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LIFT ENHANCEMENT BY TRAPPED VORTEX

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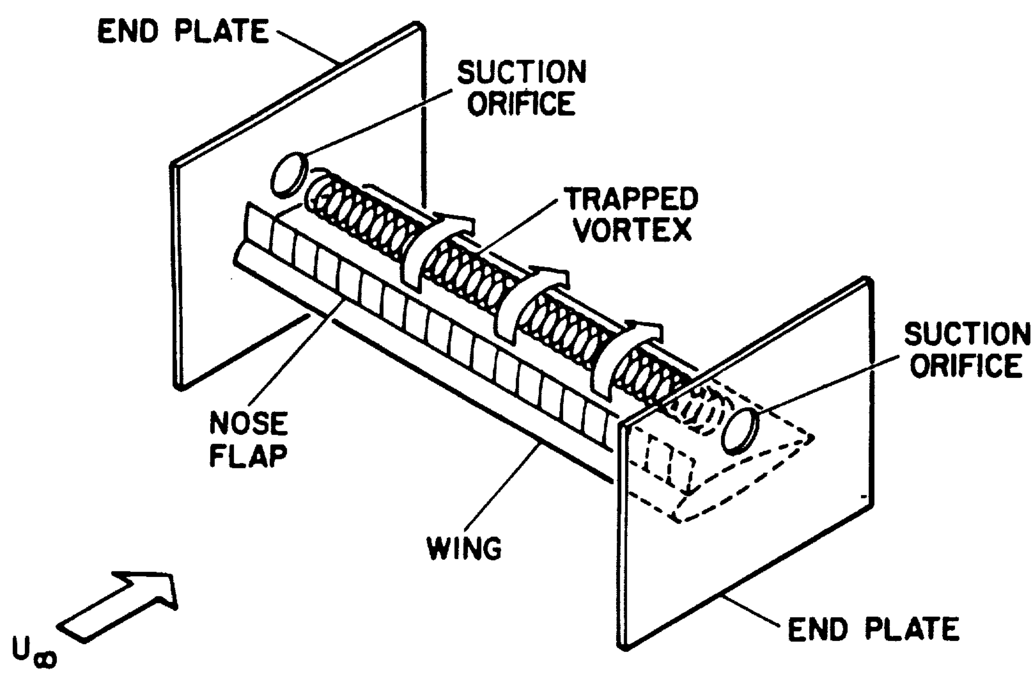
Efforts are continuously being made to find simple ways to convert wings of aircraft from an efficient cruise configuration to one that develops the high lift needed during landing and takeoff. The high-lift configurations studied here consist of conventional airfoils with a trapped vortex over the upper surface. The vortex is trapped by one or two vertical fences that serve as barriers to the oncoming stream and as reflection planes for the vortex and the sink that form a separation bubble on top of the airfoil. Since the full three-dimensional unsteady flow problem over the wing of an aircraft is so complicated that it is hard to get an understanding of the principles that govern the vortex trapping process, the analysis is restricted here to the flow field illustrated in the first slide. It is assumed that the flow field between the two end plates approximates a streamwise strip of the flow over a wing. The flow between the endplates and about the airfoil consists of a spanwise vortex located between the suction orifices in the end plates. The spanwise fence or spoiler located near the nose of the airfoil serves to form a separated flow region and a shear layer. The vorticity in the shear layer is concentrated into the vortex by withdrawal of fluid at the suction orifices. As the strength of the vortex increases with time, it eventually dominates the flow in the separated region so that a shear or vortical layer is no longer shed from the tip of the fence. At that point, the vortex strength is fixed and its location is such that all of the velocity contributions at its center sum to zero thereby making it an equilibrium point for the vortex. This presentation describes the results of a theoretical analysis of such an idealized flow field.

