RESEARCH STUDIES

on

MORPHING UNMANNED AERIAL VEHICLES

and

SMART STRUCTURES APPLICATIONS

in the

Department of Aerospace Engineering

MIDDLE EAST TECHNICAL UNIVERSITY

ANKARA - TURKEY

Aim of the Presentation

As of 22 June 2011

this presentation summarises:

the studies conducted on *Morphing Unmanned Aerial Vehicles* and *Smart Structures Applications* by using the infrastructure of "Structures Laboratory" in Aerospace Engineering Department of Middle East Technical University.

Structures Laboratory

Structures Laboratory Infrastructure

The available software and hardware in "Structures Laboratory" for the research studies are:

- **SOFTWARE**
  - AutoCAD 2000
  - MATLAB 2009a
  - CATIA V5r18
  - ANSYS 11.0
  - MSC PATRAN/ NASTRAN/ Flight Loads 2007r1
  - NI LabVIEW 8.6

Structures Laboratory Infrastructure

- **HARDWARE**
  - B&K 6 channel Pulse portable data acquisition unit with special software of FFT Analysis, Time Data Record, Modal Test Consultant, Operational Modal Analysis
  - B&K Modal Vibration Exciter
  - B&K Impact Hammer
  - Various B&K Single-axis and Triaxial accelorometers
  - Keyence Laser Displacement Sensor
  - Agilent Signal Generator
  - Hameg Oscilloscope
  - Various Uni-axial Strain Gauges and Installation Kits.

Structures Laboratory Infrastructure

- **HARDWARE –** *con't*
  - Dedicated equipment for smart structure applications comprising programmable controller (SS10), high voltage power amplifiers, high voltage power supplies, preamplifiers and piezoelectric (PZT) patches in various size and shape.

Research Studies

Studies mainly focused on the subjects of:

- **Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical Unmanned Aerial Vehicle Mission-Adaptive Wings (TÜBİTAK Project)**
- **Morphing Twist for Active Wing (TWIST-FP7 Project)**
- **Design, Development, Production and Testing of Morphing UAVs and Materials**
- **Structural Health Monitoring Applications (EESHM-FP7 Project)**
- **Active Vibration Control (NATO/RTO/AVT Projects)**

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

TÜBİTAK (The Scientific and Technological Research Council of Turkey)
Project 107M103

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Department of Aerospace Engineering

Middle East Technical University

Starting Date: 01.10.2007, End Date: 31.03.2011

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

.The air vehicle was indigeneously designed in

METU, Aerospace Engineering Department

.The structural modelling and analysis were conducted by MSC®PATRAN/ NASTRAN Package programs.

.The aerodynamic analysis was conducted by ANSYS®/FLUENT Package program.

.The aeroelastic analysis was conducted by MSC®PATRAN/ FLDS Package programs.

.The Ground Vibration Tests of the wing was conducted in METU Aerospace Engineering for the verification of the design.

.The production of the Unmanned Aerial Vehicle was done by Turkish Aerospace Industries, TAI.

.The flight tests of the Unmanned Aerial Vehicle were conducted by TAI.

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

- Low speed, non-aerobatic airplane with a conventional configuration:
  - Rectangular, mid aspect ratio high wing,
  - Circular fuselage,
  - Conventional tail attached to the fuselage with a boom,
  - Conventional elevator and rudder, deflectable ailerons and flaps
  - Tricycle landing gear,
  - Metal structure, composite skin.
  - 6.5 hp gasoline engine.

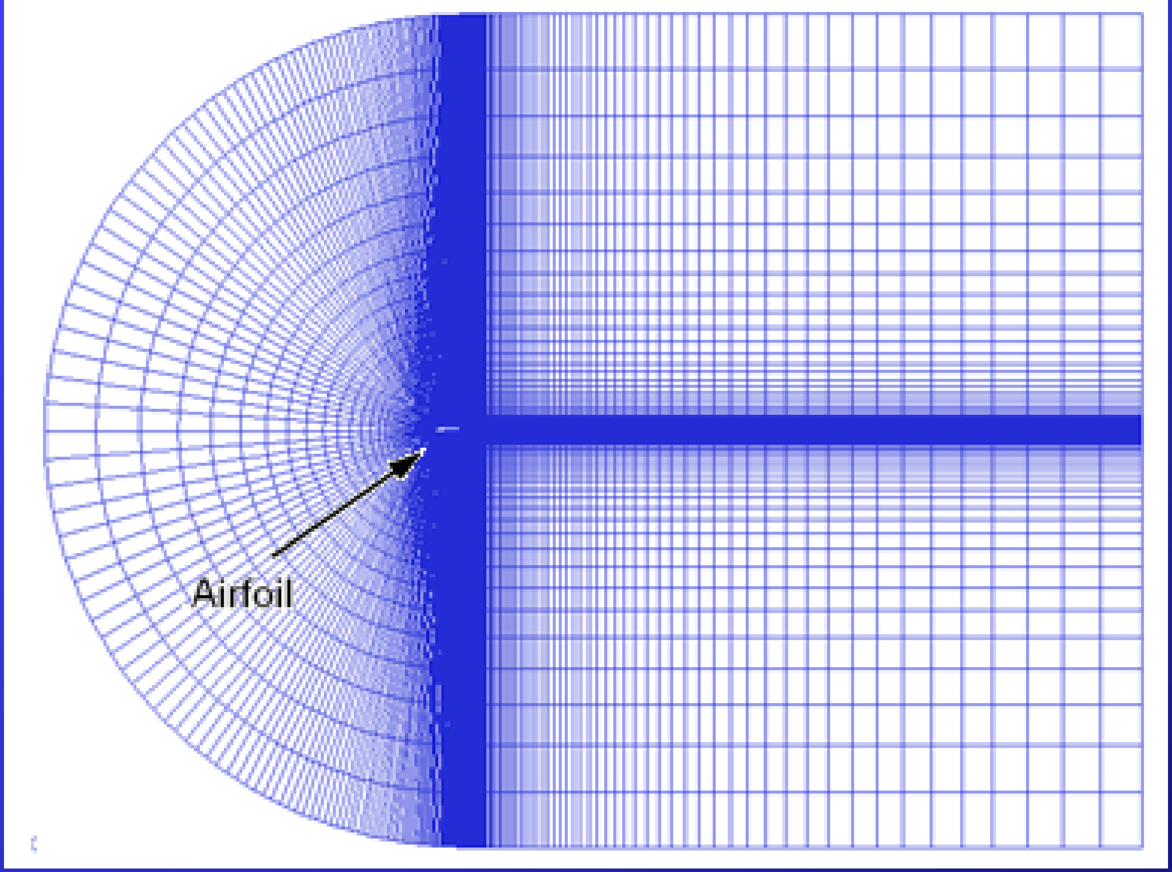
Initial Design Specifications

Specifications	Value
Take-off gross weight	37.8 kg
Empty weight	36.3 kg
Fuel weight	1.5 kg
Wing span	3 m
Wing chord	0.5 m
Total length (excluding propeller hub)	2 m
Height	1.0 m
Horizontal tail volume ratio	0.37

Performance Specifications

Specifications	Value
Maximum speed	**75 knots**
Cruise speed (@ 4000 ft)	**60 knots**
Stall speed	**40 knots**
Service ceiling	**5000 ft**
Endurance (@ 4000 ft)	**3 h**

