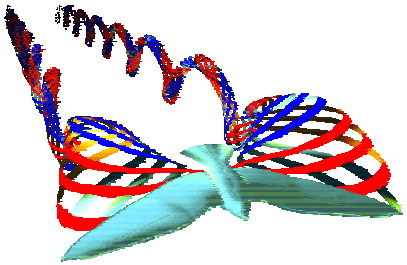
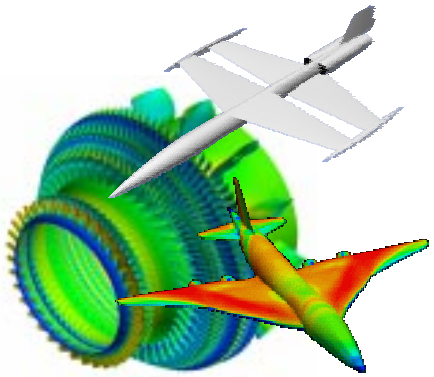


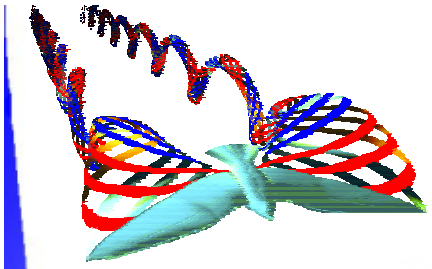
- ACTIVE AEROELASTIC AIRCRAFT STRUCTURES
- FLUID-STRUCTURE INTERACTION
- SMART STRUCTURES IN AERONAUTICS



Afzal Suleman, PhD, PEng

Associate Professor

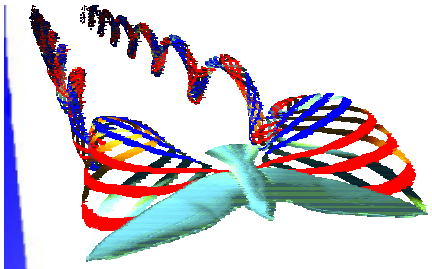
Instituto Superior Tecnico



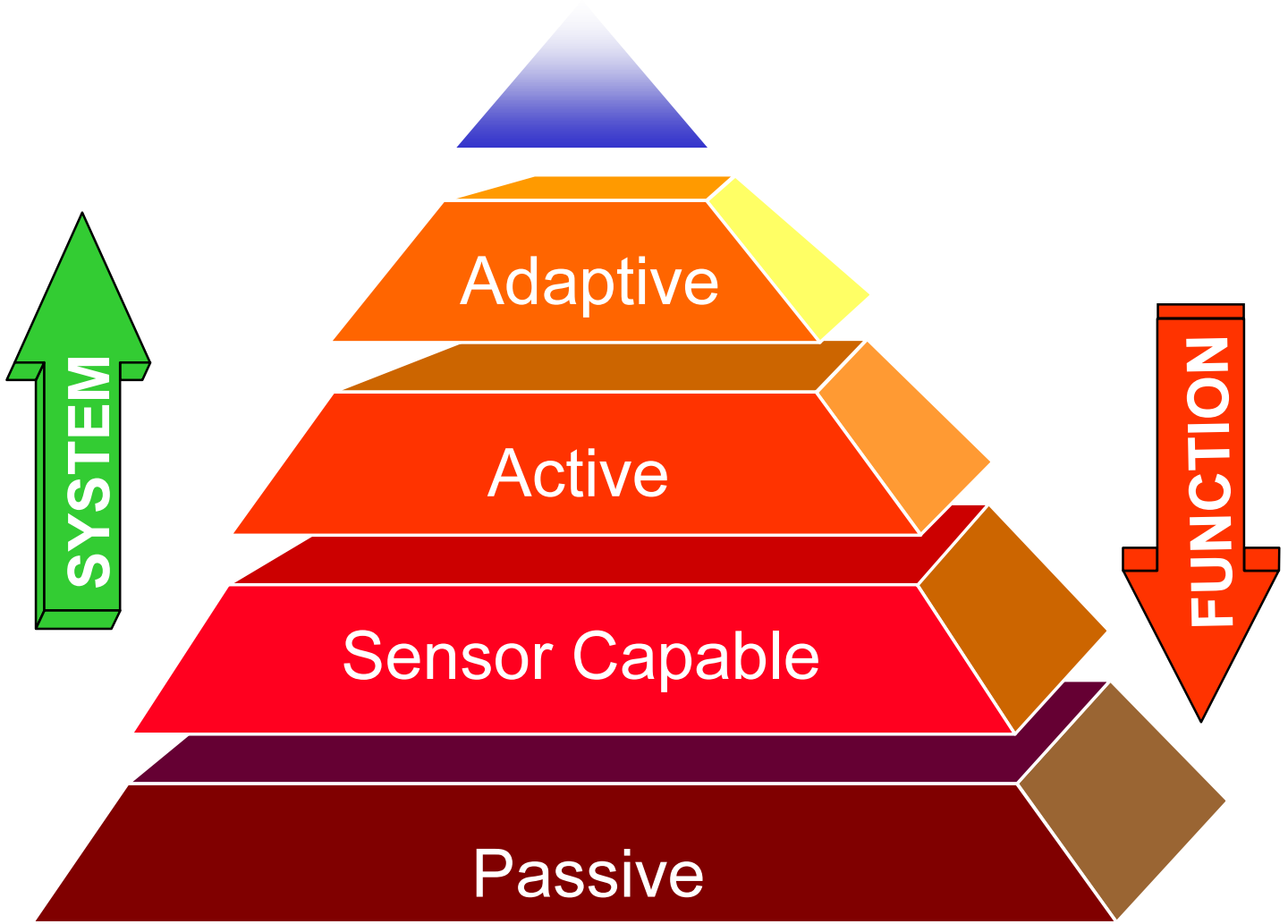
ACTIVE AEROELASTIC AIRCRAFT STRUCTURES

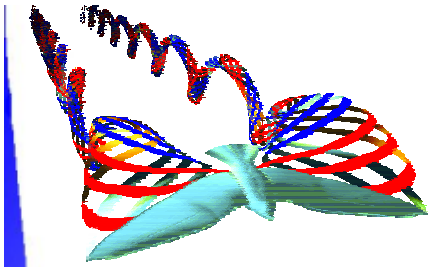
A. Suleman. P. Moniz and P. Costa

- Experimental aeroelasticity
- Computational aeroelasticity
- Smart structures

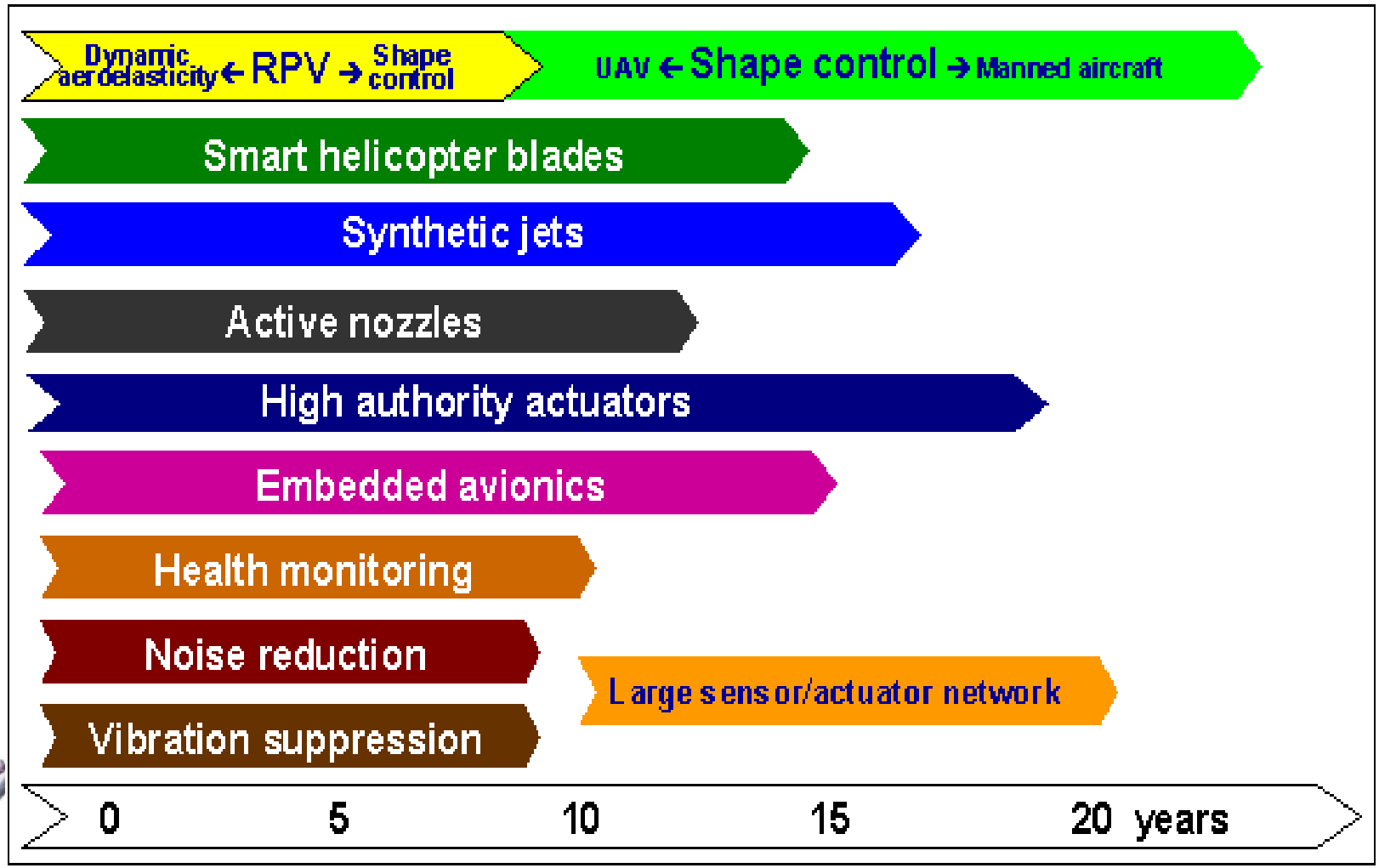


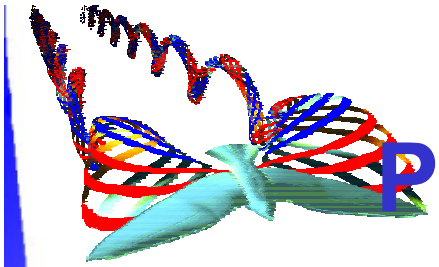
Smart Structures



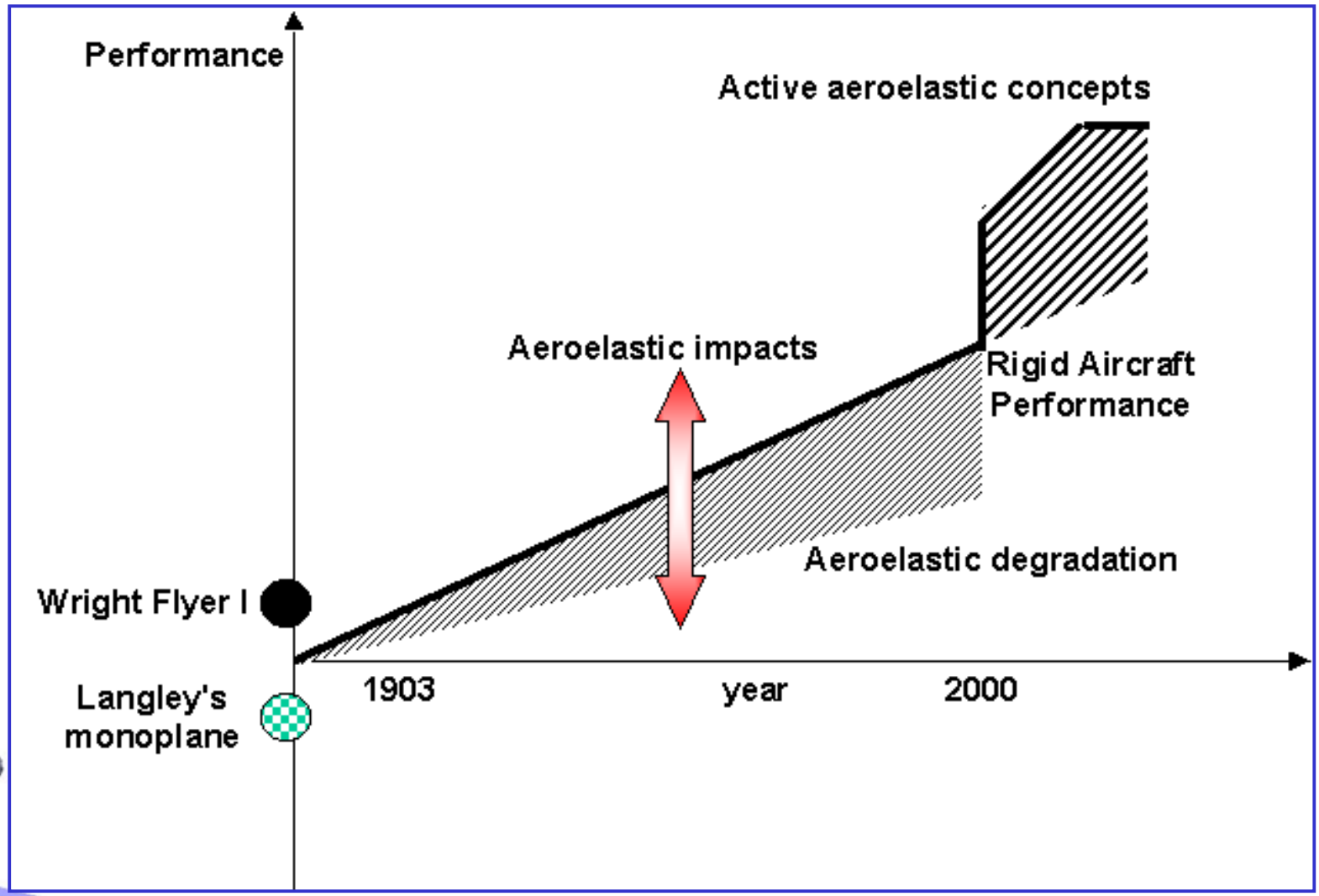


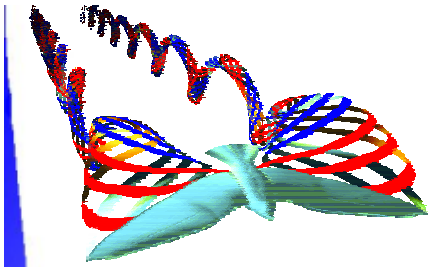
Timeline


Dynamic aeroelasticity ← RPV → Shape control
UAV ← Shape control → Manned aircraft
Smart helicopter blades
Synthetic jets
Active nozzles
High authority actuators
Embedded avionics
Health monitoring
Noise reduction
Vibration suppression
Large sensor/actuator network
0
5
10
15
20 years

