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Investigation of the Discrete Effects of Suction in Large Scale Arrays for Laminar Flow Control

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An experimental investigation of the destabilising effects of discrete suction perforations for laminar flow control applications was performed. This research was aimed at investigation of the flow physics of large arrays of discrete perforated suction arrays in globally two-dimensional flows. This research also investigated the effect of varying perforation size, free-stream velocity and suction volume flow rate on the amplification and attenuation of excited travelling waves in a two-dimensional laminar flow. It was found that instead of creating local instabilities that destabilise all frequencies, strong suction had the effect of introducing low frequency disturbances while attenuating naturally produced and excited travelling waves for all test cases considered. If the suction was sufficiently strong these low frequency disturbances would appear to dominate over the stabilising effect of suction (on the natural and excited modes). Possible explanations for these disturbances include viscous or acoustic disturbances located within the suction system. Future experiments will attempt to isolate the effect of the plenums to determine if this is the source of these low frequency disturbances.

Nomenclature

A	=	Amplitude of travelling wave
A_0	=	Amplitude of travelling wave at baseline no suction case
C	=	Chord length
PSD	=	Power Spectral Density
v_A	=	Average velocity through suction surface
U_e	=	Free-stream velocity
d_h	=	Perforation diameter
f_k	=	Exciter frequency
u	=	Mean velocity component (averaged in time)
u_f	=	Fluctuating velocity component
u_{mean}	=	Average of mean velocity component across all span-wise stations
x	=	Displacement from origin in stream-wise direction
z	=	Displacement from origin in span-wise direction
δ_1	=	Displacement thickness

I. Introduction

SUCTION in the form of mass flow through the surface of an aerodynamic body is an effective and relatively mature means of laminar flow control. It stabilises the boundary layer and prevents transition in two ways: it reduces the boundary layer thickness which lowers the Reynolds number, and it alters the shape of the velocity profile (and its derivatives) making it stable up to a higher critical Reynolds numbers.[14] This improved stability characteristic is predicted by linear stability theory for the case of perfectly homogenous suction, where the suction is assumed to be uniformly distributed across the aerodynamic surface. However, in practice this is not feasible to design as real surfaces must be porous and therefore discrete and non-uniform.

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Historically, discrete suction has taken three forms: porous media, slits/slots, and surface perforations.[5] Porous media consists of woven fabrics or meshes where air can permeate through gaps in the weave; these gaps tend to be less than 100μm in equivalent diameter. Porous media best represents the concept of homogeneous suction as represented in the theory, because of the small pore sizes and spacing present. Researchers found that it cannot easily support structural load and tends to clog with dust and ice particles in flight, reducing its porosity over time.[5] Slots and slits were favoured as a form of discrete suction through the 1950's and 1960's because of the relative two-dimensionality of their local flow fields, and their better aerodynamic performance compared to perforated surfaces.[5,10] However, the largest issue associated with implementation of slots and slits is their effect on the structural strength of the aircraft skin; as they induce large structural stress concentrations and are highly susceptible to fatigue failure. Perforated surfaces are very similar to porous media, in that the suction permeates through locally three-dimensional pores or perforations. However, perforations tend to be much larger than pores and have much wider and more structured spacing/patterning. Historically suction perforations were closely spaced and relatively large (between 0.5mm-1.5mm in diameter); but in recent studies small perforation diameters of 50μm-100μm have been used.[1,2,6,13] The implication of larger gaps, in comparison to porous media, is that they are less likely to fill and clog with particulate. The smaller perforation sizes used more recently require specialised manufacturing techniques and suffer from particulate problems similarly to porous media.[2,13] For relatively large hole diameters, perforated surfaces present a problem, in that, their size causes discrete effects which introduce localised instabilities which may overcome the useful stabilising effects of suction.[4,5,8] As a result there has been considerable study to identify the exact nature of these instabilities, and characterise them such that they can be avoided in the design of suction based laminar flow control systems.[2,8,9,12]

Perforated surfaces have been found to destabilise the boundary layer through three currently identified mechanisms. The first two apply to (globally) two dimensional flows where it is assumed that there is no wing sweep. The first of these mechanisms is attributed to reversed flow behind the cores of counter-rotating vortices shed from individual suction perforations.[8] If suction is sufficiently strong the reversed flow behind the vortices will destabilise the flow and trigger premature transition to turbulence. This mechanism is suggested to dominate if the perforations are sufficiently widely spaced such that they do not interact with one another. The second mechanism is based on the interaction between closely spaced suction perforations where the counter-rotating vortices interact and link to form unsteady horseshoe vortices.[5] These vortices intermittently shed from the perforations and travel down-stream and trigger premature transition to turbulence. Research has shown that the optimal perforation spacing for such two-dimensional suction cases is either very closely spaced (typically less than 3 perforation diameters) or very widely spaced (typically greater than 10 perforation diameters).[3,6,12] In the closely spaced configuration it is suspected that localised suction velocities are more moderate, so that induced vortices are too weak to overcome the stabilising effects of suction. However, in the widely spaced configuration there are presumably no strong vortical interactions taking place between individual perforations. The third mechanism dominates in the case of globally three-dimensional flows (i.e. swept wing flows). Here, the counter-rotating vortices are affected by the induced span-wise pressure gradient, causing one vortex to grow, while the other is attenuated.[9] Thus, an array of suction perforations produces a set of co-rotating vortices, which interact with the existing cross-flow vortices [9] As far as the author is aware this mechanism has only been studied numerically by Messing and Kloker[9]. This work seems to suggest that the natural cross-flow vortices are attenuated by suction (under certain configurations) and suction induced co-rotating vortices dominate in the flow-field.

