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EXPERIMENTS ON ACTIVE CONTROL OF TOLLMIEN-SCHLICHTING WAVES: CANCELLATION BY WAVE SUPERPOSITION AND SPACE-TIME TRANSFER FUNCTIONS FOR FEEDBACK LOOP

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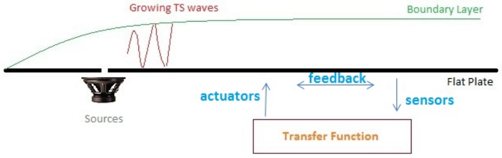
INTRODUCTION

Amplification of Tollmien-Schlichting waves is one of the paths of transition and this can be delayed by controlling the linear stage of disturbance amplification. In this study, growing three-dimensional TS waves are artificially excited using speakers in a Blasius boundary-layer and an active closed-loop control mechanism is attempted downstream. The control-loop consists of actuators and sensors connected in feedback as shown in Figure 1. Hot-wire measurements are taken in the 3ft x 3ft low turbulence wind tunnel on a 1.5 m long flat-plate model with an elliptic leading edge and dual trailing edge flap.

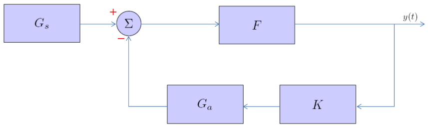
Figure 1: Schematic of the set-up.



FEEDBACK CONTROL

The controller is being designed based on the simulation models [1] of the system because is no straight-forward way to get the numerical-model directly from linearised Navier-Stokes equations. The feedback control loop [6] for the current approach is shown in Figure 2.

Figure 2: Control loop.



- G_s: Original Unstable wave generated by the source
- G_a: Cancelling waves generated by actuators.
- K: Controller
- F: Krohn-Hite Filter
- $y(t)$: Residual time signal measured by sensors
- It can be shown that:

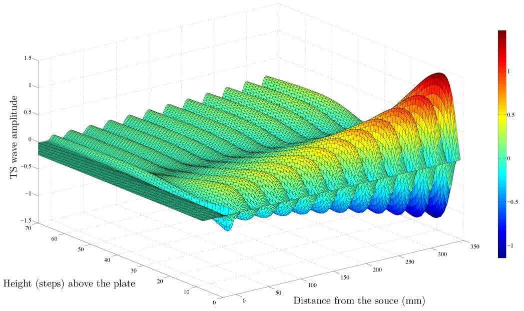
$$Y(s) = (I + F \times G_a \times K)^{-1} \times (F \times G_s) \qquad (1)$$

where I is the identity matrix of the order of the number of number of sensors.

NUMERICAL RESULTS

In order to design experiments carefully, some numerical calculations have been performed in MATLAB. These are crucial for designing the source location to excite TS waves, measurement of growth rates [2] etc. and they provide a sensible approach to determine placement of sensors and actuators for control of TS waves. Figure 3 shows a two-dimensional Tollmien-Schlichting wave generated by exciting a 2D source sinusoidally in the boundary layer. Details of the numerical scheme can be found in [4].

Figure 3: Growing two-dimensional TS wave at 150 Hz, $Re_{\delta_1}(source) = 875$.



EXPERIMENTAL RESULTS

Base flow

Initial experiments carried out are to ensure that the flap angle, incidence etc. are correctly adjusted in order to obtain flow conditions that are closely Blasius-like [3]. Figure 4 shows a comparison of boundary-layer profiles, growth and shape-factors with theoretical Blasius values.

Excitation of TS waves

A pin-hole (point) source of 1 mm diameter is excited sinusoidally using a mini-speaker buried into the plate to generate growing three-dimensional Tollmien-Schlichting waves. Figure 5 shows the rms amplitude of the normalised streamwise

Figure 4: Flow at 12 m/s, $X = 450(15)885$ mm. Left: Boundary-layer profiles vs Blasius; Right: Boundary-layer growth and shape factors.