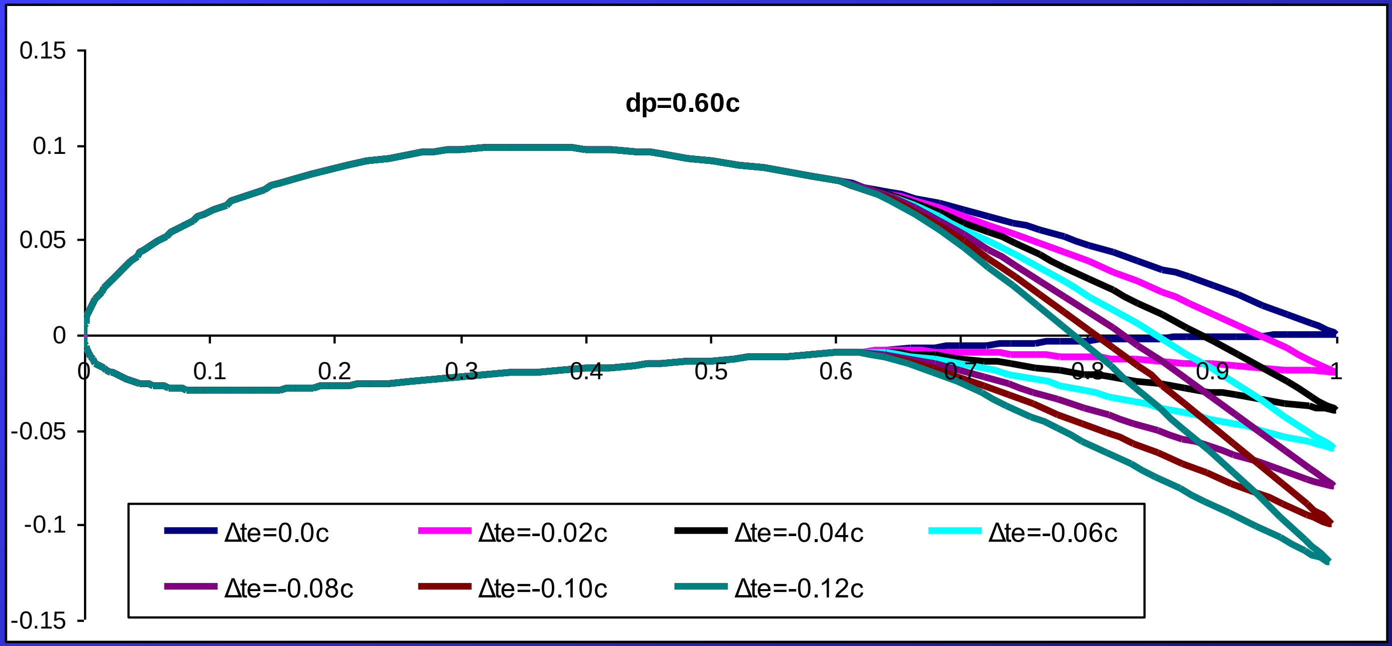
Aerodynamic Analysis



2D Analysis, NACA 4412 Airfoil and the Solution Domain

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Aerodynamic Analysis



2D Analysis, Cambered NACA4412 Airfoils, deflection from 0.6c

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

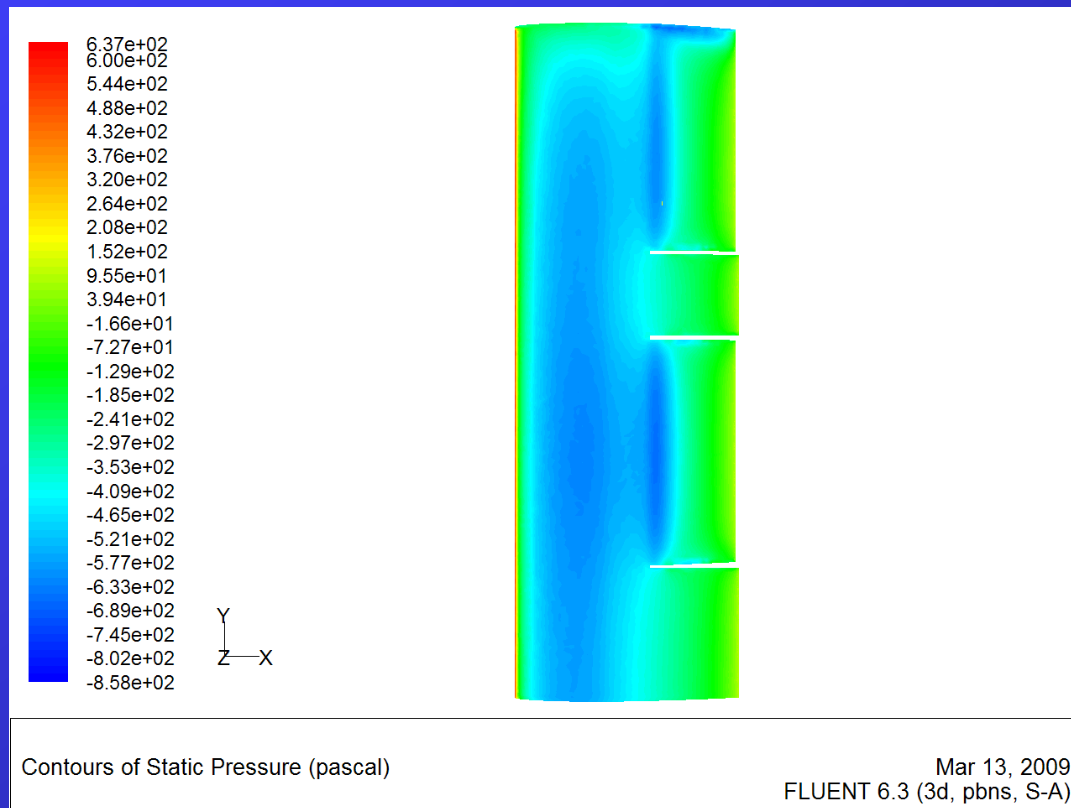
Aerodynamic Analysis

Δte	0.0c	-0.02c	-0.04c	-0.06c	-0.08c	-0.10c	-0.12c
C_l	0.4502	0.6904	0.9193	1.1344	1.3050	1.5574	1.6922
C_l [Raymer]	0.4000	0.6652	0.920	1.1696	1.4244	1.6688	1.9184
C_d	0.0111	0.0124	0.0142	0.0169	0.0210	0.0578	0.0714
C_m	0.2133	0.3039	0.3941	0.4813	0.5520	0.6798	0.7426
C_l / C_d	40.7201	55.6774	64.7394	67.1243	62.1429	26.9446	23.7009

2D Analysis, Calculated Aerodynamic Coefficients for Camber deflection from 0.6c

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

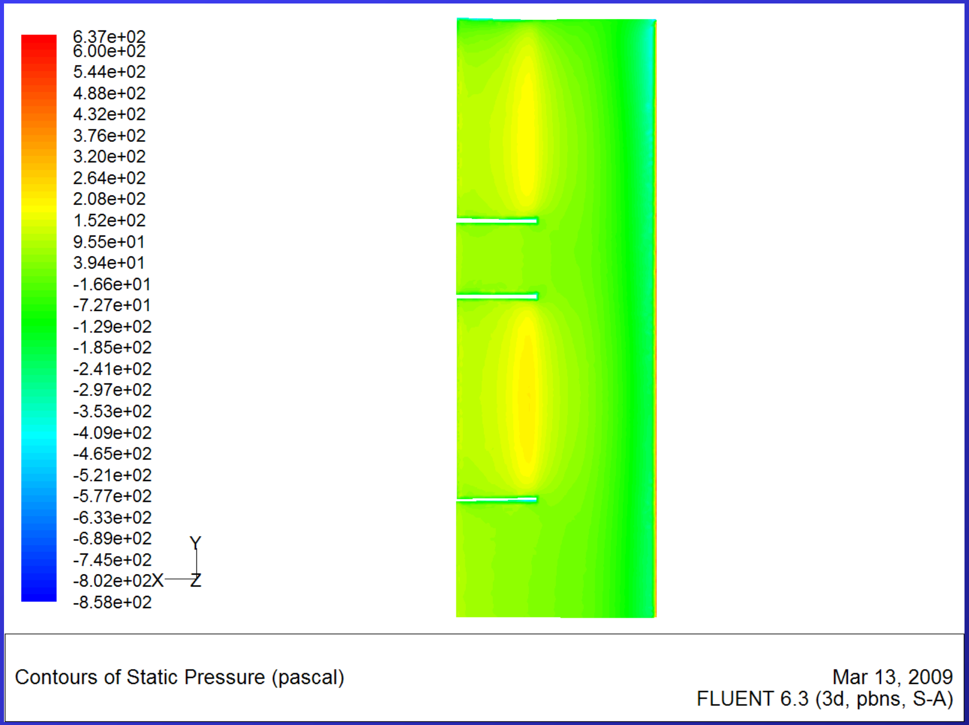
Aerodynamic Analysis



3D Analysis, Upper Surface Static Pressure Contours, deflection from 0.6c

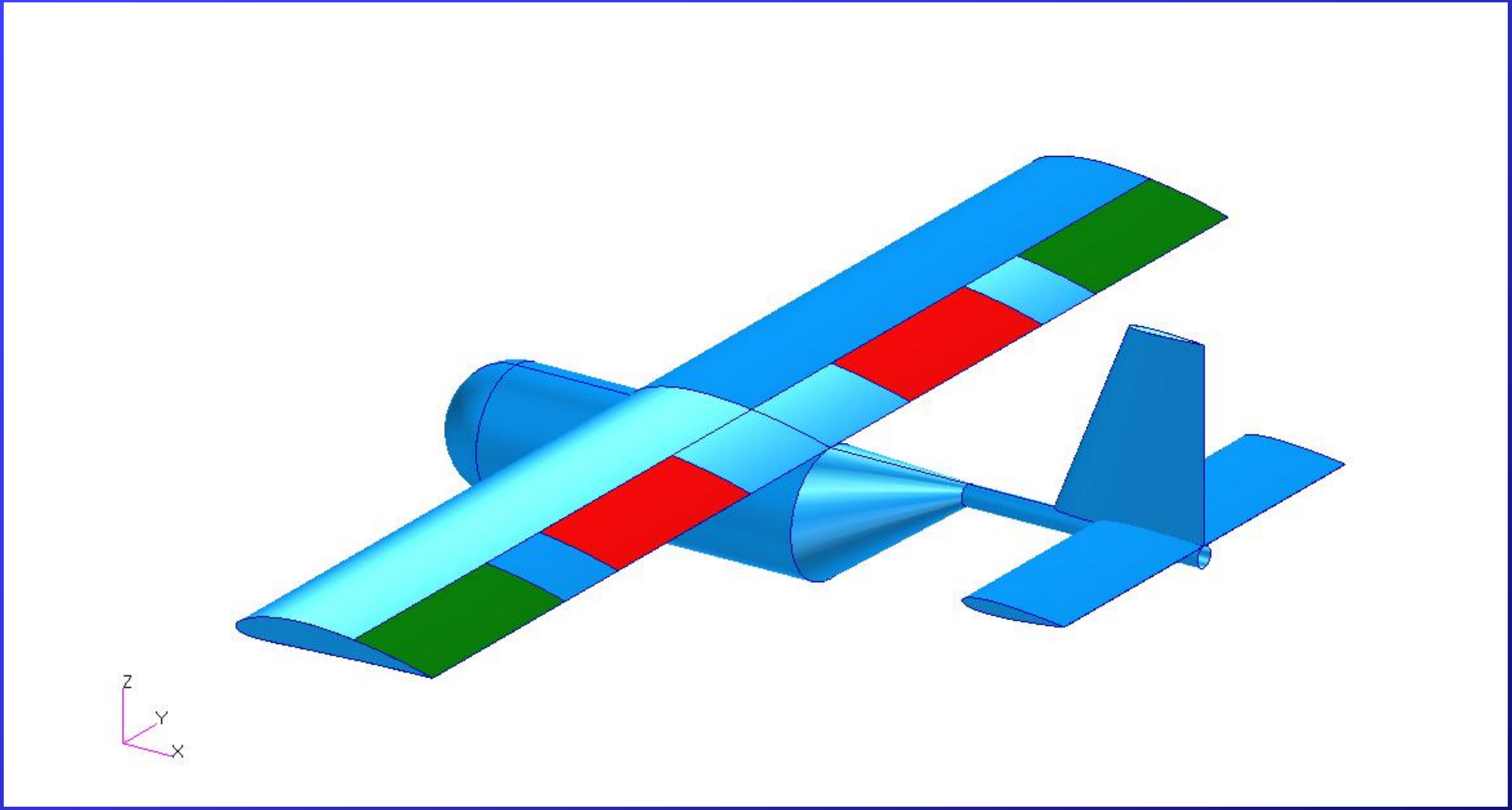
Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Aerodynamic Analysis