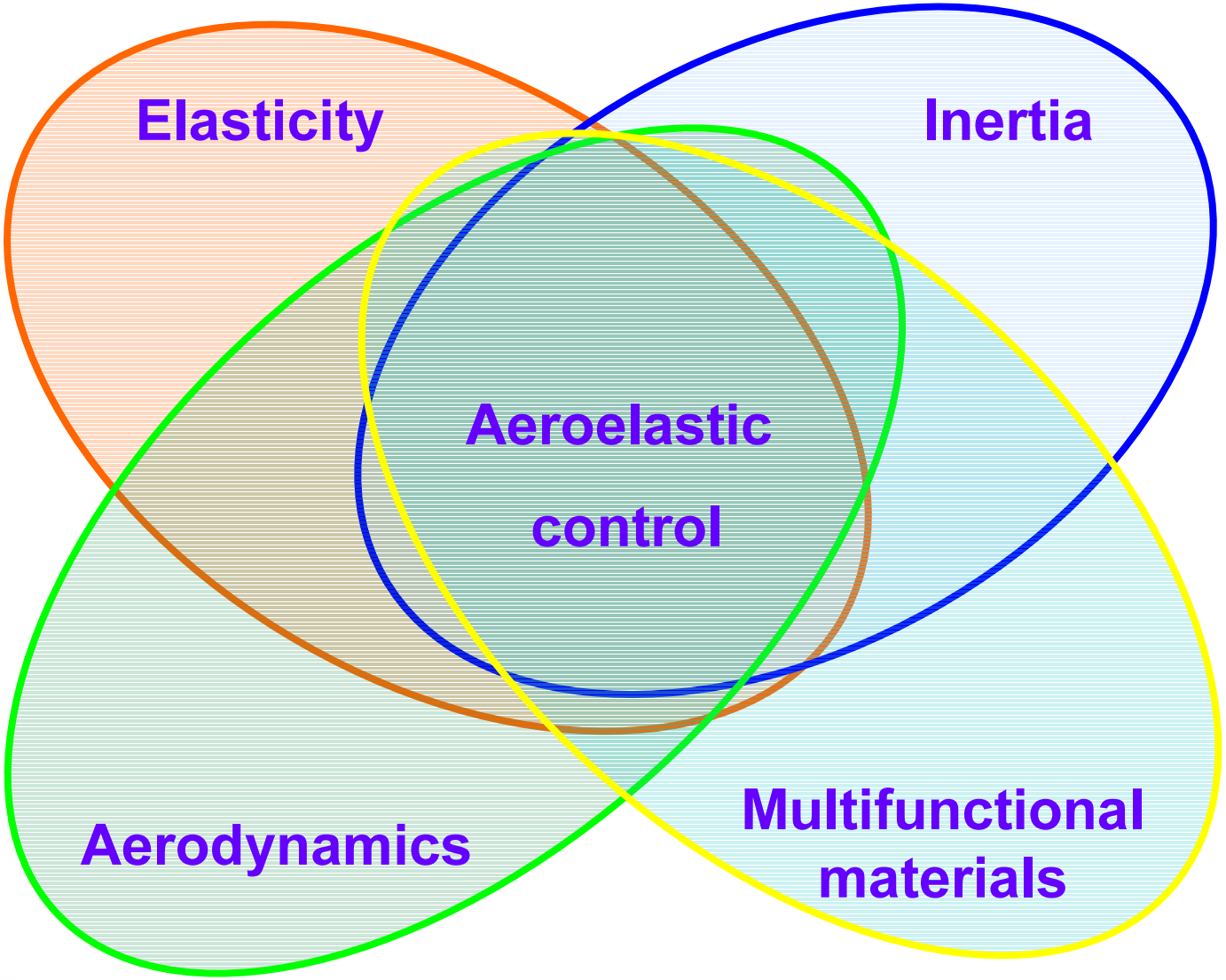


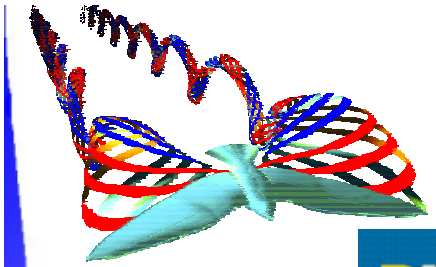
Paradigm Shift in Aircraft Design



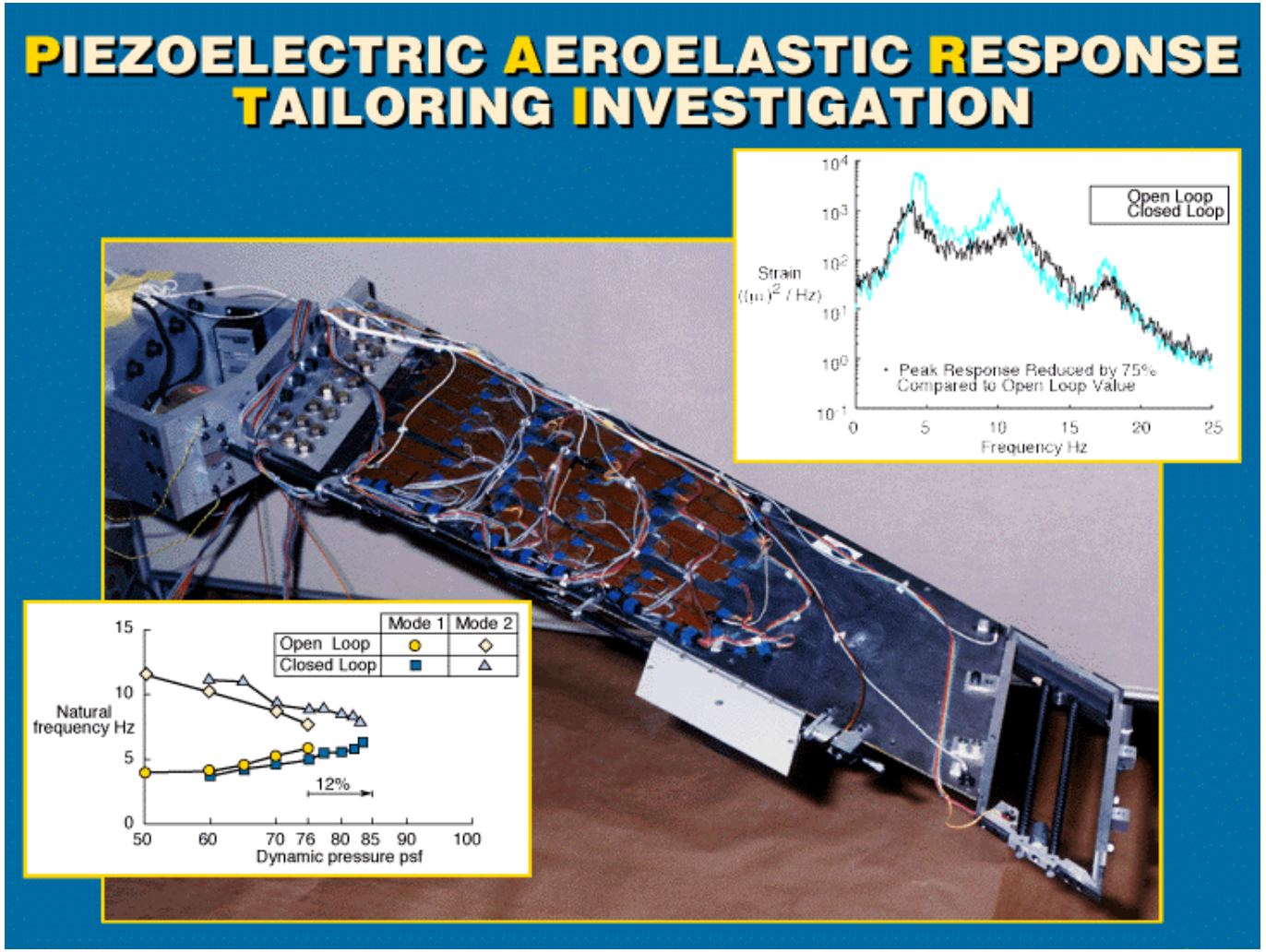


Active Aeroelastic Control

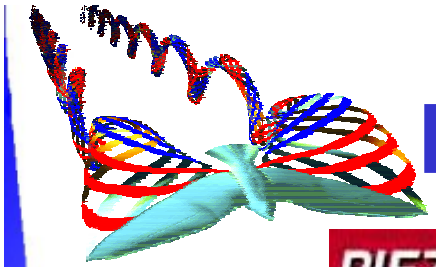




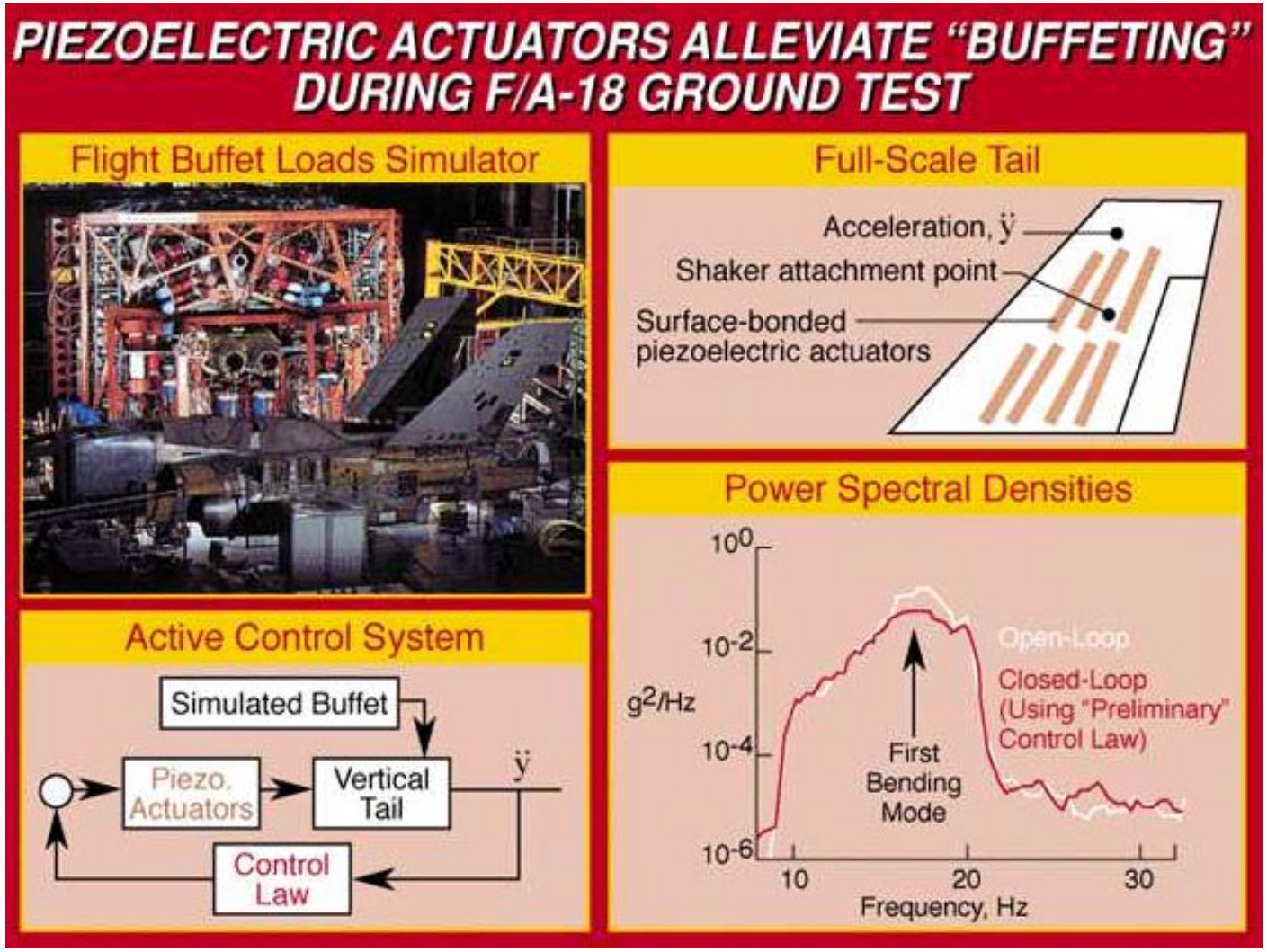
Previous Experimental Work



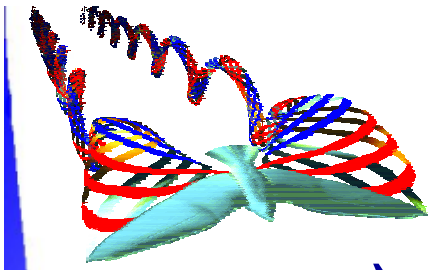
http://sonicboom.larc.nasa.gov/AeroelasticityBranch/SmartStructures



