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EXPERIMENTAL INVESTIGATION OF SPANWISE FENCES FOR VORTEX LIFT

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Abstract

An experimental investigation has been performed to study the aerodynamic performance of spanwise fences for vortex lift on a wing-body model by means of wind tunnel testing. This research concept was investigated within the EU project "HELIX - Innovative Aerodynamic High Lift Concepts" as a collaboration between QinetiQ Ltd, United Kingdom and VZLU, Aeronautical Research and Test Institute, Czech Republic.

The main objective of the concept is to trap a stable, coherent vortex on the upper surface of a wing, in order to generate a large suction, increase circulation and thereby increase lift. This investigation is based upon the work and mechanism proposed by Rossow [1]. The vortex-trapping process is an extension of the flow past a three-dimensional, highly swept wing. However, for zero or low-sweep wings, as found on transport type aircraft, the reduced spanwise pressure gradient leads to an unstable vortex that, if formed at all, is prone to vortex shedding and breakdown. An alternative mechanism is therefore required in order to create and trap stable vortices on low-sweep wings.

During the experiments a large number of parameters were examined. Fences were used on the wing and the flap. The rear fence was nearly always rectangular and 'vented' 10% chord at its outboard end. The front fences were variable with 10% chord vent at the inboard end. The shape of the front fence was varied between rectangular, single-tooth, double-tooth and quadruple-tooth. The investigation was focussed on the effects of the following parameters: variable wing sweep angle (30, 45, 60 degrees), variable front fence geometry, inclined rear fence and different height of the fences. All these parameters were tested and examined within the experimental investigation.

Nomenclature

c	chord
C_L	lift coefficient
C_D	drag coefficient
C_m	pitching moment coefficient (based on MAC)
MAC	mean aerodynamic chord
Re	Reynolds number based on MAC
α (alpha)	angle of attack
δ (delta)	flap deflection
°	degree
ψ	wing sweep angle

Introduction

The EU 5th Framework Programme HELIX – Innovative Aerodynamic High Lift Concepts was designed to challenge the conventional high-lift system comprising a slat and single-element flap. Over 25 concepts were selected for examination within the programme, which comprised both old concepts to be analysed using more modern techniques and brand new concepts under consideration for the first time.

Through regular performance assessments, each concept was analysed and compared with a baseline high-lift system. A down-selection process took place at the end of the first and second years of the three-year programme, discarding those concepts that showed little promise and concentrating activity on those that did. The programme will culminate in a series of wind tunnel tests of the winning concept, initially at low Reynolds number in a conventional facility, and then at high Reynolds number in a pressurised facility.

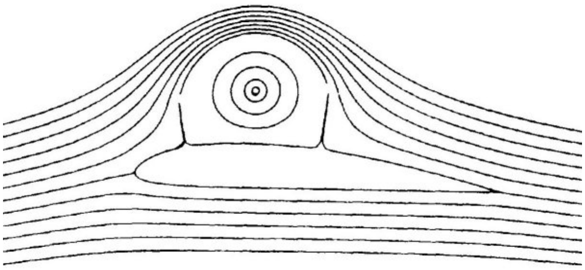

Fig.1: Potential flow around two fence concept [A]

The concept described in this paper makes use of that proposed by Rossow and makes use of a spanwise vortex trapped on the wing upper surface by a pair of spanwise fences as shown in Fig.1. The front fence is used to generate the vortex and the rear fence provides the downstream limit and reattachment point of the free shear layer. Lift enhancement arises from the massive increase in circulation and low-pressure region induced by the rotating flowfield. The modified flowfield leads to additional benefits arising from an effective increase in thickness and camber of the wing. The proposed system is mechanically simple and potentially light, requiring only simple actuation mechanisms as used for spoilers. The fences are stowed conformal to the wing upper surface to provide the original cruise section when required. The spanwise fence concept is in contrast to conventional high-lift devices and distinct from conventional vortex generators, which are generally used to delay separation using streamwise vortices.