In relation to the study of these three mechanisms there remain some gaps in the literature: thus far there is no experimental work the author is aware of that verifies and explores the three-dimensional mechanism. There is also very little experimental research concerning the mechanisms that dominate in widely spaced perforation configurations, where the number of perforations is very large. Most research on large arrays of suction perforations focus on the effect that varying suction perforation parameters (e.g. diameter, spacing, array size, displacement thickness) has on the location of the transition front. The only research on the details of the flow physics in widely spaced configurations was presented by MacManus and Eaton[8]. However, only a small array of three large diameter perforations was studied in this experiment. Thus, additional research is required to extend findings from this research to large arrays. MacManus and Eaton[8] used Direct Numerical Simulation as a means to extend their findings to larger arrays using periodic boundary conditions. This may overlook previously unidentified mechanisms that manifest from practical design considerations for large arrays of suction perforations.

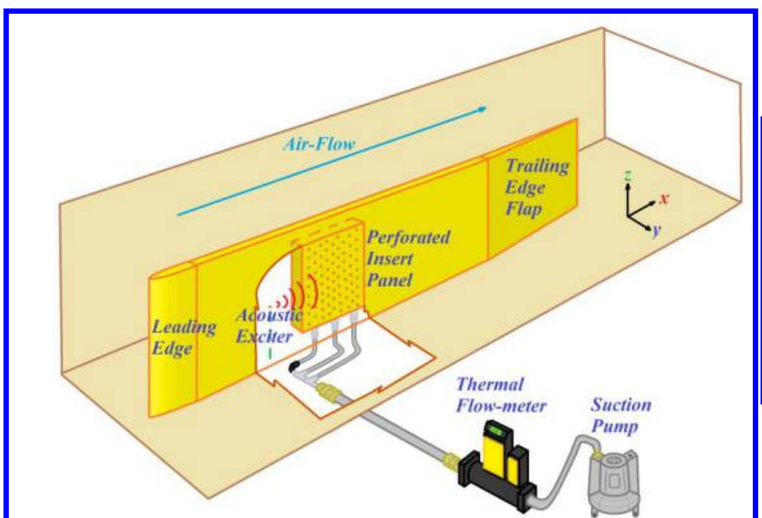
The purpose of the presented study is on the flow physics of large suction arrays where the perforations are widely spaced. These experiments may also serve as an experimental base-line for research into the destabilising effects of suction in globally three-dimensional boundary layers.

II. Experimental Apparatus and Methodology

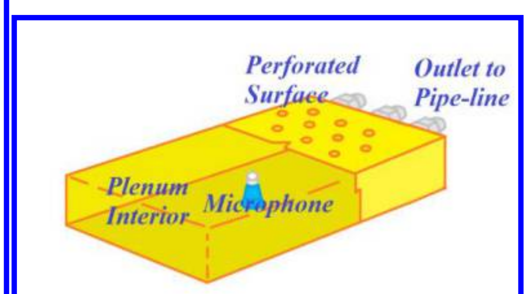
A. Experimental Apparatus

The experiments were conducted in the UK national low turbulence wind tunnel in the Gaster laboratory at City University London. This facility consists of a closed circuit wind-tunnel with interchangeable working sections and a turbulence intensity of 0.007% within the frequency band of 2Hz-2kHz. The apparatus for this experiment consisted of: a flat plate with a large opening designed for fitting test panels; perforated test panels with different hole diameters; an acoustic point exciter; a suction system; and a flowmeter (with an in-built solenoid valve) for measuring and controlling the amount of applied suction.

The flat plate is 1650mm long with a 1:14 elliptical asymmetrical leading edge. A trailing edge flap and trim tab was used to adjust the position of the stagnation point to avoid leading edge separation. A backing plate was used to hold the test panels and was fixed directly to the plate. This backing plate also consisted of a built-in suction plenum, which could be divided into three independently controlled plenums. The perforated test panels were inserted into the backing plate and fixed. Adjusting screws on the backing plate were used to adjust the height of the inserts. This was to remove any surface discontinuities between the plate and the test panels. *Plasticine* was used to fill any remaining gaps between the surfaces. In the current experiment a test panel with 1313 suction perforations of 0.6mm diameter was studied (see Figure 2 for details of array dimensions/geometries). A 750W_e Becker SV5.130/2 centrifugal pump was used to achieve suction, and an Aalborg GFC thermal flow controller was used to measure and control the total volume flow rate through the perforated test panel. The piping predominately had an internal diameter of 18mm but reduced to 8mm in some sections. The acoustic exciter was located 126mm upstream of the test panel. This exciter consisted of a loudspeaker mounted in a cavity inside the plate, with a 2mm hole linking the cavity to the surface of the plate where measurements are performed. Sound produced by the loud-speaker travels through the small hole and forms an outward wedge of oblique travelling waves which propagates down-stream to interact with the test panel. An amplifier was used to provide sufficient power to drive the loud-speaker. A general layout for this setup can be seen in Figure 1 (a). In later experiments, a microphone located inside the suction plenum, shown in Figure 1 (b), was used to investigate to possibility of acoustic or viscous disturbances inside the plenum. Figure 2 (a) shows the dimensions of the perforated insert panel used in these experiments: it includes additional information about the overall dimensions of the flat plate. Figure 2 (b) shows information about the nominal spacing and pattern of the suction perforations: the triangular pattern used is defined such that the base of the triangle is equal to its height. Triangular patterns were used as it has been reported that staggered perforation arrays are less susceptible to mechanisms of destabilising suction[5,12].