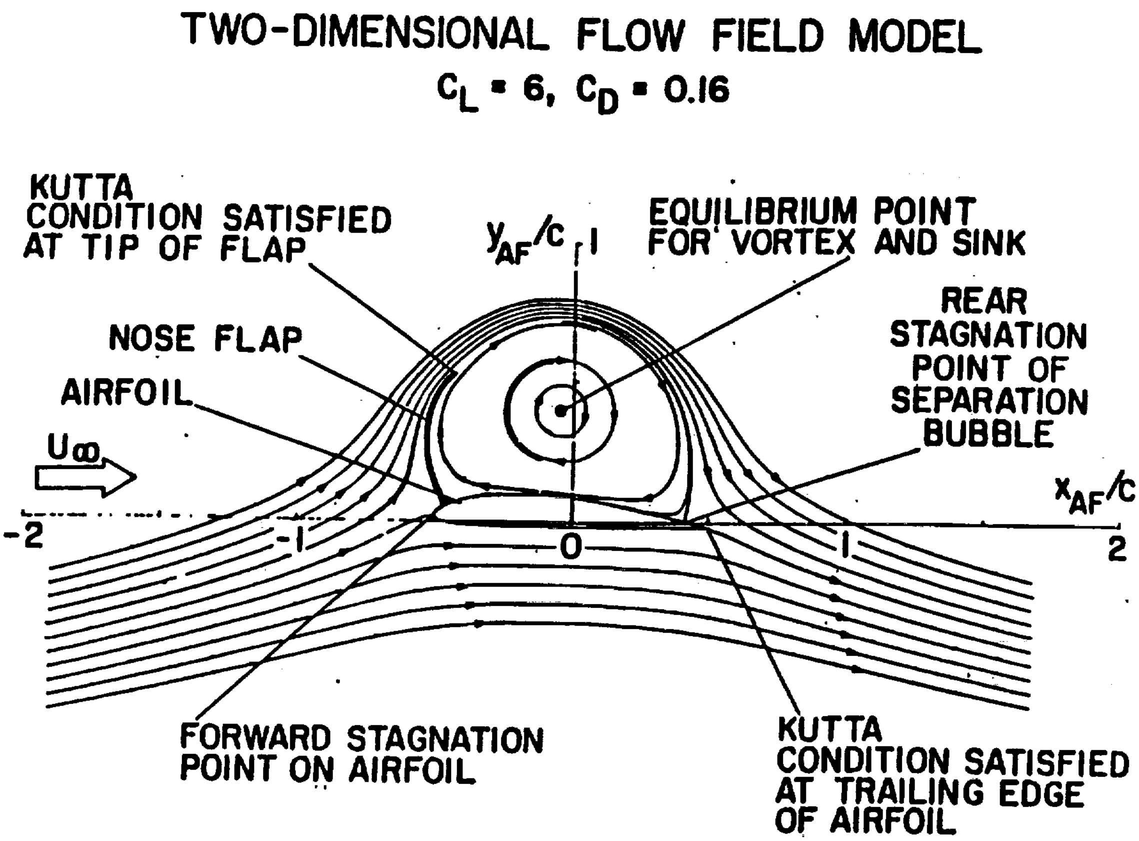
WING WITH TRAPPED VORTEX



This slide presents a two-dimensional idealization of the experimental configuration presented in the previous slide that will be used in the theoretical analysis. A large trapped-vortex bubble is shown over the airfoil to emphasize the fact that the analysis is most interested in those configurations wherein the vortex bubble covers a large fraction of the upper surface of the airfoil. If such a flow field can be established, the lift enhancement by the trapped vortex is substantial enough to yield lift coefficients that are in the range of the value, $C_\ell = 6$, shown in the slide. The two-dimensional flow field is assumed to be inviscid and incompressible so that it can be represented by potential flow theory. Conformal mapping techniques can then be used to develop the desired flow-field configuration from the flow about a circular cylinder. A substantial advantage of the conformal mapping technique is that it yields directly the location of the equilibrium point for the center of the vortex/source combination, the circulation, Γ, of the vortex, and the source strength, $\dot{m}$. Knowlege of Γ and $\dot{m}$ then yield the lift due to the trapped vortex and the drag attributed directly to the trapping process which is designated by C_d. As indicated in the slide, the flow is assumed to depart smoothly from the tip of the fence and from the trailing edge of the airfoil in order to satisfy the Kutta condition at those locations.

The single fence case was first studied, Ref. 1, in order to gain an understanding of the nature of the flow field and to obtain an estimate of the magnitude of lift enhancement that can be achieved by means of a trapped vortex.