Previous Experimental Work

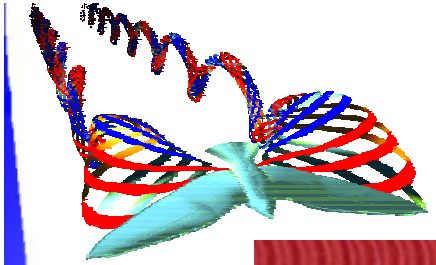


http://sonicboom.larc.nasa.gov/AeroelasticityBranch/SmartStructures

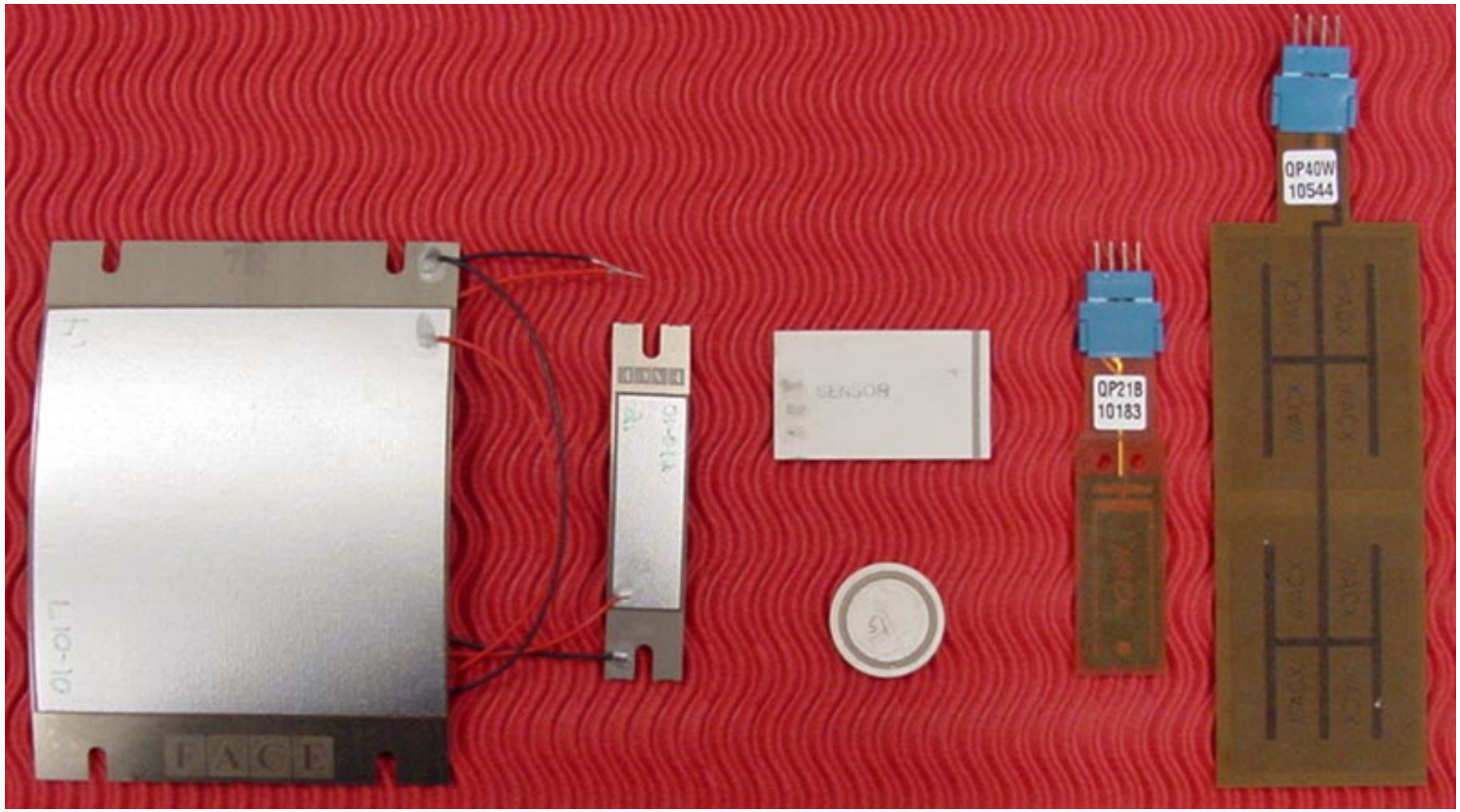


Present Research

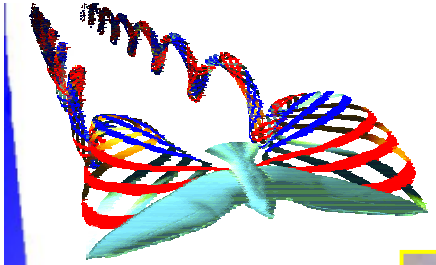
- 2D adaptive wing
  - Flutter
  - Buffeting
- 3D adaptive wing
  - Gust response
  - Buffeting
  - Engine induced mechanical vibration.
- Adaptive RPV
  - Gust response



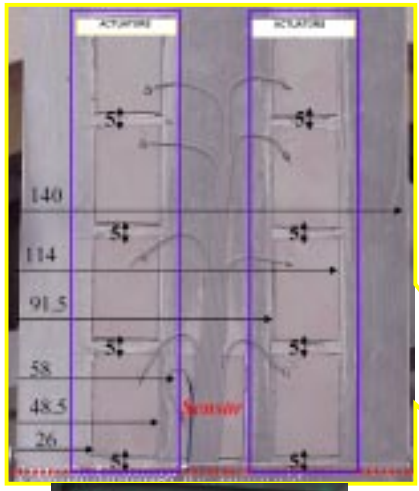
Piezoelectrics

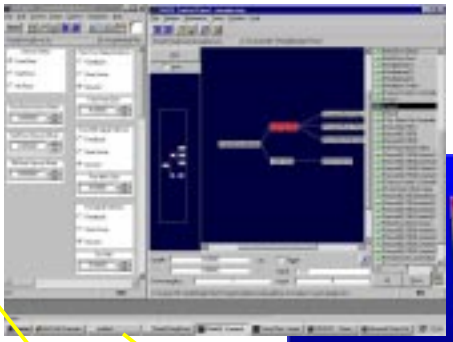


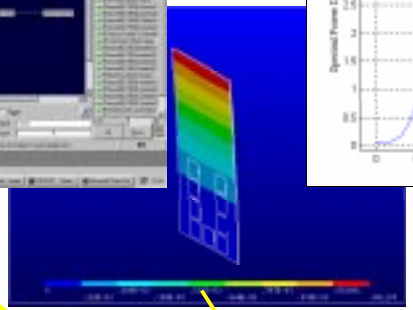
- higher bandwidths
- more compact
- they are bidirectional

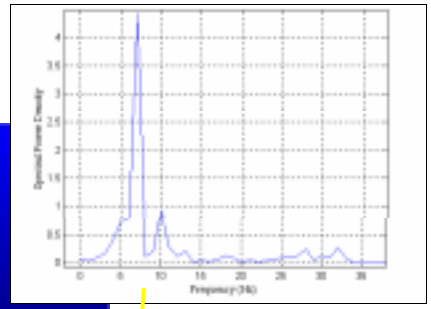


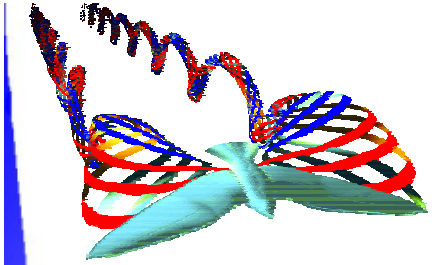
Vibration Control



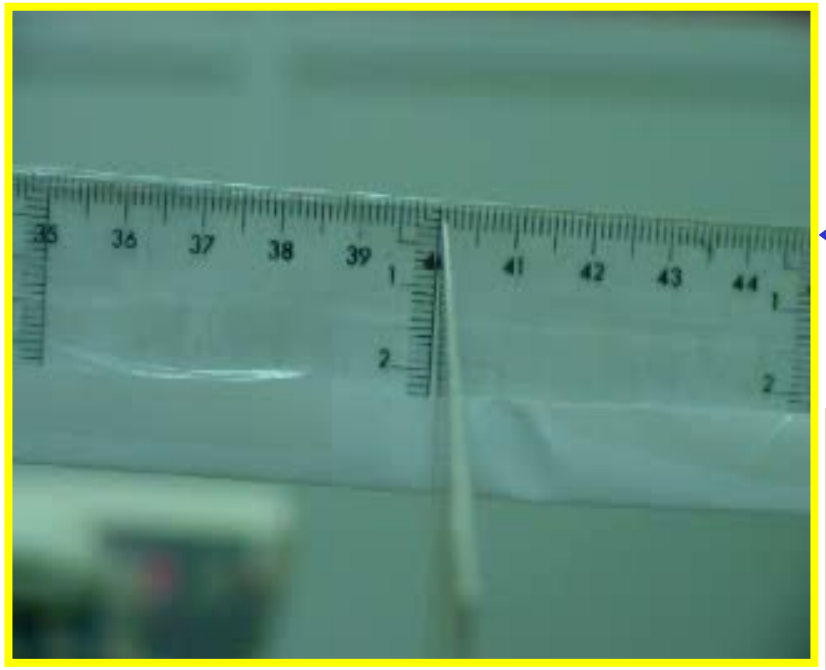






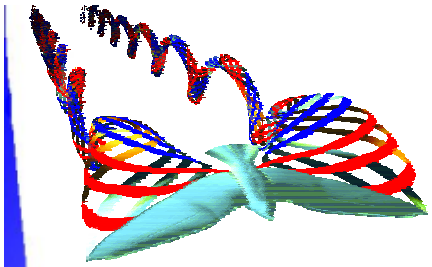


Optimal Piezo Layout



10 Hz, 80 V

5.5Hz, 60 V

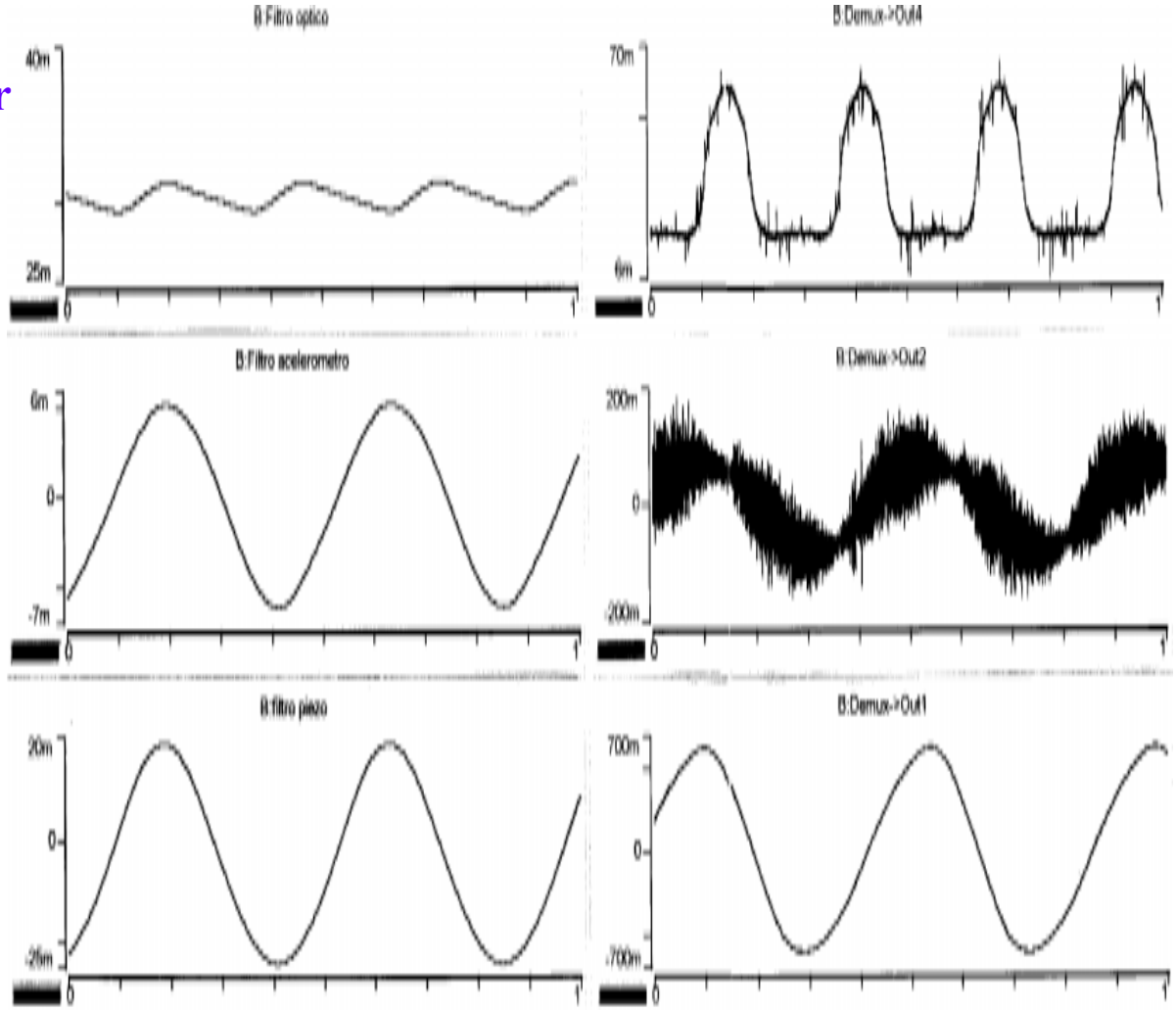


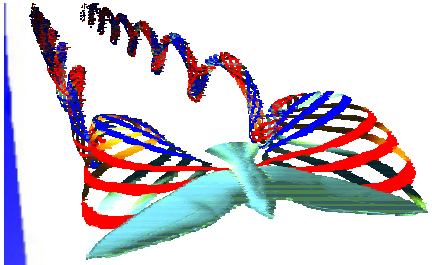
Sensor Characterization

Optical displacement sensor
Philtec ® D100
(output < 250 mV)