Previous work had examined the concept using potential CFD methods[1-8], but the initial work within HELIX was aimed at a physical demonstration. The concept was significantly less mature than many others within HELIX and was therefore an unlikely candidate for the proposed high Reynolds number tests. However, the HELIX framework provided an ideal opportunity to investigate and extend the understanding of the physics of the spanwise fence concept. Good initial results from a simple water tunnel experiment [9] led to the wind tunnel tests described in this paper, and a structural and kinematic assessment of the concept. The wind tunnel model was designed by QinetiQ and VZLU in collaboration and is shown in Fig.2. The wind tunnel tests were performed in the VZLU low speed wind tunnel.

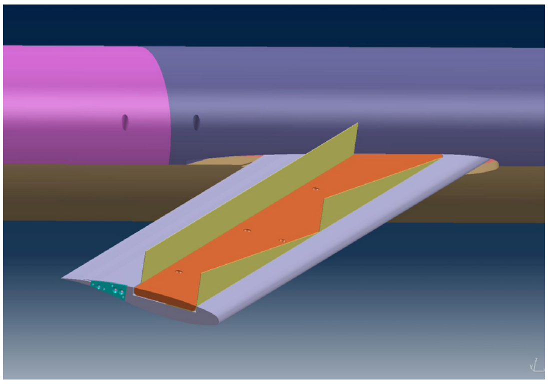

Fig.2: Spanwise fences mounted on wind tunnel model

The wind tunnel test programme had several aims. The first was to provide detailed video and still image flow-visualisation data with a view to giving a clearer understanding of the physics of the concept. Secondly, it was intended to provide aerodynamic data for comparison with the baseline performance of a conventional high-lift system and for validation of computational simulations carried out as part of the overall research programme.

Concept benefits and risks

The vortex-trapping concept may provide several advantages over conventional devices. If it functions as intended then the increase in circulation and lift, normally achieved by pitching a wing and deploying high-lift devices, would be attained at zero incidence. This would have a profound effect on undercarriage and horizontal tail requirements.

The proposed system is mechanically simple and potentially light, requiring only simple actuation mechanisms as used for spoilers. The wing should provide a level of noise shielding between the high lift system and the ground and the concept should potentially impose very few constraints on the external shape of the high speed wing.

However, a kinematic and structural assessment of the concept [10] identified a number of challenges and risks associated with it. The concept may require excessive power to establish and maintain a vortex, which may not be stable across the full range of operating conditions. The fences may produce potentially high drag and the fence structure may reduce the fuel volume in the wing by intruding into the wing box. Finally, unsteady flow over the wing upper surface during fence may require them to be much stiffer than anticipated and thereby prove to be unacceptable.

Wind tunnel model

The aerodynamic effect of spanwise fences for vortex lift was measured on a variable sweep wing-body, sting-mounted model, as shown in Fig.3 and Fig.4.

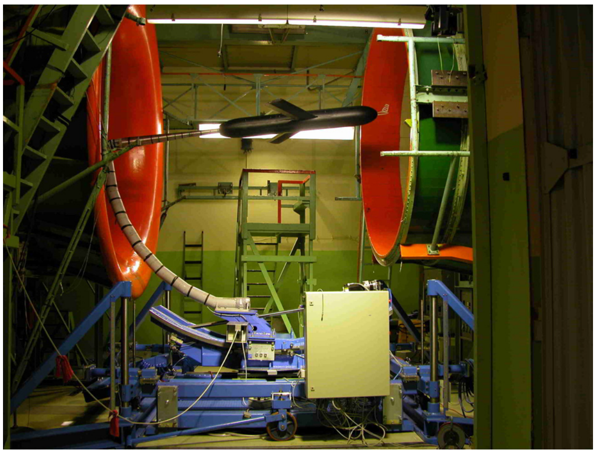

Fig.3: Wind tunnel model mounted in the VZLU 3m Wind Tunnel

- Model dimensions
    - span (0° sweep angle) = 2000 mm
    - length = 2000 mm
    - diameter of fuselage = 250 mm
    - aerofoil chord = 250 mm

- Sweep angle range
    - sweep angle range was variable: from 20to 60 degrees
    - three sweep angles were tested: 30, 45 and 60 degrees

- Flaps configurations
    - three pairs of flaps for three sweep angles (30, 45 and 60 degrees) were used

- Spanwise fences
    - the rear fence was nearly always rectangular
    - the shape of the front fence was varied between rectangular, single-tooth, double-tooth and quadruple-tooth.