3D Analysis, Lower Surface Static Pressure Contours, deflection from 0.6c

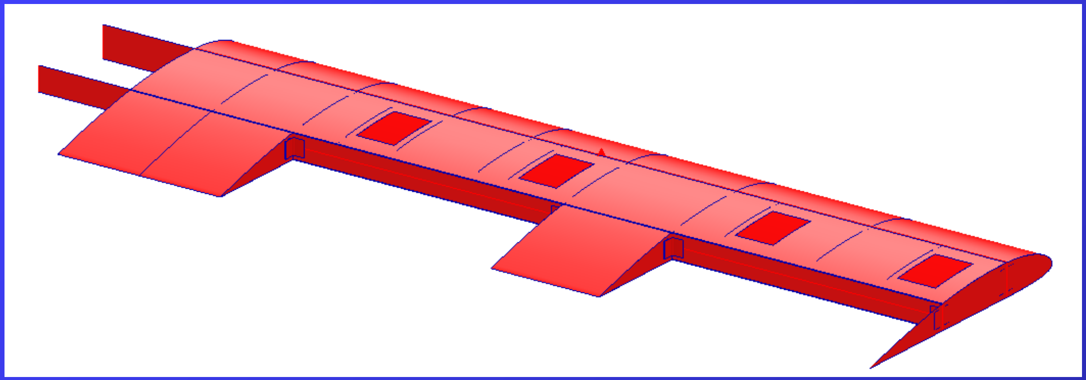
Aerservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings



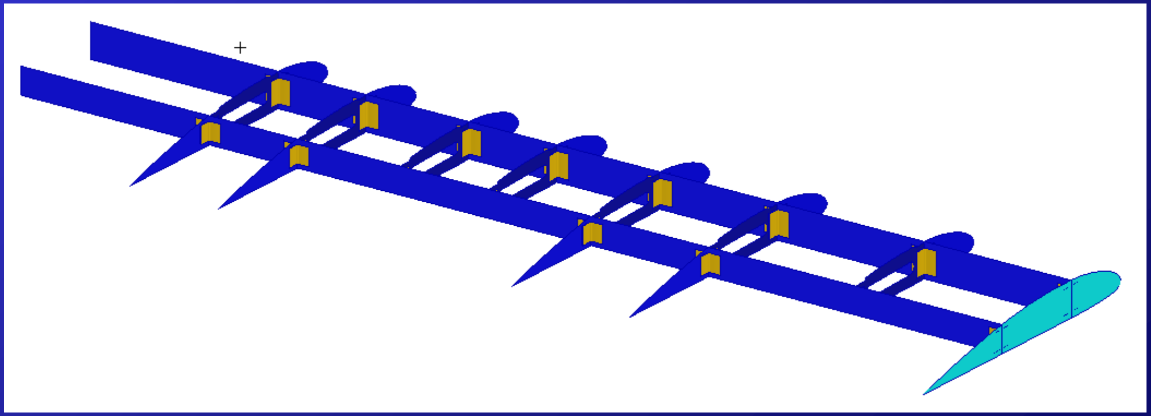
Tactical Unmanned Aerial Vehicle (TUAV)

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Structural Models



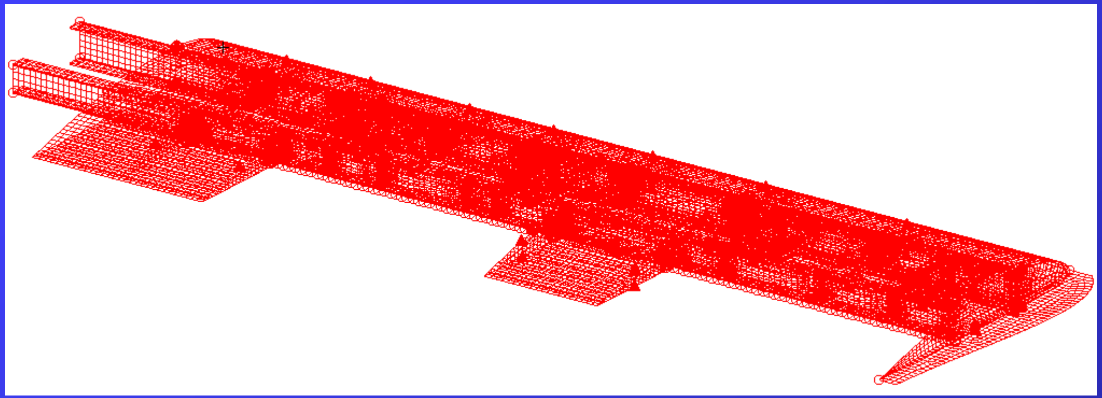
Isometric view of the
external geometry of the right wing



