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ADAPTIVE SECONDARY PATH FOR ADAPTIVE CONTROLLERS IN LAMINAR BOUNDARY LAYER CONTROL

B. Simon, T. Nemitz, S. Grundmann
Center of Smart Interfaces, Technische Universität Darmstadt, Germany

J. Rohlfing, F. Fischer
Institute for System Reliability and Machine Acoustics SzM, Technische Universität Darmstadt, Germany

D. Mayer
Smart Structures Division, Fraunhofer Institute for Structural Durability and System Reliability LBF, Darmstadt, Germany

INTRODUCTION

Starting with the first investigations on the attenuation of artificially induced harmonic Tollmien-Schlichting (TS) waves with the DBD plasma actuator (PA) by Grundmann [3], the control algorithms for this kind of flow control have been developed further over the years. While the numerical investigations mainly focussed on model based control techniques [1], the experimental community mostly used adaptive control algorithms such as the fxLMS [6]. The use of adaptive algorithms for wind-tunnel and flight experiments is based on the robustness of the control algorithms and their ability to adapt to slight changes of the flow parameters which results in changes of the growth rates and propagation velocities of the disturbances in the boundary layer.

Active flow control in future technical applications will have to cope with changing flow conditions and should work reliably over a certain range of operation conditions. The presented work demonstrates the extension of the range of operation of an fxLMS controller by adapting the impulse response $\hat{H}_{ec}$ of the previously identified secondary path H_{ec} during operation.

SETUP AND CONTROL THEORY

The experiments have been conducted on a 1,600 mm long flat plate with a free stream velocity of the Blasius boundary layer U_∞ varied from $8\,\mathrm{m/s}$ to $17\,\mathrm{m/s}$. Figure 1 shows the experimental setup of the 2D experiment. A broad band disturbance is generated by a disturbance source d, as described in [2]. Three surface hot wire sensors (p, r and e) capture the induced velocity fluctuations as they propagate downstream. A single DBD plasma actuator c is placed between the reference sensor r and the error sensor e. By modulating the amplitude of the PAs AC operating voltage, the generated body force can cancel out the artificially created disturbances by superposition [4]. The adaptive fxLMS algorithm (sketched in Figure 1) is implemented on a digital signal processor (dSPACE).

Before running the controller, the secondary path H_{ec} has to be identified by modeling the impulse response, measured at the error sensor e introduced by the plasma actuator c, with a FIR filter. This modeled transmission behavior of the boundary layer is changing with U_∞ as shown in Figure 2. The shape of the curves in Figure 2 stretches in time for lower flow speeds due to the decreasing phase speed. Another observation is the changing amplitude. The disturbances grow faster at higher free-stream velocities, which can be explained by linear stability theory.

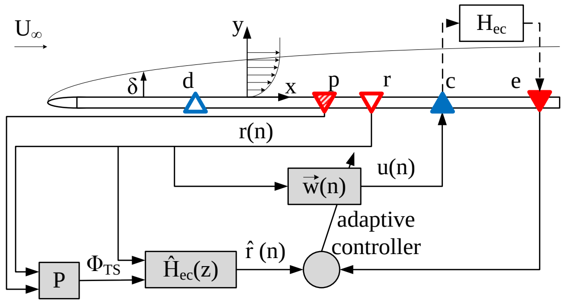


Figure 1: Flat plate setup, equipped with a disturbance source d, two upstream sensors p and r, the plasma actuator c and a downstream error sensor e. The extended fxLMS controller is sketched below the flat plate.

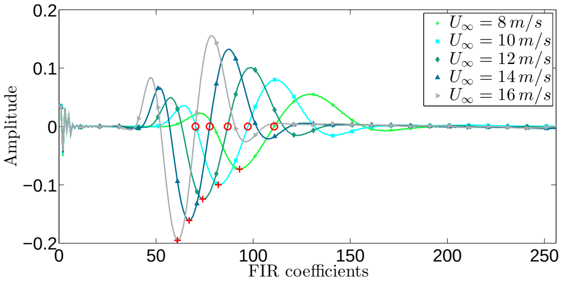
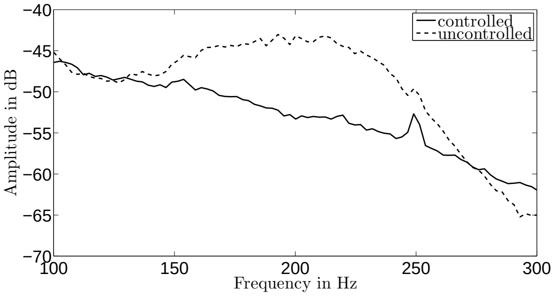


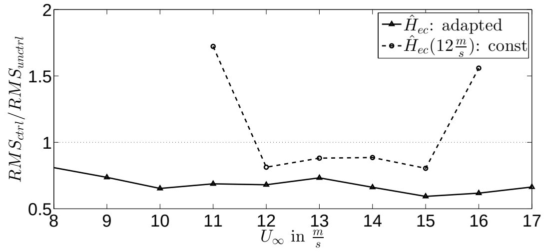
Figure 2: Impulse response of the secondary path $\hat{H}_{ec}$ for different flow speeds. The red circles mark the characteristic zero crossings while the red crosses show the global minimum of each curve.

