREE MODEL CONTROL THEORY

MODEL I

EVALUATION MODEL – CFD (COBALT)

Used to simulate real system, for evaluation of candidate controller design

MODEL II

HIGH-ORDER MODEL – POD

For analytical predictions of controller performance

MODEL III

LOW-ORDER MODEL – TRUNCATED POD

For control design

MODELING ASSETS

- **TRUTH MODELS**
  - COBALT: Translating Cylinder (Navier Stokes)
  - FEMLAB: Wake Instability (Ginzburg-Landau)
- **LOW-DIMENSIONAL MODELS**
  - POD Model of an Actively Controlled Cylinder
  - POD Model of Ginzburg-Landau Equation

The Ginzburg-Landau Model
Main Motivation

- The complex Ginzburg-Landau (GL) equation, with suitable coefficients, has been found to model well many phenomena of vortex dynamics in bluff-body (such as a circular cylinder) wakes.

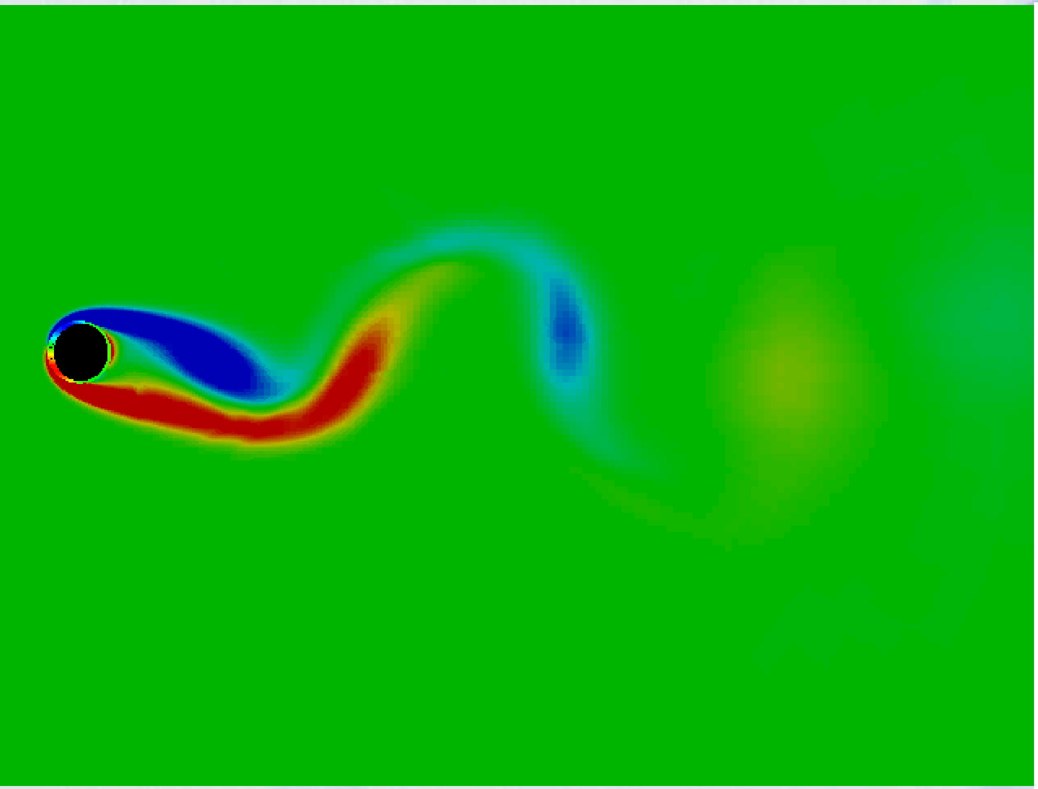
- The 1D GL equations have proved useful insight for the description of global modes for purely 2D shedding where the spatial coordinate in the GL equation coincides with the streamwise direction (Roussopoulos and Monkewitz, 1996).

- The 1D GL equation, which is derivable from the Navier-Stokes equations, can be modeled to contain all of the stability features of the 2D cylinder wake pertinent to control.

- Furthermore, the GL model is frequently used in literature for wake control studies and has been shown to allow semi-qualitative predictions of the wake with feedback (Gillies, 2000).

- An attractive characteristic of the GL model is that it is relatively straightforward to integrate numerically and allows *relatively rapid* prototyping of control strategies.

TRUTH MODEL – COBALT
Translating Cylinder (Navier Stokes)



	Experimental	Computational
Strouhal #	**0.18**	**0.18**
Shedding Frequency	**20 Hz**	**20 Hz**
C_D	**1.6**	**1.35**

C1C Elliott Leigh & C1C Lucas Kippert
under supervision of Maj. Jim Forsythe

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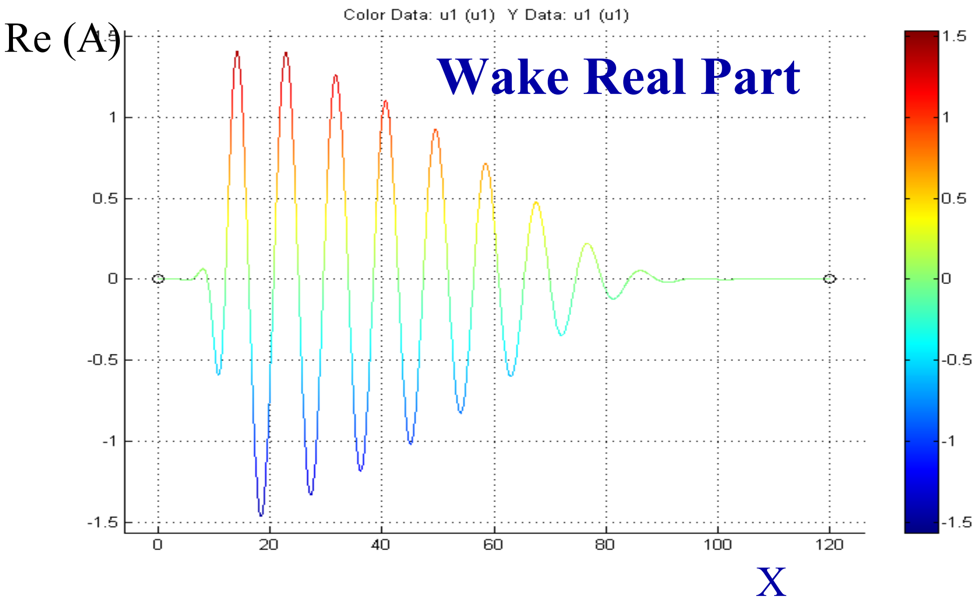
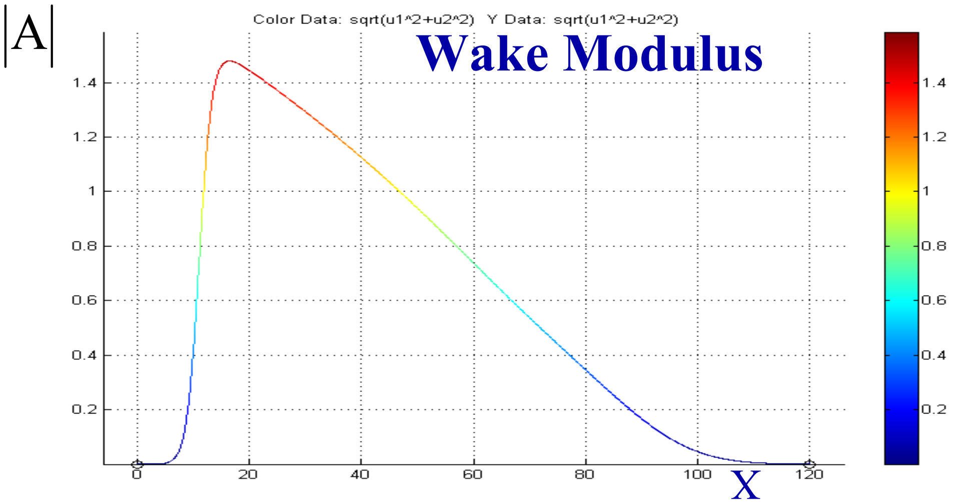
TRUTH MODEL - FEMLAB

Wake Instability (Ginzburg-Landau)





- A FEMLAB model was developed to solve the Ginzburg-Landau equation that contains all the stability features of the 2-D cylinder wake pertinent to control.

