



RESEARCH STUDIES

on

SMART STRUCTURES APPLICATIONS

in the

Department of Aerospace Engineering

MIDDLE EAST TECHNICAL UNIVERSITY

ANKARA – TURKEY

As of 22 June 2011



Structures Laboratory Infrastructure

SOFTWARE

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

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 accelerometers
- Keyence Laser Displacement Sensor
- Agilent Signal Generator
- Hameg Oscilloscope
- Various Uni-axial Strain Gauges and Installation Kits
- Dedicated equipment for smart structure applications comprising programmable controller, high voltage power amplifiers, high voltage power supplies, preamplifiers and piezoelectric (PZT) patches in various size and shape.



Structural Health Monitoring

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

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Structural Health Monitoring

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.



Structural Health Monitoring

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

WP8: Target end case verification and fine tuning

WP9: System Implementation

WP10: Dissemination and Exploitation

WP11: Project Management



Active Vibration Control

Active Suppression of in-vacuo Vibrations

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



Active Vibration Control

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]

- 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

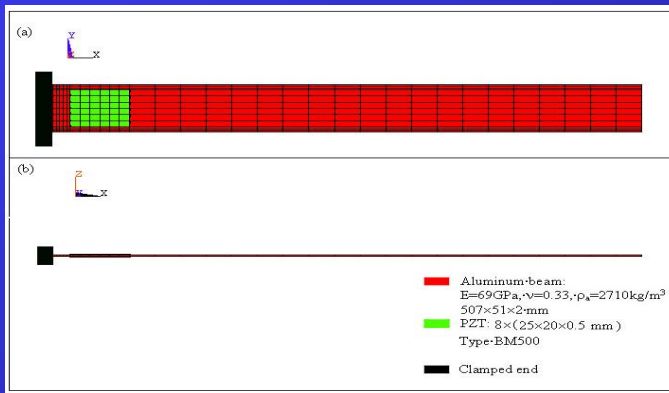
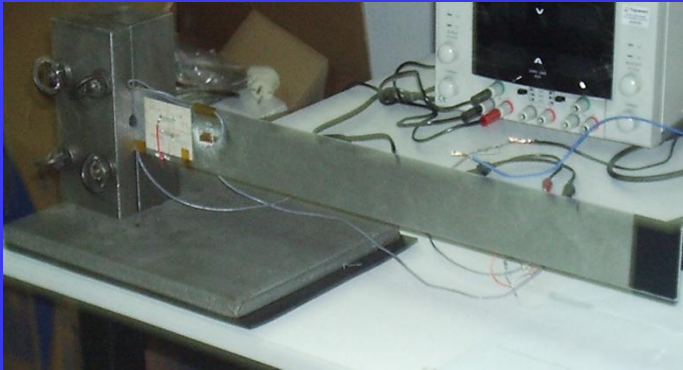
[Project Final Report]



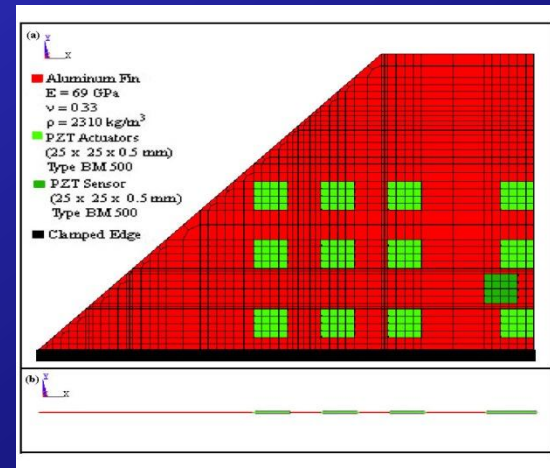
Active Vibration Control

Active Suppression of in-vacuo Vibrations

Aluminum beam-like structure (Smart Beam)



Aluminum plate-like structure (Smart Fin)