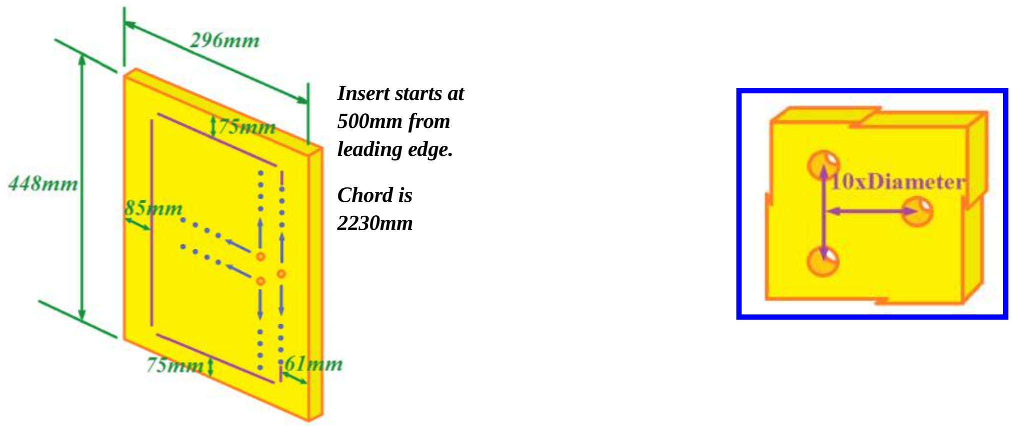


(a)



(b)

Figure 1. Overview of experimental apparatus for suction experiment: (a) shows test model with cut-away of suction system; (b) shows detailed view of plenum and perforated insert panel, and illustrates the mounting of the microphone.



(a) (b)

Figure 2. Details of experimental apparatus for suction experiment: (a) shows dimensions for the insert panel, (b) shows perforation spacing and pattern definition.

A *DISA Type 55M01* hot-wire anemometry system was used for taking point velocity measurements; this system consisted of a single wire boundary layer probe moved to different locations in the boundary layer by a three-dimensional stepper motor controlled traversing mechanism. 50,000 samples were acquired at a frequency of 10kHz per hot-wire measurement, with a low pass cut-off frequency of 5kHz and a high pass cut off frequency of 2Hz. A *Dantec* Miniature boundary layer probe was used, with a 5μm diameter, 1.5mm long sensor. A RTD temperature sensor was used to measure the ambient temperature inside the tunnel to account for drift in the hot-wire calibration; it was also used in converting the voltage signal from the pressure transducer to a pressure signal. A Pitot-static tube connected to the manometer was used to measure the free-stream velocity, which could be fedback to the fan when changing the free-stream velocity; furthermore, it was used in hot-wire calibrations.

B. Experimental Methodology

As constant temperature anemometry was used in these experiments the hot-wire probe had to be calibrated using the Pitot-static tube. This was achieved by moving the hot-wire probe into the free-stream and calibrating it to find the appropriate King's law coefficients. Laminar flow was ensured by changing the trim on the flap to ensure the stagnation point was on the measurement surface, and was verified using a stethoscope connected to a pressure transducer.

In previous experiments such as by Ellis and Poll[2], and Gregory and Walker[6] the change in transition front has been used as a measure of the stabilising and de-stabilising effects of discrete suction, and to parameterise these effects. In this experiment, the change in amplitude of travelling waves in an acoustically excited boundary layer is used as a measure as to whether suction has a net stabilising or de-stabilising effect in the boundary layer. This method involved first moving the probe down-stream of the test panel; velocity profiles are then measured for different free-stream velocities and perforation sizes, and total suction volume flow rates. This method was used as the transition front is difficult and time consuming to measure with great accuracy, as the region where high resolution span-wise measurements are needed changes as experimental test parameters are varied. To complement these single profile measurements larger stream-wise scans were taken along the centre-line of the plate to show the development and growth of induced and naturally occurring travelling waves. Span-wise scans were taken to observe stationary vortices shed from the suction perforations as reported by Gregory[5] and MacManus and Eaton[8] (see Figure 6). These scans consisted of measuring wall-normal profiles at multiple stations across the span.

After finding that low frequency disturbances were seemingly generated by the suction perforations (see Figure 3), further experiments were undertaken in an effort to determine the physical mechanism introducing these disturbances. Gregory[5] and MacManus and Eaton[8] have described mechanisms of destabilising suction governed by spacing of the perforations. In widely spaced configurations it was believed that the vortices shed from the perforations acted in isolation where inflectional velocity profile behind the vortex cores led to destabilising suction. It seems reasonable to assume that if this mechanism dominating: it would amplify travelling waves at all frequencies including the excited wave, which is consistently attenuated in the authors' experiments (see Figure 3).

In the closely spaced configuration described by Gregory[5] the vortices link up and periodically shed horseshoe/hairpin vortices downstream of the perforations. Therefore, it does not seem unreasonable to expect these vortices to be shed at low frequency. Based on data from Reneaux and Blanchard[12] the porosity of the plate was defined with a spacing of 10 perforation diameters between perforations to ensure that the widely spaced configuration was in effect. To confirm that the closely spaced mechanism was not in effect, the porosity was increased to 20 perforation diameters between perforations (See Figure 6). A microphone was used to check if there were low frequency disturbances inside the suction plenum that could relate to those found in the hot-wire measurements (see Figure 3 (d)).

III. Results and Discussion

Cases with and without suction are shown in Figure 3 (a), (b), and (c). These plots are the resulting spectral content of the flow after measuring a set of stream-wise velocity profiles across the plate. This data was Fourier transformed to show the distribution of energy across the frequency domain. Only up to 200Hz is shown, as little of interest was observed at higher frequencies. It can be seen in Figure 3 that as suction rate was increased, disturbances excited (or induced naturally) were attenuated, however, at low frequency (below 40Hz) disturbances appeared to be introduced or amplified by the suction. The low frequency distributed over the suction surface is strongest in Figure 3 (c), and absent in Figure 3 (a). There is a 20Hz tone in all cases: the source of this wave is unknown and is believed to be unrelated to suction as it was only significant, in amplitude, for the 18m/s case. These plots are representative of entire travelling wave profiles, as the maximum amplitude of the profile is displayed. Typically the amplitude of travelling waves increases towards the wall up until a maximum, after which it decays as a result of viscous effects. This maximum was found in Fourier space (see Figure 7 (d) for relevant illustration) and was used in Figure 3 to show the growth of travelling waves across the spectrum.