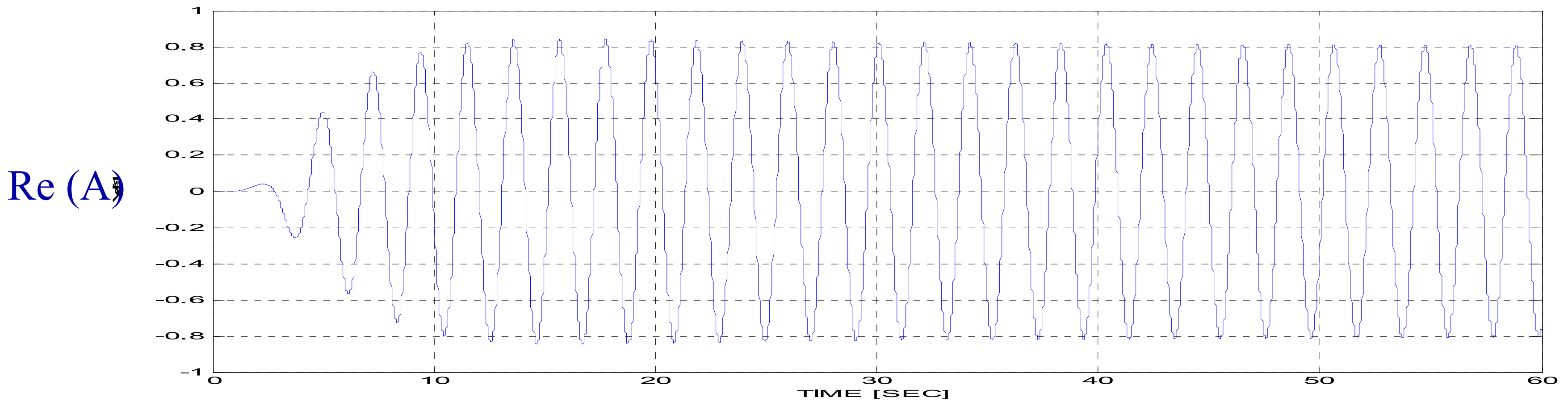
- The developed model was exported to SIMULINK where the open loop behavior was examined.

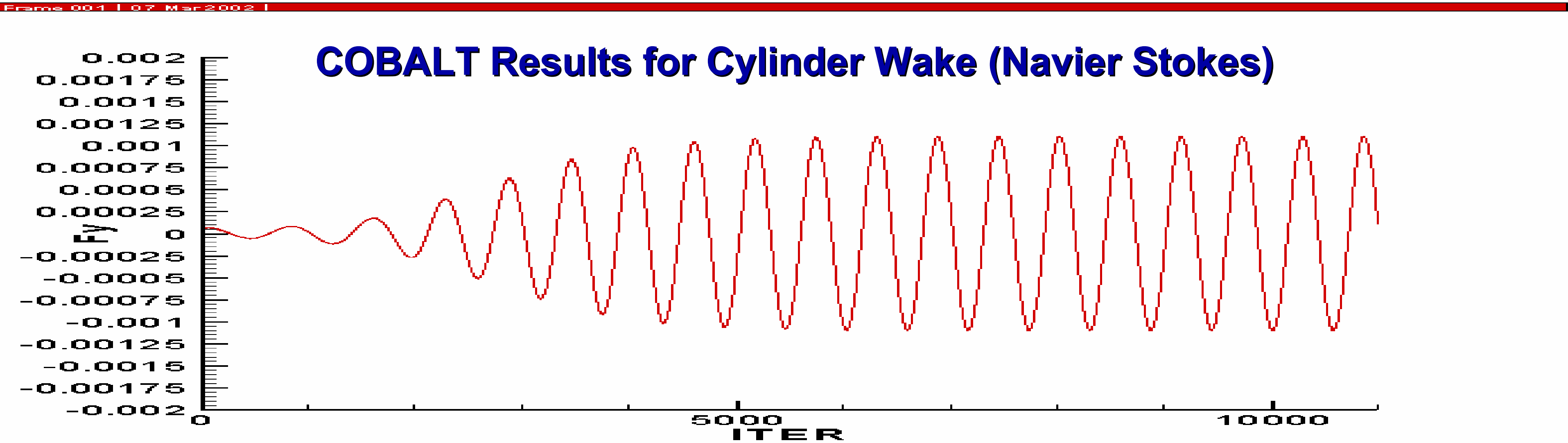
- Simulation results show that the FEMLAB model predicted the value of $\mu_o = \mu_{crit} = 3.42$ to within 0.3% of that obtained by Gillies (2000) based on the same coefficients of the Ginzburg-Landau equation.

- The SIMULINK model will now be modified for the closed-loop studies.

QUALITATIVE LOOK AT WAKE OSCILLATIONS

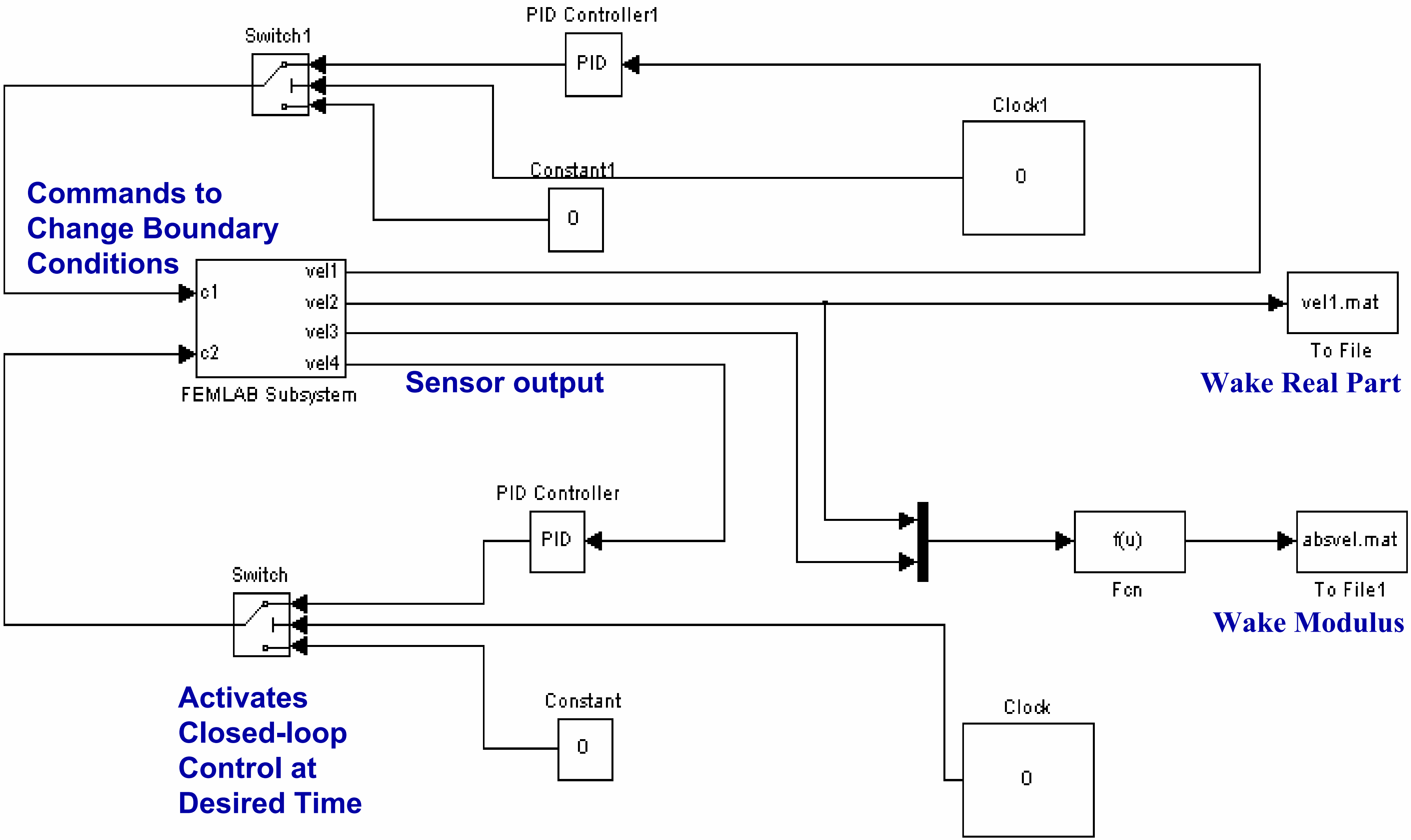
FEMLAB Results for Ginzburg-Landau Equation





