NATO/RTO/APPLIED VEHICLE TECHNOLOGY PANEL

PROJECT

T-133

Development and Verification of Various Strategies for the Active Vibration Control of Smart Aerospace Structures Subjected to Aerodynamic Loading

STARTING DATE: 01 April 2006

COMPLETION DATE: 30 September 2008

1. PURPOSE AND OBJECTIVES

The previous two projects jointly conducted by the same team, *AVT/T-121 Application of Smart Materials in the Vibration Control of Aeronautical Structures* (April 2000- March 2002) and *AVT/T-129 Development of Control Strategies for the Vibration Control of Smart Aeronautical Structures* (April 2002- March 2004), form the basis of this project. During these, first the smart beam-like structures were studied in T-121. The smart beam structural models were obtained and $H_{infinity}$ active vibration control strategy was applied. This work was extended to smart plate-like structures (smart fins) which were studied within the framework of T-129. In that project, the fin was subjected to mechanical shaker vibration. No aerodynamic loads were considered. This new project is intended to complement the previously obtained results by also considering the effects of true aerodynamic loading. Although mechanical shaker input enables a simple implementation of loads, aerodynamic loads provide a much more challenging dynamic input that will vary not only in amplitude but also in frequency. The following goals were achieved in T-133:

a) Application of smart materials (PZT ceramic actuators) in the active vibration control of smart beam-like (smart beam) and smart plate-like (smart fin) aerospace structures subjected to aerodynamic loading.
b) Development of passive and active (smart) beam and (smart) fin structural/ aerodynamic models by using finite element packages (MSC®/PATRAN/NASTRAN) and comparing the effectiveness of different modelling strategies.
c) Development of new control strategies by using $H_{infinity}$ control technique for the active vibration control of smart fins subjected to aerodynamic loading.
d) Theoretical and experimental verification of developed models based on testing to compare the effectiveness of the control strategies developed.

2. PARTICIPATING NATIONS, INSTITUTIONS/FACILITIES, INDUSTRİES

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3. MAJOR RESULTS

The response of the smart structures to aerodynamic loads was investigated by using the Finite Element Method. The PZT patches, which were originally modelled in T-121 and T-129 as solid elements by considering features of ANSYS®, were now modelled by the thermal analogy method and the new finite element models of the smart structures were obtained by using MSC®/PATRAN. Studies on active flutter suppression of the smart fin were performed. In order to obtain state-space representation of the aeroelastic model of the smart fin, the unsteady aerodynamic loads acting on the structure were calculated for a range of reduced frequencies and a Mach number by using a linear two-dimensional Doublet-Lattice Method available in MSC®/NASTRAN/Aeroelasticity-I, and the loads were extracted using Direct Matrix Abstraction Programme (DMAP) from MSC®/NASTRAN. Those discrete air loads were approximated as rational functions of the Laplace variable by using one of the aerodynamic approximation schemes, Roger's approximation, with least-squares method. By using the approximated air loads along with the structural matrices obtained with finite element method by using MSC®/PATRAN-NASTRAN, the state-space representation of the aeroelastic model was constructed for the smart fin. In order to verify the state-space approach, flutter characteristics of the smart fin were investigated with root-locus analysis by using the state-space model. The results obtained by the developed state-space approach were compared with the results obtained from the MSC®/NASTRAN/Aeroelasticity-I flutter solution, and very good agreement was observed.

After obtaining the state-space aeroelastic model of the smart fin, H_∞ robust controllers were designed for the flutter suppression of the smart fin by using piezoelectric actuation. Flutter control was performed in order to stabilize the system over a wide range of operating conditions and to attenuate disturbances throughout the operation envelope. The controllers were designed considering both SISO (Single-Input Single-Output) and MIMO (Multi-Input Multi-Output) system models. In the SISO case, it was considered that the smart fin was excited by all the PZT actuators on one face and the control input was the displacement of the upper corner point at the trailing edge of the fin, whereas MIMO system model was constructed by considering that the PZT actuators were grouped into two actuator sets, actuator groups 1 and 2, and the controller inputs were the displacements of two points at the upper two corners of the smart fin. The robust $H_{infinity}$ controllers for the reduced SISO and MIMO system models were designed at a flow velocity quite close to the flutter boundary by using MATLAB® μ-Analysis and Synthesis Toolbox. Theoretically the flutter speed of the fin (84.1 m/s) was increased to 89.1 m/s (6.0 % enhancement) for SISO model, and increased to 93.6 m/s (11.3 % enhancement) for MIMO model by using $H_{infinity}$ controllers.

Some wind tunnel experiments were also conducted. Two new robust $H_{infinity}$ controllers were designed. Controller 1 was designed to suppress the flexural vibrations mainly due to the first flexural mode by considering all PZTs at one face as one actuator. Controller 2, on the other hand, was designed to suppress the vibrations due to the first bending, first torsional and second bending modes by grouping the PZTs. The common design objective of both controllers was not to excite the higher order modes. During the experiments the smart fin was located inside the wind tunnel and exposed to both free stream and turbulent flow which was created by a tubular Von Karman vortex generator located up stream of the smart fin. In the free stream case, the velocity was varied from 10 m/s to 45 m/s with the smart fin orientated at 0° and 10° angle of attack (α) relative to the free stream. In the turbulent flow case, due to the high level of vibration caused by the vortex generator, the wind speed was varied from 10 m/s to 15 m/s only, at angle of attacks of 0° and 10°. The vibration of the smart fin was monitored by using two accelerometers, one located at the fin tip trailing edge and called the accelerometer 1 and the other at the mid-span leading edge designated as accelerometer 2. The designed controllers were implemented by using xPC Target Box. The experimental frequency response functions of the closed and open-loop systems were obtained. Both controllers achieved the desired performance levels and robustness properties.