LAMINAR-TURBULENT TRANSITION MECHANISMS OVER WIDELY-SPACED SUCTION HOLES

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Abstract

An experimental study was performed on a large array of discrete suction perforations mounted on a flat plate with no sweep. Suction is a useful technology for stabilizing laminar boundary layers, thus delaying the onset of transition to turbulence, and the associated drag increase. This study did not focus on the stabilizing effects of suction, but rather the destabilizing effects associated with localized flow fields around individual perforations.

Historically two distinct transition mechanisms have been identified associated with destabilizing suction or 'over-suction': which mechanism dominates is decided by the perforation spacing. In this study new insights are provided into the physical nature of the widely spaced 'over-suction' mechanism. In addition a second/new mechanism associated with widely spaced perforations has been discovered and the physical process of which is explained.

In summary, the pre-existing mechanism is dominated by secondary instability of counter-rotating vortices generated by the suction perforations. In the new mechanism, transition through 'over-suction' is governed by non-linear interactions between low frequency modes analogous to travelling cross-flow waves, generated by the suction and low frequency oblique modes generated by a resonant triad in an N-type transition process.

1. Introduction

With the growing danger associated with climate change, there is need for initiative to develop clean energy sources for use across all energy sectors. Energy supply for buildings can be made cleaner through the commissioning of renewable and carbon neutral power stations. In the automotive industry, electric drive systems are being developed to eliminate dependency on fossil fuels, however, for aircraft no suitable electric based power plant exists that can compete with fossil fuel derived gas turbine engines. As a result, in the aircraft sector: fossil fuel reduction must be obtained by alternative means.

Drag reduction technologies are considerably more developed than electric power plant systems for aircraft, and may help alleviate problems with their implementation, by lowering the design requirements for long distance flight. In this study, Laminar Flow Control (LFC) drag reduction technologies are described, with boundary layer suction being the focus of this work. LFC technologies operate by delaying the onset of transition to turbulence, where turbulent boundary layers are known to have significantly increased drag. Suction delays the onset of transition through two mechanisms, firstly it reduces boundary layer thickness, effectively reducing the Reynolds number of the wall bounded flow. Secondly, the suction effectively induces an accelerated flow, which is inherently stabilizing.

In the study of 'over-suction' there have been historically been two distinct avenues of research. The first was to study the flow field around isolated, or single rows of suction perforations to qualitatively study the underlying physics leading to transition [1,2,3]. The second involved varying critical suction parameters, to observe the effect on transition to turbulence, and develop a non-dimensional criterion to predict 'over-suction' for manufacturers [4,5,1,6]. The reason for two separate distinct sets of studies for qualitative and quantitative measurements, was due to the time required to both vary a great many critical parameters over a large number of values, and perform high resolution measurements over a large volume, with a long sample time.

MacManus and Eaton [2,7] developed a numerical model to study the quantitative model, and did measurements around isolated suction perforations to benchmark the model, and qualitatively study the physics of ‘over-suction’. Based on this study, the non-dimensional criterion proposed by Goldsmith [6] was proposed as the best tool for predicting the onset of ‘over-suction’. However, Butler [8] predicted that in for suction perforations on a swept wing, the sweep would interact with the counter-rotating vortices, turning them into co-rotating vortices, which may interact with the stationary waves, in the cross-flow transition process that occurs over swept wings.

In the presented study, the widely spaced ‘over-suction’ mechanism identified by MacManus and Eaton [7] is expanded upon with the addition of information regarding the spectral content of the flow during this type of ‘over-suction’ process. The interaction between a pre-established transition front and the physics of ‘over-suction’ has not been covered in the literature: transition fronts have been simply used as a means of quantifying ‘over-suction’ in parametric studies, investigating critical suction criteria. For this reason, and because the transition front will be close to the leading edge in an actual wing, where LFC is to be applied: the effect of a nearby transition front on the mechanism of ‘over-suction’ is a main subject of this research.