Note: A converged solution has a periodic sine wave (Lift vs Iterations)

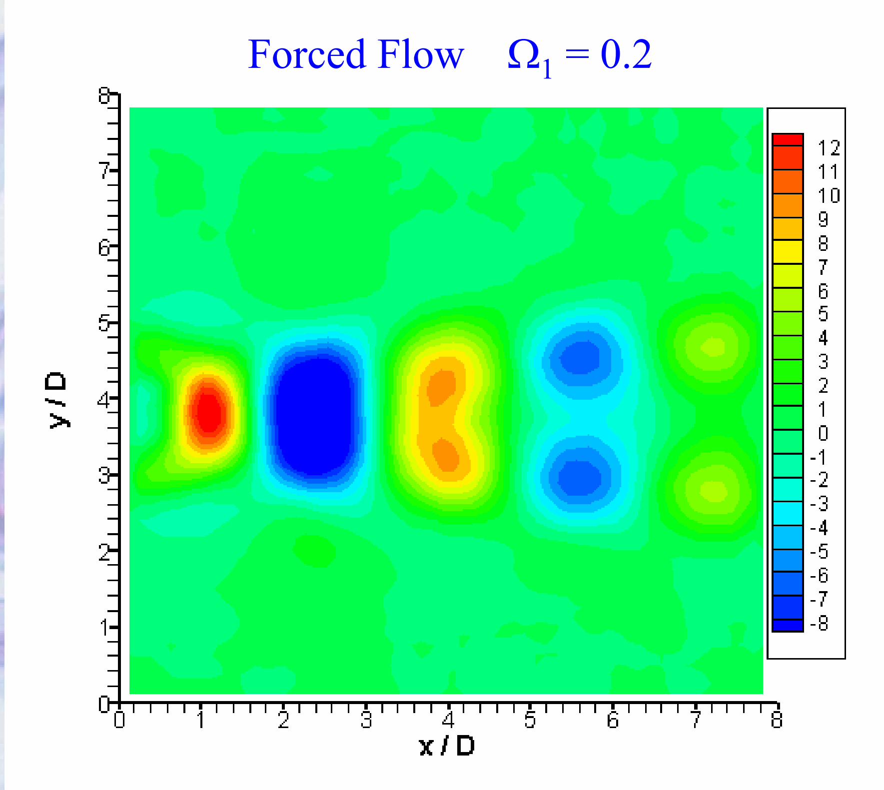
Closed-Loop Control of the Ginzburg-Landau Equation SIMULINK MODEL



LOW-DIMENSIONAL MODEL

POD of an Actively Controlled Cylinder

- To find the characteristic features of the flow field, one requires a rational approach for identifying these features.
- In this effort, we used the proper orthogonal decomposition, or POD, to identify the characteristics features, or modes, of a cylinder wake.
- This method is an optimal approach in that it will capture the largest amount of the flow energy in the fewest modes than any other decomposition of the flow.
- The figure shows the reconstructed velocity in the wake of the forced cylinder based on water tunnel experiments.



POD Reconstruction – Mode I

TWO MODE POD MODEL

BASED ON WATER TUNNEL DATA

$$\frac{da_k}{dt} = -[B^{kn} - (Re)^{-1} D^{kn}]a_n - C^{knm}[a_n a_m - \delta_{nm} \overline{a_n a_m}]$$

$$\frac{da_k}{dt} = -(B^{kn} - (Re)^{-1} D^{kn}) a_n - C^{knm}(a_n a_m - \delta_{nm} \overline{a_n a_m})$$

FOR TWO MODES (N = 2),

$$\dot{a}_1 = -(B^{11} - Re^{-1} D^{11}) a_1 - (B^{12} - Re^{-1} D^{12}) a_2 - C^{111}(a_1^2 - \overline{a_1^2}) - C^{112}(a_1 a_2) - C^{121}(a_2 a_1) - C^{122}(a_2^2 - \overline{a_2^2})$$

$$\dot{a}_2 = -(B^{21} - Re^{-1} D^{21}) a_1 - (B^{22} - Re^{-1} D^{22}) a_2 - C^{211}(a_1^2 - \overline{a_1^2}) - C^{212}(a_1 a_2) - C^{221}(a_2 a_1) - C^{222}(a_2^2 - \overline{a_2^2})$$

WHERE $Re = 125.$

AT $t = 0$: $a_1 = -0.635578$, $a_2 = 1.21620$ $\quad (\Delta t)_{STEP} = 0.2647$, $T = 5.294$

THE COEFFICIENT MATRICES ARE:

$B^{11} = -0.0334837$ $\quad B^{12} = -1.12702$

$B^{21} = 1.11426$ $\quad B^{22} = -0.0198025$

$D^{11} = -4.57852$ $\quad D^{12} = -0.0921018$

$D^{21} = 0.0318796$ $\quad D^{22} = -4.61154$

$C^{111} = 0.398792 \times 10^{-3}$ $\quad C^{112} = -0.770657 \times 10^{-2}$

$C^{121} = -0.125791 \times 10^{-2}$ $\quad C^{122} = 0.101361 \times 10^{-2}$

$C^{211} = 0.625359 \times 10^{-2}$ $\quad C^{212} = -0.662198 \times 10^{-4}$

$C^{221} = -0.245154 \times 10^{-3}$ $\quad C^{222} = -0.747293 \times 10^{-3}$

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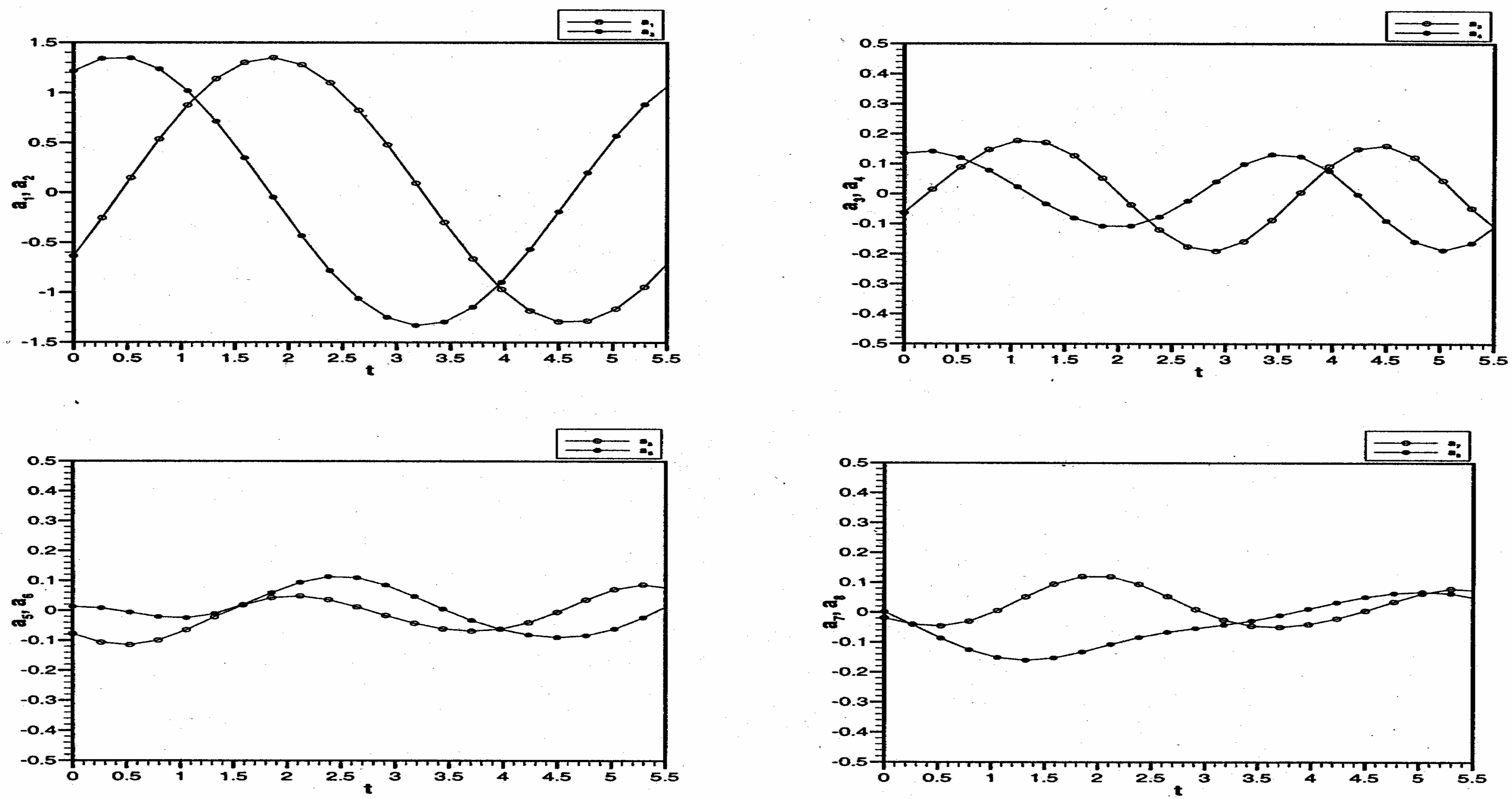
POD MODEL OF CYLINDER