Active Vibration Control

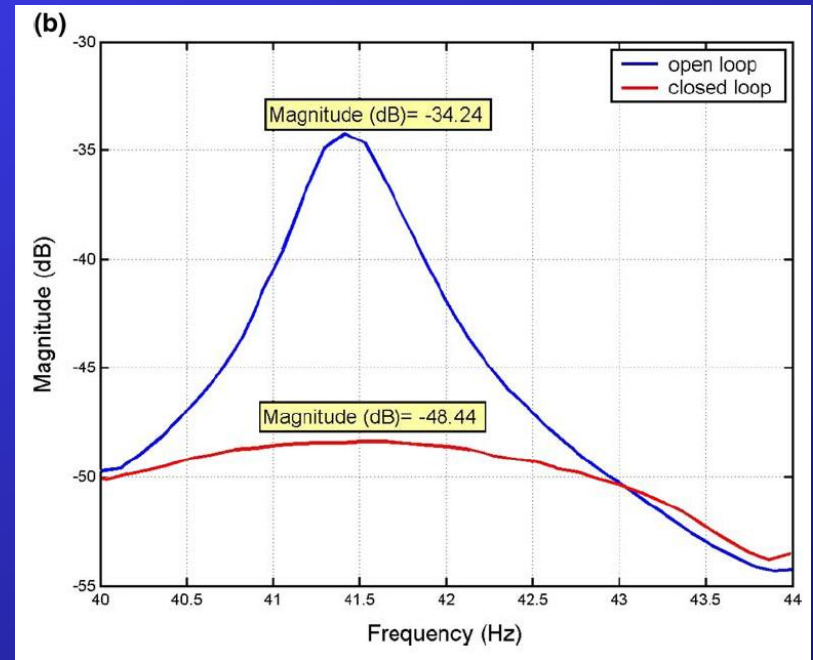
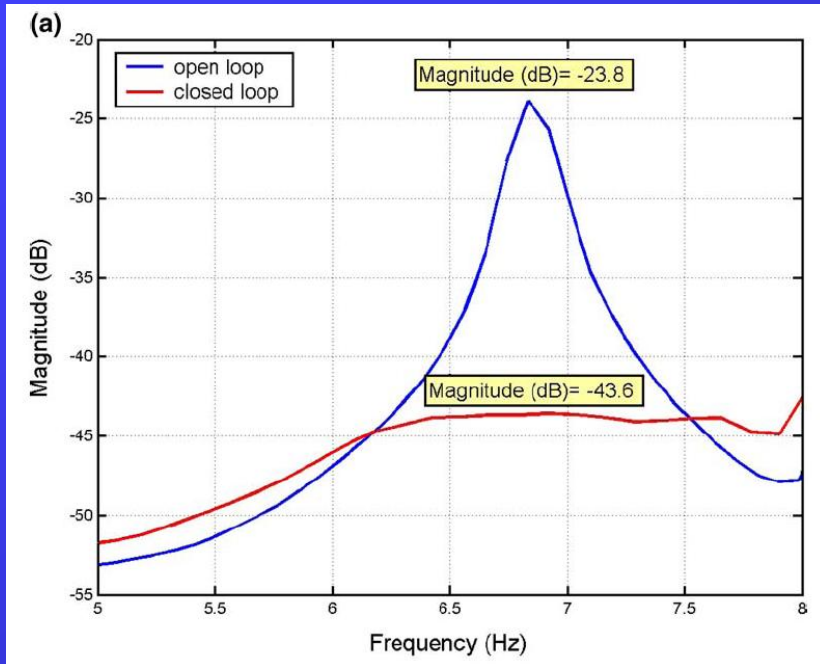
Spatial Control of in-vacuo Vibrations

- *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*
-
- MSc. Thesis: [“Active Vibration Control of a Smart Beam: A Spatial Approach”](#)
by Ömer Faruk Kırcalı – METU – 2006.