The range of fences tested is indicated in Fig. 4, it being necessary to have a complete set of fences for each sweep angle since there is an effective change in wing span at each of the sweep angles.

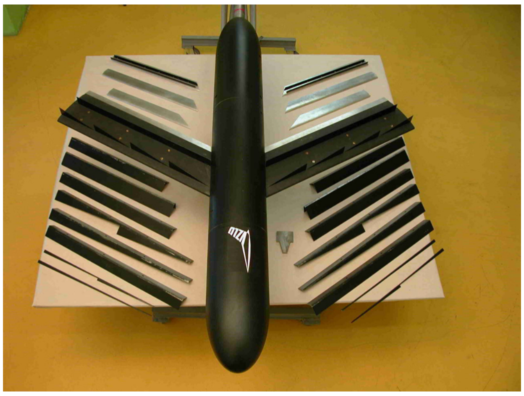

Fig.4: Wind tunnel model with array of fences

Experimental method

The tests were performed in the 3m diameter low-speed wind tunnel at VZLU, Aeronautical

Research and Test Institute in Prague, Czech Republic [11]. The wind tunnel is an atmospheric, open test section, closed return type, as shown in Fig.5.

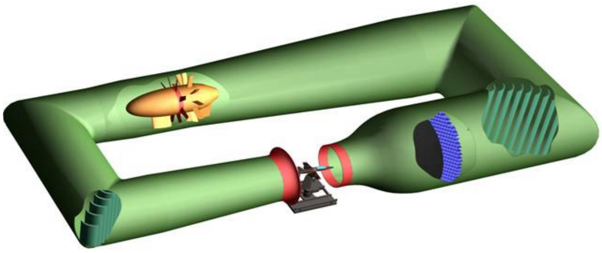

Fig.5: VZLU 3m Wind Tunnel

The force and moment tests were performed at a free stream Reynolds number of 9 x 10^5. A 5-component strain gauge balance was used to measure forces and moments over a range of angle of attack from -10 degrees to +30 degrees.

The flow visualisation was performed at low speed (approximately 4 m/s) using a smoke wand to introduce smoke at points of interest.

Test configurations

The experimental investigation was divided into two stages. The initial stage was focused on understanding the behaviour of the concept and to determine whether a trapped vortex would form on a three-dimensional swept wing. Consequently four different front fences were tested at each of the three possible sweep angles: 30, 45 and 60 degrees.