Isometric view of the
internal structure of
the right wing

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Structural Models

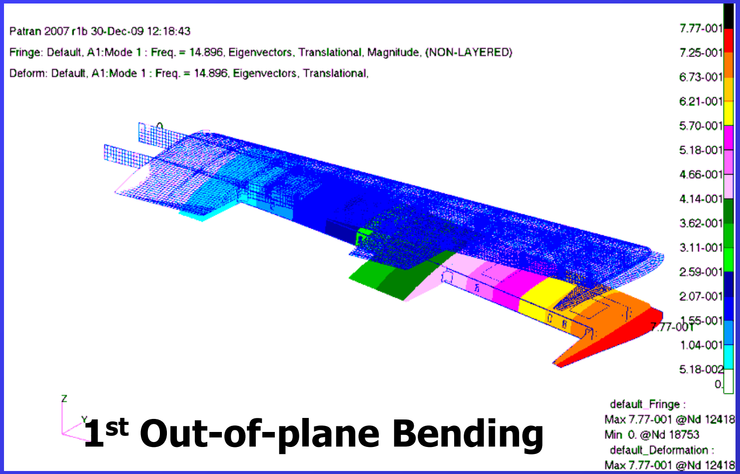


Generated mesh for the finite element analysis

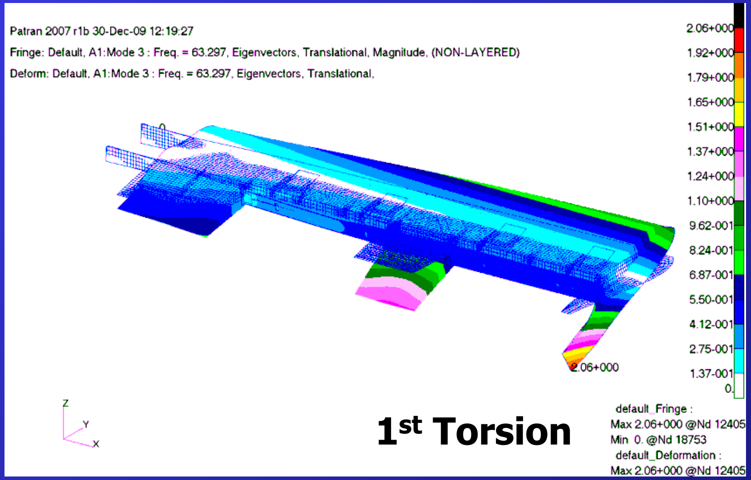
Ground vibration tests of the wing

Aerosérvoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

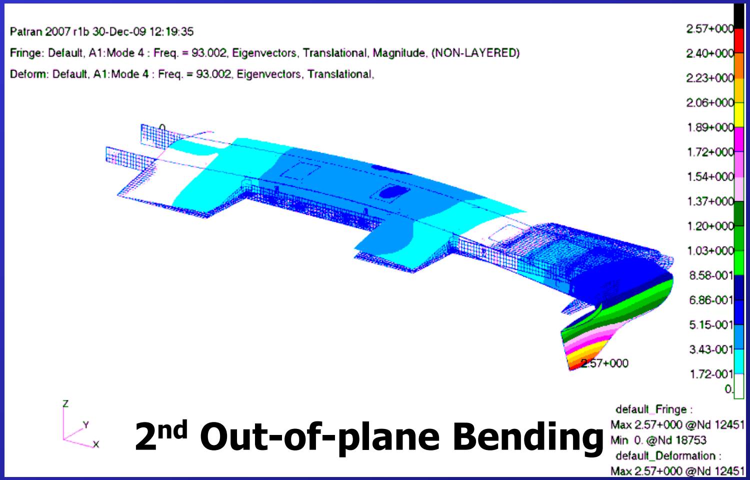
Finite Element Analysis: Mode Shapes



1st Out-of-plane Bending



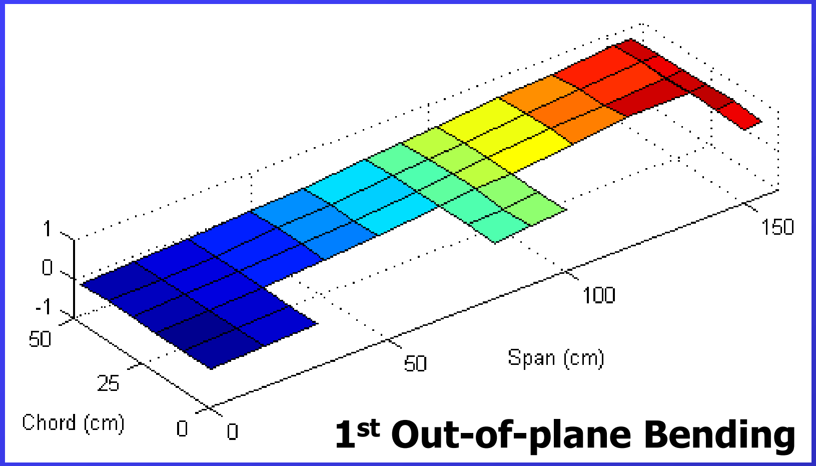
1st Torsion

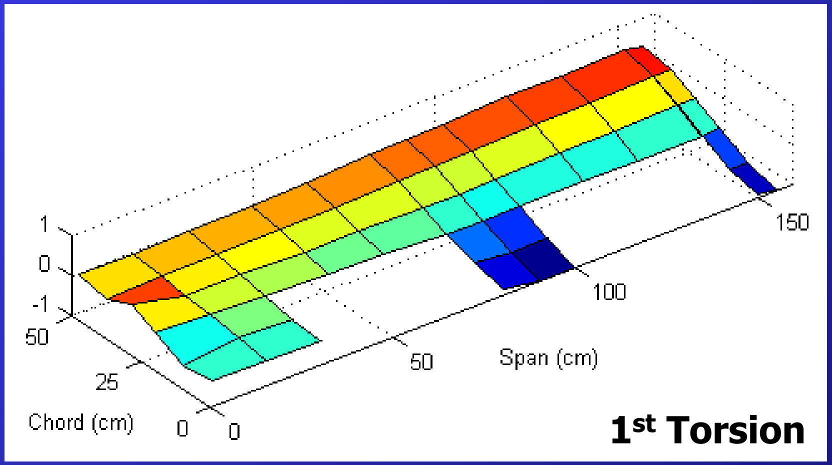


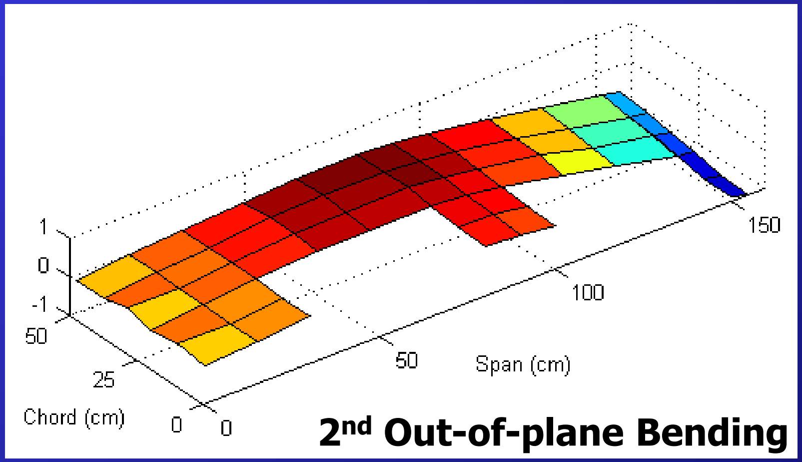
2nd Out-of-plane Bending

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Experimental Modal Testing: Mode Shapes







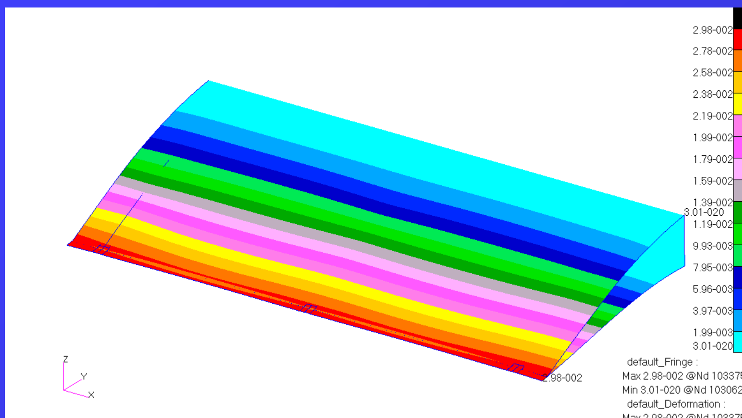
Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Comparison of Resonance Frequencies

Mode Shape	FEA Frequency [Hz]	Experimental Frequency [Hz]	Percentage Difference wrt Experimental Value
1. Out-of-plane bending	14.90	14.75	~ 1.02
1. Torsion	63.30	66.75	~ - 5.17
2. Out-of-plane bending	93.00	93.00	~ 0.00

Aerosevoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Unconventional Control Surface: Camber Change Case

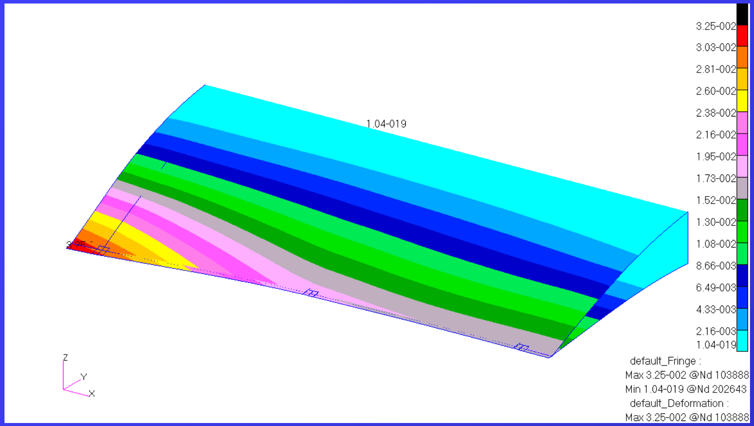


Finite element analysis

Testing

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

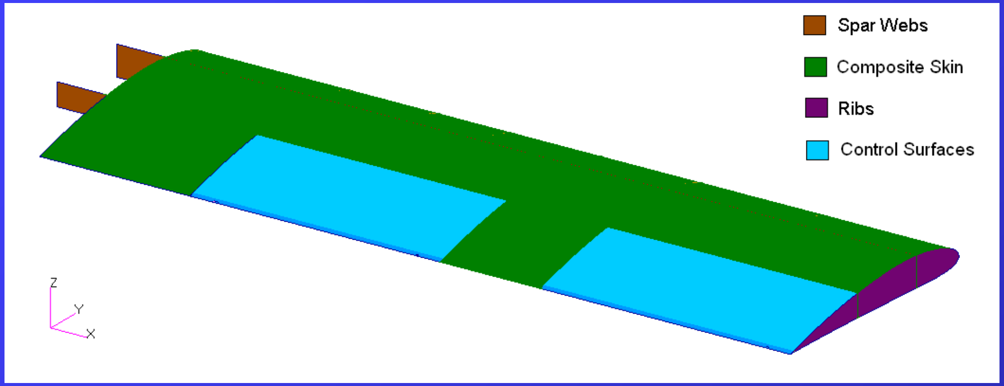
Unconventional Control Surface: Twist Change Case