Active Vibration Control

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



Active Vibration Control

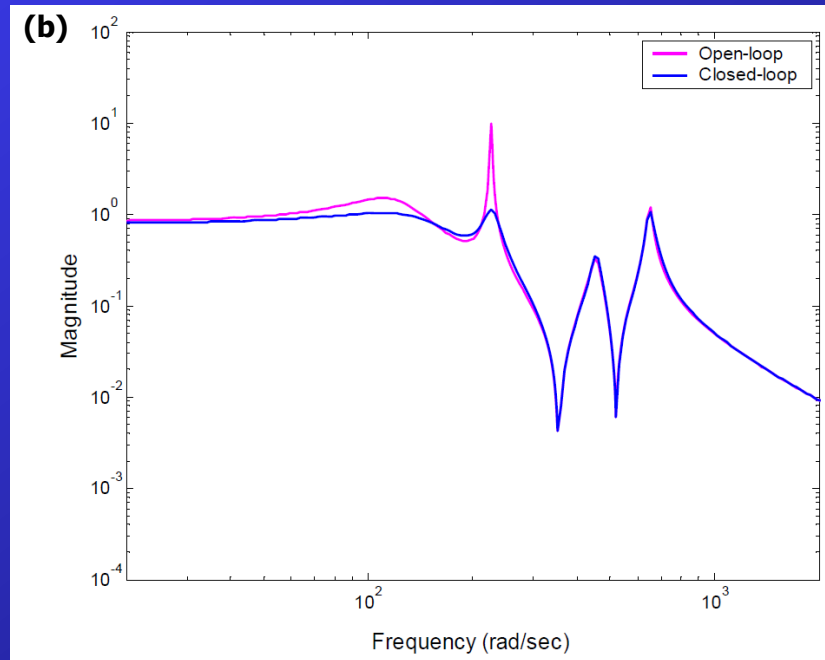
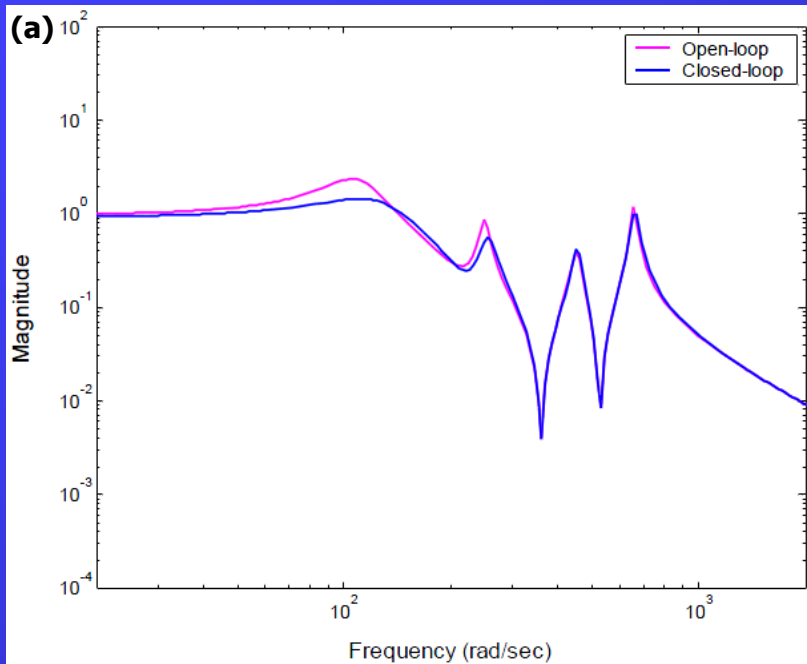
Active Flutter Suppression

- *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*
-
- MSc. Thesis: "Active Flutter Suppression of a Smart Fin" by Fatih Mutlu Karadal – METU – 2008.