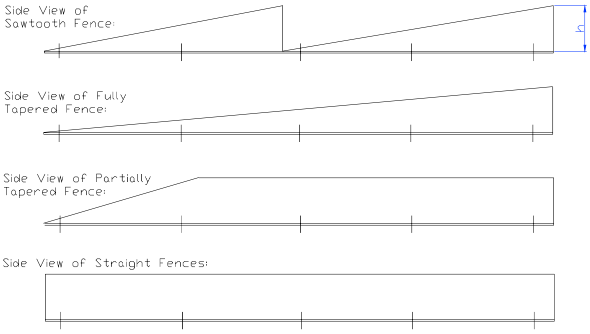

Fig.6: Initial front fence configurations

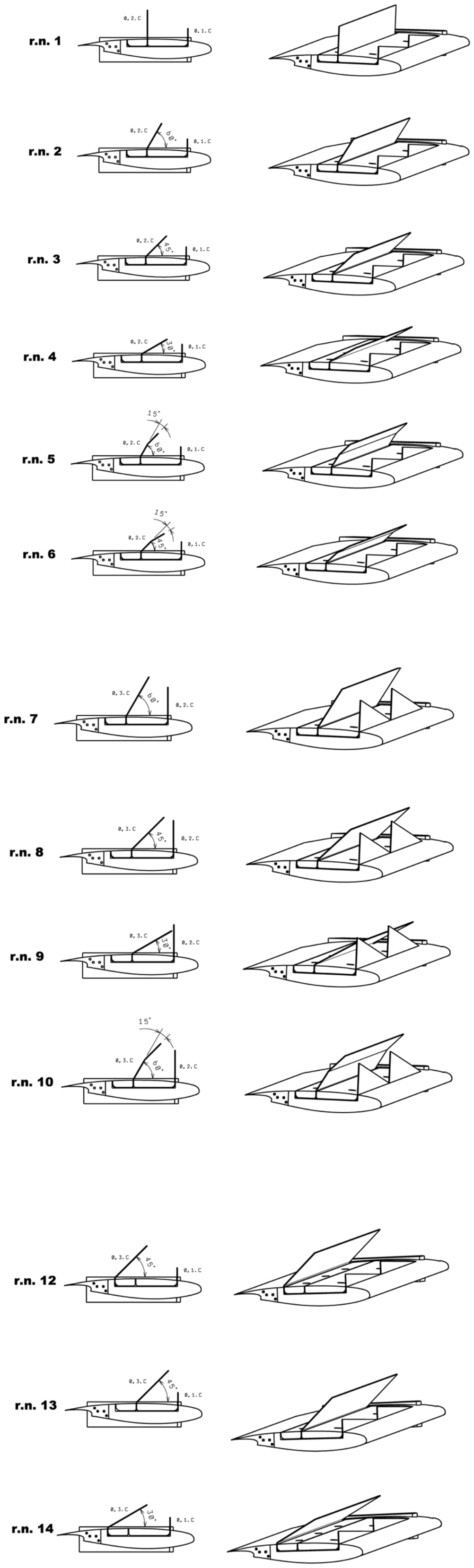

Fig.7: Configurations tested in Stage 2

The four different front fence shapes were: rectangular, single-tooth, double-tooth and quadruple-tooth. They are shown in Fig.6. The rear fence was always rectangular.

Equivalent fences were also mounted on a flap (with those on the main element removed), scaled to the flap chord.

These second stage tests were conducted only at the single sweep angle of 45 degrees and investigated further combinations of various fence shapes, incorporating different chordwise fence separations and fence inclinations. These additional configurations are shown in Fig.7.

Results

The initial task was to determine whether a trapped vortex could be generated by the proposed concept. To this end, the first tests conducted used smoke flow visualisation to examine the flowfield around the wing with the fences in place. While little coherent structure was visible with a rectangular front fence, the single and multiple 'tooth' front fences each produced strong coherent vortices in the cavity between the front and rear fences. Examples are shown in Fig.8.

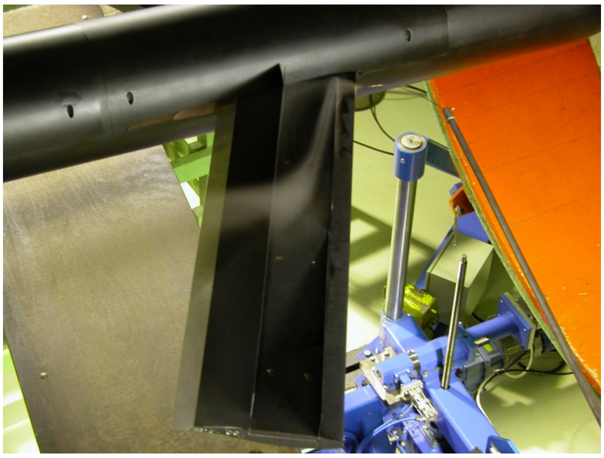

Fig.8a: Vortex generated by inner tooth of the double-tooth front fence (time lapse photograph)

Despite the successful trapping of a stable, coherent vortices at low sweep angles, without the need for spanwise blowing, the flow visualisation indicated two problems. The first was associated with configurations with the 'multiple-tooth' front fences.