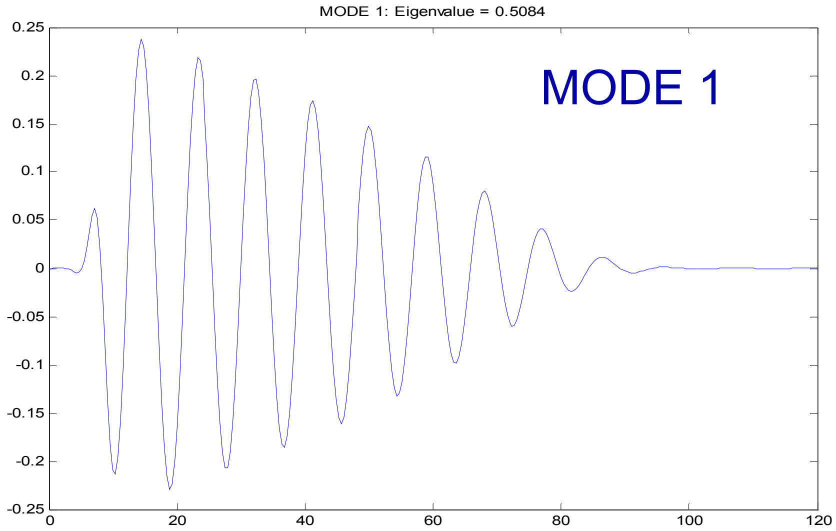
TIME DEPENDENT COEFFICIENTS OF FIRST 8 MODES BASED ON WATER TUNNEL DATA

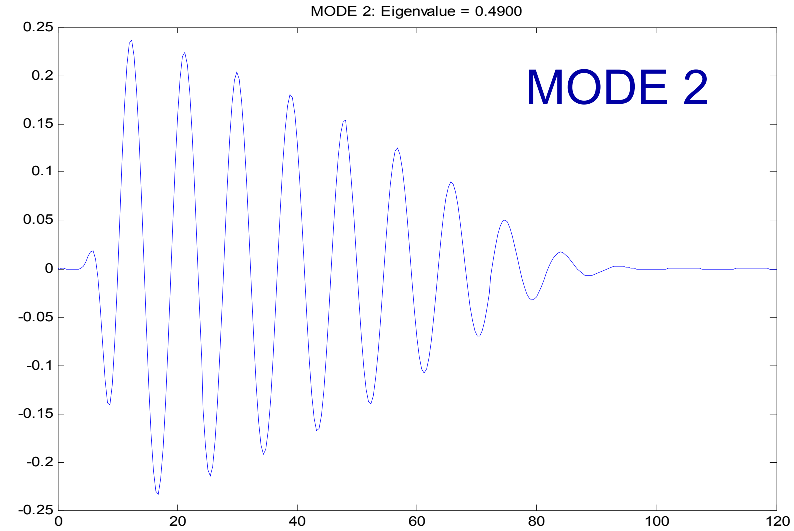
$$\Omega_1 = 0.5$$

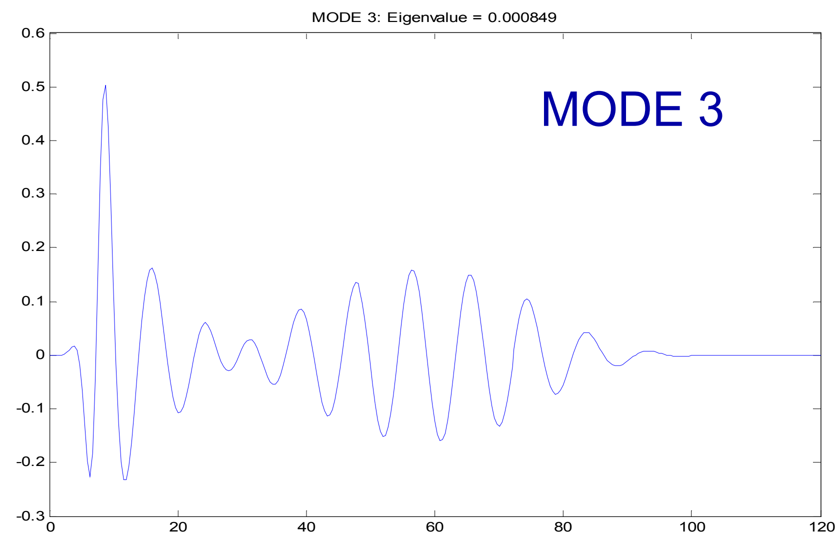


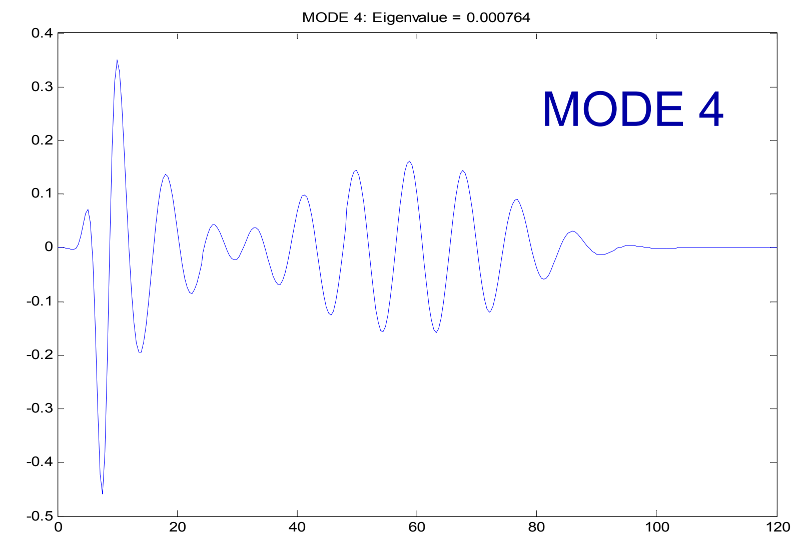
LOW-DIMENSIONAL MODEL

POD of Ginzburg-Landau Equation Based on Data from Non-Linear Analysis Using FEMLAB









MODELING ISSUES UPCOMING EFFORT

- **TRUTH MODEL**
  - On-going effort with COBALT-CFD to modify software in order to enable closed-loop control.
  - Experimental verification of the modified COBALT CFD Model.
  - <u>PAYOFF</u>: Enable extensive closed-loop studies.

- **LOW-DIMENSIONAL MODEL**
  - Further development of POD Model to quantitatively incorporate the control input.
  - Develop conditions for Observability and Controllability of POD Model
  - Experimental verification of the modified POD Model.
  - <u>PAYOFF</u>: Enable enhanced controller design.

ADDRESSING THE ESTIMATION PROBLEM

- **A State Estimator** is required to accept the sensor measurements and produce an estimate of the state, since the states of the POD model are not measurable.
- As Re increases, more global modes contribute.
- Sensor outputs are contaminated by the residual modes (*Observation Spillover)*.
- Beyond a critical Re, the effort necessary to control the most dominant mode or modes merely destabilizes the next most unstable mode (Spillover Phenomenon).
- As a result, oscillations may be suppressed at a particular sensor location but are aggravated elsewhere. Therefore, spatially distributed sensors are needed. Conditions for **OBSERVABILITY** and the number and placement of the sensors is another major issue.
- The is non-linear and this characteristic needs to be accounted for during the development of the estimator.
- Due to the non-linear nature and complexity of the spatio-temporal response of the wake, a robust non-linear estimator is required to obtain the necessary state estimation.