Active Vibration Control

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

Active Flutter Suppression

- 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

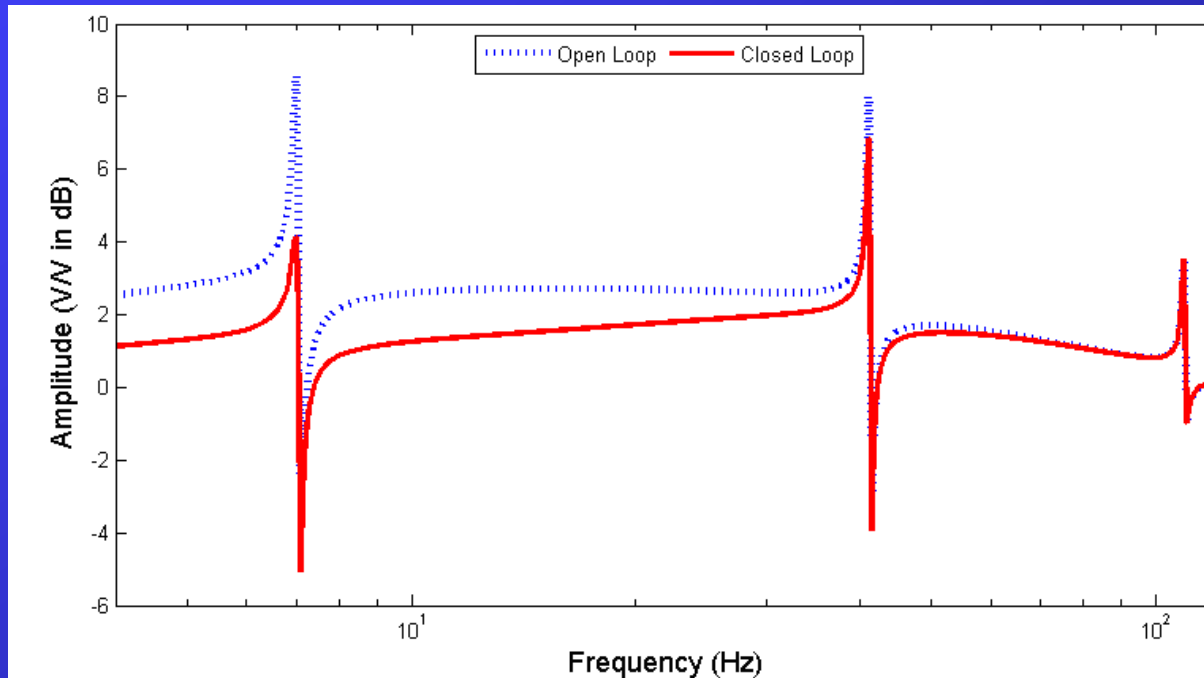
Active Vibration Control via PZT sensor/actuator pair and Self-sensing PZT Actuator

- *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 resonance frequency forced vibration of the smart beam*
 - *Effective vibration suppressions with both PZT sensor/actuator pair and self-sensing PZT actuator*
-
- MSc. Thesis: "Performance Evaluation of Piezoelectric Sensor/Actuator on Investigation of Vibration Characteristics and Active Vibration Control of a Smart Beam" by M. Uğur Arıdoğan – METU – 2010



Active Vibration Control

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 bandwidth of 2Hz - 115 Hz.



