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Active vibration control of a full scale aircraft wing using a reconfigurable controller

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ABSTRACT

This work highlights the design of a Reconfigurable Active Vibration Control (AVC) System for aircraft structures using adaptive techniques. The AVC system with a multichannel capability is realized using Filtered-X Least Mean Square algorithm (FxLMS) on Xilinx Virtex-4 Field Programmable Gate Array (FPGA) platform in Very High Speed Integrated Circuits Hardware Description Language, (VHDL). The HDL design is made based on Finite State Machine (FSM) model with Floating point Intellectual Property (IP) cores for arithmetic operations. The use of FPGA facilitates to modify the system parameters even during runtime depending on the changes in user's requirements. The locations of the control actuators are optimized based on dynamic modal strain approach using genetic algorithm (GA). The developed system has been successfully deployed for the AVC testing of the full-scale wing of an all composite two seater transport aircraft. Several closed loop configurations like single channel and multi-channel control have been tested. The experimental results from the studies presented here are very encouraging. They demonstrate the usefulness of the system's reconfigurability for real time applications.

1. Introduction

Vibration is an undesirable energy, which can sometimes lead to aeroelastic instability like flutter, when it interacts with unsteady aerodynamic forces. Flutter can affect the performance, stability and safety of an aircraft, eventually leading to catastrophic destruction. Vibration in aircraft can also induce fatigue; create unwanted noise; besides causing discomfort to the passengers. One has to resort to vibration control methods in order to ensure structural and vehicle safety. Hence, design of vibration control systems for aircraft in particular is important and has to optimize the structural parameters such as size, weight and volume. The cost of such systems decides the use/induction of such systems on an aircraft. Until the Micro-controllers/DSPs/FPGAs became cost effective solutions, passive control techniques were preferred methods for the control of aircraft vibrations. However, passive solutions are not very efficient in the low frequency band vibrations, which are most often seen in aircraft/helicopters etc. AVC systems are therefore more suitable in 0 to 500 Hz range, helping to minimize the undesirable effects due to external disturbances. Subsequently reduced structural vibrations can lead to enhanced fatigue life as well as flutter margin, which also ensure the safety of the aircraft structures. Such AVC systems are generally designed using analog as well as digital filters. With the advent of cost effective electronic devices like Micro controllers/Digital Signal

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Processors (DSPs), design of efficient AVC systems has become feasible by exploiting the digital filters. The modern controllers are software reprogrammable, namely Micro controllers/DSPs and hardware reprogrammable in case of FPGAs. FPGAs have an added advantage of saving lot of cost due to reconfiguration feature; otherwise similar situations would have required redesign of the entire system in passive control systems. FPGAs are compact in size and weight, which are very much the requirements in aircraft domain, though they are an order of magnitude costlier than the conventional passive systems. AVC systems rely on the principle of super position in which primary vibration levels are controlled by actively superimposing anti-vibration forces in the opposite phase [1,2]. The use of conventional electro-dynamic or hydraulic actuators for structural control applications is not suitable due to their volume and weight. Application of smart structures with built in actuation, sensing and control capabilities leads to weight/volume optimized active control systems. Thus the advancements in the field of "Smart Structures" have ushered in change of approach to control system design. In the initial years, the piezoelectric (PZT: Lead Zirconate Titanate) based actuators and Poly Vinylidyne Flouride (PVDFs) have been used in the control of vibration using feedback control strategy in military and aerospace applications [3]. There have been studies leading to the design of active flutter suppression systems using classical control concepts such as root locus approach, as well as modern control technique [4–6]. In mid 1990s, the monolithic piezoelectric actuators have been used in feedback control strategy using LQR algorithm for flutter velocity enhancement on a composite wing [7]. Supersonic panel flutter control using piezoelectric patches as actuators/sensors in collocated configuration has been demonstrated by feedback control [8]. The monolithic piezoelectric patches (single layer/or bender forms) have limitations in terms of induced strain ($\sim$0.1 to 0.2%), block force ($<$10 N) and they are brittle in nature. In multi-layered form, the PZT based stack actuators develop higher dynamic forces ($\sim$1000 to 10,000 N) with limited stroke ($\sim$10 to 200 μm). The integration of these stack actuators onto wing type structure poses many mechanical related issues, which may reduce the actuator performance, in case of any free play. However, PZT patches are good for sensing and hence they are surface bonded on the wing structure to collect its dynamic responses. Developments in the smart structure field have led to the availability of Macro Fiber Composites (MFCs) [9], which are capable of imparting relatively higher forces ($\sim$200 to 400 N) required to drive full-scale aircraft structures. MFC is a piezoelectric based composite patch actuator, in which rectangular piezo fibers are embedded in a polymeric matrix system (Epoxy) and then it is packaged with finger electrodes and environmental protective layers on both sides. Hence they are chosen as control actuators. The charge signals acquired using PZT sensors are conditioned before being acted upon by a controller in the digital domain and the output is fed back to the structure using Digital to Analog Converters (DACs)/MFC actuators to cancel the vibration. Nevertheless the characteristics of the vibration source, the control system path and environment may be time varying. In order to take care of this scenario, adaptive implementations of active techniques are required, since these are self-adjustable in tracking the system dynamics [10–13]. Tichy and Sommerfeldt [14] have successfully illustrated the use of adaptive control for the control of vibration isolation mount.