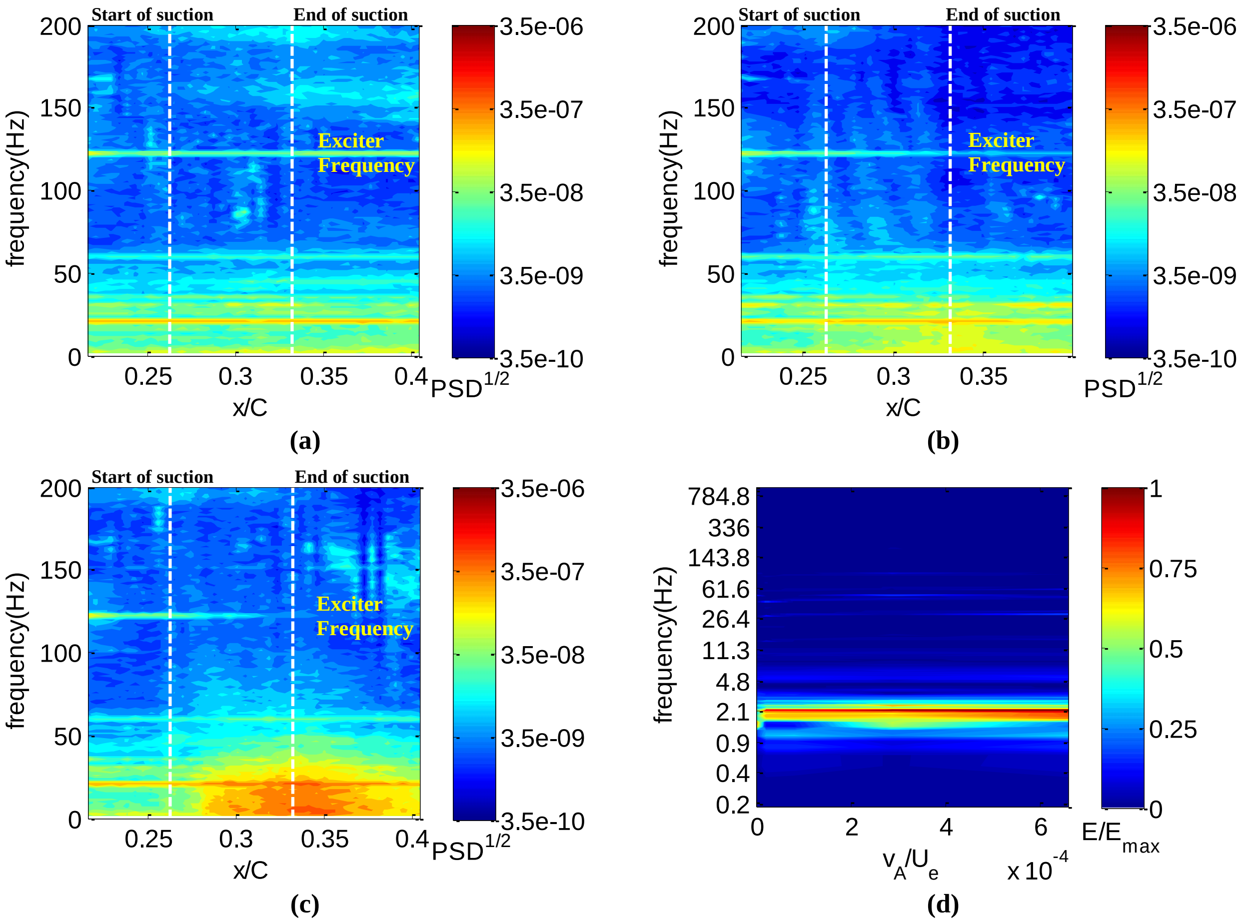
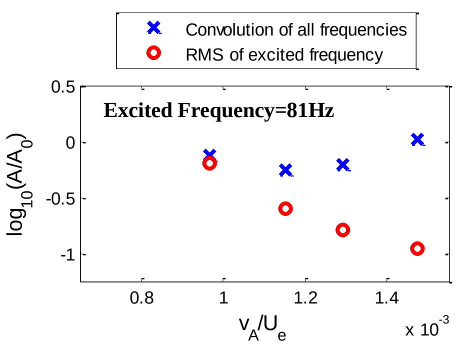


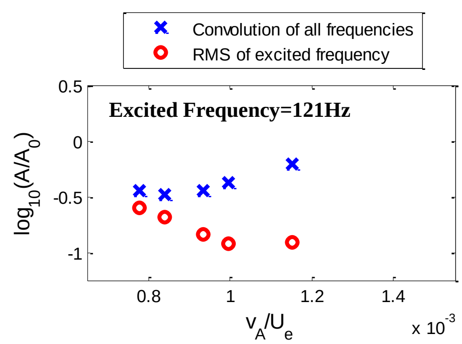
Figure 3. Power Spectral Density plots of Hot-wire and microphone sensors at z=0mm, Ue=18m/s, d_h=0.6mm, and fk=121Hz: (a) shows no suction with perforations covered, (b) shows v_A/U_e=0.0824E-3, (c) shows v_A/U_e=0.2886E-3 of suction, (d) shows microphone energy for different suction rates.

In Figure 3, it can be seen that these low frequency disturbances are spread across a relatively large frequency band, compared to typical travelling waves. This may suggest that this not a linear amplification problem in which existing disturbances grow because of the discrete effects of suction, but may instead be disturbances newly introduced into the boundary layer through interaction with the suction perforations. Thus, they may produce a strong near-field effect which may rapidly decay in the far-field. Figure 3 (d) shows the microphone energy for different suction rates: this microphone is mounted inside the plenum used to distribute low pressure across the suction perforations. The mounting of the microphone can be seen in Figure 1 (b). The purpose of the microphone is to see if any of the low frequency content in the mean flow can be related to similar low frequency energy inside the suction plenum. It can be seen in Figure 3 (d) that the strongest Fourier modes are at low frequency and increase only slightly in intensity with increasing suction rates. This increase is very slight and not strongly represented by the rest of the spectrum, as such it is difficult to make any strong conclusions based on this result.