Active Vibration Control

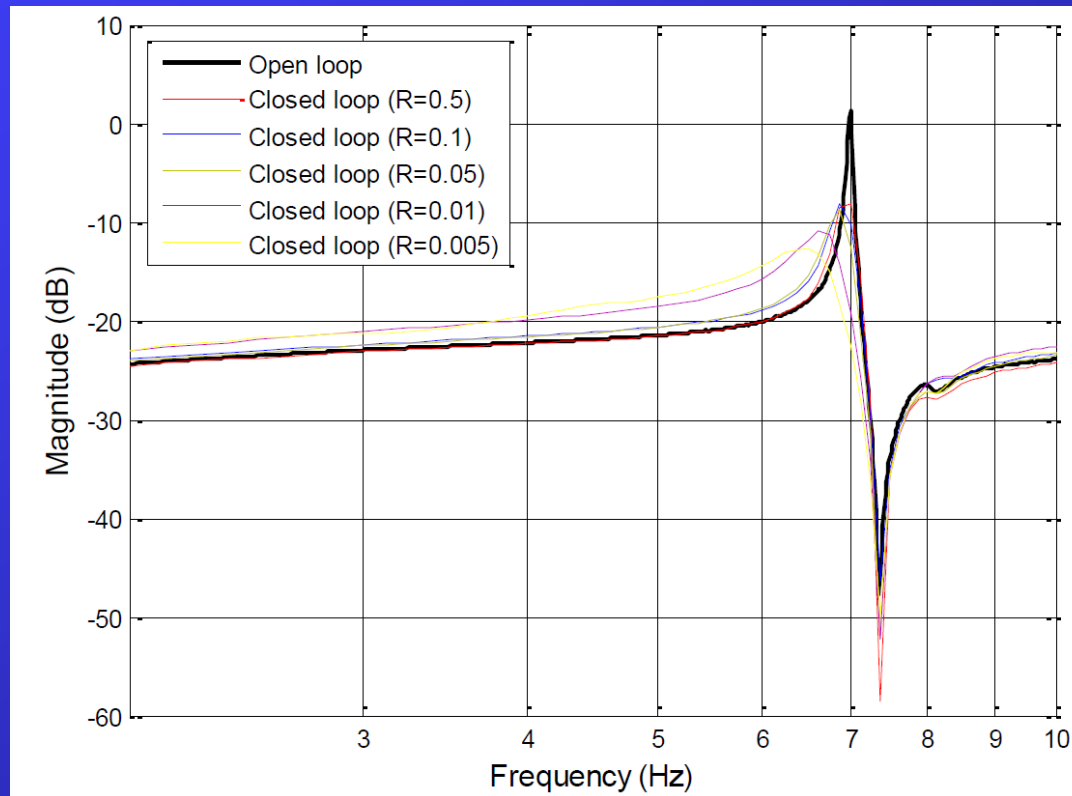
Active Vibration Suppression with various control strategies via PZT sensor/actuator pair

- *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 resonance frequency forced vibration of the smart beam*
- *The fractional controllers designed for suppressing the free and the first resonance frequency forced vibration of the smart beam*
- *Effective vibration suppressions achieved*