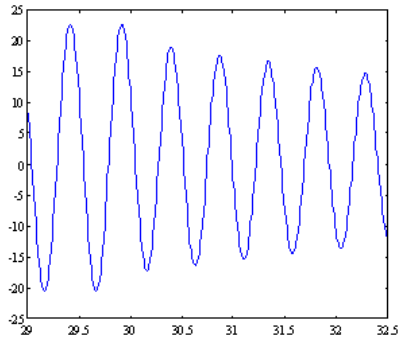
Accelerometer
Endevco Isotron ® 61A-100
(output < 200 mV)

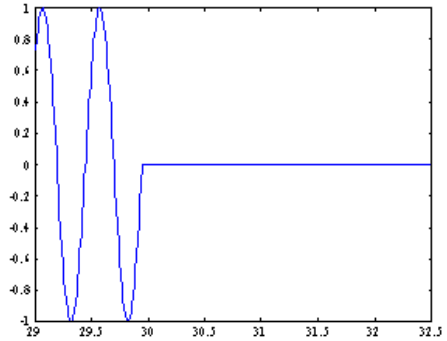
Piezoelectric sensor
Sensor ® Tec. Plate
1.5” x .9”x .015”
(output < 700 mV)

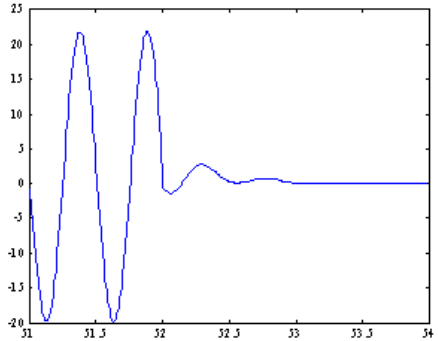




Vibration Control



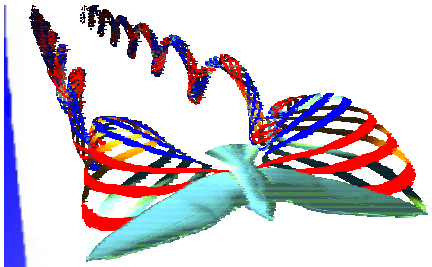




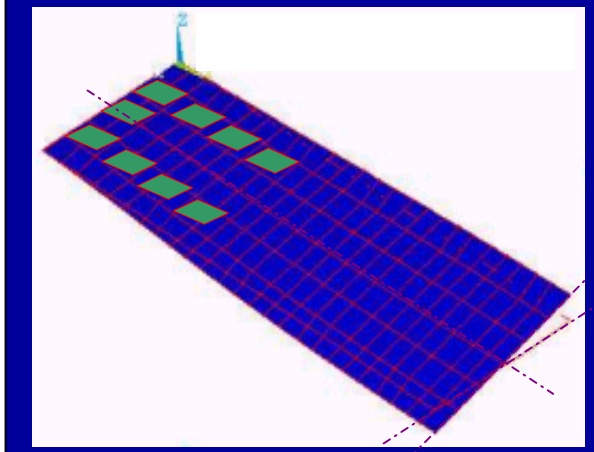
a) Natural damped vibration response excited with a sine wave input through the piezoelectric actuators (controller off).

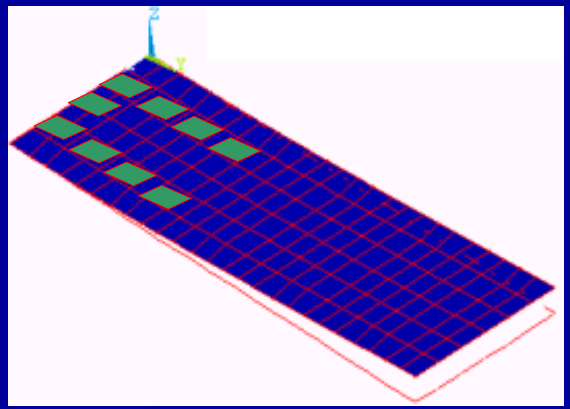
b) Actuator input signal (turned off at t = 30 s).

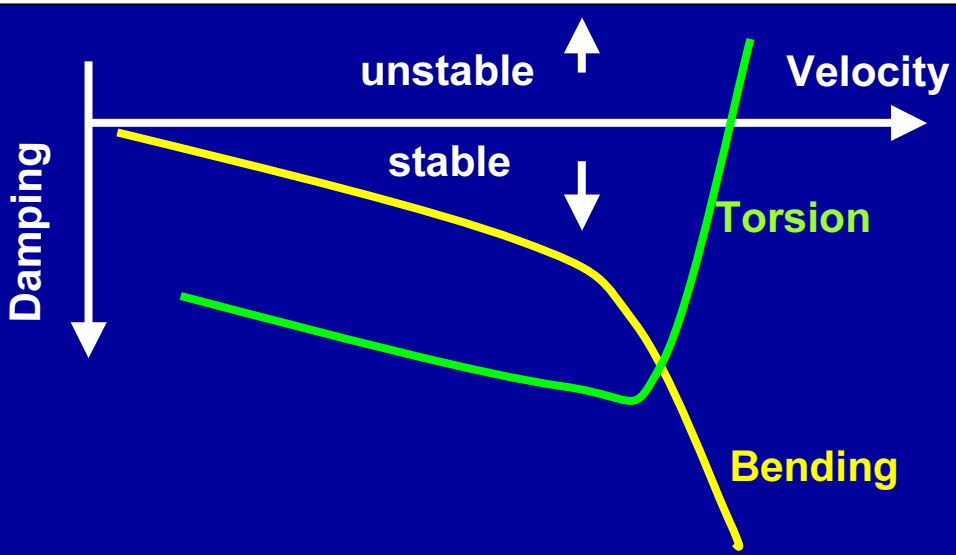
c) Controller active (time for the wing to stop oscillating reduced from 37 seconds to 1.5 seconds).

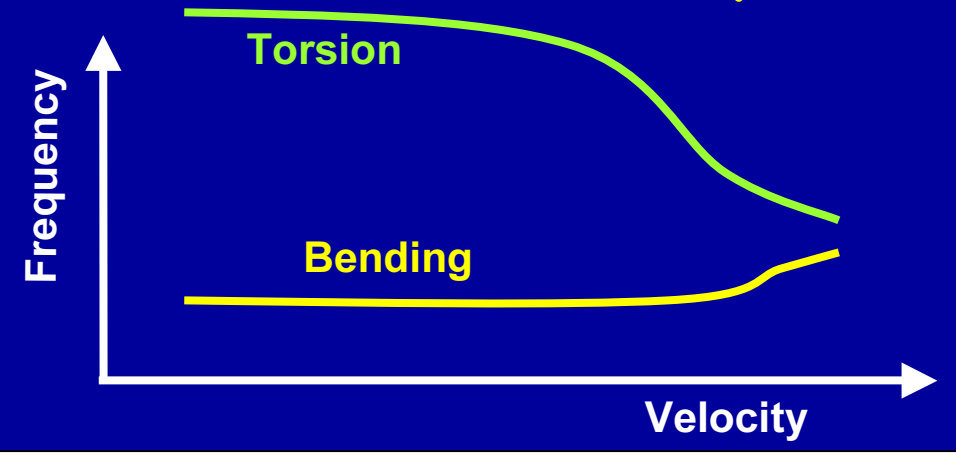


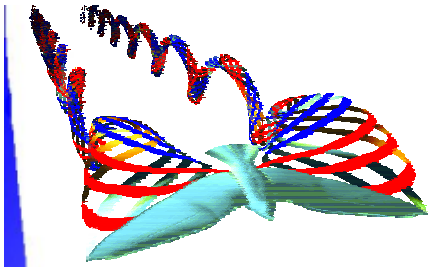
Flutter Analysis



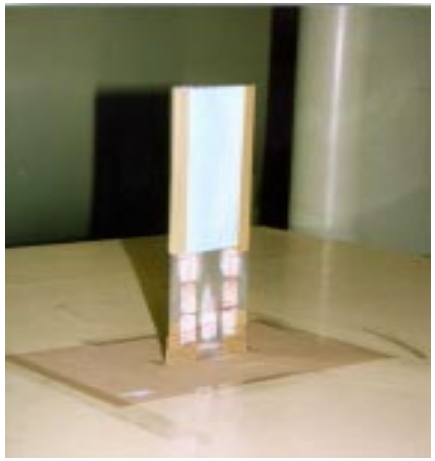






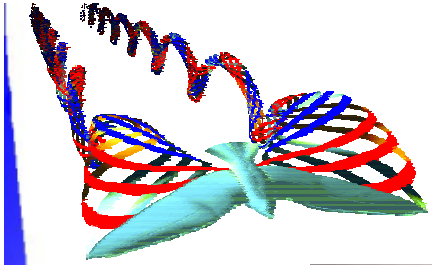


Flutter Results

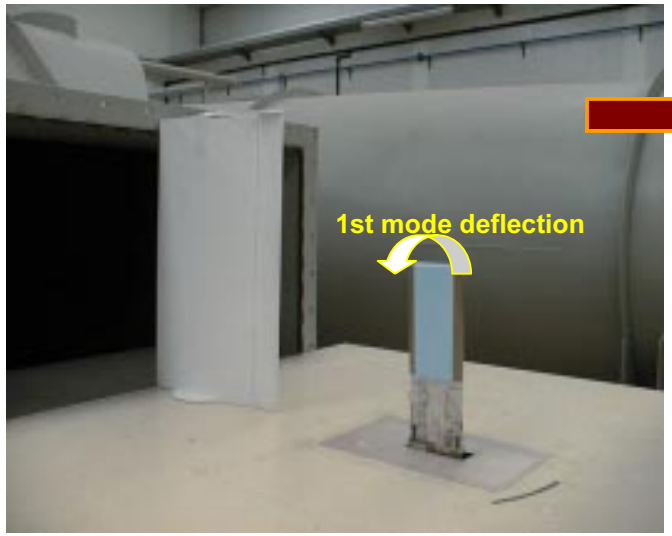


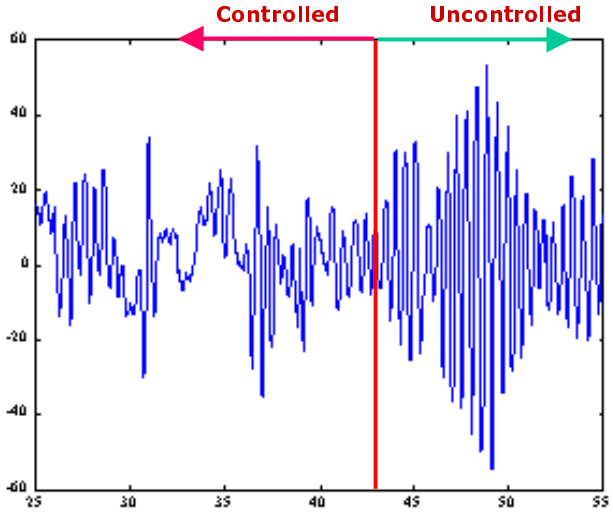
Test article

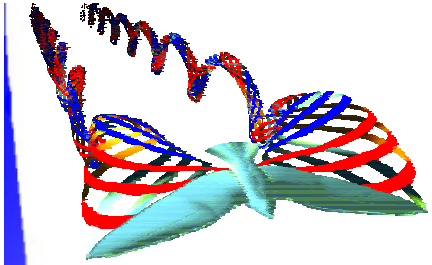
CONTROL		SINGLE INPUT SINGLE OUTPUT		DOUBLE INPUT DOUBLE OUTPUT	
		0º	10º	0º	10º
OFF	V_f	31.5	12.2	31.5	12.2
ON	V_f	32.9	12.9	33.4	12.6
	G	225	300	300-550	500-550
	%	4.4%	5.7%	6.03%	3.3%



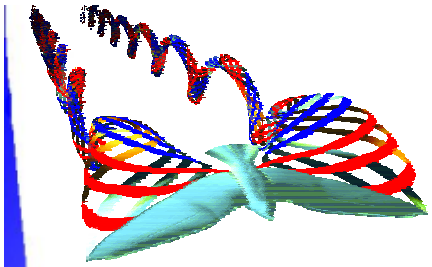
Buffeting Suppression





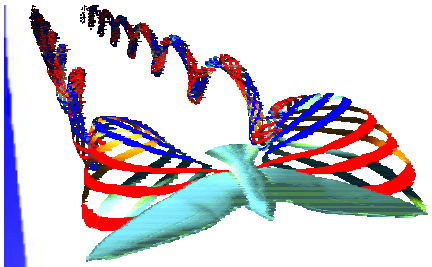


2D Wing with Sweep and Taper



Buffeting Results

CONTROL	Piezo damping		Piezo damping & shape control	
	Amplitude mm	Frequency Hz	Amplitude mm	Frequency Hz
OFF	5,85	1	6,20	1
ON	3.95	0.9	3.25	0.66
Improvement	32%	10%	47.5%	34%



