Learning from Dolphin Skin – Active Transition Delay by Distributed Surface Actuation

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Abstract. The goal of this project was the development of an active laminarisation method in order to reduce skin friction drag. Laminar-turbulent boundary layer transition on unswept two-dimensional wings is mainly caused by Tollmien-Schlichting (TS-) waves. Based on an actively driven compliant wall as part of the wing’s surface, a method for attenuation of these convective instabilities was developed. Different arrangements of piezo-membrane actuators were investigated with an array of highly sensitive surface flow sensors and appropriate control strategies. Spanwise differentiated and streamwise cascaded actuation were used as well as inclined wall displacement. The onset of transition could be shifted downstream by 100 mm or six average TS-wave lengths. Additionally, the investigation of the boundary layer flow downstream of the active wall area and an efficiency estimation are presented in this contribution.

1 Introduction

Depending on the Reynolds number, transition can cause a tenfold increase in skin friction. Since friction drag accounts for 50% of an aircraft’s overall drag, even a slight delay of laminar-turbulent transition towards a wing’s trailing edge promises a significant improvement. TS-instability waves, which are small, frequency-dependent velocity fluctuations, are responsible for transition on many two-dimensional flow configurations. Their streamwise amplification can be reduced by some kind of damping.

Natural role models provide motivation for the development of TS-damping methods. Dolphins are well-known for their low overall drag, which results, amongst other mechanisms, from a combination of body shape and their specific skin properties [4]. By a certain muscle contraction, blood pressure or temperature

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variation, these marine mammals are able to control local damping and compli-
ance of their surface. By coupling the oscillating boundary layer flow instabilities
to the damping surface, an energy transfer from the flow into the structure stabilises
the boundary layer. The first to demonstrate this effect was Gaster in 1988 [5].
Later Carpenter designed compliant coatings for transition delay and developed an
anisotropic plate-spring model of the surface [2]. One example is depicted in Figure
2(b). Maximum transition delay was obtained for one defined combination of spring
constant, damping coefficient and alignment relative to the flow direction.

The requirements for transition delay on an aircraft’s wing differ from water
flows, because Reynolds number and relevant pressure forces are not compa-
rable. The goal of the research project was the transfer of adjustable dolphin’s
skin properties to a wing in wind tunnel experiments by means of active wave
control.

In the course of the project, required active wall properties were determinated out
of base flow investigation. Slot actuator arrays proved to be unsuitable for producing
clean counter waves. Only with piezo-polymer membrane actuators transition could
be delayed. Since first unimorph type actuators could not be cascaded well, more
compact cymbal type actuation elements were developed. At the same time, signal-
to-noise ratio was improved and structural plus electronic coupling between sensors
and actuator elements was removed. Newly developed model predictive control al-
gorithms were applied.

2 Principle of Active Wall Damping

Dynamic stabilisation of transitional boundary layers has proved to be an effective
method of drag reduction in past research [8, 10, 9, 3]. Destructive interference of
naturally occurring boundary layer instabilities (TS-waves) and artificial counter
waves resulted in a significant delay of transition. While manipulating the fluctua-
tion profile of the boundary layer, the mean velocity distribution remains unmodi-
fied, see Figure 2(a). The counter waves were generated by discrete actuation strips
with intermediate sensors on the wing. In the project, the locally restricted actuation
method was meant to be extended towards large continuous ‘active compliant wall’
areas. Besides the enlargement of the actuation area, and thereby laminar flow re-
region, the power consumption decreases.

For the determination of appropriate wall deflections, the detection of oncoming
TS-waves upstream of the active wall was required, see Figure 1. The active wall
consisted of several streamwise actuator elements which are linked by one com-
mon and continuous surface membrane. Up to five actuator elements were cascaded
within one average TS-wave length. By deflection at different nodes, convective
travelling counter waves were generated and TS-control was not constricted to a
discrete position. The actuator-induced velocity fluctuation v’ was then transformed