Active Vibration Control

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

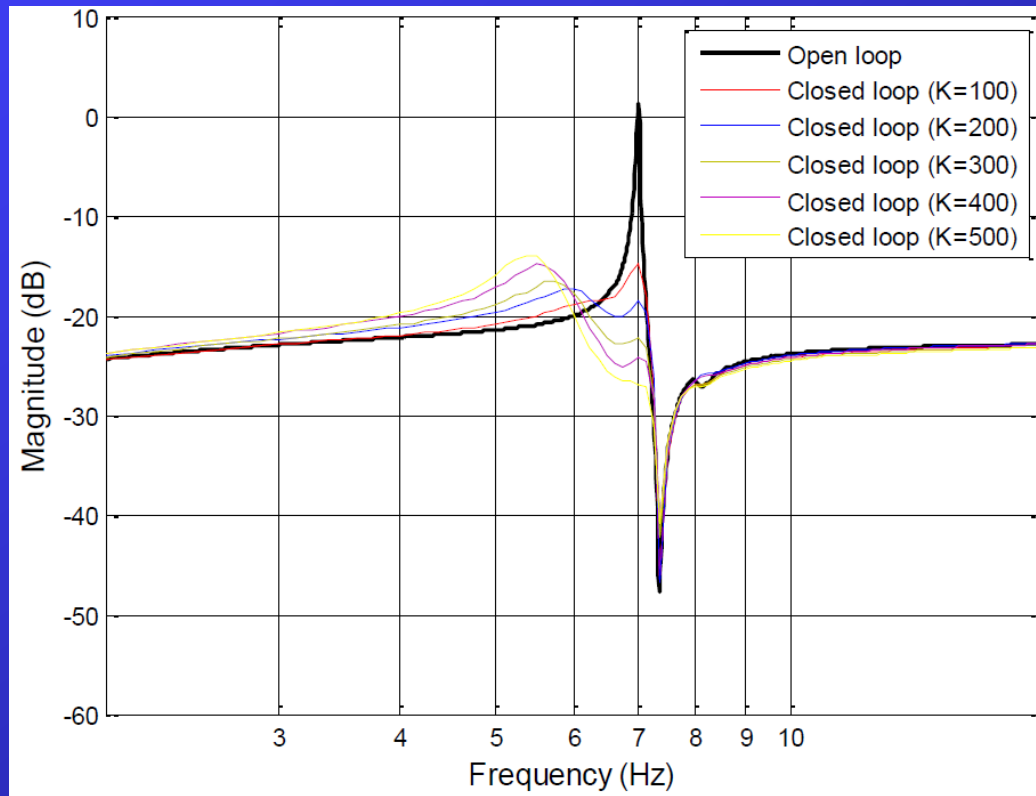


Open and closed loop experimental frequency responses of the smart beam.



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.



Publications

- [1] T. Çalışkan, V. Nalbantoğlu, Y. Yaman, *Akıllı Yapılar Yardımıyla Aktif Titreşim Kontrolü*, 10. Ulusal Makina Teorisi Sempozyumu, Selçuk Üniversitesi, Konya, Türkiye, 2001. (UMTS2001, 10th Machine Theories Symposium - in Turkish).
- [2] T. Çalışkan, Y. Yaman, V. Nalbantoğlu, *Akıllı Yapıların Sonlu Elemanlar Tekniği Kullanılarak Modellenmesi*, 10. Ulusal Makina Teorisi Sempozyumu, Selçuk Üniversitesi, Konya, Türkiye, 2001. (UMTS2001, 10th Machine Theories Symposium - in Turkish).
- [3] Y. Yaman, T. Çalışkan, V. Nalbantoglu, E. Prasad, D. Waechter, *Active Vibration Control of a Smart Beam*, CanadaUS CanSmart Workshop on Smart Materials and Structures, Montreal, Canada, 2001.
- [4] T. Çalışkan, F.D. Ülker, Y. Yaman, V. Nalbantoğlu, E. Prasad, *Sonlu Elemanlar Tekniğiyle Elde Edilen Akıllı Kiriş Modelinin Hassasiyetinin İyileştirilmesi*, Kayseri IV. Havacılık Sempozyumu Kayseri, Türkiye, 2002. (Kayseri IV. Aeronautics Symposium - in Turkish).
- [5] Y. Yaman, T. Çalışkan, V. Nalbantoğlu, F.D. Ülker, E. Prasad, *Akıllı Yapıların Havacılık ve Uzay Mühendisliğindeki Uygulamaları*, Savunma Teknolojileri Kongresi, ODTÜ, Ankara, Türkiye, 2002. (SAVTEK2002, Conference on Defense Technologies, - in Turkish).



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- [6] Y. Yaman, T. Caliskan, V. Nalbantoglu, F.D. Ulker, E. Prasad, D. Waechter, B. Yan, *Active Vibration Control of Smart Plates by Using Piezoelectric Actuators*, ESDA2002, 6th Biennial Conference on Engineering Systems Design and Analysis, Paper APM018, Istanbul, Turkey, 2002.
- [7] Y. Yaman, T. Caliskan, V. Nalbantoglu, E. Prasad, D. Waechter, *Active Vibration Control of a Smart Plate*, ICAS2002, International Council of the Aeronautical Sciences, Paper 424, Toronto, Canada, 2002.
- [8] F.D. Ülker, V. Nalbantoğlu, T. Çalışkan, Y. Yaman, E. Prasad, *Akıllı Bir Kirişin Zorlanmış Titreşimlerinin Aktif Kontrolü*, 11. Ulusal Makina Teorisi Sempozyumu, Gazi Üniversitesi, Ankara, Türkiye, 2003. (UMTS2003, 11th Machine Theories Symposium - in Turkish).
- [9] Y. Yaman, F.D. Ulker, V. Nalbantoglu, T. Caliskan, E. Prasad, D. Waechter, B. Yan, *Application of H_{inf} Active Vibration Control Strategy in Smart Structures*, AED2003, 3rd International Conference on Advanced Engineering Design, Paper A5.3, Prague, Czech Republic, 2003.
- [10] Y. Yaman, F.D. Ulker, V. Nalbantoglu, T. Caliskan, E. Prasad, D. Waechter, B. Yan, *Application of μ -synthesis Active Vibration Control Technique to a Smart Fin*, 6th CanSmart Meeting, International Workshop on Smart Materials and Structures, Montreal, Canada, 2003.