3D Adaptive Wing

Basic Design

Design with Adaptive Concepts

3D Wing

3D Adaptive Wing

Adaptive Concepts

e.x: shape control and structural stiffening

Results Evaluation

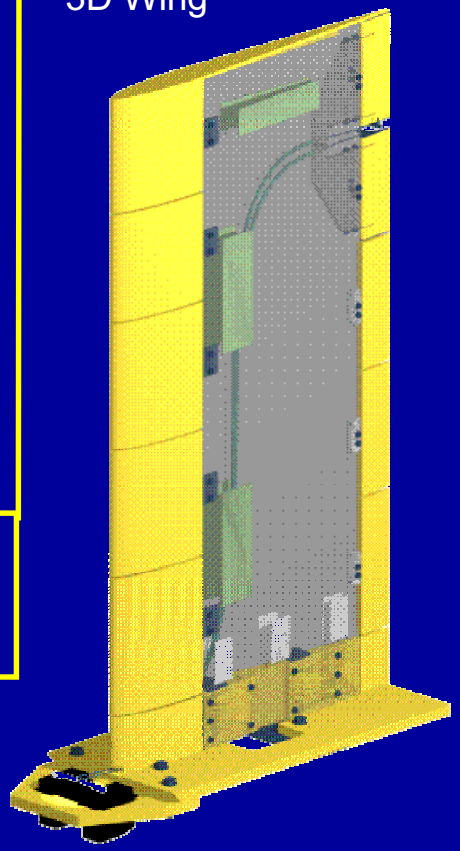
Analysis model

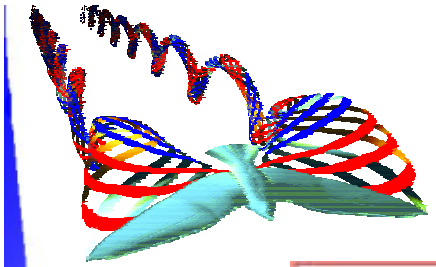
Verification Tests

Requirements

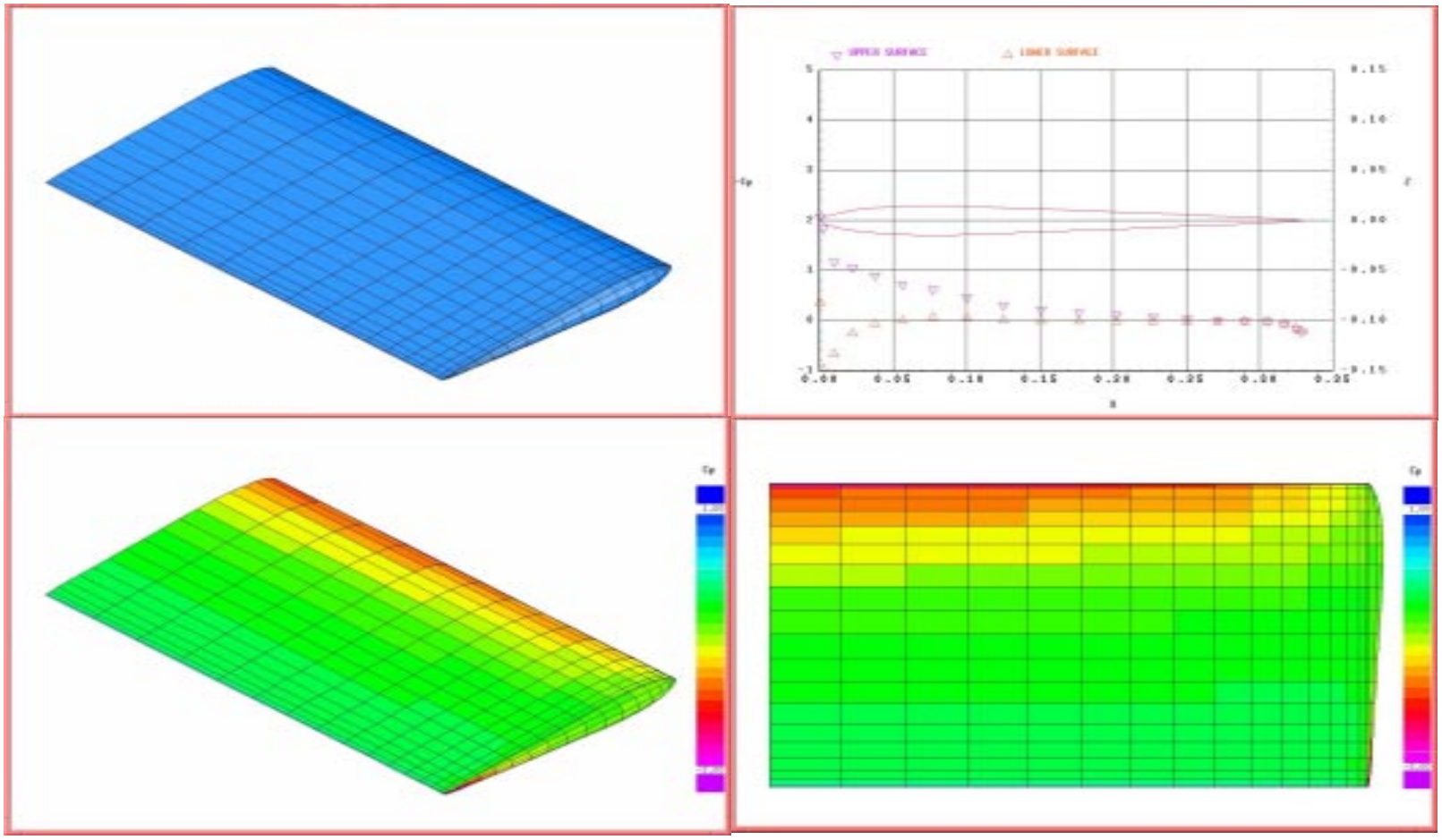
e.x: Wind tunnel (speed, dimensions, turbulence)

Demonstration Tests

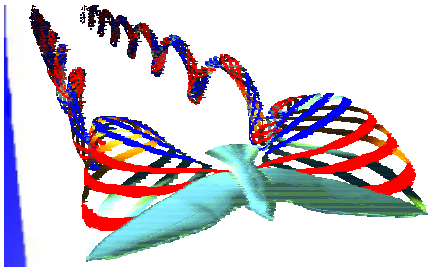




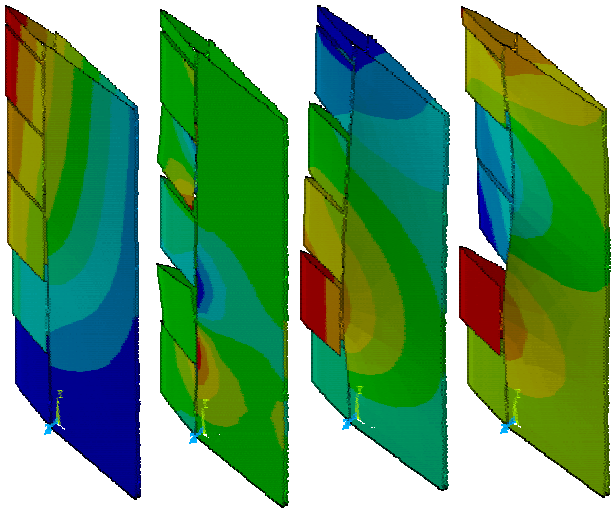
Aerodynamic Modelling

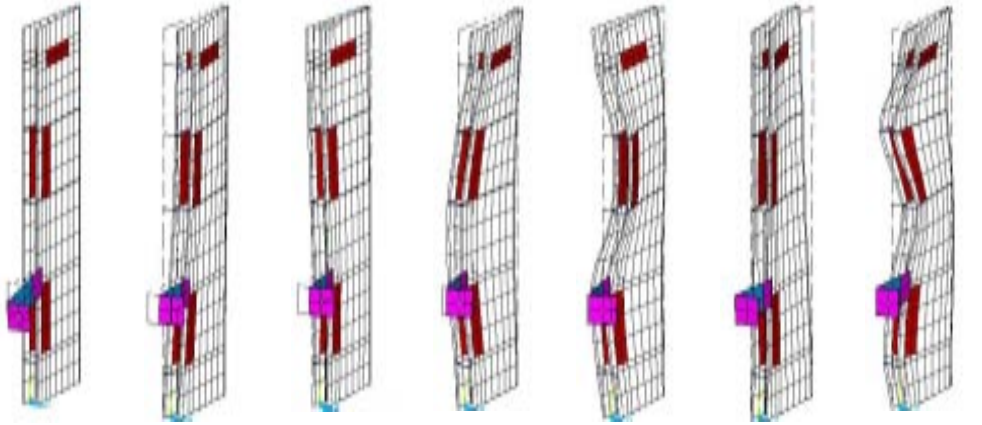


Wing analysis to compare the performance of the nominal NACA 0009 profile and modified ones.

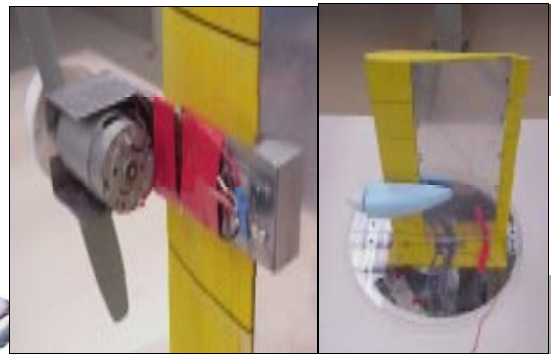


Finite Element Modelling



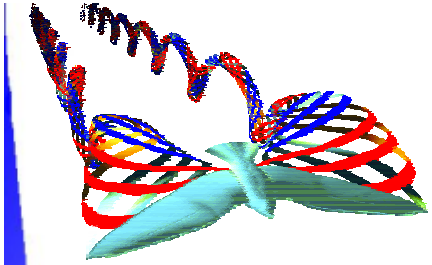


1.44 Hz 4.18 Hz 7.52 Hz 17.54 Hz 28.16 Hz 38.6 Hz 45.9 Hz

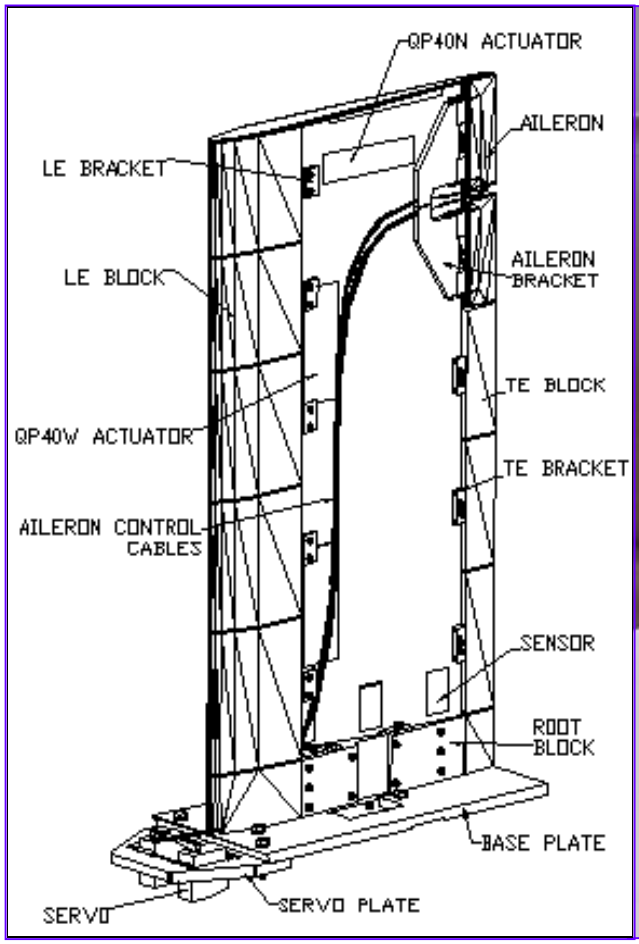


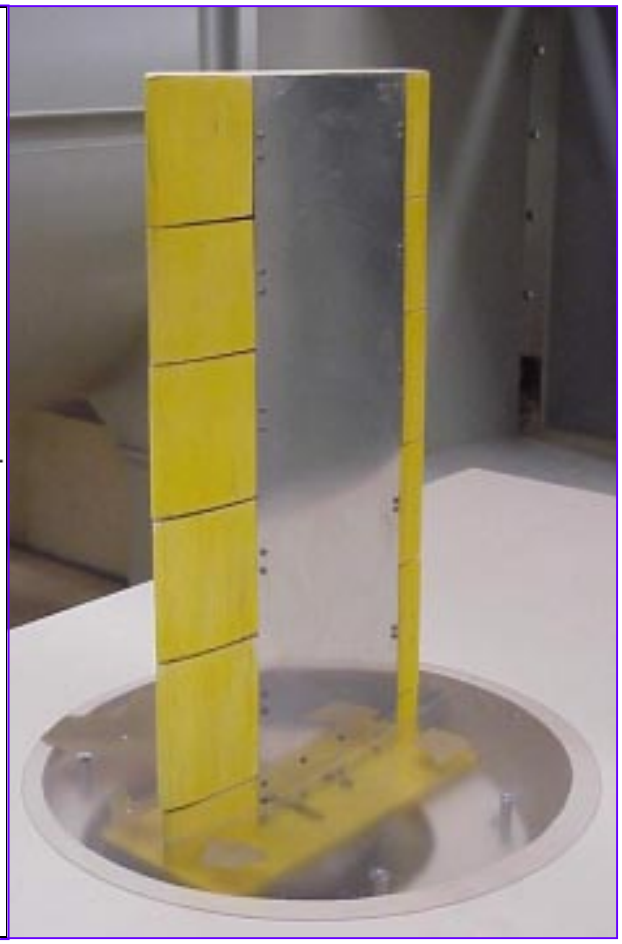
Mode Number	Natural Frequency (Hz)	
	Experimental	Analytical
1	6.00	4.64
2	16.36	15.95
3	28.50	28.10
4	39.00	38.56
5	46.25	45.90