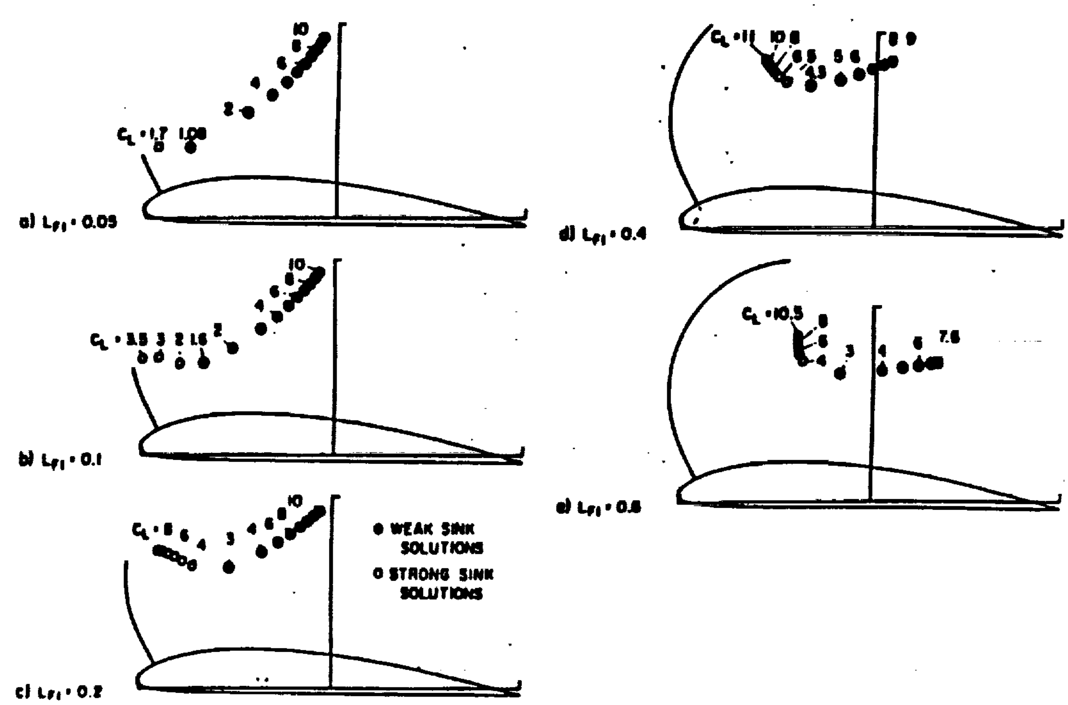
Ref. 1: Rossow, Vernon J., "Lift Enhancement by an Externally Trapped Vortex", AIAA Journal of Aircraft, Vol. 15, No. 9, Sept. 1978, pp.618-625.



The results presented here for the single fence case illustrate the location of the equilibrium point for the vortex/source combinations for several different fence lengths and lift coefficients. It is to be noted that the lift coefficient has been specified but the downstream extent of the vortex bubble has not been fixed. It was assumed that the length of the fence and location of the equilibrium point would be enough to fix the size of the vortex bubble. However, when experiments were conducted in a water channel, it was found that a trapped vortex could be formed in some cases but that a large amount of fluid had to be withdrawn from the center of the vortex to not only form the vortex but also to sustain it. This result was predicted by the theory through the magnitude of the sink required to achieved an equilibrium condition at the center of the vortex. Not immediately apparent is the fact that the sink flow also respresents a drag that is attributable to the vortex trapping process. It was then reasoned that not only is the drag undesirable, but a large amount of fluid moving along the vortex core can disrupt the vortex formation and, if large enough, can actually occupy the entire trapped vortex region at spanwise stations near the wingtip where the core flow spills into the free stream. Research was then started on finding ways by which the mass flow at the source/vortex location could be made to vanish.