2. Experimental Apparatus and Methodology

In this study a flat plate which will accept insert panels is used as the basic flow model. A perforated insert panel is used and mounted flush with the rest of the plate to act as the suction media for this experiment. This perforated panel had 1313 600μm diameter perforations. The suction is driven by a pump, though suction has been achieved and tested using natural pressure difference. A flow-meter is used to measure the suction mass-flow through all perforations. The flat-plate is mounted in the Gaster low turbulence wind-tunnel at the national wind-tunnel facility at City, University of London. This tunnel had a turbulence intensity of approximately 0.014% with the flat plate mounted inside the test section and a filter range of 2 to 5000Hz, on the output from the hot-wire anemometer.

All measurements were performed using hot-wire anemometry, and a point exciter was used to both fix the transition front and perform phase reconstruction of the hot-wire signal. This exciter consisted of a loudspeaker mounted in a cavity with a single perforation as an outlet directly into the boundary layer. Sinusoidal forcing was used predominately, and this exciter was located 150mm upstream of the insert panel. Two microphones were also used for phase reconstruction, one was mounted on the surface of the model, downstream from the suction perforations, the second was mounted inside the suction plenum. A two-element flap was used to achieve small adjustments to the pressure gradient, and to move the stagnation line onto the measurement side of the model.

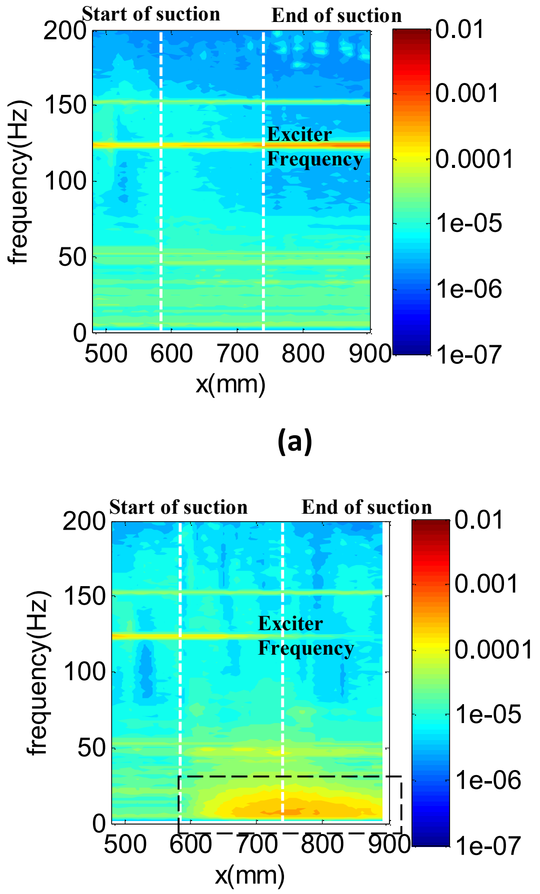
Volumetric and planar measurements were performed to map the flow-field around the perforations. Volumetric measurements were performed to identify three-dimensional structures associated with ‘over-suction’ and stream-wise planar measurements were performed to capture rapidly changing stages of the transition process, in a practical amount of facility time. A slanted-wire was used for measuring the stream-wise velocity in some cases. This was used in conjunction with a straight wire to resolve the two components. The slanted-wire was rotated such that the length of the wire was perpendicular to the free-stream for calibration using the Pitot-static tube. King’s law was used for the calibration. The slanted-wire was rotated back such that the wire was at 45 degrees to the free-stream direction for measurements. Care was taken to ensure that the alignment of both sensors was consistent, however, alignment in the wall-normal direction is most likely to contain errors, due to the need to repeat the near-wall alignment procedure for the second hot-wire probe.

In terms of methodology the premise of these experiments was originally to introduce an unstable wave into the flow using the point exciter, and see how it would interact with different suction rates.

3. Results and Discussion

During the course of this investigation it was found that at high suction rates, the excited wave did not become immediately unstable, and bring the transition front forward. It was found that for increasing suction, while the unsteady flow-field could be described as linear, that the excited frequency was consistently attenuated. The negative consequence of increasing suction rate instead manifested as a low frequency disturbance that increased proportionally to the amount of suction applied. This low frequency can be seen in Figure 1, where it is highlighted with a hatched black box.