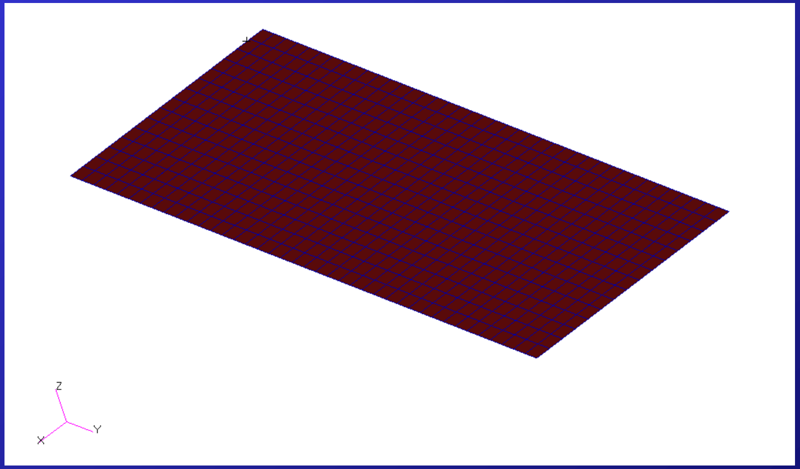


Finite element analysis

Testing

Aeroelastic Analysis



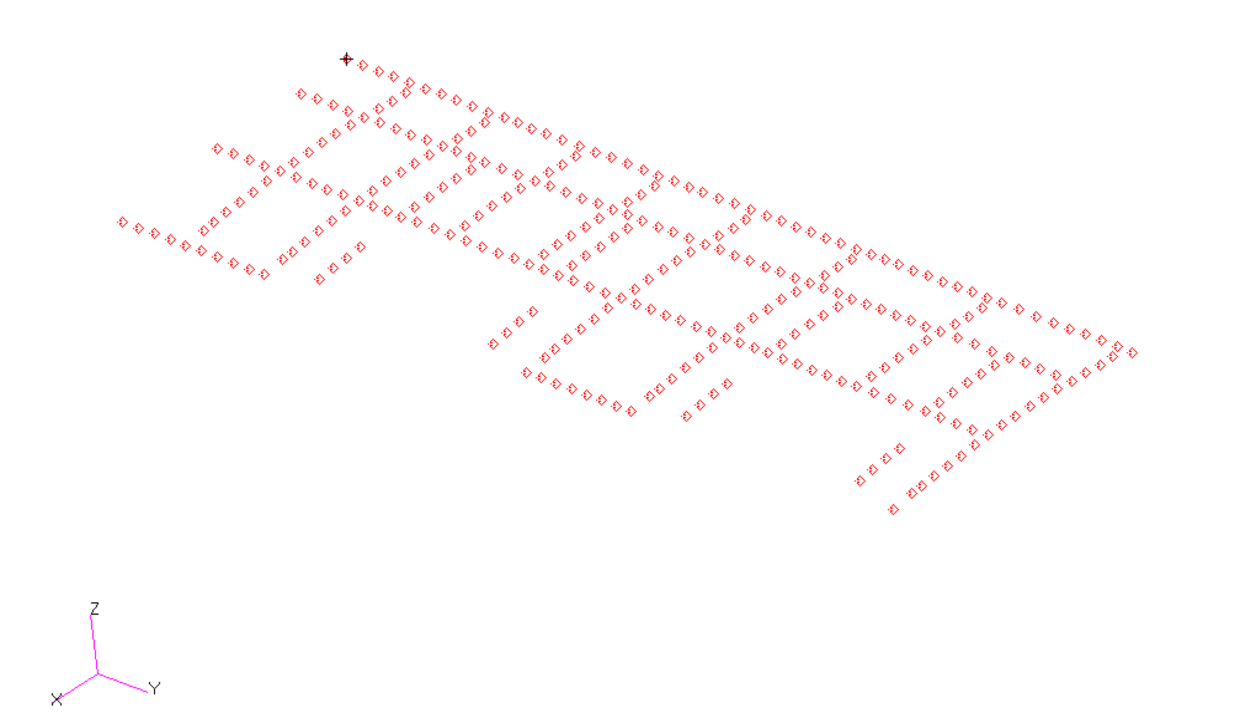


Aeroelastic Model and the Lifting Surface

Used in the Aeroelastic Analyses

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

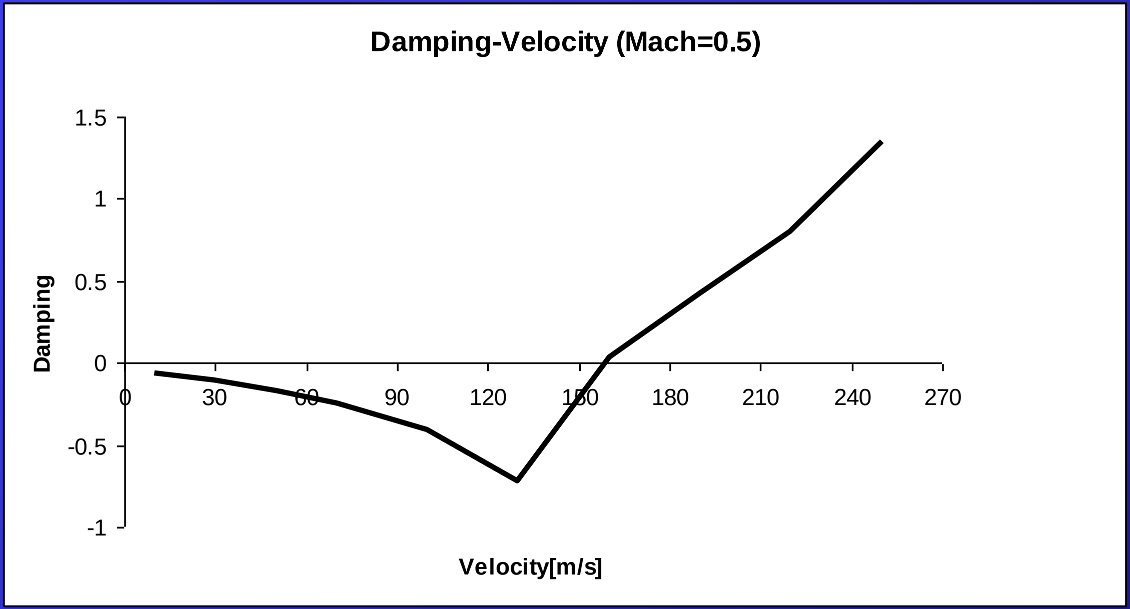
Aeroelastic Analysis



Grid Points Used to Generate Splines for Aeroelastic Analysis

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Aeroelastic Analysis



Possibility of flutter around 160 m/s,

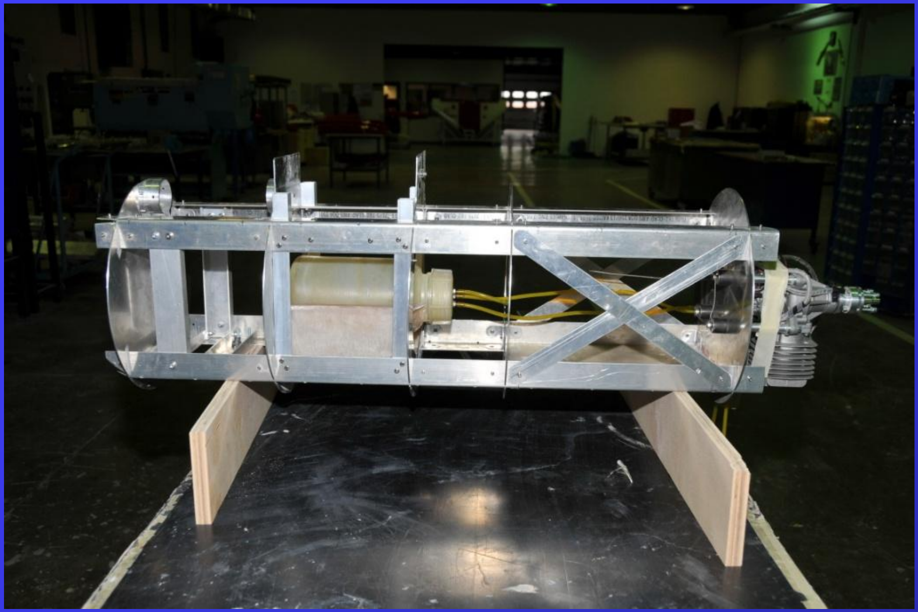
outside the operational range,

SAFE !!

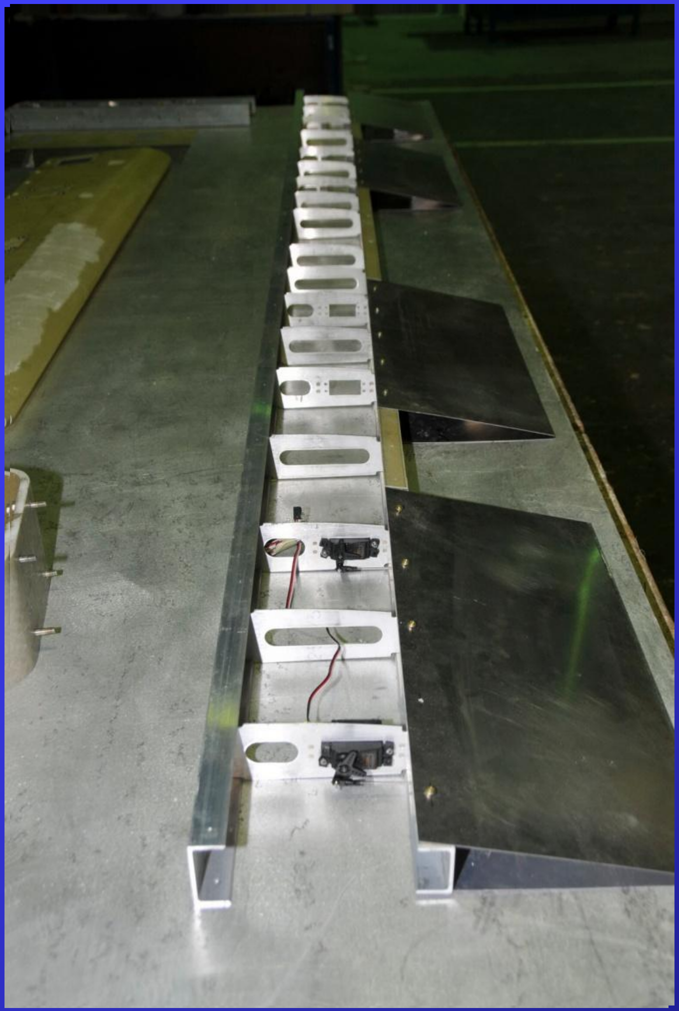
Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Production Stages

Production Stages



Production Stages



Production Stages

Production Stages

08 March 2010

Flight Tests

17 March 2010

Aircraft

Taxi Test

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Flight Tests

17 March 2010

Thanks for their efforts

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Flight Tests

05 May 2010

Taxi and Jump Tests

Aerosservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Flight Tests

05 May 2010

Taxi and Jump Tests

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Flight Tests

05 May 2010

Thanks for their efforts

Flight Tests

26 May 2010

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Flight Tests

26 May 2010

Thanks for their efforts

Flight Tests

03 February 2011

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Flight Tests

03 February 2011

Unmanned Aerial Vehicle with Overwing Camera

Flight Tests

03 February 2011

Flight from Overwing Camera

Flight Tests

03 February 2011

Flight from Overwing Camera

Flight Tests

03 February 2011

Flight from Overwing Camera

Aeroservoelastic Analysis of the Effects of Camber and Twist on Tactical UAV Mission-adaptive Wings

Flight Tests

03 February 2011

Thanks for their efforts

Published Work

- MSc. Theses:

✓ "Aero-Structural Design And Analysis of an Unmanned Aerial Vehicle and its Mission Adaptive Wing" by E. Tolga İnsuyu – METU – 2010.

✓ "Structural Design And Analysis of The Mission Adaptive Wings of an Unmanned Aerial Vehicle" by Levent Ünlüsoy – METU – 2010.

✓ "Structural Design And Evaluation of an Adaptive Camber Wing" by Evren Sakarya – METU – 2010.

- International Journal Articles: 1
- International Conference Papers: 3
- National Conference Papers: 8

Morphing Twist for Active Wing

Seventh Framework Programme (FP7) - Collaborative Project

Submitted on 14 January 2010

No.	Participant organisation name	Short name	Type	Country
1 (coordinator)	Centro Italiano Ricerche Aerospaziali	CIRA	RES	ITA
2	Alenia Aeronautica	Alenia	IND	ITA
3	ATARD	ATARD	SME	TUR
4	University of Bristol	UNIBRISTOL	HES	GBR
5	TU Delft	TU Delft	HES	NED
6	EASN	EASN	NOP	BE
7	ENSAIT/GEMTEX	ENSAIT	HES	FRA
8	Fraunhofer Institute	FhG	RES	GER
9	Middle East Technical University	METU	HES	TUR
10	Università di Napoli	UNINA	HES	ITA
11	University of Patras	LTSM-UP	HES	GRE
12	Technion - Israel Institute of Technology	TECHNION	HES	ISR
13	Israel Aerospace Industries	IAI	IND	ISR
14	Marotta	Marotta	SME	ITA

Prof. Dr. Yavuz YAMAN

Assist. Prof. Dr. Melin ŞAHİN

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Morphing Twist for Active Wing

The TWIST project aims to control the wing twist distribution in next generation wings, leading to the manufacturing and testing of a significant scale demonstrator.

The main aim is broken down into three major technical objectives:

- *the development of the inner wing structure;*
- *the development of the morphing skin;*
- *the development of the smart actuator.*

Morphing Twist for Active Wing

Expected benefits from the TWIST wing concept are as follows,

- *Improvement in stall performance*
- *Weight reduction*
- *Simplification of wing structure*
- *Synergy with morphing wing*
- *Application to other aerodynamic surfaces*
- *Compensation to varying flight conditions for drag reduction*

Morphing Twist for Active Wing

METU Responsibilities

WP1: Concepts and harmonization

- Detailed definition of demonstrator size, shape and performances
- Aerodynamic and aeroelastic review of achieved demonstrator layout
- Evaluation of load distribution acting on elastic morphing wing

METU Responsibilities

WP2: Inner structure

- Critical review of state of the art of morphing concepts for inner structure design
- Development and analysis of suitable concepts for demonstrator inner structure design
- Performance assessment of selected concepts. Selection and design of inner structure concept to be implemented in the morphing twist demonstrator. Development of a detailed numerical model of the demonstrator inner structure

Morphing Twist for Active Wing

METU Responsibilities

WP4: Smart actuation

- Review of the state of the art of morphing technologies
- Identification and development of candidate solutions for smart actuator. Identification of suitable materials for obtaining required performances, numerical simulation and coupon tests on identified candidates
- Numerical simulation of actuation candidate technologies
- Iterative development of chosen candidate(s) to meet performance requirements
- Selection of the solution to be implemented in the morphing twist wing demonstrator, detailed numerical modeling and optimization of demonstrator components. Design of demonstrator components

Design, Development, Production and Testing of Morphing UAVs and Materials

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Assoc. Prof. Dr. Göknur BAYRAM
Assoc. Prof. Dr. Yusuf ULUDAĞ
Department of Chemical Engineering
Middle East Technical University

Assist. Prof. Dr. Ayşen YILMAZ
Department of Chemistry
Middle East Technical University

and

TURKISH AEROSPACE INDUSTRIES INC. (TAI)

Design, Development, Production and Testing of Morphing UAVs and Materials

This project is intended to design, develop and build fully morphing air vehicles and acquire the associated technologies.

