A PIEZO-ACTUATED CLOSED LOOP MEMS SYSTEM FOR ACTIVE DELAY OF TRANSITION

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ABSTRACT

This paper presents the design, fabrication and application of a highly integrated closed loop MEMS system for an active control of aerodynamic flow instabilities across airfoils. A special piezo-polymer-composite (PPC) technology was used for the fabrication of powerful piezo-microactuators that were integrated with hotwire flow sensors and a digital control system. This work shows first wind tunnel experiments that prove the principal suitability of the developed device for dampening disturbances in the boundary layer. The local amplitudes of natural disturbances, so called Tollmien-Schlichting (TS) waves, have been reduced by 42%.

KEYWORDS

Piezo actuators, active transition control, TS waves

INTRODUCTION

The active delay of transition has been a major topic in aerospace research throughout the last decades. Boundary layer instabilities (TS waves) in 2D airfoil boundary layers can cause a transition from laminar to turbulent flow, which increases the drag significantly. By launching an opposed surface wave into the boundary layer, the amplitude of the TS waves can locally be reduced and hence, the transition from laminar to turbulent flow can be delayed [1]. Current research uses loudspeakers which displace a flexible membrane to create a counter wave in the boundary layer [2,3]. These experiments have been successful but the approach using loudspeakers is limited regarding its miniaturization potential. For creating a traveling surface wave, an array of downstream cascaded actuators is desired. Loudspeakers cannot be cascaded as densely as required, what creates the need for a new, miniaturized actuator concept.

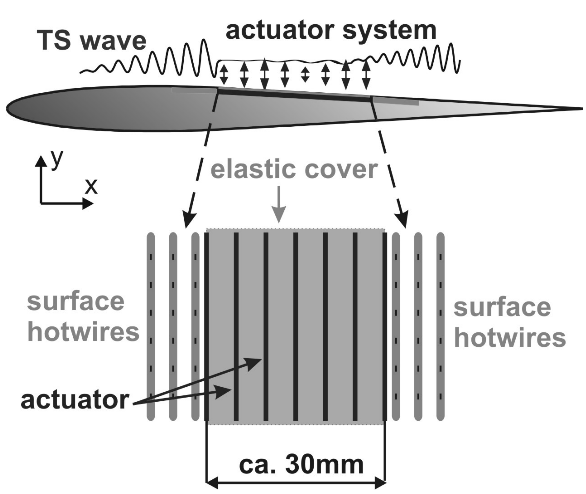

Figure 1) Principal desired setup for active cancellation of TS waves with hotwire sensors, elastic cover, and cascaded actuators within one wavelength of a TS-wave.

Active delay of transition demands a combined sensor-actuator system to detect the TS wave pattern and to cancel them by a suitable wave-like movement of the wing surface. The principal setup is shown in Figure 1. The amplitude of the TS-waves is increasing while traveling downstream across the airfoil. An array of hot wire sensors detects the incoming TS waves. Downstream of the first sensor array (reference sensor) an actuator system is placed. This system locally displaces an elastic cover. In order to induce a real traveling surface wave into the boundary layer, several actuators that are cascaded within one TS wavelength (in the performed experiments typically in the range of a few cm) are needed. Downstream of the actuator system, at least one further sensor (error sensor) is necessary. This sensor measures the success of reducing the disturbance amplitudes and feeds back the information to the control. A schematic of the control principle is shown in Figure 2. The control uses a filter based approach (finite impulse response, FIR [4]) to calculate an actuator signal that minimizes the signal amplitude of the error sensor. As the TS-waves occur randomly, the calculated transfer function of the control for driving the actuator has to be continuously adapted.

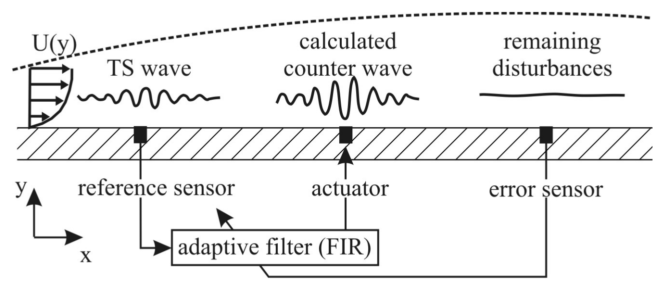

Figure 2) Schematic of control principle [5].

As a first step within this project, an actuator prototype has been developed that consists of only one piezo-polymer-composite (PPC) actuator. The goal is to prove the principal suitability of the PPC technology for active delay of transition. This paper presents the development of this prototype and its evaluation in first wind tunnel experiments. Based on the gained experiences and insights, a system with cascaded actuators, like outlined in Figure 1, will be developed in a next step.