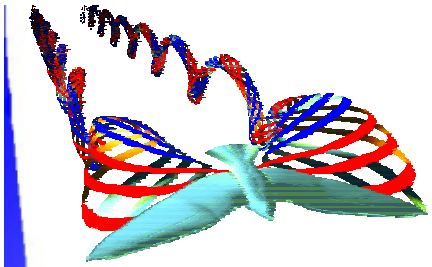
Experimental tests (FFT real time analysis) validated the finite element method



3D Wing Details

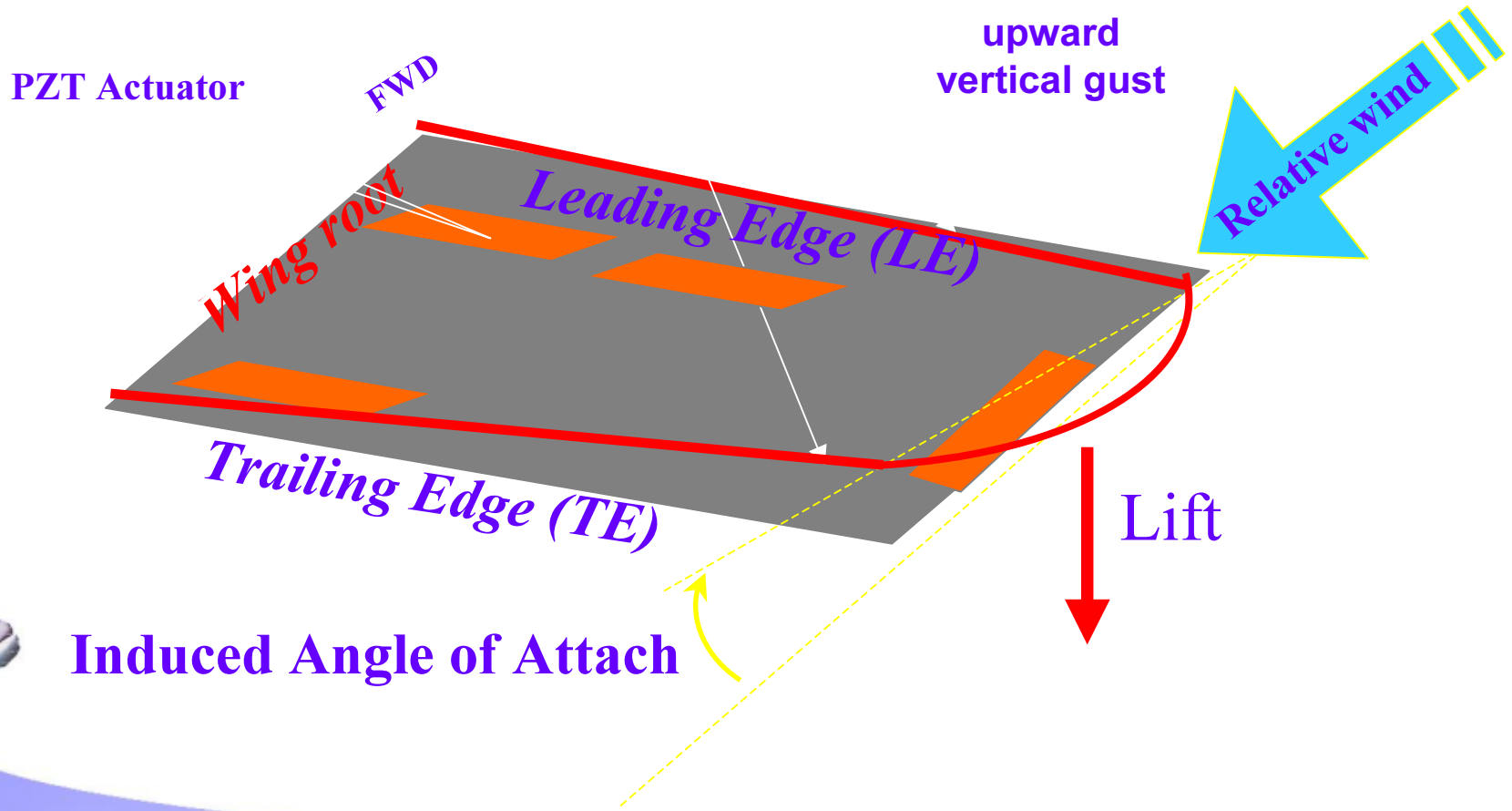


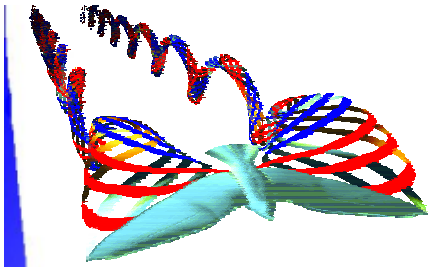




Gust Mechanism

control authority
LE > TE

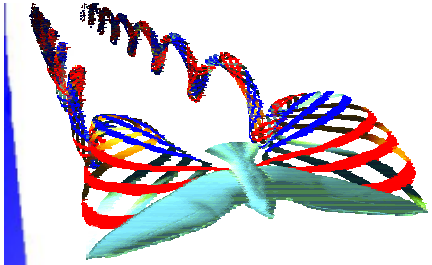




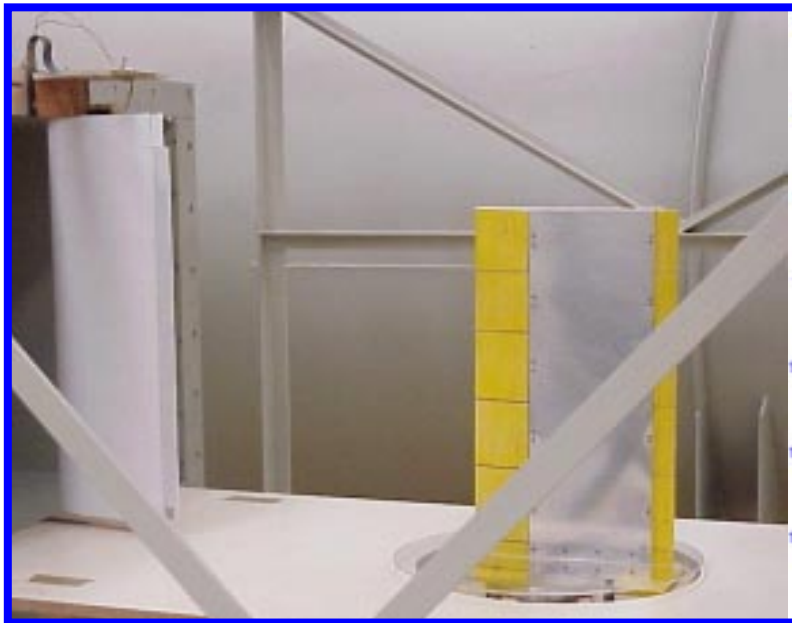
Gust Response

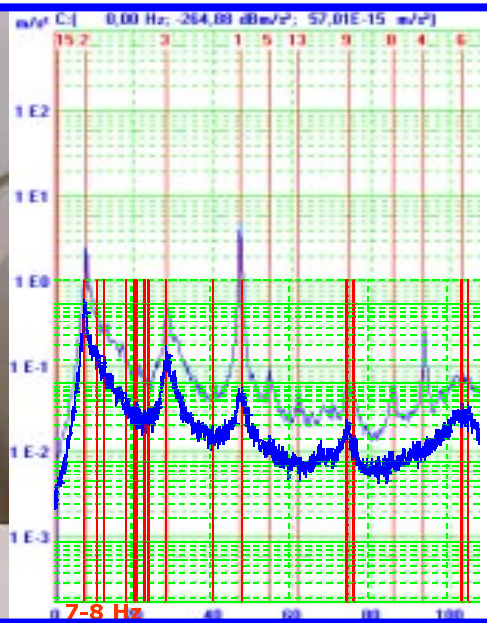
Test *(Re)*	Piezo Control		Aileron Control
	Steel Bracket *(% reduction)*	Aluminum Bracket *(% reduction)*	Aluminum Bracket *(% reduction)*
$Re = 2,6x10^5$ (V = 11,4 m/s)	48.3	37.5	12.5
$Re = 4,2x10^5$ (V = 18,3 m/s)	34.5	42.7	15.4
$Re = 5,7x10^5$ (V = 24,6 m/s)	38.5	51.8	8.5

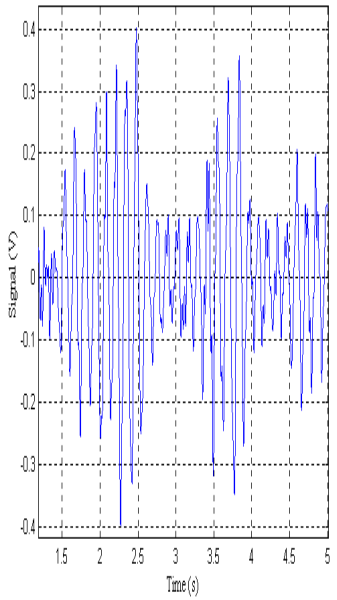
Without wing shape control the reduction in the wing dynamic response is 3%



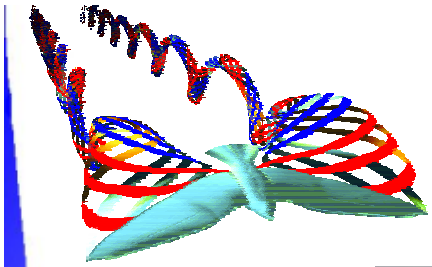
Buffeting Results



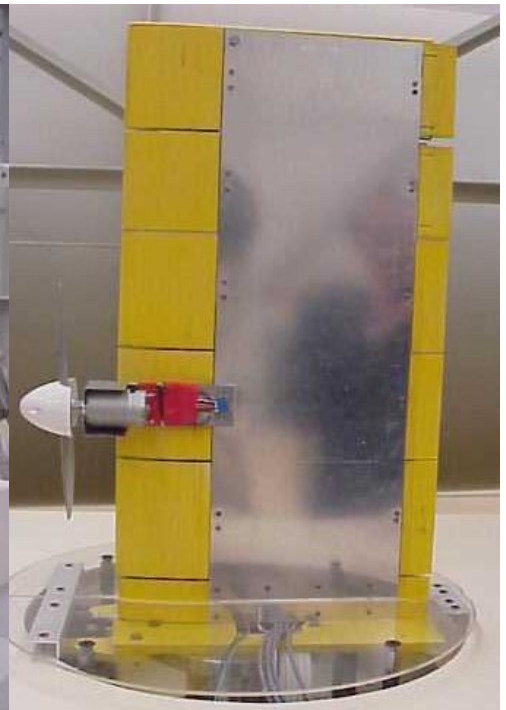




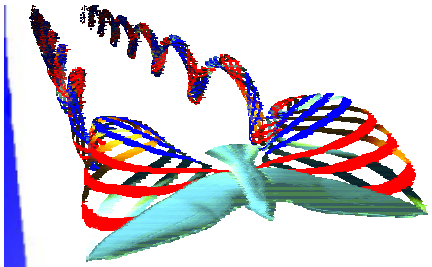
Test Vel. (m/s)	Piezo Control		Aileron Control
	Steel Bracket *(% reduction)*	Aluminum Bracket *(% reduction)*	Aluminum Bracket *(% reduction)*
12	30.5	40.8	N/A