Structural Health Monitoring Applications

Seventh Framework Programme (FP7) - Collaborative Project

Submitted on 07 May 2010

Participant No.	Participant Organisation Name	Short name	Country
1 (coordinator)	The Technion, Israel Institute of technology	Technion	Israel
2	Mondragon Unibertsitatea	MGEP	Spain
3	Middle East Technical University	METU	Turkey
4	(VZLU)Vyzkumny a Zkusebni Letecky Ustav Aeronautical Research and Test Institute	VZLU	Czech republic
5	Alenia Aeronautica	Alenia	Italy

Assist. Prof. Dr. Melin ŞAHİN
Prof. Dr. Yavuz YAMAN

Middle East Technical University
Department of Aerospace Engineering

Structural Health Monitoring Applications

The project aims to develop a new system for performing Structural Health Monitoring for Airborne structures.

It is believed that the use of this technique will result in increased confidence in the detection ability and will have the following beneficiary effects;

- Increased safety, longer life at lower costs
- Less frequent structural maintenance procedures
- Less time on ground for the Aircraft
- More time in the air for the Aircraft
- Lower danger of accidents resulting from structural damages.

METU Responsibilities

WP1: Identification and definition of target end cases

WP3: Design and manufacturing of the laboratory test set-up for Composites/Laminates

WP5: Numerical simulations and sensitivity analysis for Composites/Laminates

WP7: Tests in Laboratory for Composites/Laminates

METU Responsibilities

WP8: Target end case verification and fine tuning

WP9: System Implementation

WP10: Dissemination and Exploitation

WP11: Project Management

Structural Health Monitoring Applications

Health Monitoring of Structures by using OMA tools

- National Research Project:

"Prediction and Verification of Dynamic Properties of Aerospace Structures via Experimental Modal Testing" METU – BAP1 – 2008-03-13-01 (January 2008 – December 2009)

Active Vibration Control Applications

Active Suppression of in-vacuo Vibrations

Studies mainly focus on;

- *System Identification based on strain measurements*
- *System Identification based on displacement measurements*
- *Application of H_{inf} and mu controllers*
- *Free vibration suppression of smart beam and fin*
- *Forced vibration suppression of smart beam in its first two (first and second flexural) modes and that of smart fin in its first two (first flexural and first torsional) modes.*

Active Vibration Control Applications

Active Suppression of in-vacuo Vibrations

Published Work

- PhD. Thesis:
  "Piezoelectric Ceramics and their Applications in Smart Aerospace Structures" by Tarkan Çalışkan – METU – 2002.
- MSc. Thesis:
  "Active Vibration Control of Smart Structures" by Fatma Demet Ülker – METU – 2003.
- International Journal Articles: 1
- International Conference Papers: 9
- National Conference Papers: 10

Active Vibration Control Applications

Active Suppression of in-vacuo Vibrations

- International Research Project:

  "Application of Smart Materials in the Vibration control of Aeronautical Structures" NATO/RTO/Applied Vehicle Technology Panel through the project **T-121** (April 2000 - March 2002), Turkish-Canadian joint project

  [Project Final Report]

Active Vibration Control Applications

Active Suppression of in-vacuo Vibrations

- International Research Project:

  "Development of Control Strategies for the Vibration Control of Smart Aeronautical Structures" NATO/RTO/Applied Vehicle Technology Panel through the project **T-129** (April 2002 - March 2004), Turkish-Canadian joint project

  [Project Final Report]

Active Vibration Control Applications

Active Suppression of in-vacuo Vibrations

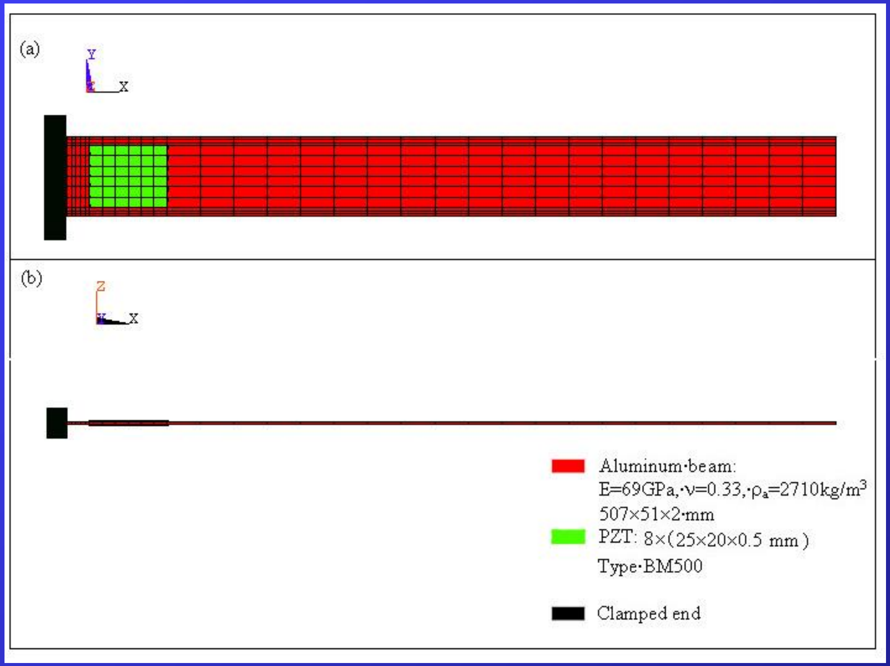
- National Research Project:

  "Establishment of an Aerospace Research & Development Centre" METU:AFP.03.13.DPT.98.K.122630" supported by Turkish State Planning Organization (DPT) (1998-2002)

Active Vibration Control Applications

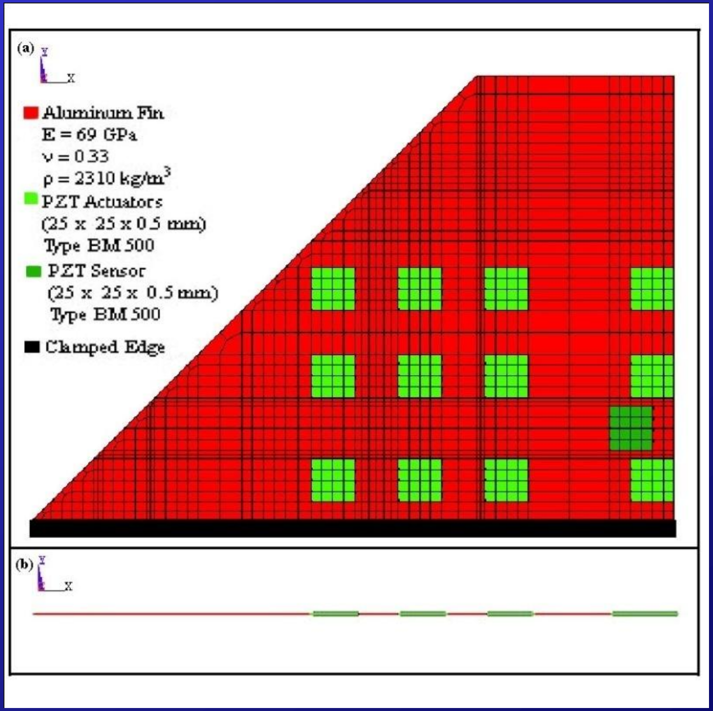
Active Suppression of in-vacuo Vibrations

Aluminum beam-like structure (Smart Beam)



FEM of the smart beam

Aluminum plate-like structure (Smart Fin)



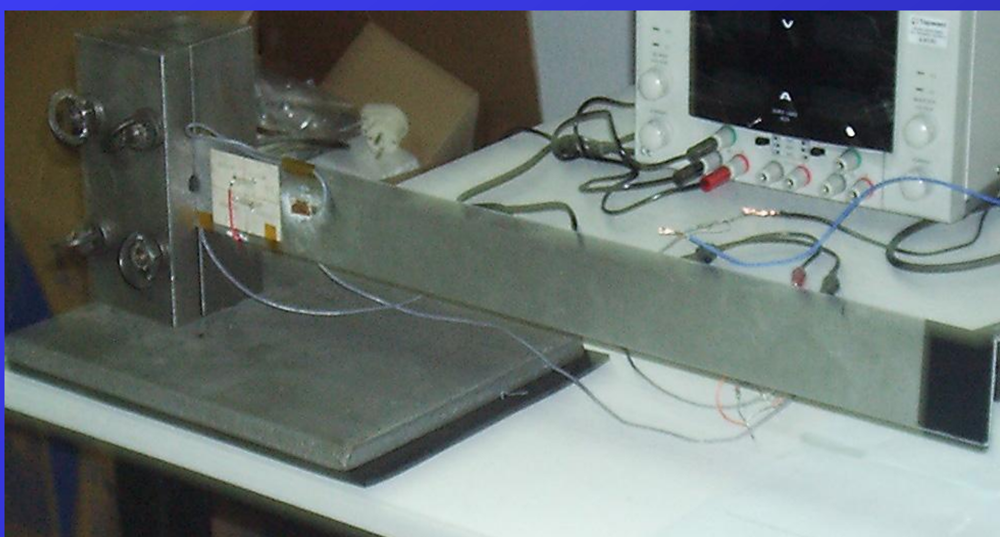
FEM of the smart fin

Active Vibration Control Applications

Active Suppression of in-vacuo Vibrations

Aluminum beam-like structure (Smart Beam)

Aluminum plate-like structure (Smart Fin)



Smart beam test specimen

Smart fin test specimen

Active Vibration Control Applications

Active Suppression of in-vacuo Vibrations

Laboratory

Active Suppression of in-vacuo Vibrations

Beam Experiments

H infinity active vibration control strategy is applied to a smart beam having 8 surface bonded Sensortech BM500 piezoceramics (PZTs) in bimorph condition. Two different experimental set-ups are used.