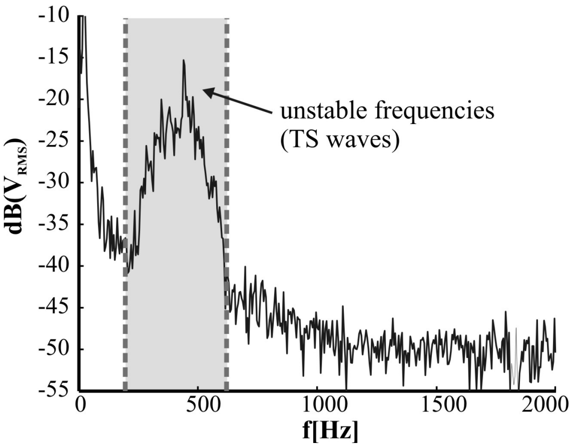

Figure 3) Characteristic spectrum of the examined TS-waves for a wind tunnel velocity of 20m/s.

PPC-ACTUATOR

The requirements on the actuator are defined by the application and the experimental setup. For active control of transition an actuator is needed that fulfills a variety of specifications. The working range depends on the frequency range of the incoming TS waves, which is determined by the flow velocity in the wind tunnel and the pressure distribution across the airfoil. A typical power spectrum for the presented experiments is shown in Figure 3. The instable frequencies (TS waves) are between 200 Hz and 600 Hz, which therefore is the required working range of the actuator. Within this working range it must be possible to displace the actuator very precisely. As the velocity amplitudes of the actuator must be in the range of 10% of the velocity fluctuations in the boundary layer (approximately up to 1m/s), an actuator velocity of 0.1m/s is required. This corresponds to an actuator stroke in the range of 100µm. A small phase gradient within the working range is mandatory. As the actuator has to displace a flexible cover, also the force of the actuator becomes a determining parameter.

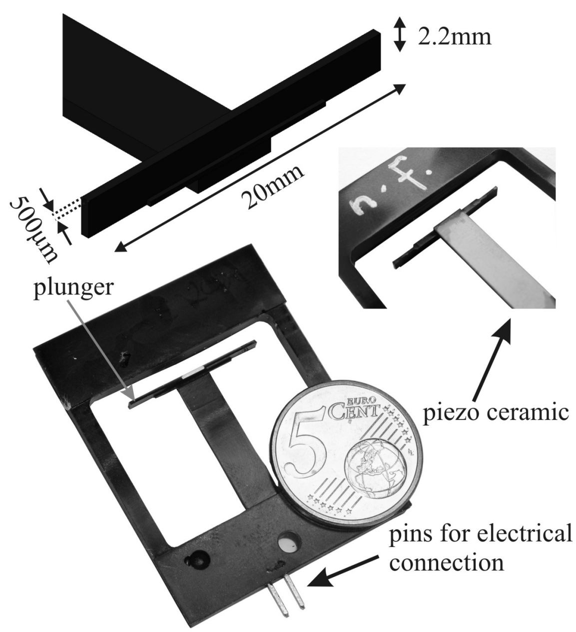

Figure 4) Photograph of fabricated PPC-unimorph actuator with piezo ceramic and plunger.

Actuator Design

For the prototype, the chosen actuator principle is a unimorph actuator made from a bilayer of piezo ceramic material and epoxy polymer. The beam has a length of 20mm and a width of 5mm. The piezo ceramic layer (VIBRIT1100 from Argillon) has a thickness of 260µm. The polymer layer is 840µm thick. At the tip of this bending beam a spanwise 20mm long and 0.5mm wide plunger is realized. The plunger is needed for locally displacing the flexible cover. As it acts as a kind of seismic mass for the actuator, it must be as light-weight as possible. A photograph of the fabricated actuator is shown in Figure 4.

The actuator is designed and fabricated using the piezo-polymer-composite (PPC) technology. The piezo ceramic is casted with a liquid polymer (epoxy resin Stycast 2057). This technology allows for high design flexibility, fast design changes, and excludes the need for a glue layer between the piezo ceramic and the composite layer. Using PPC technology the very fragile plunger can easily be fabricated together with the actuator within the same fabrication step. The PPC technology was first proposed by Friese et al. [6], first applications are presented in [7,8].