In case of adaptive control based AVC Embedded electronic systems, use of Least Mean Square (LMS) algorithm is the most suited due to its simplicity and ease of implementation. A feed forward tapped delay line structure is preferred, which can provide significant reduction in selective disturbance of each and every mode of vibration. This is achieved by the introduction of 'secondary' sources into the system along with the original 'primary' sources, which will lead to a modification called Filtered- X (input) LMS (FXLMS) [15]. Initially system identification is performed to identify the impulse response of the structure under consideration. Then control parameters are adaptively updated by incorporating the identified secondary filter in the input signal path to the control filter. Adaptive systems are capable of being tuned to the variations in the secondary sources and can provide optimal control over much broader range of conditions. Adaptive control using modifications of the basic LMS algorithm has been successfully applied by various researchers for achieving active noise control [16,17].

In large structures like the wing, fuselage, tail etc., single channel control will not be appropriate to achieve good control. In such circumstances, one has to resort to multichannel control methods, in order to control several low frequency modes. The FXLMS algorithm can be easily extended to realize a multichannel control system with suitable modifications to the equations. In multichannel control, several sensors are used to acquire the responses and many control actuators are employed in loop to impart the control signals into the structure. This requires computationally complex calculations.

The embedded adaptive AVC controller design should consider the complexities involved in the design of multichannel systems. Simulation studies for multichannel control using LMS based control algorithm have been reported [18]. During the years 1980–2000, DSPs became more popular for designing the controllers. In DSPs high performance computing challenges are addressed using software pipelining techniques and these are effectively implemented in multichannel vibration control applications [19]. In spite of this, the ultimate execution in DSPs is serial in form in terms of hardware. This poses limitations. A high performance Application Specific Integrated Circuit (ASIC) hardware design is one alternative, providing high throughput and low power consumption. However, ASIC does not have design flexibility and consumes longer design cycles [20]. The availability of FPGAs at reasonably low cost and fast development in 90 nm technology has made it feasible and cost effective to design controllers using them. In this situation, FPGA design is getting more attention due to its flexibility of achieving better performance than using general purpose DSP processors, leading to shorter design cycles.

FPGAs offer high performance and are having highly reconfigurable parallel hardware architecture [21–23]. The FPGA based controller system can be implemented by using high level software tools such as Lab VIEW graphical programming environment with National Instruments Compact RIO system [24], MATLAB™/Simulink™ environments with Xilinx System Generator [25] or C/C++ algorithm on a Soft-core processor such as Micro Blaze [26]. However, in these controllers, either