Figure 3(a) shows the spectral results of the wave cancelation with and without control for broad banded disturbances. There is a significant reduction of the error sensor signal of about 10 dB in the TS-wave band (130 Hz to 270 Hz). On the other hand it is noticeable, that the plasma actuator causes additional disturbances in frequencies above and below the TS-wave band. These disturbances are damped by the band-pass behavior of the flow further downstream and do not effect the stability of the boundary layer significantly.

The stability of the basic fxLMS control algorithm is based on $\hat{H}_{ec}$ as a model of the boundary layer transmission behavior. Because of its ability to adapt, the control algorithm also works well with slight changes of the flow velocity but becomes unstable for larger velocity deviations (dashed line in Fig.3(b)). If the transfer function $\hat{H}_{ec}$ is adapted online corresponding to the current U_∞, the velocity range with a successful cancelation of disturbances can be increased significantly (solid line in Fig.3(b)).



(a) Power density spectra of the error sensor signals for controlled/uncontrolled case at $U_\infty = 12\frac{m}{s}$



(b) Error sensor signal reduction/amplification based on the RMS ratio of the controlled ($\mathrm{RMS}_{\mathrm{ctrl}}$) and the uncontrolled case ($\mathrm{RMS}_{\mathrm{unctrl}}$) for a broad banded amplification at different free stream velocities U_∞. The dashed curve shows the classic fxLMS approach while the solid curve shows the controller operation with adapted secondary path $\hat{H}_{ec}$.

Figure 3: Error sensor signals for flow control cases

During the experiments $\hat{H}_{ec}$ is adapted by stretching and scaling the reference impulse response $\hat{H}_{ec,\mathrm{ref}}$, based on characteristic points. This approach is depicted in Fig. 2: The zero crossing (red circle) is a measure for the temporal stretching while the global minimum (red cross) is the characteristic parameter for the amplitude scaling. As a comparison Fig. 4 shows stretched and scaled impulse responses $\hat{H}_{ec}$ for $U_{\infty,\mathrm{ref}} = 12\,\mathrm{m/s}$ and the corresponding measured curves. The presented procedure matches the shape of measured impulse responses quite well. It is updated every second during the controller operation in the experiment. This also allows a dynamic adaption to changing flow conditions.

ADAPTION OF THE SECONDARY PATH BASED ON WALL BOUNDED MEASUREMENTS

Other than based on the free-stream velocity, the adaption of the secondary path $\hat{H}_{ec}$ can also be done based on the measurement of the two wall mounted sensors p and r by calculating the phase shift Φ between the two sensor signals. Φ changes with U_∞ because of a change in the phase speed of the disturbances [5]. This technique allows to adapt $\hat{H}_{ec}$ based on signals measured locally by wall mounted sensors other than based on the free-stream velocity. Therefore it predestinates its use for flight experiments, where not only U_∞ but also the pressure distribution can vary in time. The phase shift Φ catches the phase speed of the disturbance by implication and therefore adapts the controller based on the phase speed (propagation speed) of the disturbances. This is an important feature because the wave cancelation success mainly depends on the correct phase angle relation between the disturbance and the counteracting force. An algorithm for the phase shift detection has been implemented successfully and it runs parallel to the fxLMS controller. The achieved attenuation rate does not differ from the experiments with an adaption of $\hat{H}_{ec}$ based on U_∞ (cmp. Fig. 3(b)), which proves the robustness of this method.

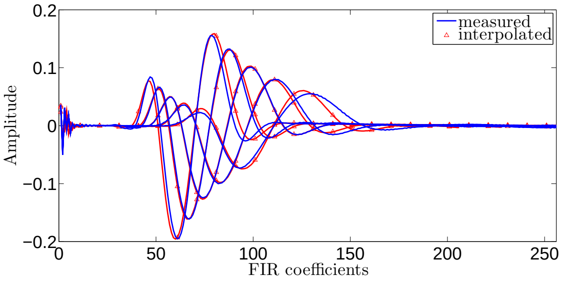


Figure 4: The impulse responses $\hat{H}_{ec}$ are calculated by applying the stretching and scaling factors, based on the reference case $U_\infty = 12\frac{m}{s}$ (cmp. Fig. 2).

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