Although Figure 3 (a), (b), and (c) only show single test case (only one perforation diameter and tunnel speed is shown) this low frequency disturbance is persistent across all investigated test cases, this can be seen in Figure 4 (for some cases). Figure 4 demonstrates how the amplitude of the disturbance field at a single point immediately downstream of the suction surface responds to increasing suction rate. Both the Root Mean Square (RMS) of the excited Fourier mode, and a convolution of all modes within the acquisition frequency band are presented. The former was determined using Fourier transformation of the time signal and computing the RMS of the excited Fourier mode. Most of this energy in the latter case is a accounted for through the excitation frequency and the low frequency disturbance. The RMS of the un-transformed hot-wire signal was used (to represent the strength of the low frequency disturbance) instead of a more direct convolution of the low frequency terms (in Fourier space) to reduce energy loss and discretisation errors in Fourier transforming the data, which would be required to digitally filter the signal. Single profile measurements were taken to facilitate large variation of dependent suction parameters, such that the relative effect of suction on the amplitude of travelling waves could be observed. The amplitude of the travelling wave for the baseline no suction case (A_0) is used to non-dimensionalise the amplitudes for various suction cases. It can be seen that there is a strong dependence on suction strength, and it appears that increasing suction does not have an adverse effect on the low frequency disturbance for very low suction rates.



(a)



(b)

Figure 4. Effect of suction on single profiles located at a fixed position down-stream (x/C= 0.3408) of the suction insert panel: (a) shows U_e=8m/s; (b) shows U_e=12m/s. A_0 represents the amplitude of the case with no suction and the perforations uncovered, and d_h=0.6mm for both cases.

Figure 5 shows the effect of relatively strong suction on the growth of the excited wave; contours of fluctuating velocity show the growth of traveling waves at the excited frequency without (a) and with (b) suction. This was obtained by determining the amplitude and phase of a single Fourier component at the excited frequency. The phase was determined by relating the phase of the hot-wire signal to the phase of the acoustic exciter signal. The blank region shown in Figure 5 is due to boundary layer growth. As the y-ordinate has been non-dimensionalised with respect to the displacement thickness, the first measurement point (far from the wall) drifts proportional to the inverse of the displacement thickness. Thus, the extent of these regions indicates the change in displacement thickness between the case with suction and without suction. In other test cases, such as those shown in Figure 3, this amount of suction is sufficient to introduce low frequency disturbances that are much larger in amplitude than the excited signal. However, Figure 5 shows that the excited frequency is still attenuated by suction irrespective of the presence of the low frequency disturbances. For different test configurations, it was consistently found that the higher frequency signals would be attenuated and the low frequency signal was amplified.

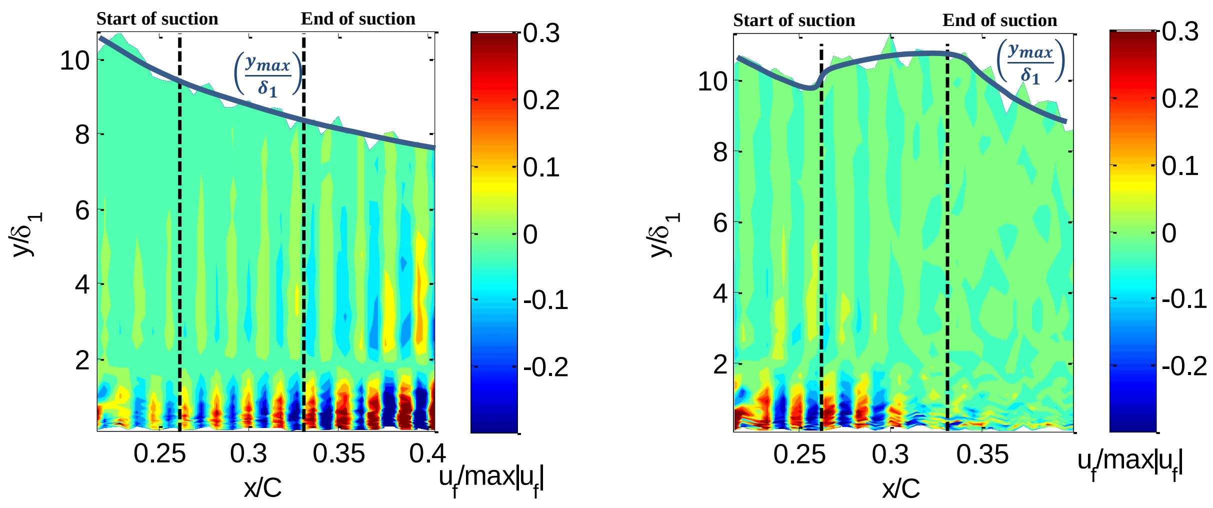


Figure 5. Scan of plate with 0.6mm perforations in the xy-plane, f_k=121hz, d_h=0.6mm, z=0mm, U_e=14m/s: (a) shows the case with no perforations, (b) shows suction for v_A/U_e=0.8480E-3.

Figure 6 shows the span-wise distribution of energy in the boundary layer, these measurements were taken downstream (at x=713mm) of the last row of suction perforations (located at x=711mm). A larger measurement domain was used in acquiring the results shown in Figure 6 (b), to show if the energy distribution was periodic for more widely spaced perforations. It can be seen that low frequency disturbances are not eliminated by increasing the spacing of the suction perforations: it could be argued that there is an increase in low frequency energy for the widely spaced configuration. This is likely a result of the same volume flow rate of suction being spread across a smaller number of suction perforations. This also seems to suggest that the closely spaced destabilising suction mode described by Gregory[5] is not in effect. As the spacing in the widely spaced configuration is far too large for such interactions to take place[3,12]. Furthermore, the increased spacing fails to diminish the strength of the low frequency disturbance. It also appears that the low frequency disturbances are convected downstream through the counter-rotating suction vortices.