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- [11] F.D. Ülker, Ö.F. Kırçalı, Y. Yaman, V. Nalbantoğlu, T. Çalışkan, E. Prasad, *Akıllı Bir Plakanın Serbest ve Zorlanmış Titreşimlerinin Kontrolü*, Kayseri V. Havacılık Sempozyumu, Kayseri, Türkiye, 2004. (Kayseri V. Aeronautics Symposium - in Turkish).
- [12] F.D. Ülker, Y. Yaman, V. Nalbantoğlu, *Akıllı bir Plakanın Titreşimlerinin Sönümlenmesinde Bağımsız Çalışan Piezoelektrik Yamaların Etkisi*, Havacılıkta İleri Teknolojiler ve Uygulamaları Sempozyumu, İstanbul, Türkiye, 2004. (HITEK2004, Symposium on Advanced Technologies and their Applications in Aeronautics - in Turkish).
- [13] F.D. Ülker, Y. Yaman, V. Nalbantoğlu, Ö.F. Kırçalı, *Akıllı Bir Plağın Burulma Titreşimlerinin Kontrolü*, 12. Ulusal Makina Teorisi Sempozyumu, Erciyes Üniversitesi, Kayseri, Türkiye, 2005. (UMTS2005, 12th Machine Theories Symposium - in Turkish).
- [14] M. İtik, M.U. Salamcı, F.D. Ülker, Y. Yaman, *Active Vibration Suppression of a Flexible Beam via Sliding Mode and H_{inf} Control*, 44th IEEE Conference on Decision and Control and the European Control Conference, Seville, Spain, 2005.
- [15] Ö.F. Kırçalı, Y. Yaman, V. Nalbantoğlu, M. Şahin, F.M. Karadal, F.D. Ülker, *Akıllı Bir Kirişin Uzamsal Sistem Modelinin Elde Edilmesi*, Kayseri VI. Havacılık Sempozyumu, Nevşehir, Türkiye, 2006. (Kayseri VI. Aeronautics Symposium - in Turkish).



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- [16] Ö.F. Kircalı, Y. Yaman, V. Nalbantoğlu, M. Şahin, F.M. Karadal, *Akıllı Bir Kirişin Varsayılan Biçimler Metodu ile Uzamsal Sistem Modelinin Elde Edilmesi ve Elde Edilen Modelin İyileştirilmesi*, Kayseri VI. Havacılık Sempozyumu, Nevşehir, Türkiye, 2006. (Kayseri VI. Aeronautics Symposium - in Turkish).
- [17] Ö. F. Kircalı, Y.Yaman, V. Nalbantoğlu, M. Şahin, F. M. Karadal, *Akıllı Bir Kirişin Titreşim Kontrolünde Uzamsal ve Noktasal Denetçilerin Karşılaştırılması*, 1. Ulusal Havacılık ve Uzay Konferansı, Ankara, Türkiye, 2006. (UHUK2006, 1st National Aeronautics and Astronautics Conference - in Turkish).
- [18] O.F. Kircalı, Y. Yaman, V. Nalbantoglu, M. Sahin, F.M. Karadal, F.D. Ulker, *Spatial Control of a Smart Beam*, IWPMA 2006, 3rd International Workshop on Piezoelectric Materials and Applications in Actuators, Eskisehir, Turkey, 2006.
- [19] M. Sahin, Y. Yaman, V. Nalbantoglu, F. M. Karadal, O.F. Kircalı, F. D. Ulker, T. Caliskan, *Smart Structures and Their Applications on Active Vibration Control: Studies in the Department of Aerospace Engineering, METU*, IWPMA 2006, 3rd International Workshop on Piezoelectric Materials and Applications in Actuators, Eskisehir, Turkey, 2006.
- [20] O.F. Kircalı, Y. Yaman, V. Nalbantoglu, M. Sahin, F. M. Karadal, *Application of Spatial Hinf Control Technique for Active Vibration Control of a Smart Beam*, ICINCO 2007, 4th International Conference on Informatics in Control, Automation and Robotics, Angers, France, 2007.