This low frequency was observed to decay exponentially, immediately downstream of the suction perforations, suggesting that the low frequency disturbance was damped downstream of the suction array. For this reason, when limited to the study of linear TS-waves, the low frequency disturbance is not harmful to the transition process. This changes however, when a non-linear process is concerned. In the literature there are several paths of transition. For two dimensional flows, the process that dominates most commonly is N-type transition [9]. The non-linear interaction in this mechanism is characterized by the presence of resonant triads consisting of a fundamental and an oblique pair with a frequency symmetrical abour the fundamental's sub-harmonic. This mechanism was discovered by Kachanov [10] and was studied in greater detail by Kachanov and Levchenko [11].



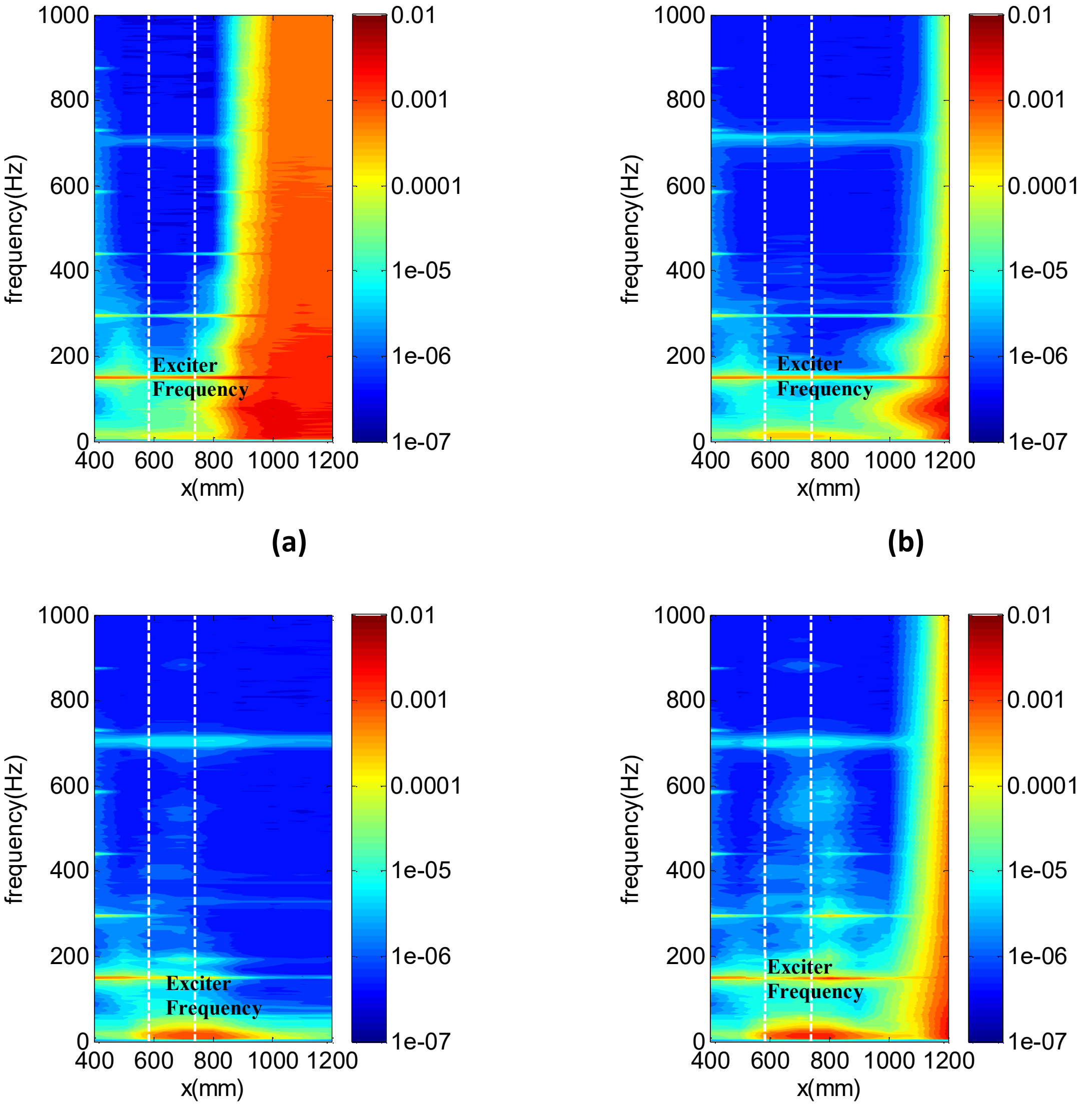
(a)

(b)

Figure 1: Spectral energy plots showing comparison between no suction (a), and a case with moderate (C_s=4.5E-5) suction (b). Free-stream velocity is 14m/s.