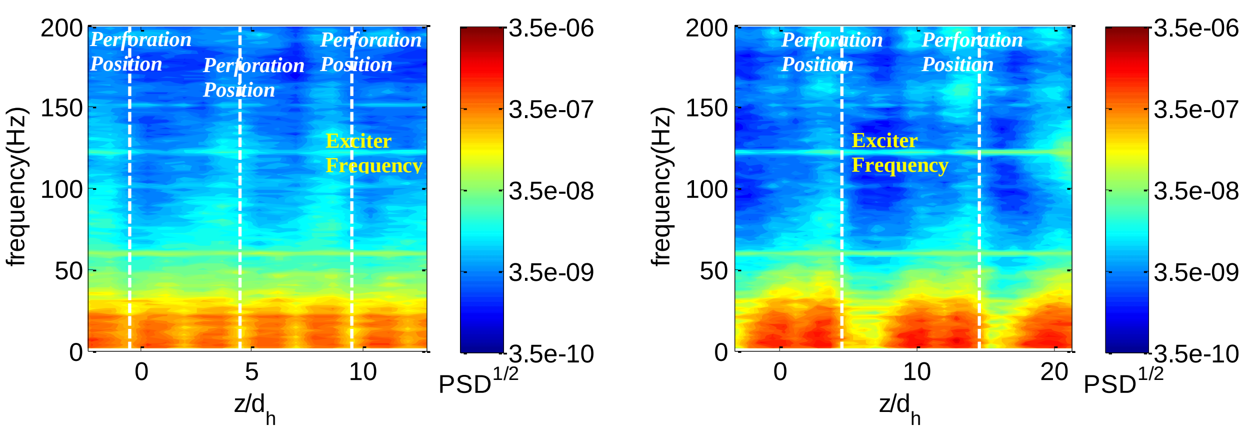


Figure 6. Spectral Energy plots for U_e=18m/s; v_A/U_e=0.1649E-3; f_k=121Hz; x/C=0.3197; and d_h=0.6mm: (a) perforation Spacing=10(d_h); (b) Hole Spacing=20(d_h).

Figure 7 shows the effects of strong suction alongside cases without the suction pump. The first no suction case (b) has a perforated insert mounted with no suction: the outlet pipe to the suction pump is simply disconnected and is at atmospheric pressure outside the wind-tunnel. In the second no suction case (c) all the suction perforations were covered with thin tape (*Scotch Magic Tape*, 0.060mm in thickness), the outlet of the suction plenum was also disconnected from the pump. It can be seen that in the case with the perforations covered (c), that there are no tones other than: from the acoustic exciter (121Hz), some very weak low frequency (perhaps caused by vibrations of the probe), and fundamental (50Hz) and odd harmonics (150Hz) of the mains supply.

The case with the perforations uncovered, in Figure 7 (b), shows that the low frequency band, from the case with suction (a), is still present but at reduced amplitude. This seems to suggest that this low frequency disturbance is unrelated to the unsteadiness of the suction pump, which could have been a source of low frequency flow oscillations. As the static pressure inside the tunnel, in the vicinity of the flat plate test model, is unlikely to be exactly atmospheric: it seems reasonable to assume that there will be a small volume flow through the suction perforations, even with the pump disconnected. This is believed to be the source of the low frequency disturbances in Figure 7 (b). The presence of weak suction, for case (b), is further supported by the presence of counter-rotating vortices at a reduced strength, downstream of the suction perforations (see Figure 8 (a)).