LOCATIONS OF EQUILIBRIUM POINTS IN AIRFOIL PLANE

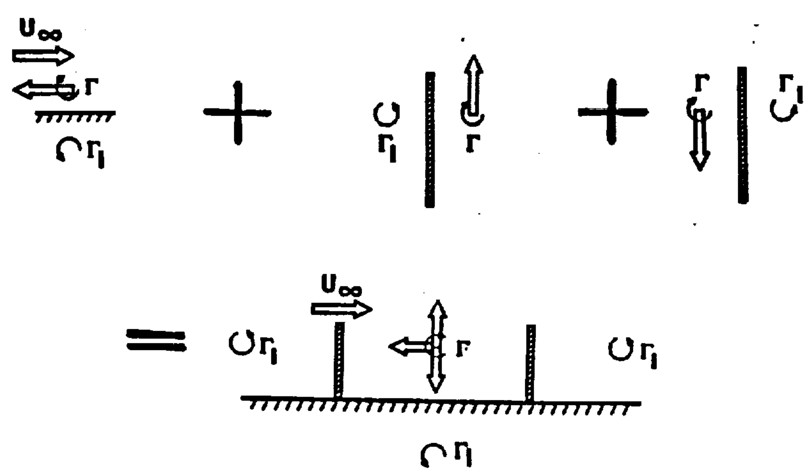
β_{fk} = −0.75 rad, x_{f1} = 0.05c, α = 0.1 rad



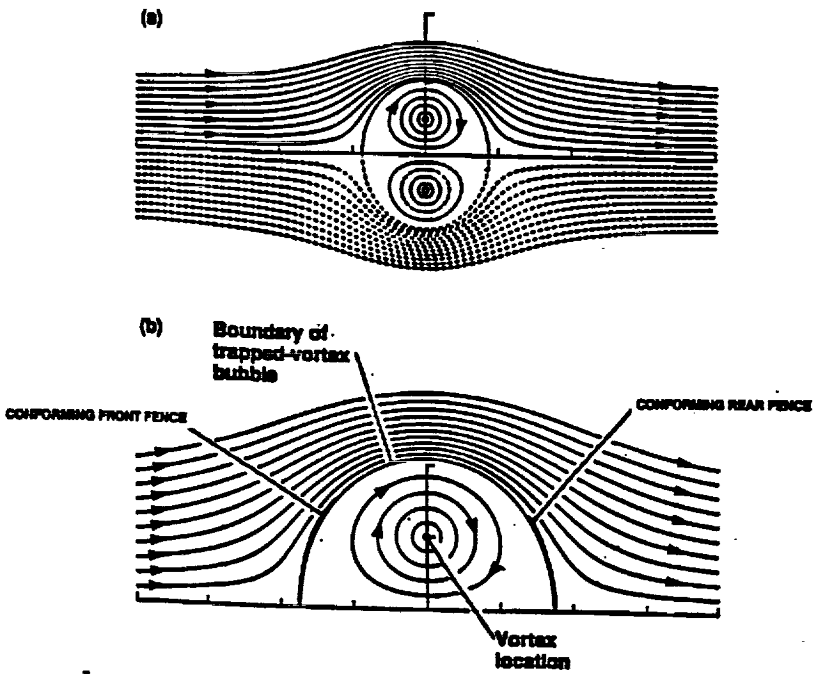
A mechanism whereby the source flow can be made to vanish and still have an equilibrium point for the vortex is illustrated here. The two-fence trapped-vortex configuration in the lower part of the figure is divided into three separate flat-plate boundaries. In the first, the horizontal flat plate serves as a reflection plane with an image vortex below the surface which induces an upstream velocity on the vortex that is exactly equal to the oncoming free-stream velocity. This configuration yields an equilibrium point without a source but requires a fence of some sort to promote the formation of the vortex. A fence upstream of the vortex provides the shear layer mentioned previously that builds the circulation in the vortex. The vertical boundary also induces an upward velocity through the influence of the image vortex needed to make the surface a streamline. The upward velocity due to the front fence needs to be offset by a sink located beneath the horizontal plane if some other artifice is not used to bring about an equilibrium condition. Such an artifice is available as a fence downstream of the vortex. As indicated in the figure, the image vortex for the rear fence induces a downward velocity on the vortex. Therefore, if the vortex to be trapped is midway between two vertical surfaces of about the same size, an equilibrium condition is achieved for the vortex without the presence of a source or sink.