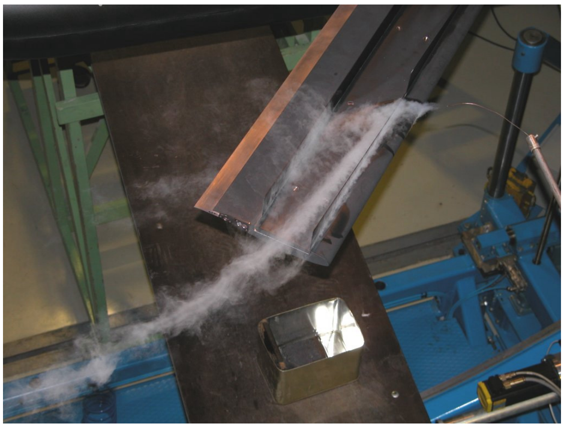

Fig.8b: Vortex generated by outer tooth of double-tooth front fence

Each of the teeth acts like a small delta wing at high incidence. Each tooth therefore generates a vortex, caught in the cavity between the two fences. The high effective incidence of the teeth and the proximity of the rear fence led to vortex breakdown and impingement of the vortex on the top of the rear fence. This meant that not all of the generated vorticity was being contained within the fence cavity. Secondly, the flow was separating from the top of the rear fence and was therefore not attached on the rear of the aerofoil. The rear of the aerofoil was therefore permanently separated, and the drag higher and lift lower than might be achievable if this separation could be avoided.

The performance of the concept compared to that of the clean aerofoil at each sweep angle is shown in Fig.9.

In an effort to remove both these sources of possible performance limitation, the rectangular rear fence was inclined forward. It was hoped that this would both better capture the vorticity shed from the front fence and provide a geometry more conducive to reattachment of the flow aft of the rear fence. The results are shown in Fig.10 where it can be seen that the main apparent effect of the inclined rear fence is to