Figure 2 (a) shows a case with no suction but with a transition front fixed using a point exciter. Ttransition process resembles N-type closely, in that high spectral energy spreads from the sub-harmonic of the excited with increasing distance from the leading edge. This is characteristic of N-type transition. In Figure 2 (b), a small amount of suction is applied, the beginning and end of the suction array is marked with white dotted lines. It can be seen that the transition front moves backward upon application of suction. Here it the spread of energy from the sub-harmonic is even clearer, in addition, a lower frequency disturbance (comparable with the disturbance in Figure 1) has developed.

In Figure 2 (c) the suction has been sufficiently increased for the transition front to disappear, however, the low frequency disturbance (introduced by suction) has grown in amplitude and downstream extent. In Figure 2 (d) the amplitude of the low frequency is sufficiently high to cause the transition front to move forward again. Here it can be seen that the transition front spreads from the sub-harmonic of the excited mode, which is energized by the low-frequency introduced by the suction. Some high frequency bands can be seen to appear between 200 and 650Hz, at this suction rate, however, these appear to dissipate completely before reaching the transition front. The possibility of this low frequency interaction is very significant for practical application of suction, as suction is only useful if used in the context of a pre-existing transition front, otherwise there would be no transition to delay.



(a) (b)

(c) (d)

Figure 2: The effect of increasing suction rates on flow with a fixed transition front through sinusoidal forcing at 145Hz. Two suction rates are shown (a) shows the case with no suction holes, (b) shows a case with Cs=0.7E-5, (c) shows a case with Cs=5.4E-5, and (d) shows a case with Cs=7E-5. Free-stream velocity was fixed at 14m/s. White lines mark beginning and end of suction.

If the case where there is no forcing is considered, it is found that transition to turbulence undergoes a different process. The main consequence of no forcing, is that there is no pre-established transition front before boundary layer suction is initiated. As there is no or minimal oblique sub-harmonic energy without the resonant triad, there is no resonant interaction between the low frequency and other low frequency waves. Instead, the high frequency dominates the transition process; the formation of a transition front due to saturation of these high frequency modes is shown in Figure 3. It can be seen that the high frequency content that forms the basis for this transition front has a consistent frequency band between Figure 3 and Figure 2, the only difference being an increase in amplitude or spectral energy as a result of the higher suction rate in Figure 3.

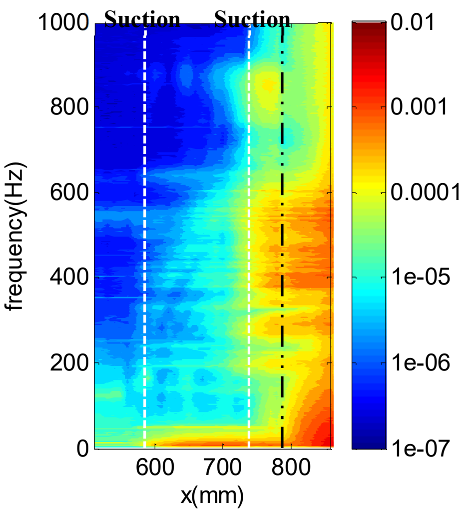
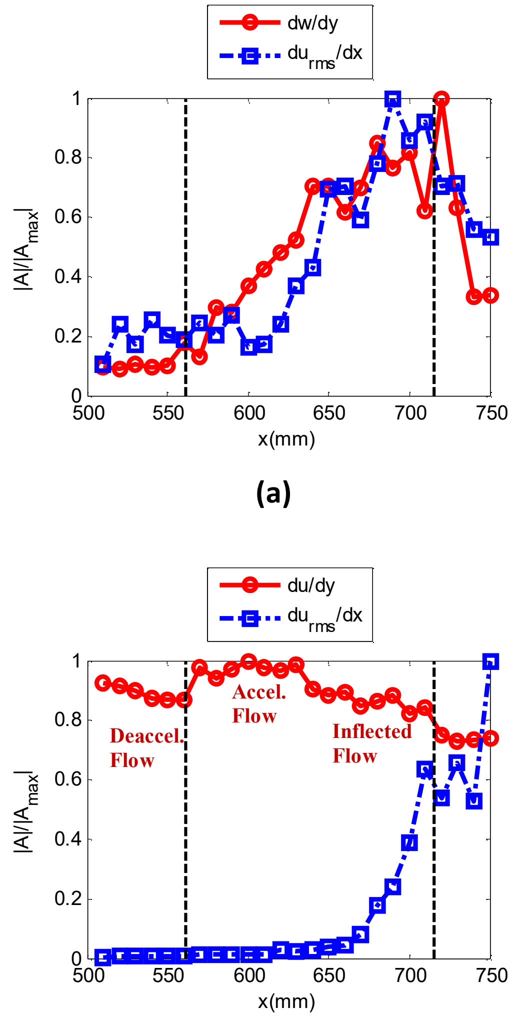