The first set-up utilizes the strain gauge as the sensor and Sensortech SS10 Four Channel Programmable Controller as the vibration controller.

Both free and sinusoidally forced vibrations are controlled.

Active Suppression of in-vacuo Vibrations

Beam Experiments

- The First Experimental Setup

  The videos at lower left represent the vibrations where there is no controller, the videos at upper right represent the controlled vibration.

- Free Vibrations of the Smart Beam (Strain Gauge & SS10 Controller)
- Forced Vibrations of the Smart Beam (Strain Gauge & SS10 Controller)

Active Suppression of in-vacuo Vibrations

Beam Experiments

The second set-up uses the laser displacement sensor as the sensor and a Labview v5.0 based program for the control purposes.

Both free and sinusoidally forced vibrations are controlled.

Active Vibration Control Applications

Active Suppression of in-vacuo Vibrations

Beam Experiments

- The Second Experimental Setup

  The videos at lower left represent the vibrations where there is no controller, the videos at upper right represent the controlled vibration.

- Free Vibrations of the Smart Beam (LDS & LabVIEW)

- Forced Vibrations of the Smart Beam (LDS & LabVIEW)

Active Suppression of in-vacuo Vibrations

Plate Experiments

Mu active vibration control strategy is applied to a smart fin having 24 surface bonded Sensortech BM500 piezoceramics (PZTs) in bimorph condition.

The experimental set-up utilizes the strain gauge as the sensor and Sensortech SS10 Four Channel Programmable Controller as the vibration controller.

Both free and sinusoidally forced vibrations are controlled.

Active Vibration Control Applications

Active Suppression of in-vacuo Vibrations

Plate Experiments

- The experimental set-up utilizes the strain gauge as the sensor and Sensortech SS10 Four Channel Programmable Controller as the vibration controller.
- Experimental Setup

The videos at lower left represent the vibrations where there is no controller, the videos at upper right represent the controlled vibration.

- Free Vibrations of the Smart Fin (Strain Gauge & SS10 Controller)
- Forced Vibrations of the Smart Fin (Strain Gauge & SS10 Controller)

Spatial Control of in-vacuo Vibrations

- *To suppress the vibration over entire beam by means of spatial control approach*
- *System Identification based on displacement measurements*
- *Modeling of the smart beam by the assumed modes method*
- *A spatial H_{inf} controller designed for suppressing the first two flexural vibrations of the smart beam*

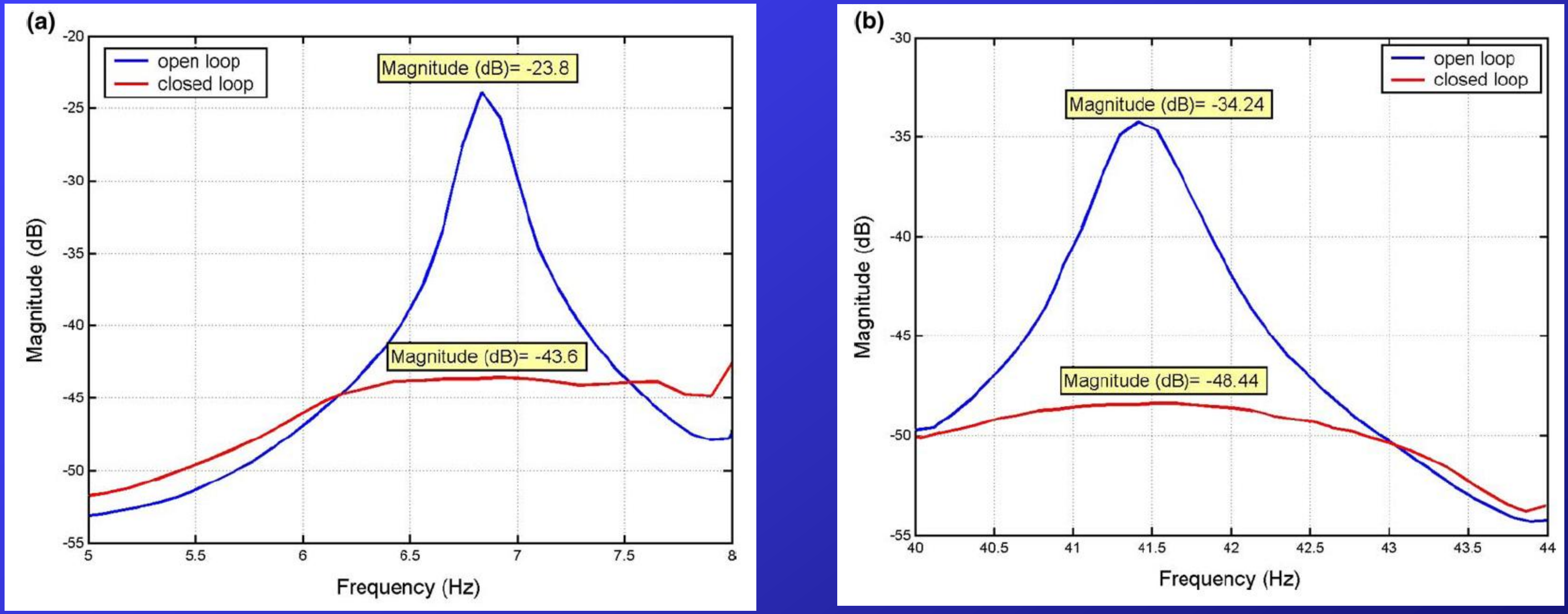
Spatial Control of in-vacuo Vibrations

Published Work

- MSc. Thesis:
  "Active Vibration Control of a Smart Beam: A Spatial Approach" by Ömer Faruk Kırcalı – METU – 2006.
- Chapter in Book: 1
- International Journal Articles: 1
- International Conference Papers: 2
- National Conference Papers: 3

Active Vibration Control Applications

Spatial Control of in-vacuo Vibrations



Frequency responses of the open loop and closed loop systems of the smart beam within excitation of

(a) 5–8 Hz (b) 40–44 Hz

(A Spatial Approach for the active vibration control)

Active Flutter Suppression

- *A thermal analogy method for the purpose of modeling of piezoelectric actuators*
- *The H_{inf} robust controllers designed for the state-space aeroelastic model of the smart fin by considering both Single-Input Single-Output and Multi-Input Multi-Output system models*
- *Satisfactory flutter suppression performance around the flutter point*
- *Significant improvement in the flutter speed of the smart fin*

Active Vibration Control Applications

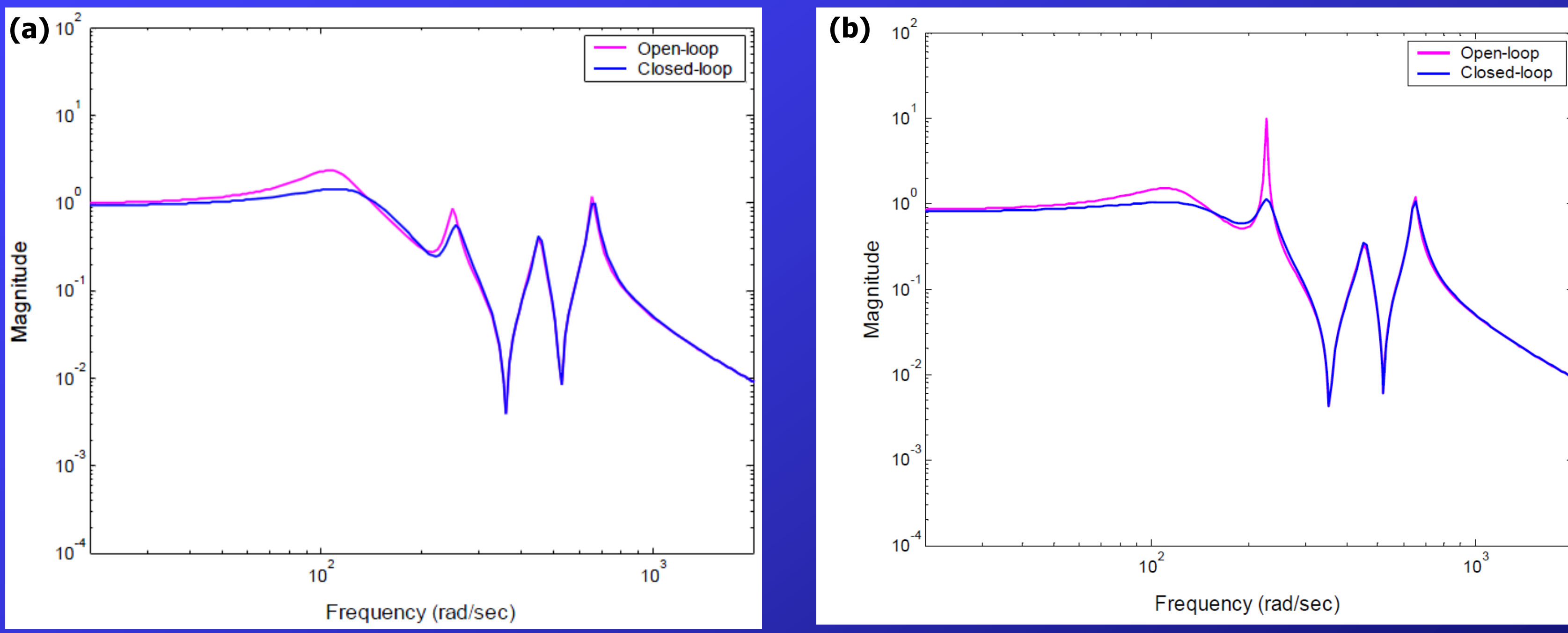
Active Flutter Suppression

Published Work

- MSc. Thesis:
  "Active Flutter Suppression of a Smart Fin" by Fatih Mutlu Karadal – METU – 2008.
- International Conference Papers: 2
- National Conference Papers: 1

Active Vibration Control Applications

Active Flutter Suppression



Comparison of the open-loop and closed-loop frequency responses of the smart fin for the SISO model for

(a) 70 m/sec (b) 83 m/sec

Active Vibration Control Applications

- International Research Project:

"Development of and Verification of Various Strategies for the Active Vibration Control of Smart Aerospace Structures subjected to Aerodynamic Loading" NATO/RTO/Applied Vehicle Technology Panel through the project **T-133** (April 2006 - September 2008), Turkish-Canadian joint project