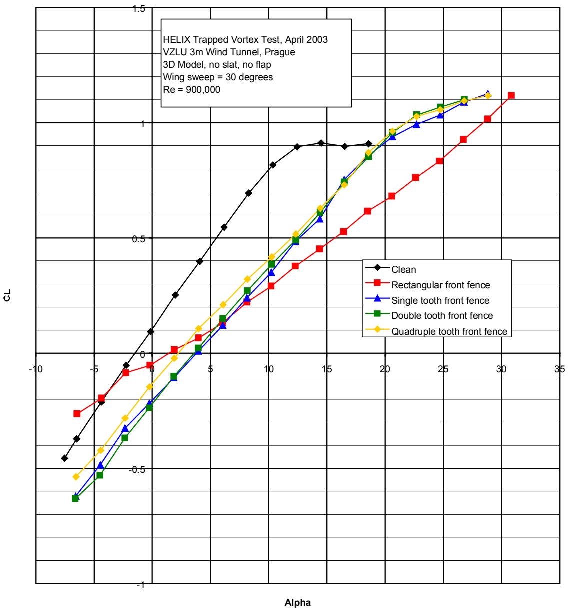

Fig.9a: Effect of front fence configuration at 30º sweep

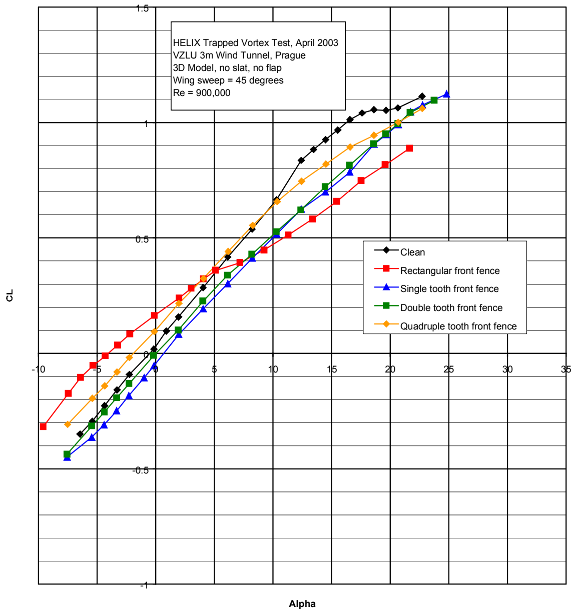

Fig.9b: Effect of front fence configuration at 45º sweep

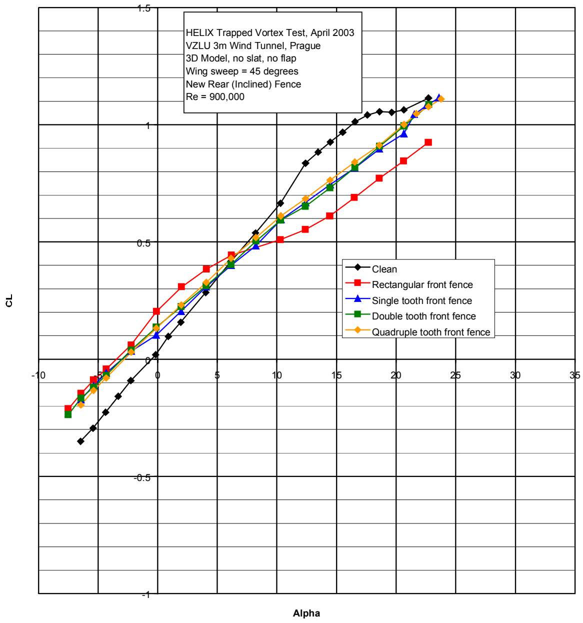

Fig.9c: Effect of front fence configuration at 60º sweep

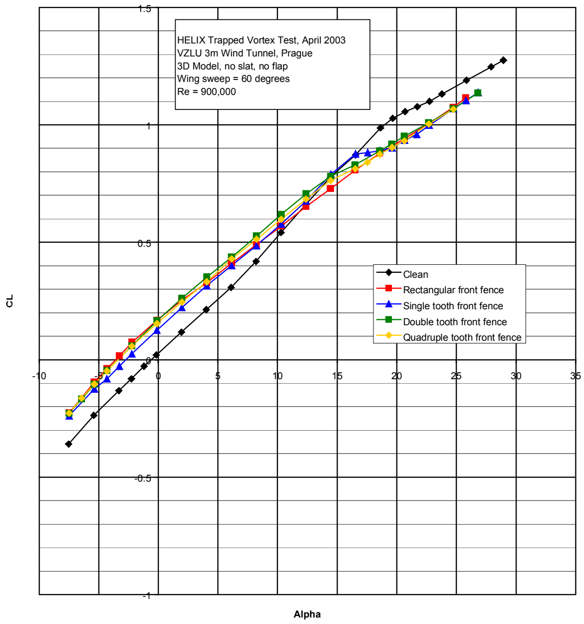

Fig.10: Effect of inclining the rear fence forward

raise the performance of the single and double-tooth front fence configurations to that of the quadruple front fence. The drag was little affected.

An additional exercise examined the behaviour of the spanwise fences placed only on the flap with the wing in a high-lift configuration. For this, VZLU manufactured a complete set of fences scaled to the dimensions of the flap. The ratios for fence height and location were kept the same as for the main fences on the baseline wing, but based on the flap chord. The flap with the fences attached was tested at a baseline landing setting.

There was little discernible structure visible within the smoke flow visualisation of this configuration. This may be due to the smaller scale of the devices and the structures they generated, but is more likely to be due to the altered circulation generated by the flap. The physical presence of the fences would have significantly altered the flow around the flap and its interaction with the main element trailing-edge. From the flow visualisation evidence it is probable that the fences triggered premature separation of the flap flow and if any vortical flow was present it was not coherent enough to be visible. Even if the devices generated some significant vorticity, the effective volume and camber of the flap will have been somewhat altered from the baseline landing case. To have gained a true appreciation of the performance potential of this configuration, it would therefore have been necessary, at the very least, to perform an optimisation of the flap to find a new optimum location and deflection. Time and budget constraints precluded this.