Actuator Characteristics

The measured frequency response of the fabricated actuator for different applied voltages is shown in Figure 5. In order to achieve the required stroke, an excitation voltage of $300V_{pp}$ is needed. The resonance frequency of the actuator is 700 Hz. It is not possible to drive the actuator at the resonance frequency with high voltages, as this would cause a permanent damage of the

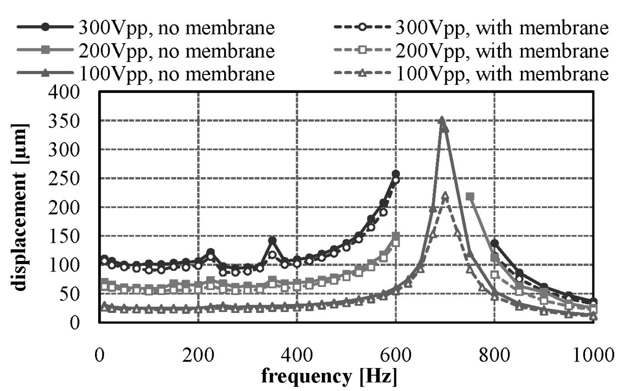

Figure 5) Frequency response of fabricated PPC unimorph actuator without and with membrane.

actuator, due to its low dampening coefficient (D ≈ 0.008). At 1/3 and 1/2 of the mechanical actuator resonance frequency, peaks in the frequency response can be observed. These peaks result from the hysteresis effect of the piezo material. The actuator is driven by a voltage source. The excitation voltage is mono-frequent, but the hysteresis of the piezo material between applied voltage and resulting charge leads to higher harmonic oscillations inside the signal of the current. These higher harmonic oscillations of the current are at least 20dB smaller than the signal at the excitation frequency. However, if the higher harmonic oscillation is at the mechanical resonance frequency of the actuator, it is mechanically amplified and becomes visible in the actuator movement. A control method that removes the higher harmonic oscillations is currently being developed.

Figure 5 also shows the behavior of the actuator when displacing a 70µm thick silicone membrane. This membrane has only very limited influence on the actuator behavior. The static displacement of the actuator is reduced by about 5 %, the resonance frequency is increased to 710 Hz.

SYSTEM IMPLEMENTATION

The actuator is glued beneath a printed circuit board (PCB) with dimensions of 700 mm x 500 mm. This PCB has a 25 mm x 3 mm large opening for the plunger. Additionally, the top layer of the PCB is structured in such a way, that small cavities for the flow sensors are cascaded upstream and downstream of the opening. The flow sensors are 5µm thick hot wire surface sensors that are welded across these small cavities. They are connected using galvanic vias at the rim of the PCB. On top of the PCB, across the opening for the plunger, a 70µm thick membrane is attached. The membrane is fabricated by spin coating liquid silicone (PDMS, Elastosil® M4642) onto a silicon wafer. The thickness of the membrane can be adjusted by adapting the spin velocity. After curing the PDMS, the membrane can be removed from the wafer and cut into the desired size. The plunger of the beam is glued to the membrane, which allows the actuator to push the membrane upwards and pull it also downwards. Figure 6 shows the complete system.

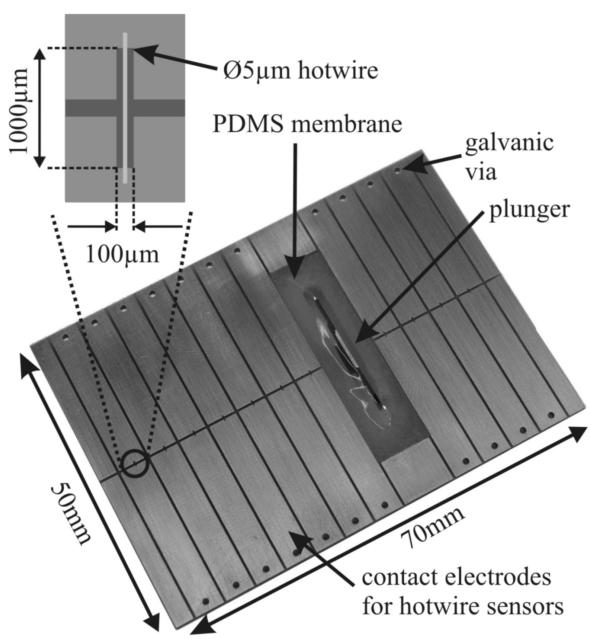

Figure 6) Complete system for active delay of transition with PCB, actuator, membrane, and hot wire flow sensors.