POD ESTIMATOR DESIGN

- For a given actuator input, a finite set of POD modes is obtained from observations of the cylinder wake velocity field.

- If the observed response of the wake to parameters of an actual control actuator is recorded from an experiment, then the physical control-mode interaction is estimated empirically using Soft Computing techniques.

- The estimator is *trained* to predict observed response of the POD modes from the physical actuation of the velocity field in an experiment.

- With adequate training, the non-linear mapping between actuation and temporal behavior of the forced wake in the POD space is obtained.

- The relationship between present, past and future flow state is predicted (for each discrete time step) as the estimator, which has the form of a one-step predictor, is continually supplied with present and past flow states.

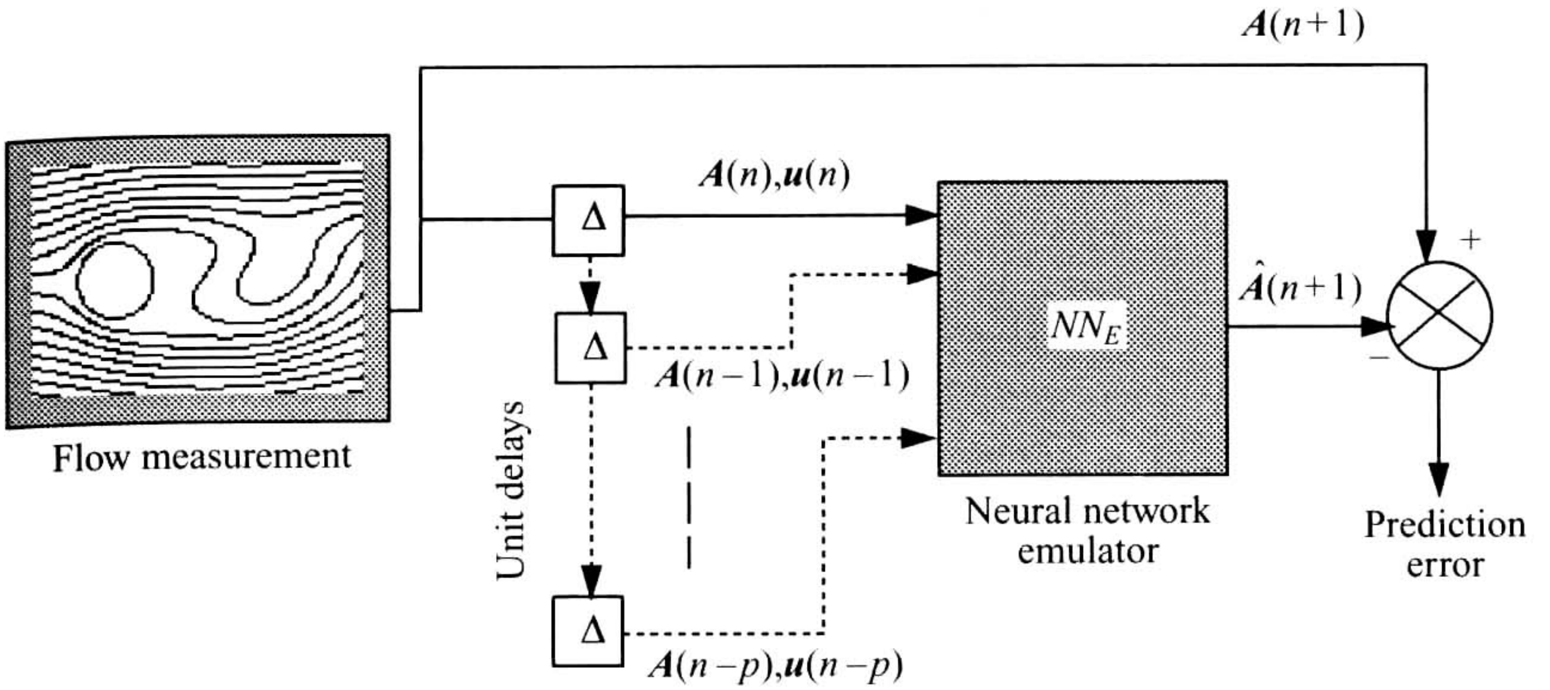
ESTIMATION ASSETS

- A Neural estimator was designed to emulate an adequate representation of the wake by POD modes generated by large enough *non-stationary data ensemble* (Gillies).

- Application of ANFIS (**A**daptive **N**euro-**F**uzzy **I**nference **S**ystem) for prediction of chaotic time series prediction. The ANFIS algorithm is part of MATLAB's Fuzzy Logic Toolbox.

Neural Emulator (Gillies)

Mapping Sensor Measurements to POD States for Cylinder Wake

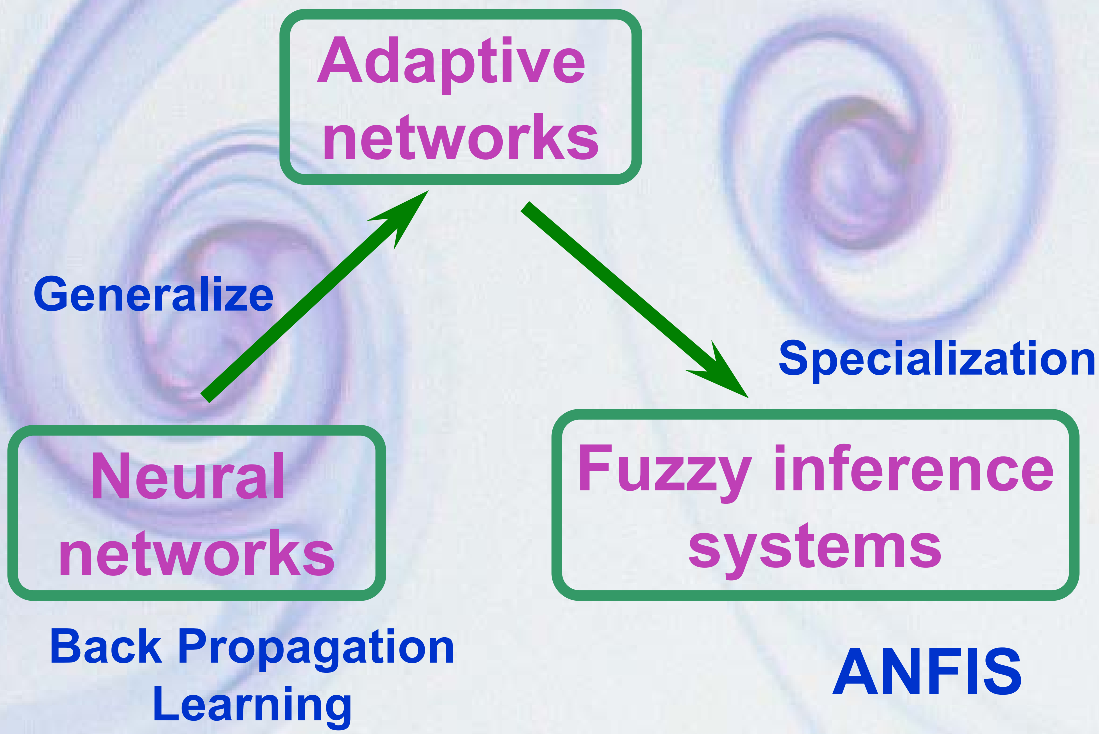


Neural emulator: one-step predictor.

ANFIS as a Neuro-Fuzzy Modeling Tool

- First we generalize neural networks architectures to obtain adaptive networks, and then we do a specialization to derive fuzzy inference systems represented by adaptive networks (ANFIS).