Figure 3: Spectral plots illustrating growth of high frequency and associated transition in the absence of acoustic forcing. Free-stream velocity was fixed at 14m/s. Cs=8.72E-5.

The generation of the low frequency disturbance has been linked to inflection of the span-wise velocity component, ‘w’, along the wall normal, ‘y’ within the counter-rotating vortices shed from individual suction perforations. This is highly analogous the mechanism of travelling cross-flow waves, which are believed to be of similar character and classifiable as primary waves.

The generation rate of the low frequency can be strongly correlated with inflection points along the wall normal ‘y’. maxima in the derivative of the span-wise velocity ‘w’ with respect to ‘y’ correspond with these inflections. Figure 4 (a) shows the growth rate of the low frequency waves alongside magnitude of ‘dw/dy’, it can be seen that changes in growth rate of the low frequency rates correlate very well with changes in span-wise velocity gradient ‘dw/dy’. This suggests that the low frequency is generated by the inflection point in ‘w(y)’.



(a)

(b)

Figure 4: Rate of growth of 1-30Hz (a), and 400-600Hz (b) unsteady modes, compared to the strength of inflections in the span-wise velocity across the wall-normal. Ue=14m/s. Cs=9.85E-5.

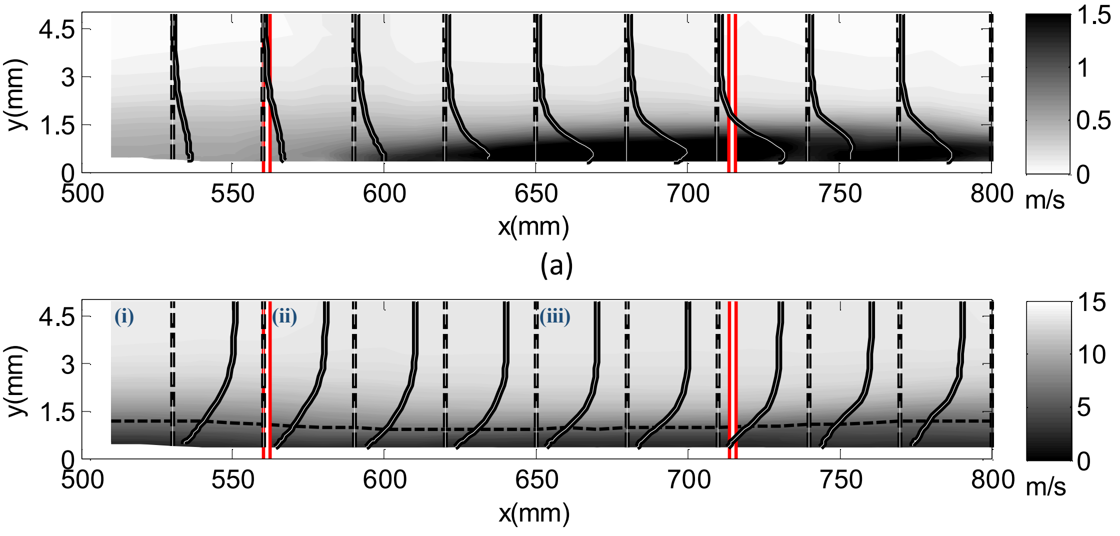
Similarly, growth of the high frequency (400-600Hz) waves can be correlated with inflection of the stream-wise, ‘u(y)’, velocity profiles. This can be seen in Figure 4 (b), in this plot the strength of inflection is calculated as the sum of the derivative of ‘u(y)’ across ‘y’. Again the normalized gradient with respect to the ‘y’ normal is plotted, it can be seen that at first the mean profile is gradually deaccelerated as the integrated velocity gradient decreases.