One final configuration was tested in this first test programme. This was the double-tooth front fence at 30° wing sweep, but without a rear fence to see whether, in light of the separation of the flow from the top of it, it actually contributed to the trapping and stability of the vortices. The results are shown in Fig.11. In marked contrast to Fig.8, the stable and coherent vortices did not form. The flow appears to be that of a separated delta wing, with some evidence of rotational flow but with vortex breakdown at the apex. Hence, it would appear that the rear fences are crucial to the generation and stability of the trapped vortex.

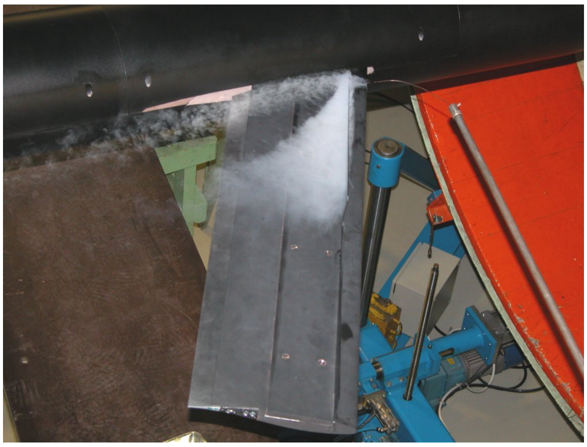

Fig.11a: Effect of no rear fence – inboard end of double-tooth front fence

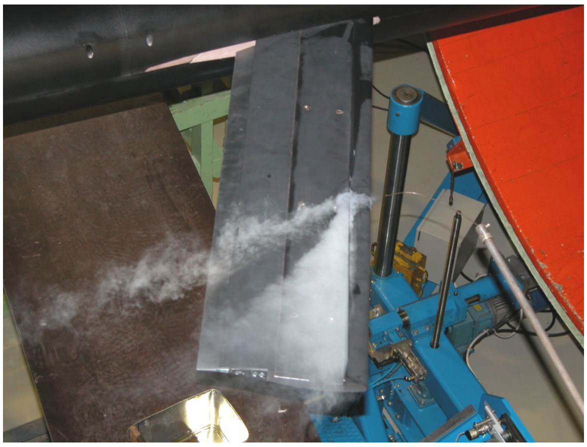

Fig.11b: Effect of no rear fence – outboard end of double-tooth front fence

Having gained a greater understanding of the physics of the concept and identified areas that could be hindering its performance, a second stage of testing was conducted on the same model in the same wind tunnel one year later. This time the model was tested only at 45 degrees wing sweep. As mentioned above, three main geometry variations were explored. Firstly, in an effort to capture all of the vorticity shed from the front fence the ratio of the heights of the front and rear fences was altered.

Previously, both fences had been 20% of the main chord high. The original front fence was now tested with a 30% rear fence, and the original rear fence tested with a 10% front fence. Secondly, again in an effort to capture and concentrate the shed vorticity, the chordwise separation between the front and rear fence was reduced from 40 to 20% chord. Lastly, to promote reattachment of the flow on the aerofoil aft of the rear fence, various rear fence inclinations were tested. The full range of test configurations was shown in Fig.7.

The results are shown as follows. Those with the reduced fence separation for a 20% rear and 10% front fence are shown in Fig.12 and those with the reduced fence separation for a 30% rear and 20% front fence are shown in Fig.13. It can be seen that in the cases where the rear fence has been more deeply inclined, the flow had at least partially reattached on the rear of the aerofoil, supported by the results of smoke flow visualisation.