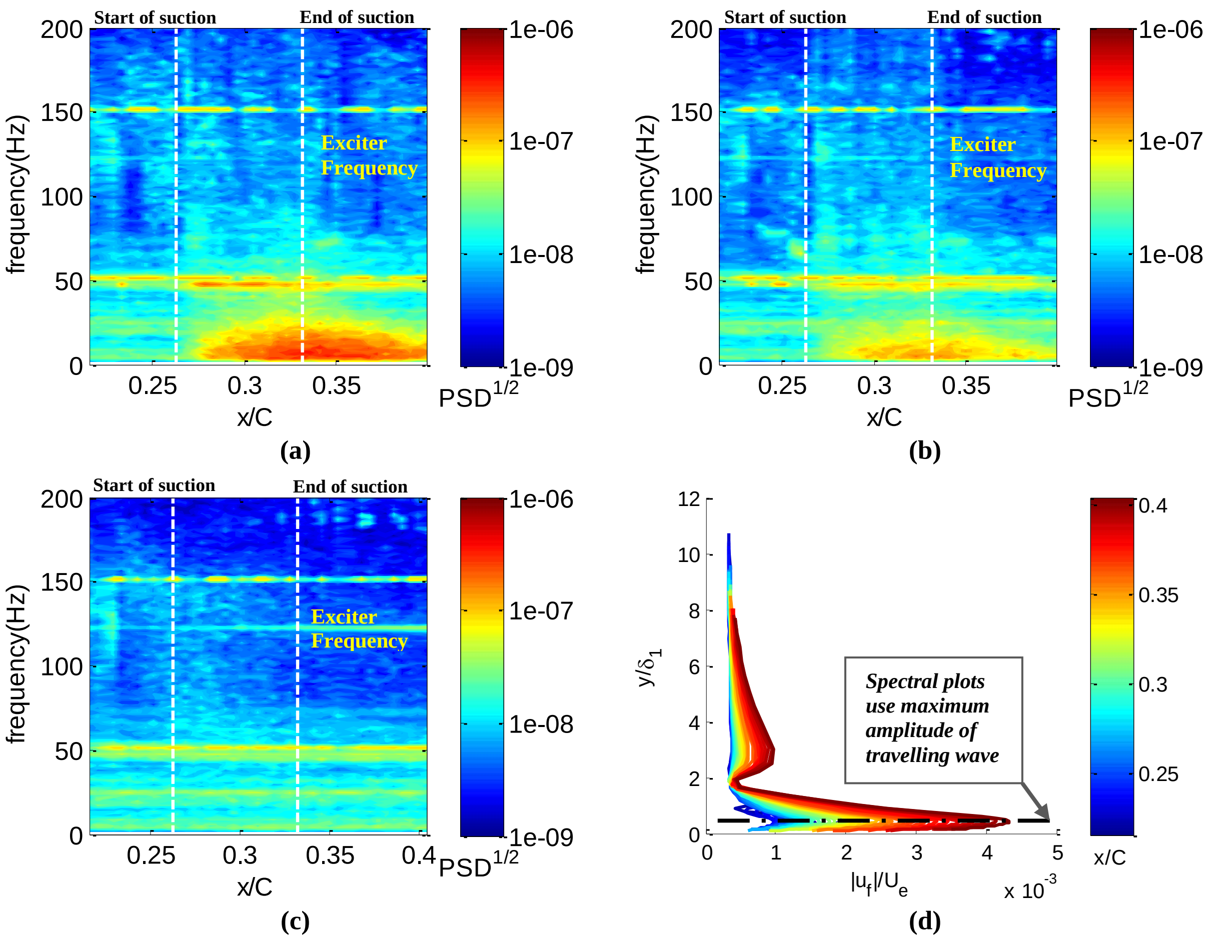


Figure 7. Three spectral plots for different cases and Travelling wave amplitude profile, all at U_e=14m/s, d_h=0.6mm, and f_k=121Hz: (a) shows with suction at v_A/U_e=0.8480E-3, (b) shows no suction but perforations uncovered, (c) shows suction but with perforations covered, and (d) shows the point in the y-ordinate at which the spectral plots are shown.

Stationary waves generated by suction can be seen in Figure 8. Figure 8 (a) shows suction induced by the leakage flow, as in Figure 7 (b). In contrast, Figure 8 (b) shows suction driven using a suction pump. These stationary waves were generated by subtracting the mean velocity profiles at specific locations across the span from the average of all mean velocity profiles taken across the span. Some low frequency energy can be seen in both Figure 8 (c) and (d): the energy is clearly higher in the latter case, this appears similar to the behaviour of the low frequency content in Figure 7; however, this is a different test case with a different free-stream velocity (U_e=8m/s) and excitation frequency (81Hz). This appears to suggest these effects are somewhat repeatable, as these results were taken at dates far removed from one another. It can be seen that there are two spatially periodic structures in Figure 8 (d): both have the same wavelength as the perforation spacing, one is co-incident with the perforations, the other is out-of-phase with the perforations. It is likely that the in-phase mode is related to local flow-field distortions around the suction perforations, and the out-of-phase mode is related to counter-rotating vortices structures commonly characterising discrete suction[5,8]. It can be seen that out-of-phase stationary waves persist in case (c), at an increased magnitude, which suggests that suction is still in effect.

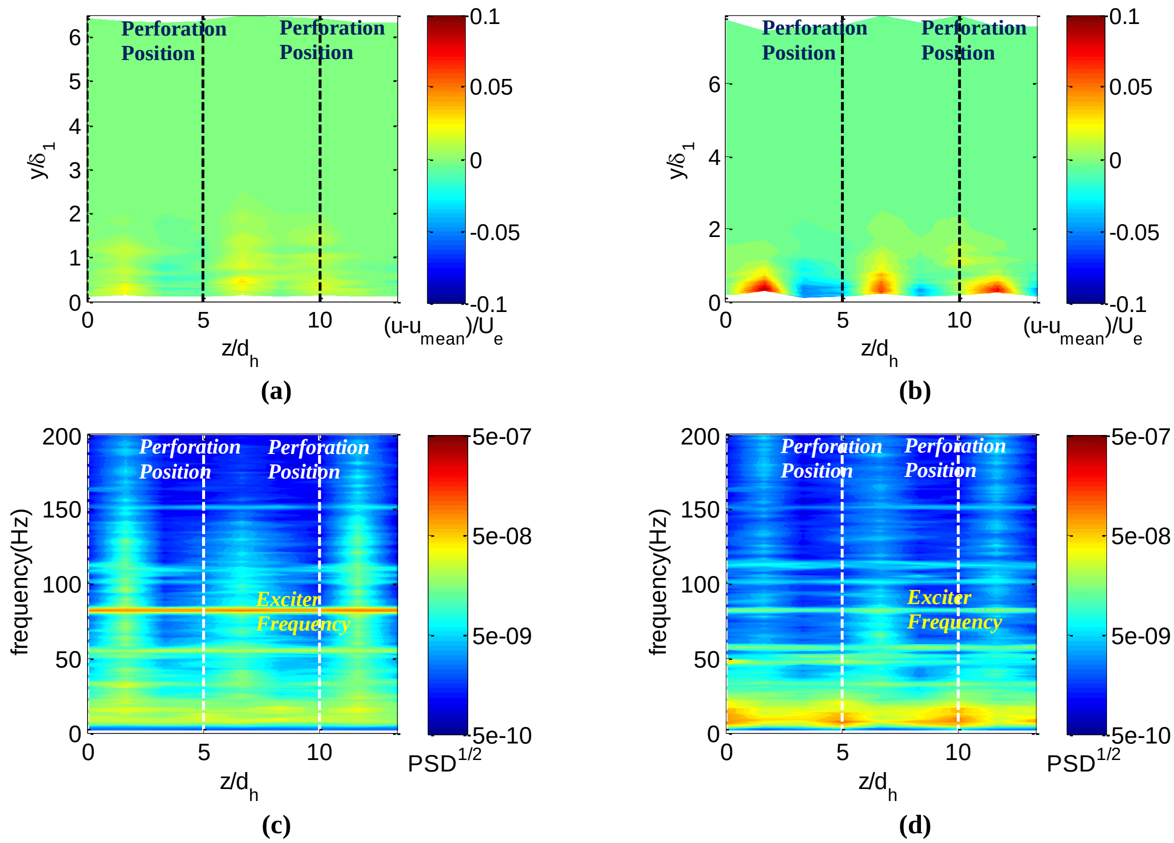


Figure 8. Stationary wave plots, indicating the presence of vortex structures: (a) shows case with disconnected pump and perforated insert panel; (b) with a connected pump, v_A/U_e=0.6595E-3 of suction, and a perforated insert panel; (c) shows spectral energy distribution for the case with no pump, (d) shows it for the case with a pump. U_e was set to 8m/s, d_h was 0.6mm, f_k=81Hz, and x was located at x/C=0.3193 for both of these cases.