Upon reaching the start of the suction array it can be seen that the integrated maximum (‘du/dy’) increases, this corresponds with the flow accelerating towards the boundary: producing a favorable pressure gradient locally.

Further downstream the maximum starts to gradually decay, alongside it the high frequency modes grow exponentially. This shows that when the stream-wise velocity profile ‘u(y)’ becomes inflected, the high frequency is amplified. At this stage in the mean flow profile, inflection points are clearly distinguishable, and it is clear that this gradual decrease is not due to an adverse pressure gradient.

Figure 5 shows the mean velocity profiles associated with the trends shown in Figure 4. These profiles shapes are super-imposed upon contours of mean velocity, the dotted black and white line marking the origin of each profile with respect to distance from the leading edge ‘x(mm)’. The dotted horizontal black line denotes the displacement thickness. Figure 5 (a) shows profiles shapes that are consistent with other external boundary layer flows with cross-flow velocity. Inflection points can be seen as the result of the profile decaying to zero velocity in the free-stream. Upstream of the suction array, there is a small residual span-wise, ‘w’, velocity. This residual could be caused by upstream effects of the suction, or conduction effects due to the hot-wire being in close proximity to a metal plate, these effects would be more significant than in stream-wise velocity measurements due to the relatively small velocities being measured.

In Figure 5 (b) it can be seen that the boundary layer thickness is gradually increasing, within close proximity to the suction array, after which it decreases until the center of the suction array, further down-stream the boundary layer thickens again. The velocity profile at station (i) appears to be similar to members of the Falkner-Skan family, once the suction array is reached, at (ii), the profile, becomes more rounded as momentum is brought lower into the boundary layer.



(a)

(b)

Figure 5: Plots of mean velocity flow profile development along the wall normal ‘y’, comparing the span-wise ‘w’ (a) and stream-wise ‘u’ (b) components. The profile shapes are super-imposed on contours of mean velocity. The red/white lines mark the beginning of suction. Stations (i), (ii), and (iii) show the deaccelerating, accelerating, and inflected profiles associated with Figure 4 (b). The black dotted line represents displacement thickness.

Close to the end of the suction array (iii) the profile starts to become inflected. The behavior at these three stations is consistent with the growth of the high frequency (400-600Hz) shown in Figure 4 (b). It is noted that the inflection is not as severe as reported in MacManus and Eaton [2], this is believed to be due to the use of a large array of widely spaced perforations, because experiments performed with a single perforation, within the presented study, find inflected profiles that compare better with MacManus and Eaton [2]. It is believed that this is due to more severe distortion of the mean-flow being required to trigger an 'over-suction' based transition mechanism when using a single perforation. This is due to more localized growth of turbulent kinetic energy in the strongly non-linear regime being more rapidly dissipated to surrounding low energy laminar flow.

4. Conclusions

The result of this study is that two separate transition mechanisms have been found associated with 'over-suction' when using widely spaced perforation configurations. The first, which has little basis in the literature, is due to interaction between oblique waves generated as part of a resonant triad in N-type transition, and low frequency waves generated by inflectional span-wise 'w(y)' profiles along the vortex core.

The second mechanism which dominates in absence of a transition front, has some basis in the literature, but a complete understanding was lacking. This mechanism as reported by MacManus and Eaton (2000) is due to inflectional stream-wise velocity profiles 'u(y)' appearing behind the vortex core. This study has shown that the inflectional profiles amplify high frequency waves, and that the overall transition process bears resemblance to cross-flow transition. Evidence suggests that inflectional stream-wise profiles only develop once the vortices grow sufficiently large to saturate, and produce a non-linear interaction. This is contrary to the proposition from MacManus and Eaton (1996) that the inflection point simply moves upward in the boundary layer the further down-stream the vortex develops.

5. Acknowledgements

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