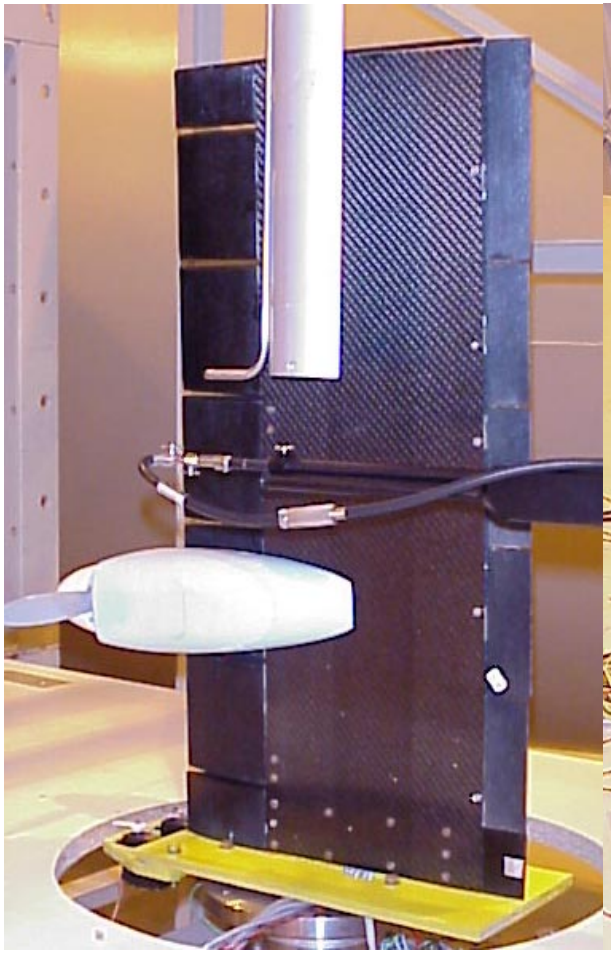
Wing with Engine Pods

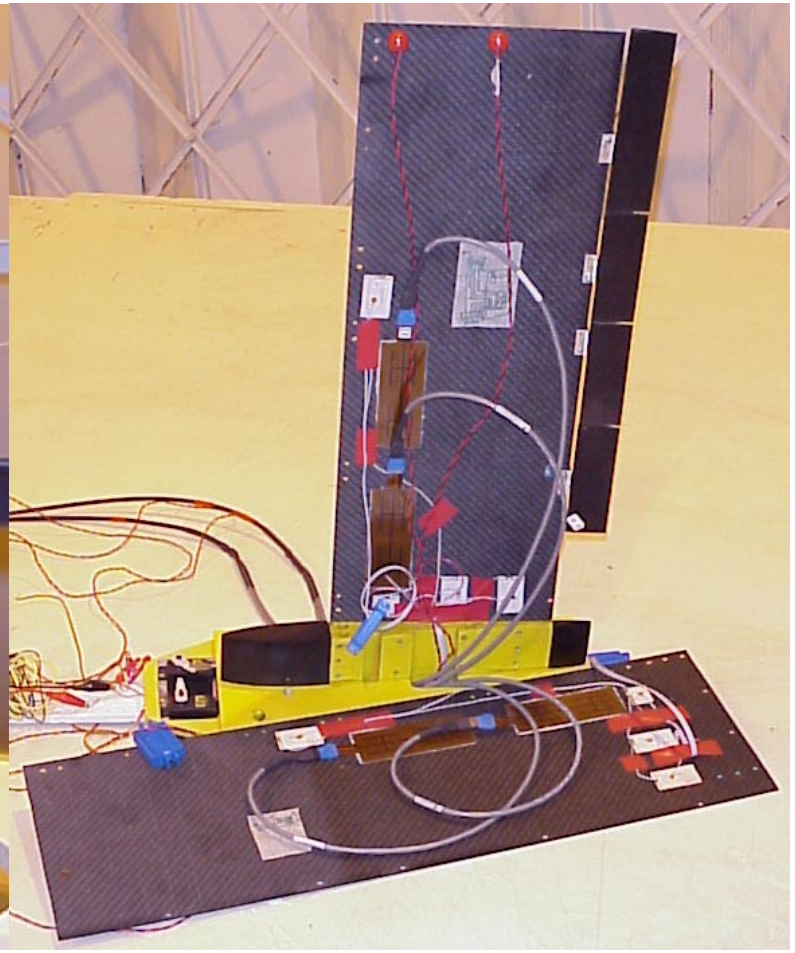


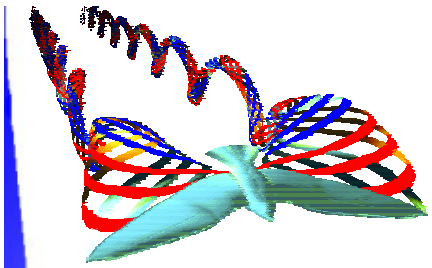
Air Velocity m/s	Rotor Speed Hz	Reduction %
0	10	77,9
0	30	49,4
25	130	48,2



3D Adaptive CFRP Wing



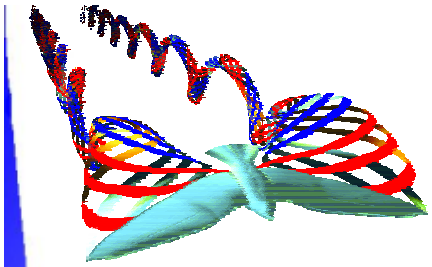




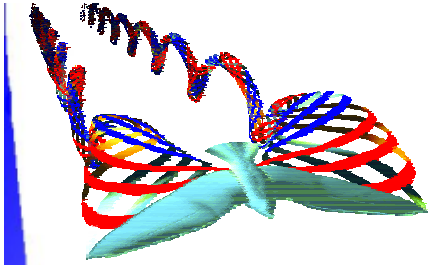
Gust Response Results

Free Stream Velocity (m/s)	% Reduction*	
	Piezo Control	Aileron Control
17	77.7	7.6
24	80.4	13.2
30	72.7	16.5

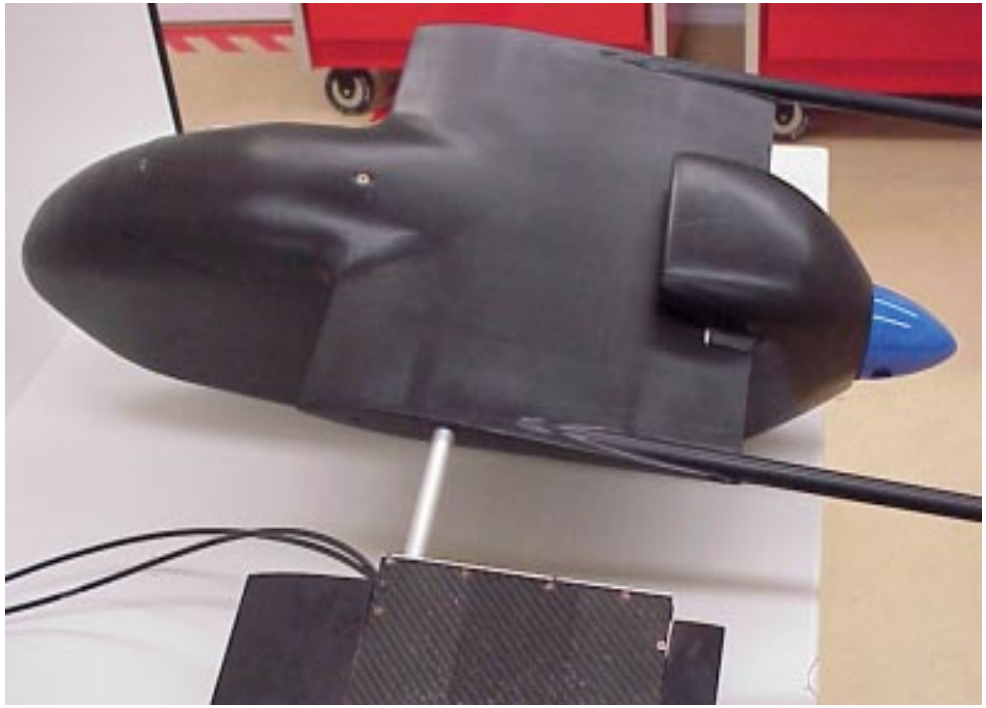
*Wing Vibration Amplitude Reduction from Uncontrolled Condition



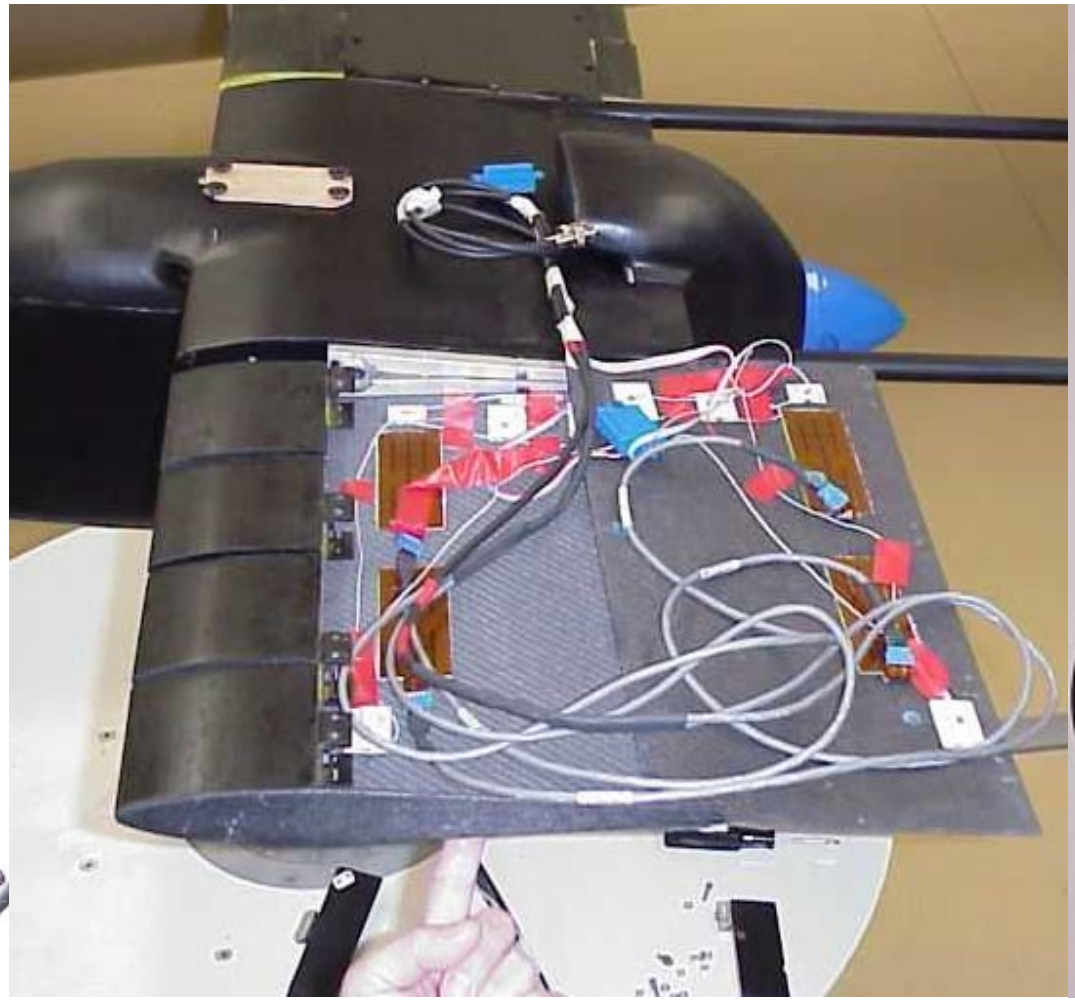
Remotely Piloted Vehicle

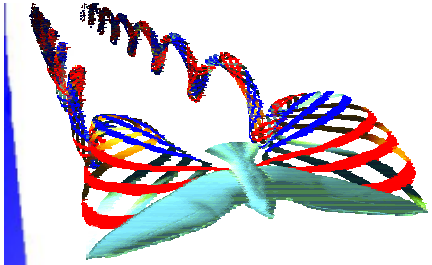


Modular Design

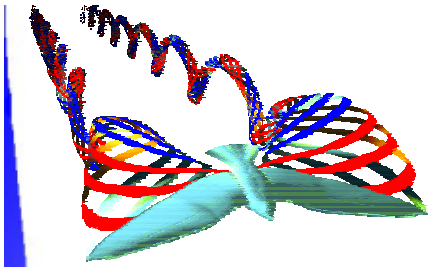


Instrumented Adaptive Wing

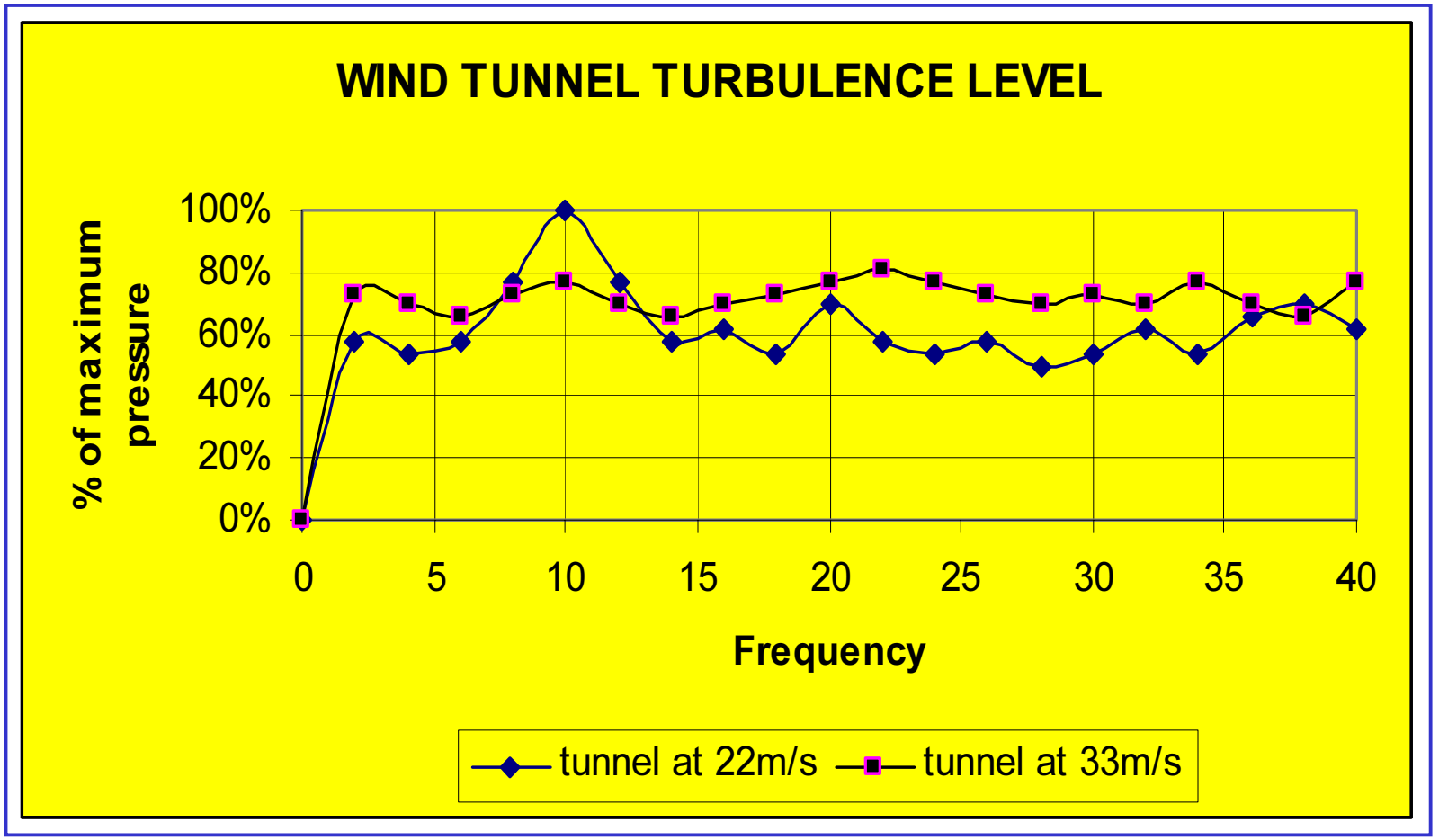


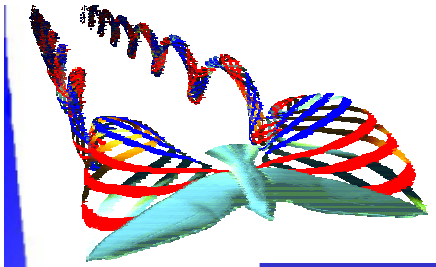


PZT Actuator and Shunt



WT Tuning

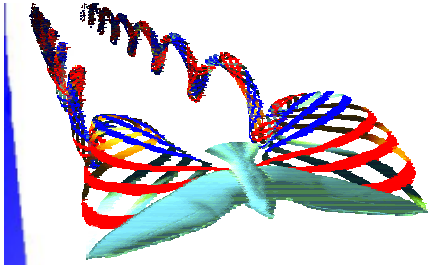

WIND TUNNEL TURBULENCE LEVEL
% of maximum pressure
100%
80%
60%
40%
20%
0%
0
5
10
15
20
25
30
35
40
Frequency
tunnel at 22m/s
tunnel at 33m/s