It is suspected that the suction plenum, used to create a constant low pressure region behind the holes, may be behaving as a Helmholtz resonator, introducing low frequency disturbances. This is somewhat supported by Figure 3 (d), and the low frequency of the disturbances. From review of the literature, this mechanism of low frequency dominated transition through suction appears to be previously unreported. Alternatively it could be caused by unsteady interaction between the boundary layer over the flat plate and unsteady vortices inside the suction perforations. Such vortices have already been reported by MacManus and Eaton[7] using Laser Doppler Anemometry: this has a slow frequency response compared to hot-wire anemometry, which may reduce its effectiveness for unsteady measurements. However, a complimentary steady laminar finite volume method solver and coupled transient analysis was also performed but would not pick up any unsteadiness associated with the vortices[7]. The possibility that the disturbances are introduced through the unsteadiness of the suction pump has also been considered, Figure 7 suggests this does not occur as the disturbance persists with the pump removed, and disappears with the perforations covered. The structure of the disturbance and its distribution relative to the suction perforations, seen in Figure 6, suggests that the phenomenon is not is caused by drag induced vibrations of the model. The trend observed in Figure 4, showing the dependence of the disturbance on suction rate across multiple test cases, builds further confidence that this phenomenon is related to the discrete effects of stabilising suction.

IV. Conclusions and Future Work

A set of suction experiments were performed utilising large arrays of suction perforations. It was found that increasing the suction rate introduces and amplifies low frequency travelling waves while attenuating waves that evolve naturally or through excitation. The results also show that the study of the amplification and stabilisation of an excited travelling mode is an insightful method of quantifying the stabilising and de-stabilising effects of suction. The spectral nature of this method seems to provide additional insight in relation to mechanisms by which suction begins to destabilise the flow: measurement of the transition front does not provide this information as broadening of the spectrum during the non-linear stages of transition can obscure the growth of potentially important developing flow structures.

The possibility of the suction plenum acting as a Helmholtz resonator and producing low frequency acoustic disturbances must be investigated in future experiments. Viscous interactions between vortices inside the suction perforations and the boundary layer must also be investigated in determining the source of the low frequency disturbance. It seems unlikely that the low frequency disturbances are caused by pump vibrations, as they appear to persist with suction driven by natural pressure gradients. Likewise, it seems unlikely that the model or probe is vibrating because the low frequency has structure clearly and periodically distributed around the suction perforations. Accelerometers could be mounted on the model and the arm holding the probe to investigate this more directly. The practicality of this mechanism may then be evaluated, as it may be more desirable to use large plenums and perforations (as opposed to large numbers of small plenum cells with small perforations) from a manufacturing design perspective. Possible methods of controlling this mechanism will also be investigated.

Acknowledgments

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References

[1]Butler, S.F. *Current Tests on Laminar-Boundary-Layer Control by Suction through Perforations.* Aeronautical Research Council 3040, 1957.

[2]Ellis, E., and Poll, D. “Laminar and laminarizing boundary layers by suction through perforated plates,” *CEAS European Forum on Laminar Flow Technology*, CEAS, Bordeaux, 1996, pp. 8.17-8.27.

[3]Goldsmith, J. “Investigation of the Flow in a Tube with Laminar Suction through 80 Rows of Closely-Spaced Holes,” Northrop Aircraft BLC-86, 1956.

[4]Goldsmith, J. “Critical laminar suction parameters for suction into an isolated hole or single row of holes,” Northrop Aircraft BLC-95, 1957.

[5]Gregory, N. “Research on Suction Surfaces for Laminar Flow,” *Boundary Layer and Flow Control*, edited by G. Lachmann, Pergamon Press LTD, Oxford, Vol. 2, 1961, pp. 924-961.

[6]Gregory, N., and Walker, W. *Experiments on the use of the use of Suction through Perforated Strips for Maintaining Laminar Flow: Transition and Drag Measurements.* Aeronautical Research Council 3083, 1958.

[7]MacManus, D., and Eaton, J. “Predictions and Observations of the Flow Field Induced by Laminar Flow Control Microperforations,” *Experimental Thermal and Fluid Science*, Vol. 13, 1996, pp. 395-407.

[8]MacManus, D., and Eaton, J. “Flow physics of discrete boundary layer suction-measurements and predictions,” *J. Fluid Mech*, Vol. 417, 2000, pp. 47-75.

[9]Messing, R., and Kloker, M. “Investigation of suction for laminar flow control of three-dimensional boundary layers,” *J.Fluid Mech*, Vol. 658, 2010, pp. 117-147.

[10]Pfenninger, W., Moness, E., and Sipe, O. “Investigation of Laminar Flow in a Tube at High Reynolds Numbers and Low Turbulence with Boundary Layer Suction through 80 Slots,” Northrop Aircraft BLC-53, 1954.

[11]Pfenninger, W., and Bacon J.W. “About the development of swept laminar suction wings with full chord laminar flow,” *Boundary Layer and Flow Control*, edited by G. Lachmann, Pergamon Press LTD, Oxford, Vol. 2, 1961, pp. 1007-1032.

[12]Reneaux, J., and Blanchard, A. “The Design and Testing of an Airfoil with Hybrid Laminar Flow Control,” *CEAS European Forum on Laminar Flow Technology*, CEAS, Hamburg, 1992, pp. 1-11.

[13]Saric, W. S., and Reed, H. L., “Effect of Suction and Weak Mass Injection on Boundary-Layer Transition,” *AIAA Journal*, Vol. 24, No. 3, 1986, pp. 383-389.

[14]Schlichting, H., *Boundary-Layer Theory*, 7th ed., McGraw-Hill Inc., New York, 1979.