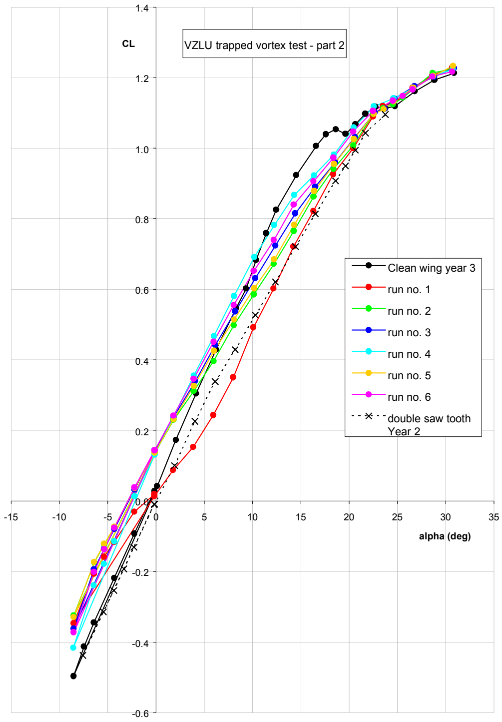

Fig.12: The performance of configurations with a smaller front fence, chordwise separation of the fences reduced.

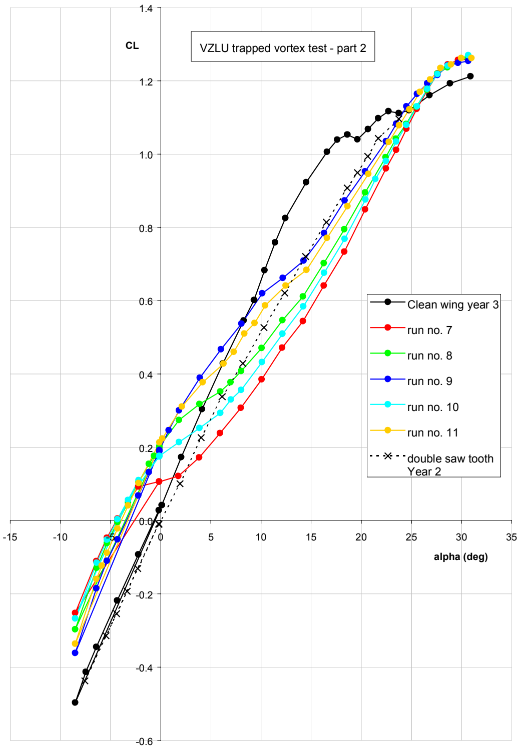

Fig.13: The performance of configurations with a taller rear fence, chordwise separation of the fences reduced.

This improved the lift at low incidence, but the drag had grown commensurately with the lift, meaning that the lift-to-drag ratio remained comparable with previous configurations. Additionally, at higher incidence the flow again separates from the rear of the aerofoil, lift drops and drag increases.

In summary, the concept has been shown to trap a stable and coherent vortex system without the need for spanwise blowing. However, while improvements to the configuration have increased its performance at low incidence, that performance is still far short of modern, multi-element high-lift system

Conclusions

The work presented in this paper shows the spanwise fence concept with a saw-tooth front fence to be capable of trapping stable spanwise vortices between the front and rear fences, without the need for any spanwise blowing. The trapped vortices led to increased lift at low incidences when compared to the performance of the equivalent clean, single element wing, but far below that provided by a conventional flap. Additionally, increases in lift were accompanied by increased drag. It is thought that the large drag is a result of the flow separating from the top of the rear fence and not reattaching on the rear aerofoil. Attempts to shape the rear fence to prevent flow separation were partially successful. The flow reattached near the wing trailing edge at low angles of incidence, but a large separation aft of the rear fence persisted. Thus any improvements in lift were not sufficient to significantly improve the lift-to-drag ratio.

This work has shown that the rear fence is essential to maintain a stable and coherent trapped vortex.

While improvements over the performance of a single element aerofoil have been demonstrated, and there remain many further permutations and combinations of fence geometry, it is thought unlikely that the spanwise fences concept will ever seriously challenge the conventional slat and flap high-lift system. However, the HELIX programme was created to investigate novel high-lift systems and this concept was the only such system to survive examination into the final stages of the programme. The remainder of the surviving concepts within HELIX are essentially variations on a conventional high-lift system. This in itself is encouraging, as a well designed conventional system has so far proven very difficult to better.

Acknowledgements

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