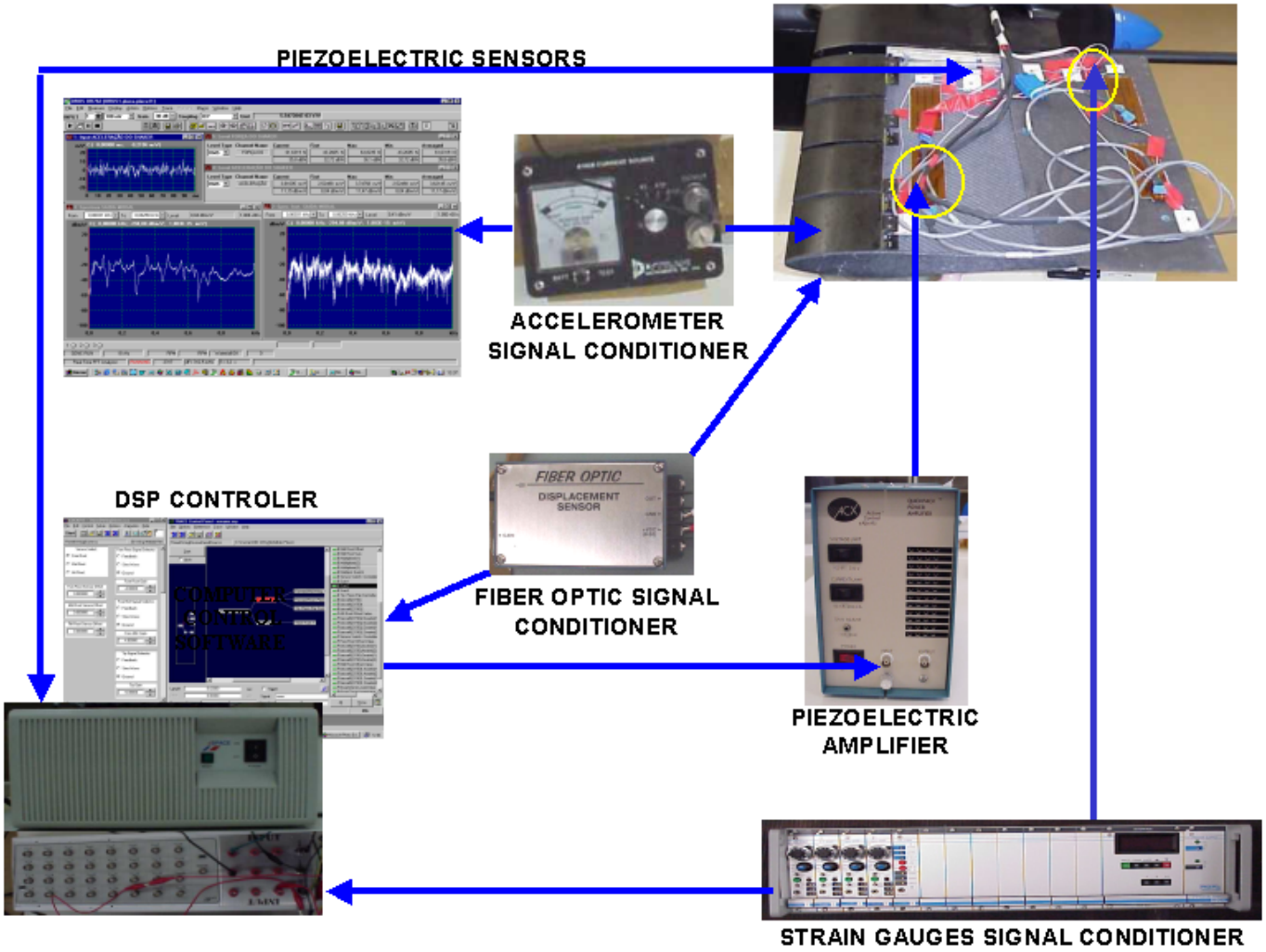
Gust Response

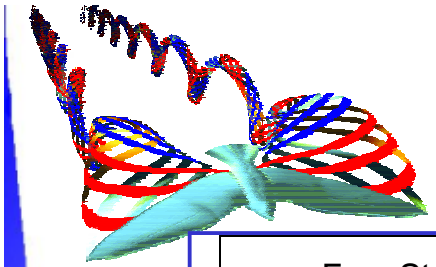
22 m/s

33 m/s



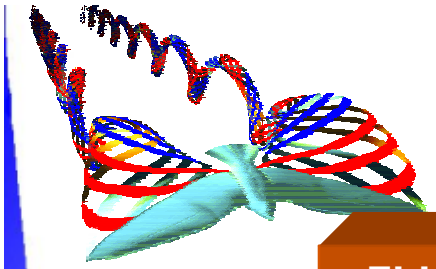
RPV WT Aeroelastic Control





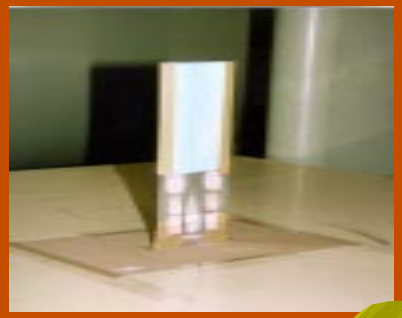
RPV WT Test Results

Free Stream Velocity (m/s)	PZT Control (Reduction in %)	Flap Control (Reduction in %)
11 (Aluminum stand alone wing)	38	13
17 (CFRP stand alone wing)	78	8
18 (Aluminum stand alone wing)	43	15
22 (Complete RPV)	13	-
22 (RPV with fixed tail)	25	-
22 (Complete RPV with shunts)	12 (shunting)	-
24 (CFRP stand alone wing)	80	13
25 (Aluminum stand alone wing)	52	9
30 (CFRP stand alone wing)	73	17
33 (Complete RPV)	4	-
33 (RPV with fixed tail)	7	-
33 (Complete RPV with shunts)	3 (shunting)	-



WT Tests Overview

FLUTTER SPEED:
6% INCREMENT



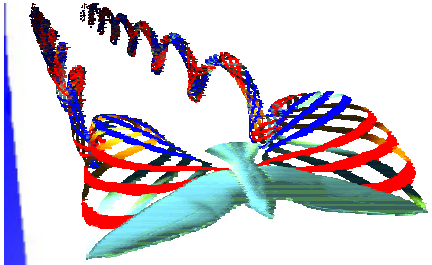
GUST RESPONSE:
52% REDUCTION

PLATFORM
STABILITY: 30%
INCREASE

BUFFETING RESPONSE:
41% REDUCTION

ENGINE INDUCED
VIBRATION:
48% REDUCTION

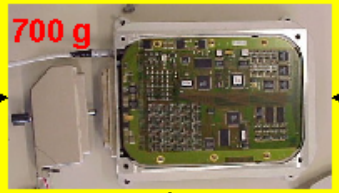
Miniaturization Issues



Flight Testing

PCMIA

DSP CONTROLER



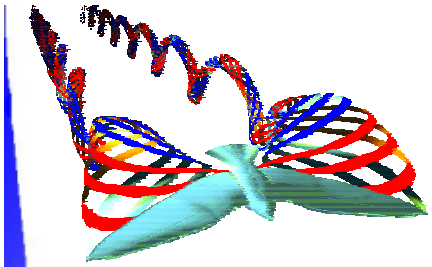
BATERY AND CONVERSOR

PIEZOELECTRIC AMPLIFIER

FM TRANSMITER / RECEIVER

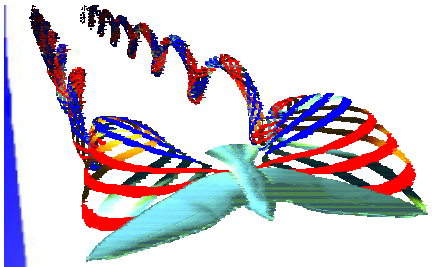
FLIGHT CONTROL ELECTRO-SERVOS

ON BOARD EQUIPMENT

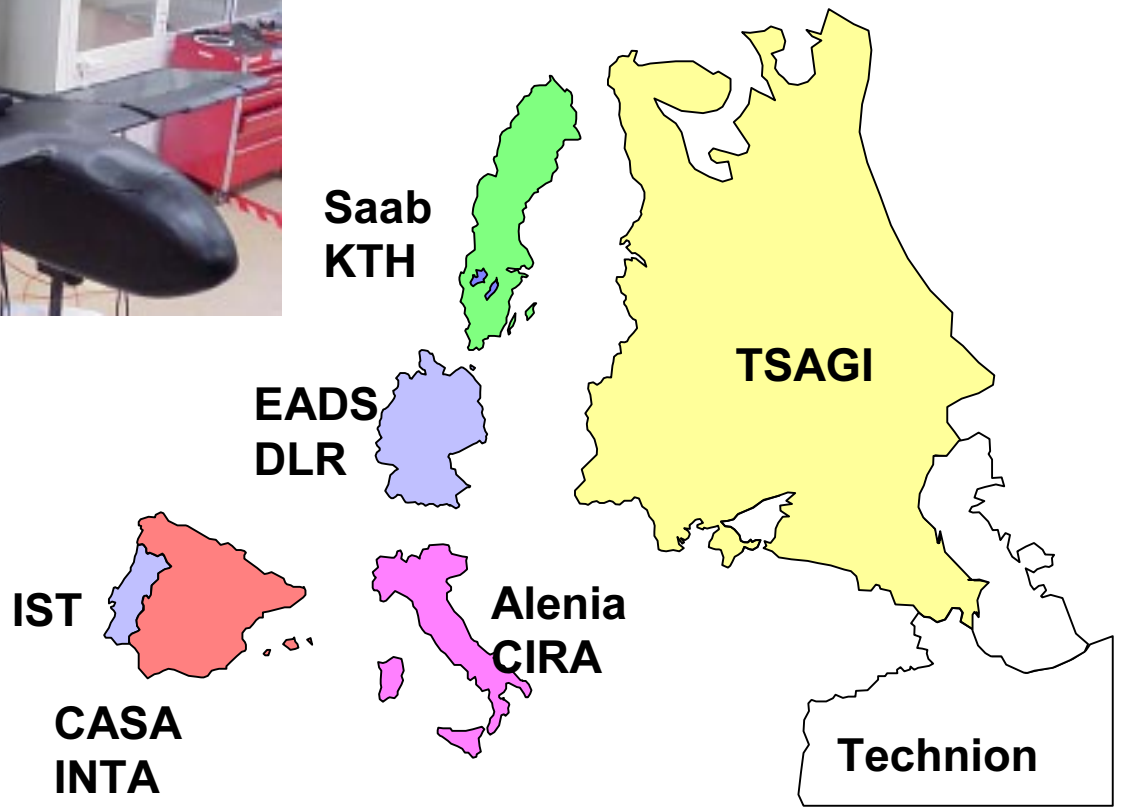


Concluding Remarks

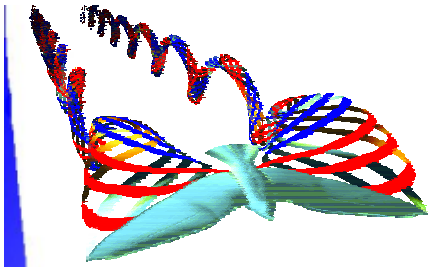
- A 3D wing structure can be effectively controlled using piezos placed on only one side of the wing skin.
- The use of bending moment control with a judicious placement of PZTs actuators and sensors was effective in controlling flutter, buffeting, gust response and engine induced mechanical vibration.
- By comparison aileron control is not a good solution for the dynamic aeroelastic control of the 3D wing.
- The 3-D wing and RPV projects were successful, and provided valuable insight for future adaptive aircraft design.



Future Work



3AS



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  - Pedro Gamboa (PhD, UBI)
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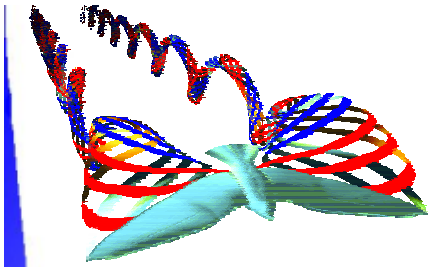
  - Marc Secanell (MSc, UVIC)



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  - Professor Ned Djilali (Faculty, UVIC)
- **Advanced Composites and Mechatronics**
  - Dr. Bernard Boueri (PDF)
  - Abdel-Rahman Mahmoud (PhD, UVIC)
  - Ernest Ng (Msc, UVIC)
  - Stan Burns (Msc, UVIC)