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- [21] F. M. Karadal, G. Seber, M. Sahin, V. Nalbantoglu, Y. Yaman, *State Space Representation of Smart Structures Under Unsteady Aerodynamic Loading*, 4. AIAC, 4th Ankara International Aerospace Conference, Ankara, Turkey, 2007.
- [22] F. M. Karadal, M. Şahin, Ö.F. Kircali, V. Nalbantoğlu Y.Yaman, *Akıllı bir Kirişin Statik Aerodinamik Yükler Altındaki Davranışı*, 13. Ulusal Makina Teorisi Sempozyumu, Sivas, Türkiye, 2007. (UMTS2007, 13th Machine Theories Symposium - in Turkish).
- [23] M. Sahin, Y. Yaman, V. Nalbantoglu, F. M. Karadal, O.F. Kircali, F. D. Ulker, T. Caliskan, *Smart Structures and Their Applications on Active Vibration Control: Studies in the Department of Aerospace Engineering, METU*, Journal of Electroceramics, 20(3-4): 167-174, 2008.
- [24] O.F. Kircali, Y. Yaman, V. Nalbantoglu, M. Sahin, F. M. Karadal, F. D. Ulker, *Spatial Control of a Smart Beam*, Journal of Electroceramics, 20(3-4): 175-185, 2008.
- [25] O.F. Kircali, Y. Yaman, V. Nalbantoglu, M. Sahin, *Active Vibration Control of a Smart Beam by Using A Spatial Approach*, New Developments in Robotics, Automation and Control, I-TECHONLINE, I-Tech Education and Publishing, Book Chapter, 377-410, 2008.
- [26] F. M. Karadal, V. Nalbantoglu, M. Sahin, G. Seber, O. F. Kircali, Y. Yaman, *Active Flutter Control of a Smart Fin*, ICAST 2008, 19th International Conference on Adaptive Structures and Technologies, Ascona, Switzerland, 2008.



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- [27] U. Arıdoğan, M. Şahin, V. Nalbantoğlu, Y. Yaman, *Piezoelektrik Yamaların Akıllı Bir Kirişin Titreşim Özelliklerinin Bulunmasında Algılayıcı Olarak Kullanılması*, XVI. Ulusal Mekanik Kongresi, Kayseri, Türkiye, 2009. (UMK2009, 16th National Mechanics Congress - in Turkish).
- [28] U. Arıdoğan, M. Şahin, V. Nalbantoğlu, Y. Yaman, *Piezoelektrik Yamaların Akıllı Bir Kirişin Titreşim Kontrolünde Algılayıcı ve Uyarıcı Olarak Kullanılması*, 14. Ulusal Makina Teorisi Sempozyumu, Güzelyurt, KKTC, 2009. (UMTS2009, 14th Machine Theories Symposium - in Turkish).
- [29] U. Arıdoğan, M. Şahin, Y. Yaman, V. Nalbantoğlu, *Active Vibration Suppression of a Smart Beam via Self-sensing Piezoelectric Actuator*, AIAC2009, 5. Ankara International Aerospace Conference, Ankara, Turkey, 2009.
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- [31] C. Onat, M. Şahin, Y. Yaman, *Piezoelektrik Yamalara Sahip Akıllı Bir Kirişin Titreşimlerinin Kesir Dereceli Bir Denetçi Yardımıyla Aktif Denetimi*. *Mühendis ve Makina*, 52(613): 52-58, 2011. (Engineer and Machinery- in Turkish).



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