[Project Final Report]

Active Vibration Control via PZT sensor/actuator pair and Self-sensing PZT Actuator

- *To suppress the vibration of beam by means of PZT sensing and actuating pair and a self-sensing PZT actuator*
- *System Identification based on PZT sensor and PZT actuator signals*
- *The H_{inf} robust controllers designed for suppressing the free and the first rezonance frequency forced vibration of the smart beam*
- *Effective vibration suppressions with both PZT sensor/actuator pair and self-sensing PZT actuator*

Active Vibration Control Applications

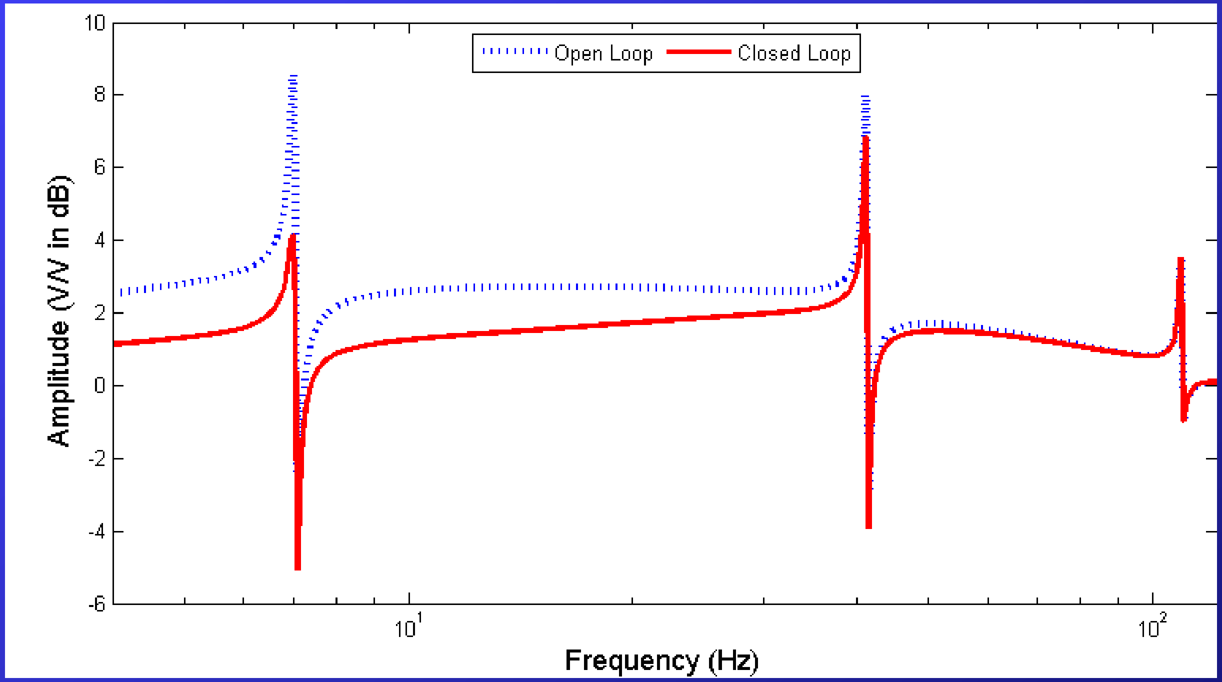
Active Vibration Control via PZT sensor/actuator pair and Self-sensing PZT Actuator

Published Work

- International Conference Papers: 1
- National Conference Papers: 2

Active Vibration Control Applications

Active Vibration Control via PZT sensor/actuator pair and Self-sensing PZT Actuator



Frequency Responses of the Open Loop and Closed Loop Systems of the Smart Beam obtained via Self-sensing Actuator within the bandwith of 2Hz - 115 Hz.

Active Vibration Control Applications

Active Vibration Suppression with various control strategies via PZT sensor/actuator pair

- *To suppress the vibration of beam by means of PZT sensing/actuating pair*
- *System Identification based on PZT sensor and PZT actuator signals*
- *The LQG controllers designed for suppressing the free and the first rezonance frequency forced vibration of the smart beam*
- *The fractional controllers designed for suppressing the free and the first rezonance frequency forced vibration of the smart beam*
- *Effective vibration suppressions achieved*

Active Vibration Control Applications

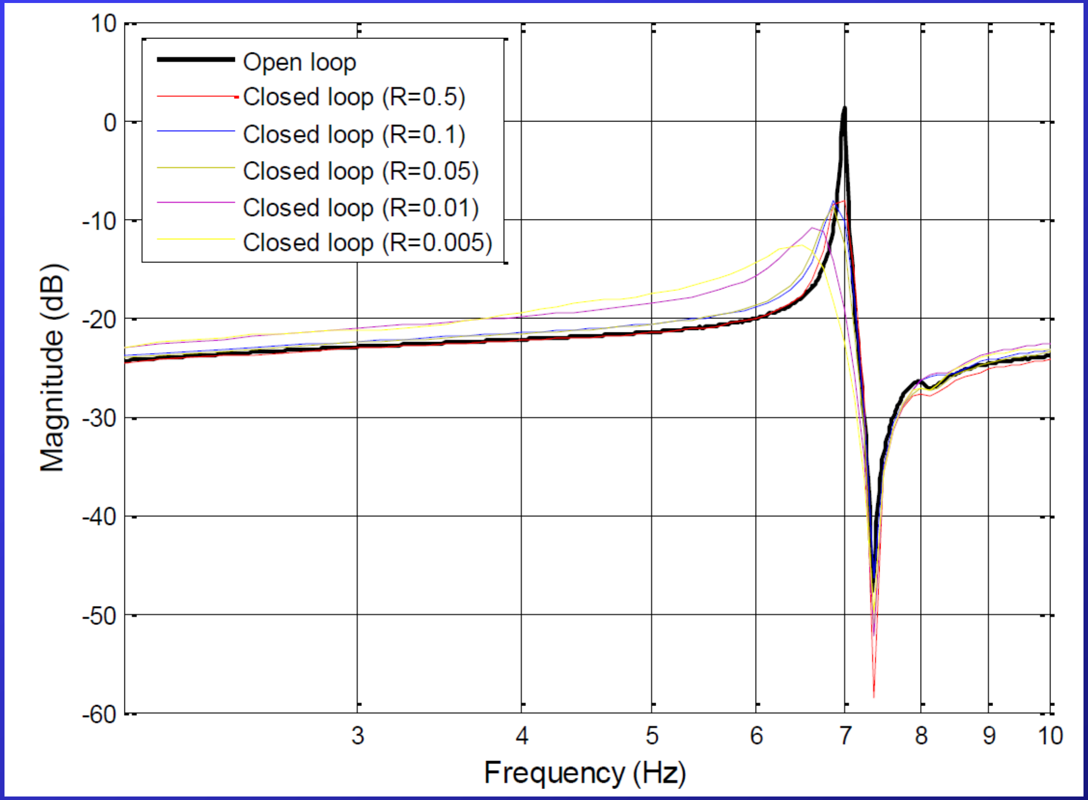
Active Vibration Suppression with various control strategies via PZT sensor/actuator pair

Published Work

- International Conference Papers: 4
- National Journal Papers: 1
- National Conference Papers: 1

Active Vibration Control

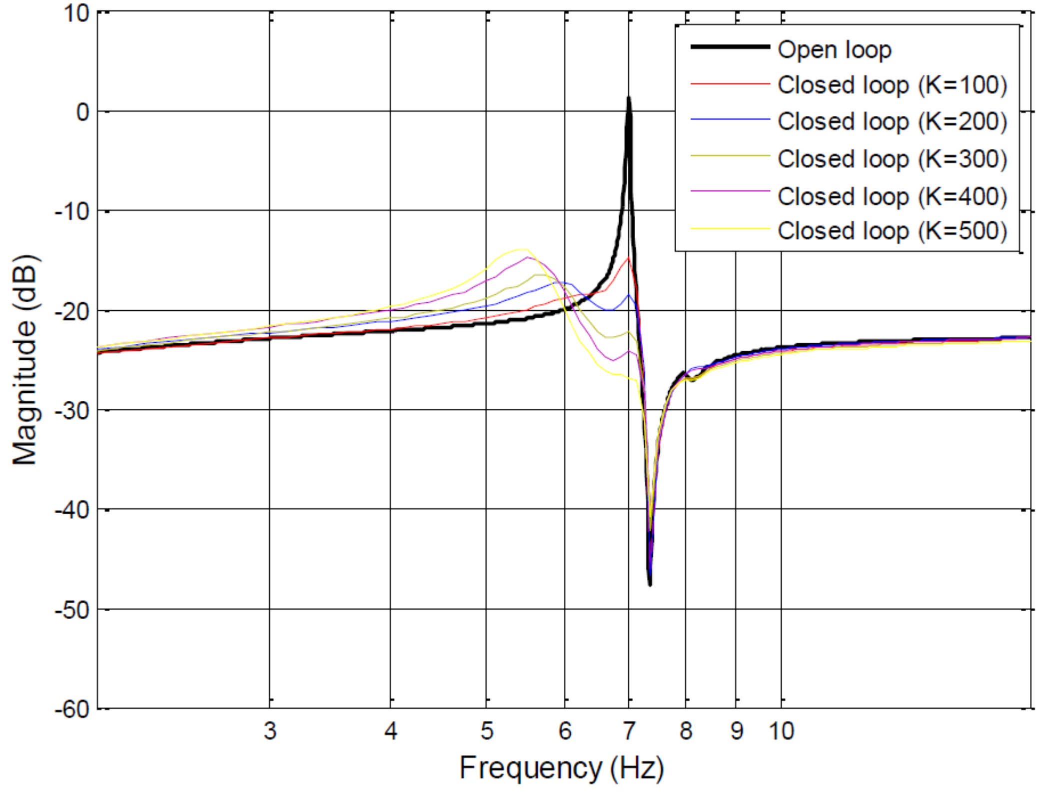
Active Vibration Suppression with LQG Controller via PZT sensor/actuator pair



Open and closed loop experimental frequency responses of the smart beam.

Active Vibration Control

Active Vibration Suppression with Fractional Controller via PZT sensor/actuator pair



Open and closed loop experimental frequency responses of the smart beam.

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