This integrated system can now be implemented into an existing wind tunnel test setup. The device is laminated into an aluminum plate that fits into the airfoil model. A DSP collects the data and drives the actuator. A high voltage amplifier is necessary to create the driving voltages. Different control algorithms can be used to achieve a maximal attenuation of the local TS-waves amplitudes. The presented results are gained by using a filter based control (FIR), already introduced in the first section. The signal of the error sensor is minimized using the least mean square (LMS) algorithm. For further experiments a model predictive control (MPC) based scheme is currently being developed [9]. This MPC will be able to predict the downstream progression of the incoming TS-waves and to calculate the required opposing travelling wave of the actuator system only based on the upstream sensor signals (reference sensor). Additionally, the MPC can control an array of cascaded actuators (as shown in Figure 1) individually, which is mandatory for creating a traveling wave.

EXPERIMENTAL RESULTS

At the beginning of the wind tunnel tests, a controlled experiment was performed. A known, mono-frequent disturbance was induced into the boundary layer by loudspeakers positioned in the airfoil upstream of the developed device. Despite the artificial disturbance, the boundary layer has to remain laminar at the position of the sensor-actuator system. As the disturbance is mono-frequent and known, it is less challenging for the control to calculate the needed counter wave. This controlled experiment enables a principal verification of the functionality of the developed device itself. In this test the amplitude of the RMS value of the error sensor was reduced by about 60 % when turning on the control. The chosen error sensor was situated 30mm downstream of the plunger.

After proving the general functionality of the developed device, experiments with natural TS waves have been carried out. The gained results are shown in Figure 7. The upper graph presents the obtained RMS value of the error sensor. The values are normalized with respect to the

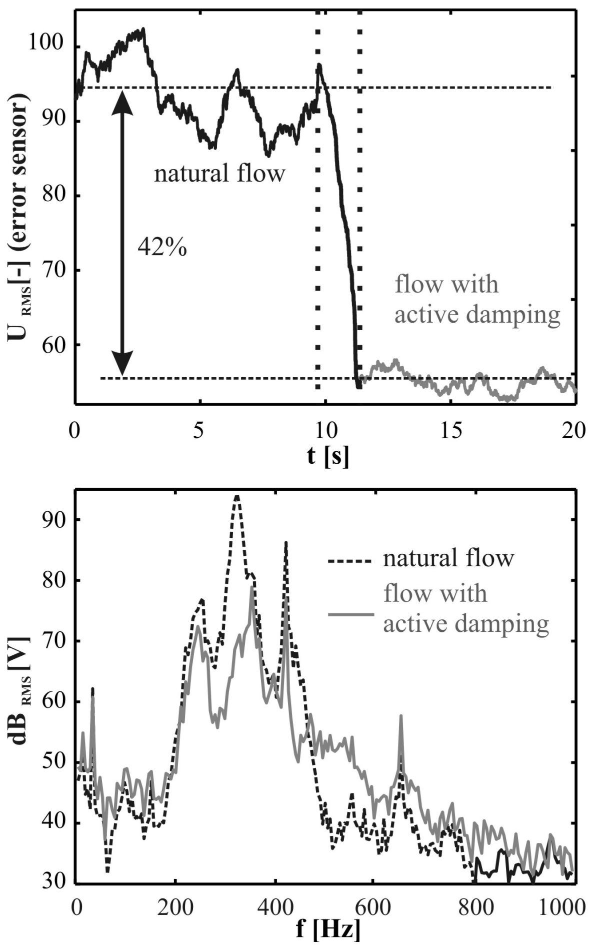

Figure 7) Sensor signal of hot-wire sensor 30mm downstream of the actuator for natural TS waves; top: RMS signal; bottom: frequency spectrum.

measured signal when the wind tunnel is shut down. After running the experiment 10 s without control, it is switched on and the actuator generates the counter waves. This leads to a significant reduction of the RMS value by 42%.

The lower graph of Figure 7 presents the amplitude spectrum of the same error sensor. Without active control, the spectrum shows the characteristic unstable area of TS waves between 200 Hz and 500 Hz. Turning on the control causes a distinct reduction of the frequency spectrum within the unstable frequencies.

CONCLUSION AND OUTLOOK

Due to the advantages of the piezo-polymer-composite technology it was possible to develop a well working prototype actuator within a short period of time. The actuator shows a sufficiently high quality regarding performance, strength and controllability. First wind tunnel experiments prove the capability of PPC actuators in combination with the developed system to suppress natural TS waves and hence, to enable an active delay of transition across an airfoil. Next, the actuator will be extended step by step to a system consisting of cascaded actuators (see Figure 1) which will allow launching a traveling surface wave with a wavelength in the range of TS waves into the boundary layer. This will enable a reduction of the local amplitudes of the TS-waves across a certain area and therefore enhance the attenuation performance of the integrated system.

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