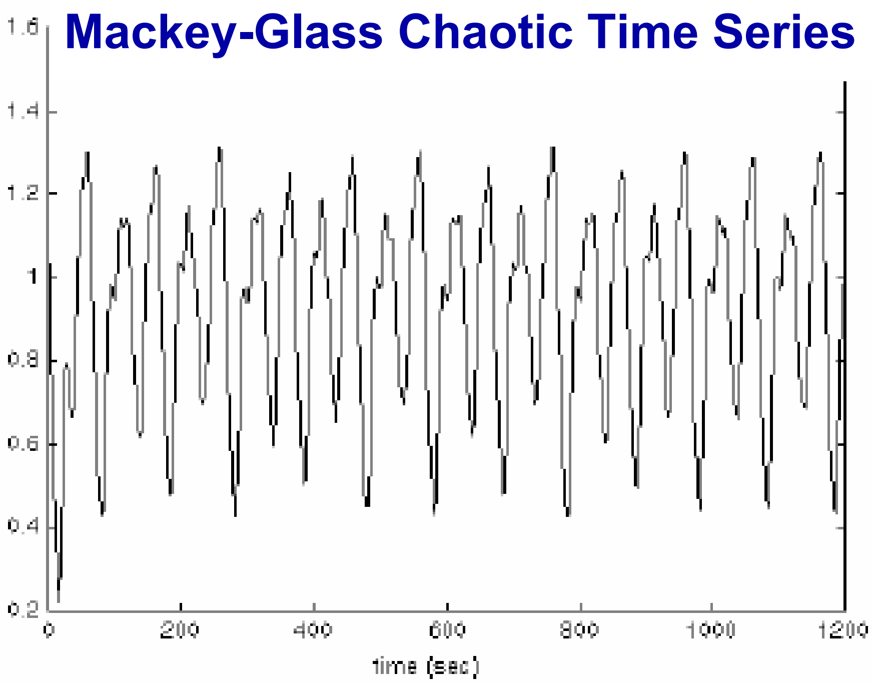
- During the processes of generalization and specialization, the backpropagation techniques used for training neural networks can be carried over directly, so ANFIS can be trained using the same techniques.



Using ANFIS for Chaotic Time Series Prediction

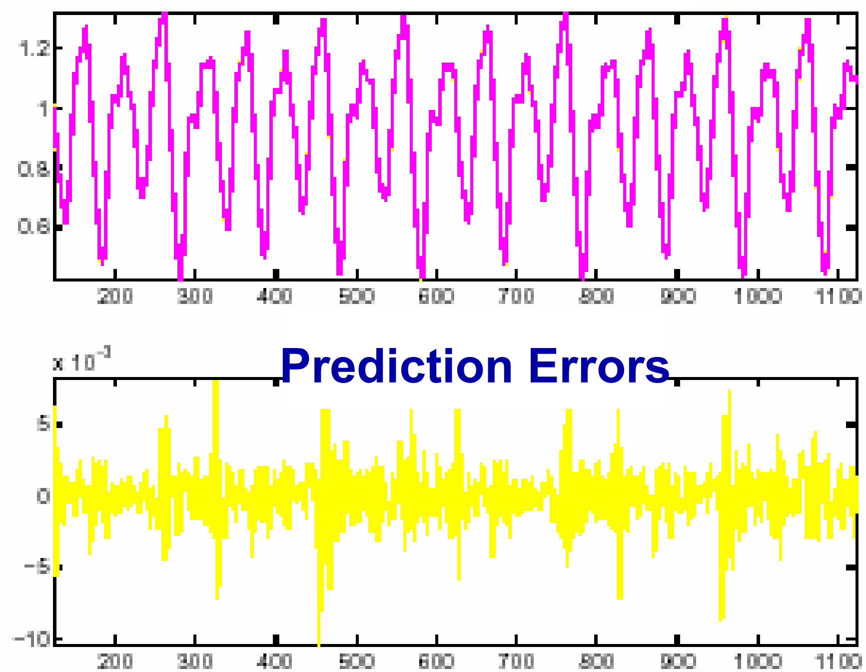
- ANFIS is used to predict a time series that is generated by the Mackey-Glass (MG) time-delay differential equation.
- This time series is chaotic, and so there is no clearly defined period. The series will not converge or diverge, and the trajectory is highly sensitive to initial conditions.
- This is a benchmark problem in the neural network and fuzzy modeling research communities.

Mackey-Glass Chaotic Time Series



ANFIS Prediction

Prediction Errors



ESTIMATION ISSUES
UPCOMING EFFORT

- Using MATLAB's ANFIS to reproduce the Emulator developed by Gillies for the Cylinder Wake (mapping of sensor measurements to POD states).
- Fine-tuning the resulting fuzzy approximator from ANFIS to *quantitatively* emulate the response to arbitrary control inputs.
- Computational Evaluation of Estimator (Benchmarks I & II)
- Experimental verification of the developed Neuro-Fuzzy Estimator (Benchmark III).

ADDRESSING THE CONTROL PROBLEM

FLOW MODEL

- Complexity
- Size (DOFs)

STATE OF THE ART CONTROL TECHNIQUES

+

THREE – MODEL CONTROL THEORY

PROBLEM AREAS

1. MODELING AREAS

* Parameter Errors
* Model-order Errors
* Neglected Disturbances
* Neglected nonlinearities

2. ERRORS IN OPTIMALITY PREDICTION

COMPENSATION USING ROBUST CONTROL TECHNIQUES

ROBUSTNESS:
AN ESSENTIAL REQUIREMENT

- The uncertainties inherent with wake flow dynamics and the effects of various disturbances make *robustness* an essential attribute of the control system.
- These uncertainties are a result of modeling errors and unforeseen changes.
- **Types of Robustness**: *Stability Robust Systems* relates to closed-loop systems that remain stable in light of uncertainty, whereas, *Performance Robust Systems* refers to closed-loop systems that maintain an acceptable level of performance.
- Although stability robustness is imperative, performance robustness can be a deciding factor in the selection of an appropriate control law.
- In order to circumvent many of the modeling and control problems mentioned, an controller strategy based on inherently robust soft computing techniques (Neural Nets and Fuzzy Logic) has been selected.