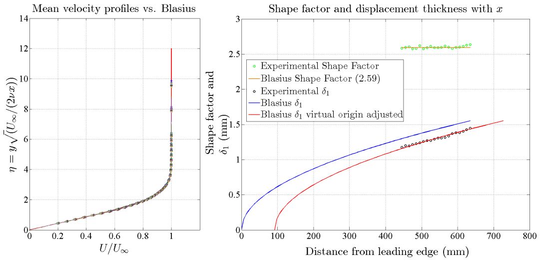
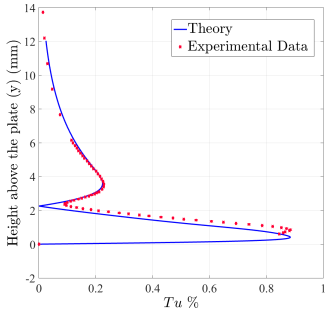


Figure 5: TS wave: experiment vs theory (16m/s, $X = 520$ mm, 250Hz forcing).

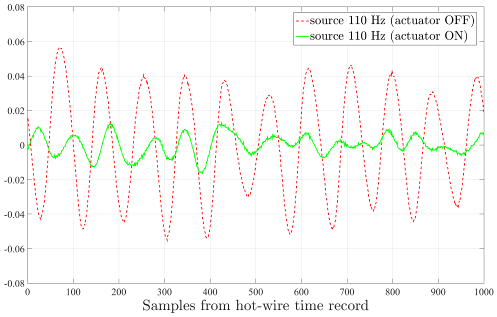


fluctuating velocity component (u') of the TS wave excited at 250 Hz after passing through a digital BP filter (narrow-band: 245 Hz to 255 Hz).

Open-loop control

Cancellation control [5] has been performed in a deterministic way using a single actuator ($X = 400$ mm) driven out-of-phase with the source ($X = 205$ mm) at the same frequency. A significant amount of attenuation is achieved as shown in Figure 6.

Figure 6: Control using one actuator out-of-phase with source at 12 m/s, measured at $X = 835$ mm, 0.2 mm from the plate (40kHz sampling frequency).



Feedback control

The space-time transfer functions between the source and sensor (G_s) and between the actuator and sensor (G_a) have to be obtained before designing the feedback controller (K). These are obtained by system identification using the traditional frequency sweep technique followed by fitting a transfer function using MATLAB to the Bode plot data. Bode plots of the transfer functions G_s and G_a measured at 12 m/s at a height of 1 mm above the plate are shown in Figures 7 and 8 respectively. Numerical simulations are being carried out to get optimal sensor-actuator configurations using the transfer functions G_s and G_a. These configurations will be tested in the wind tunnel for performance of the controller in real-time.

Figure 7: Bode plot of the transfer function G_s at $X = 697$ mm.

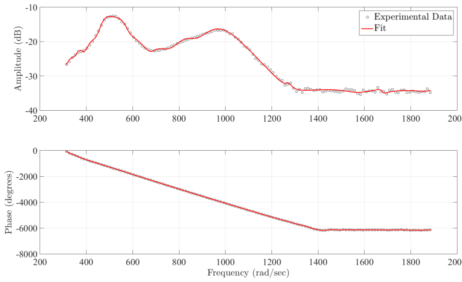
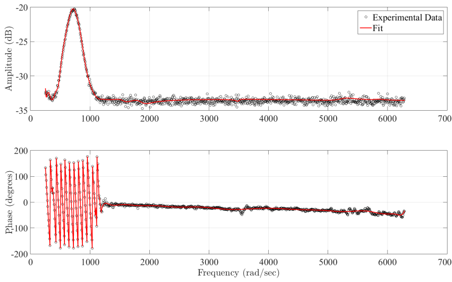


Figure 8: Bode plot of the transfer function G_a at $X = 800$ mm.



ACKNOWLEDGEMENTS

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