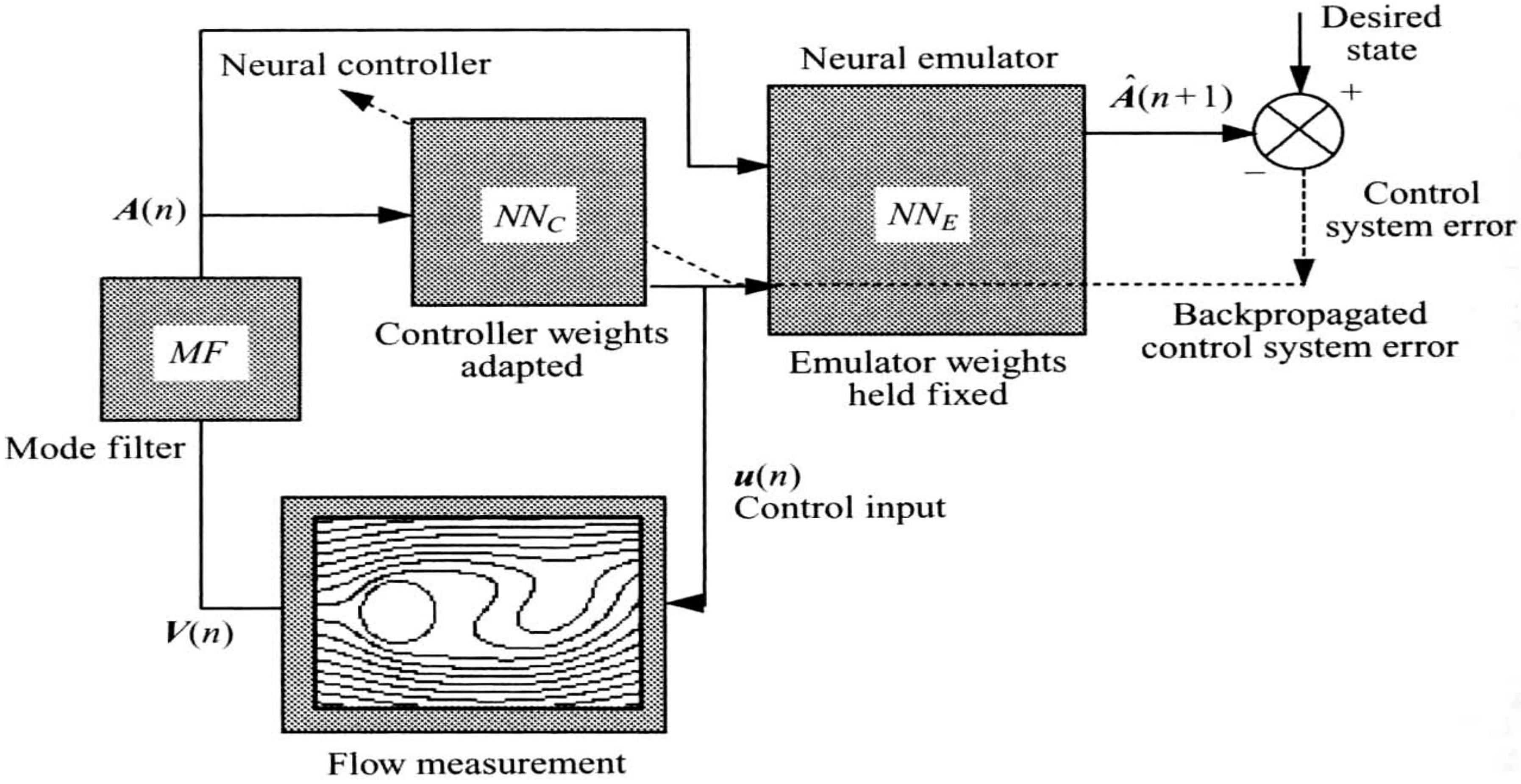
CONTROLLER ASSETS

- A Neural controller was designed to provide real-time mapping of POD states to actuator commands (Gillies).

- First-hand experience in successfully developing and applying fuzzy logic for control of flexible structures (vibration suppression, flutter suppression and noise attenuation).

- Modification of the above fuzzy logic tools for non-linear system control. Successful application for control of the chaotic Van der Pol oscillator, which is often used as a simple model for wake instability studies.

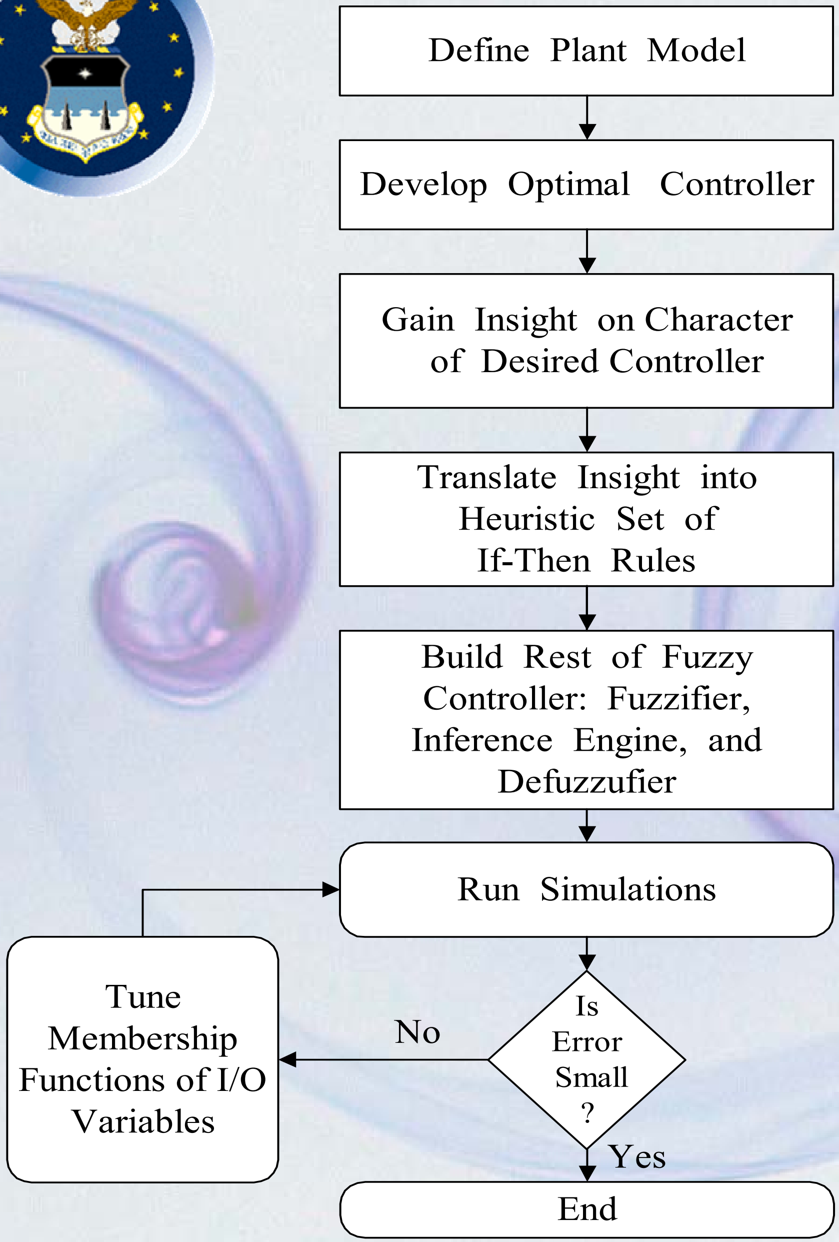
Neural Controller (Gillies)
Mapping of POD States to Actuator Commands

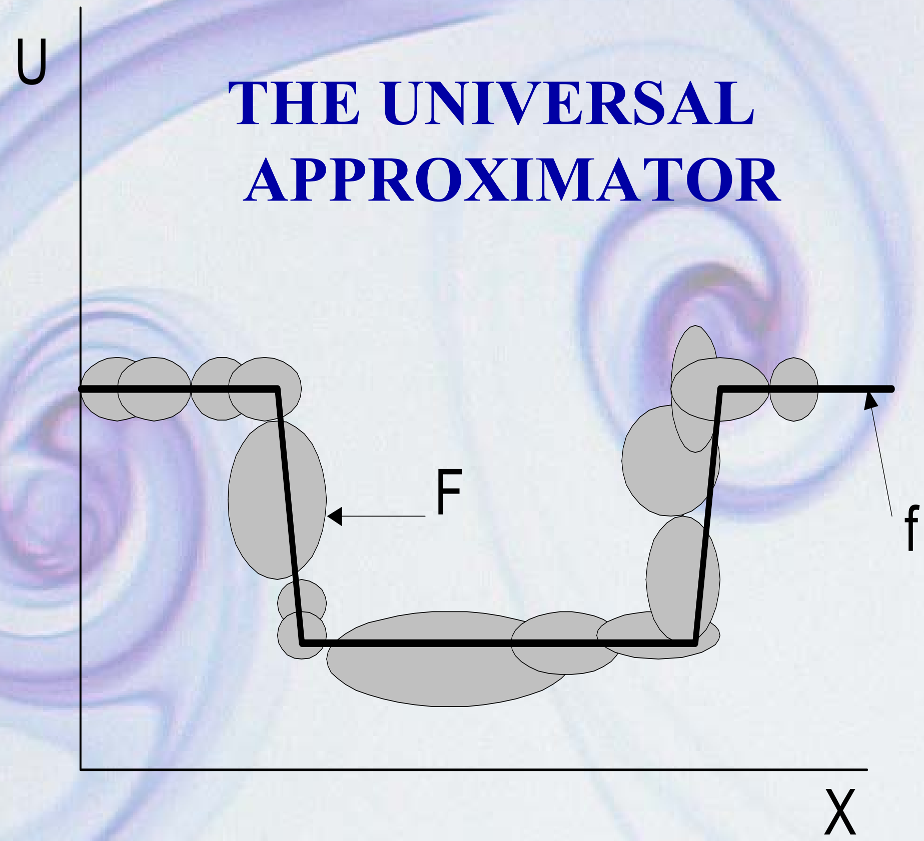


IMPLEMENTING A FUZZY CONTROLLER

- Relative ease and simplicity of implementation and robustness characteristics.
- The “gains” of fuzzy controller may be adapted in real-time to provide fairly fast control for large deviations, of the measured state of the plant from the desired state, and a minor amount of control for small deviations.
- The successful implementation of a fuzzy logic controller depends, among other design aspects, on the heuristic rule base from which control actions are derived.

TRAINING A FUZZY LOGIC CONTROLLER





FUZZY LOGIC CONTROL

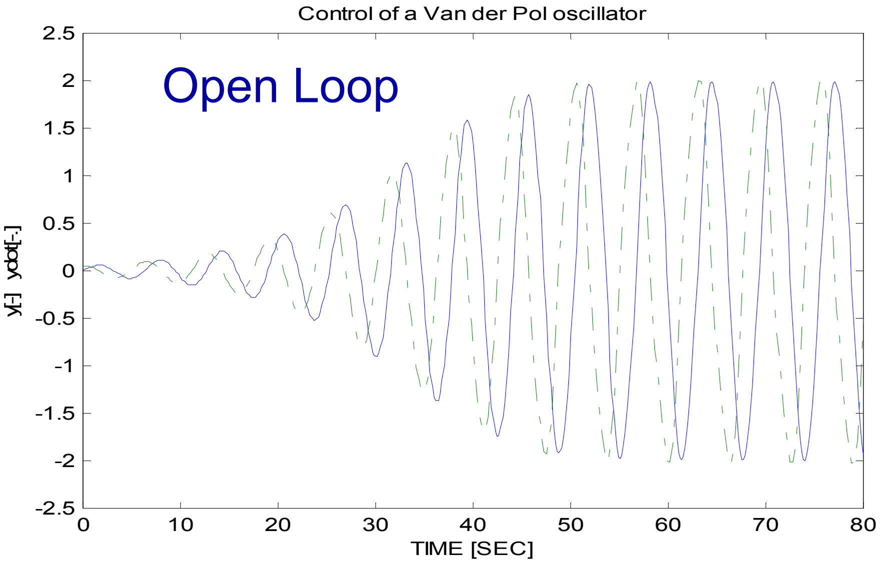
FIRST HAND EXPERIENCE

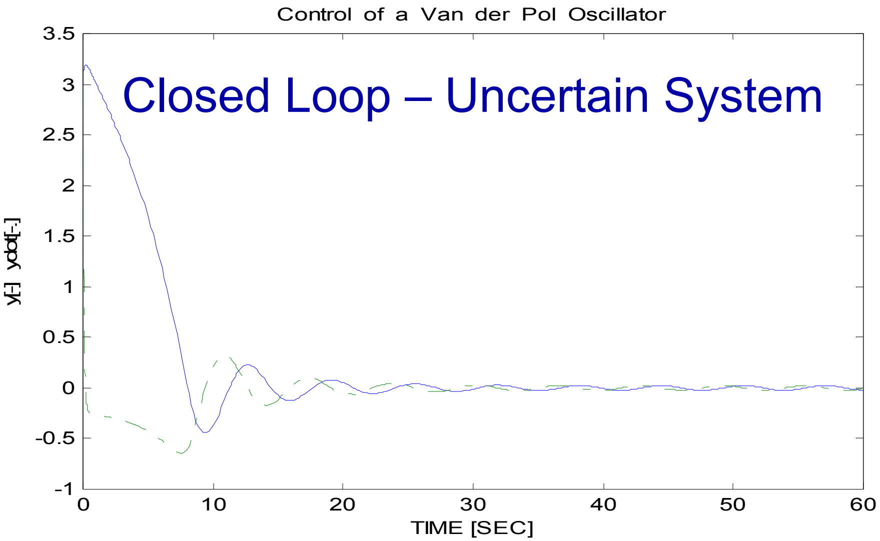
Type of System Studied	Treatment	Robust Control (PU, SN, NC)	Comparison with other Control Methods	Observer	Monte Carlo Stability Analysis
Two-Mass Spring (ACC Benchmark)	Numerical	PU, SN, NC, TE	LQG/LTR, H_∞	Yes	Yes
Vibration Suppression of a 10-Bar Truss	Numerical	PU,TE	LQG/LTR, H_∞	Yes	---
Cabin Noise Attenuation	Numerical	PU,SSE	“Passive” LTI	---	---
Active Flutter Suppression - BACT Problem	Numerical	PU, SN, NC,TE	LQG	Yes	---
Cantilever with Piezo-Ceramic Sensors/ Actuators	Experimental	PU, SN,TE	---	---	---

PU - Plant Uncertainties; **SN** - Sensor Noise; **NC** - Non-Collocation of Sensor/Actuator
TE - Transient Excitation; **SSE** – Steady-State Excitation

Fuzzy Control of The Van der Pol Oscillator

- The non-linear Van Der Pol oscillator has been used to provide a simple model for the cylinder wake flow.
- In this closed-loop study of the chaotic oscillator, control strategies were designed using both a constant gain approach as well as a variable gain fuzzy logic controller.
- It was found that a variable gain fuzzy logic controller (see response in figure) is more robust and effective in handling plant uncertainty and the inherent nonlinearity.





CONTROLLER ISSUES UPCOMING EFFORT

- Using MATLAB's Neural Network Toolbox to reproduce the Controller developed by Gillies for the Cylinder Wake.
- Further developing the fuzzy logic control approach, based on MATLAB's Fuzzy Logic Toolbox.
- Computational Evaluation of Controller (Benchmarks I & II).
- Experimental verification of the developed Fuzzy Controller (Benchmark III).

Note: The Benchmarks include Robustness Testing

SUMMARY OF ASSETS AND EFFORTS

	ASSETS	EFFORT
Modeling	**TRUTH MODELS** 1. COBALT: Translating Cylinder 2. FEMLAB: Wake Instability **LOW-DIMENSIONAL MODELS** 1. POD Model of Cylinder 2. POD Model of Ginzburg-Landau Equation.	**TRUTH MODEL** Modify COBALT to enable extensive closed-loop control studies. **LOW-DIMENSIONAL MODEL** 1. Quantitatively introduce control input into POD Model. 2. Observability and Controllability
Estimator	1. Neural estimator provides representation of the wake by POD modes generated by non-stationary data ensemble (Gillies). 2. Application of MATLAB Fuzzy Logic Toolbox for prediction of chaotic time series prediction.	1. Reproduce the Emulator developed by Gillies for the Cylinder Wake. 2. Tuning the resulting fuzzy approximator for *quantitatively* emulation. 3. Benchmark test and evaluation of the Estimator.
Controller	1. Neural controller provides mapping of POD states to actuator commands (Gillies). 2. Successful application of fuzzy logic for control of flexible structures. 3. Fuzzy Logic control of the chaotic Van der Pol oscillator.	1. Reproduce the Controller developed by Gillies for the Cylinder Wake. 2. Further developing controller using MATLAB's Fuzzy Logic Toolbox. 3. Benchmark test and evaluation of the Controller.

MODELING AND CONTROL IDENTIFICATION OF RISK AREAS

	EFFORT	RISKS
Modeling	**TRUTH MODEL** Modify COBALT to enable extensive closed-loop control studies. **LOW-DIMENSIONAL MODEL** 1. Quantitatively introduce control input into POD Model. 2. Observability and Controllability	**TRUTH MODELS** Low - Medium **LOW-DIMENSIONAL MODELS** **High**
Estimator	1. Reproduce the Emulator developed by Gillies for the Cylinder Wake. 2. Tuning the resulting fuzzy approximator for *quantitatively* emulation. 3. Benchmark test and evaluation of the Estimator.	1. Reproduction of Gillies Emulator: Low 2. Quantitatively Emulation: Medium 3. Estimator T&E: Medium-High.
Controller	1. Reproduce the Controller developed by Gillies for the Cylinder Wake. 2. Further developing controller using MATLAB's Fuzzy Logic Toolbox. 3. Benchmark test and evaluation of the Controller.	1. Reproduction of Gillies Controller: Low 2. Development of Controller: Medium 3. Controller T&E: Medium-High.

CONCLUSIONS

- A structured approach has been developed to advance the state-of-the art of closed-loop flow control.
- The approach addresses the multi-disciplinary challenges associated with this research effort.
- Currently, the versatile team at USAFA armed with the necessary computational and experimental assets hopes to realize the vision of effective closed-loop flow control.

References

- FEMLAB, Version 2.2, COMSOL AB., November 2001 (for further information try URL: http://www.femlab.com).
- Gillies, E. A., “Multi Sensor Control of Vortex Shedding”, 6th AIAA/CEAS Aeroacoustics Conference, Lahaina, Hawaii, AIAA Paper 2000-1933, June 12-14, 2000.
- Gillies, E. A., “Low-dimensional control of the circular cylinder wake”, Journal of Fluid Mechanics, vol. 371, pp. 157-178, 1998.
- Roussopoulos K. and Monkewitz P. A., “Nonlinear Modeling of Vortex Shedding Control in Cylinder Wakes”, Physica D 97, pp. 264-273, 1996.