The two-fence concept does several things for the flow field. First, it makes it possible to trap a vortex at its equilibrium location without the use of a source or sink. The front fence serves as an upstream limit on the trapped-vortex flow field and as a means for generating a shear layer that supplies vorticity to the vortex. The second fence serves as a downstream limit on the size of the vortex bubble and as a reflection plane for the vortex so that trapping can be achieved without the need for a source or sink. Since a source or sink is not required for the establishment of an equilibrium point, the drag due to vortex trapping is negligible which means that efficient lift enhancement has been achieved. Another big advantage is that the flow along the core of the vortex is also negligible making it much easier to establish and maintain the vortex flow field. Mass removal from the core is then only necessary to establish the vortex and to remove low energy fluid generated by viscous losses.

TWO-FENCE CONCEPT



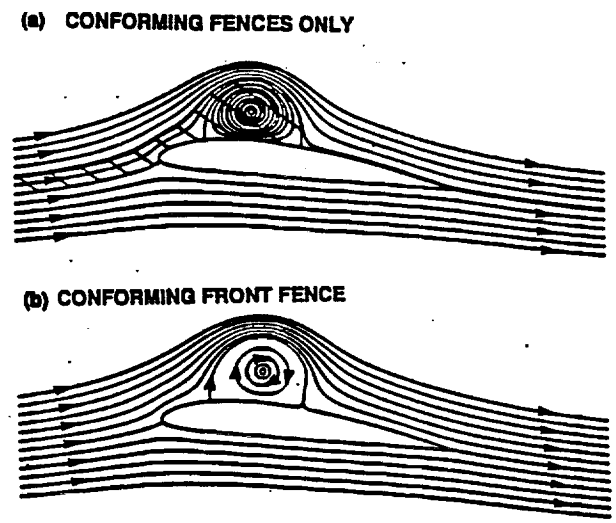
Before proceeding to airfoil-type trapped-vortex configurations, consider the simple case wherein a vortex is trapped over an infinite plane. As mentioned previously, a source is not needed in order to achieve an equilibrium condition. In practice however, fences are needed to fix the upstream and downstream extents of the vortex bubble and to provide a separated flow region with a shear layer to supply the vorticity that builds into the circulation for the vortex. Fences can be added to the flow field without disturbing the equilibrium condition or the streamline pattern if the fences are placed upstream and downstream of the vortex on the surface of the vortex bubble as shown in the lower part of the figure. If the fences are thin and fit, or conform to, the surface of the vortex bubble, the flow field characteristics are unchanged by addition of the fences. A number of the solutions to be presented will be noted to have only one fence that is flat and that is needed to make $\dot{m} = 0$. The other fence is assumed to be of the conforming type that fits the vortex bubble so closely that no appreciable change in the flow field is brought about.



a. Image and physical streamlines for trapped vortex flow field.

b. Fences fore and aft that conform to shape of vortex separation bubble.

The procedure that was used to calculate the trapped-vortex flow field over an airfoil wherein a source or sink is not needed is illustrated in the figure below. The first step in the procedure is to calculate the flow field when only the front and rear stagnation points of the vortex bubble are specified. In such a case, the vortex bubble is assumed to have conforming fences that do not interfere with the equilibrium condition. Under those conditions, if a sink is required in order to achieve an equilibrium condition for a source/vortex combination as shown in the upper figure, the height of the rear fence (which is approximately flat) is increased in steps until the sink flow is negligibly small. The sink flow is highlighted in the upper figure by cross-hatching the streamtubes entering the sink. When the proper height of the flat plate rear fence has been found by such an iterative process, it is retained as the most efficient, or, $\dot m = 0$, solution for a vortex bubble of a specified size and location on an airfoil at a given angle of attack. Conversely, if the flow field solution for the conforming-fence geometry had required a source rather than a sink, the height of a flat front fence would have been increase until $\dot m = 0$. The foregoing procedure was used to obtain all of the $\dot m = 0$ trapped-vortex solutions presented here.



a. No fences; $h_1/c = 0, h_2/c = 0$; $x_{ps} = -0.197$, $y_{ps} = +0.216$, $\Gamma/cU_\infty = -1.749$, $\Gamma_s/cU_\infty = +0.869$, $\dot m/cU_\infty = -0.054$; $C_L = 1.761$, $C_D = 0.108$.

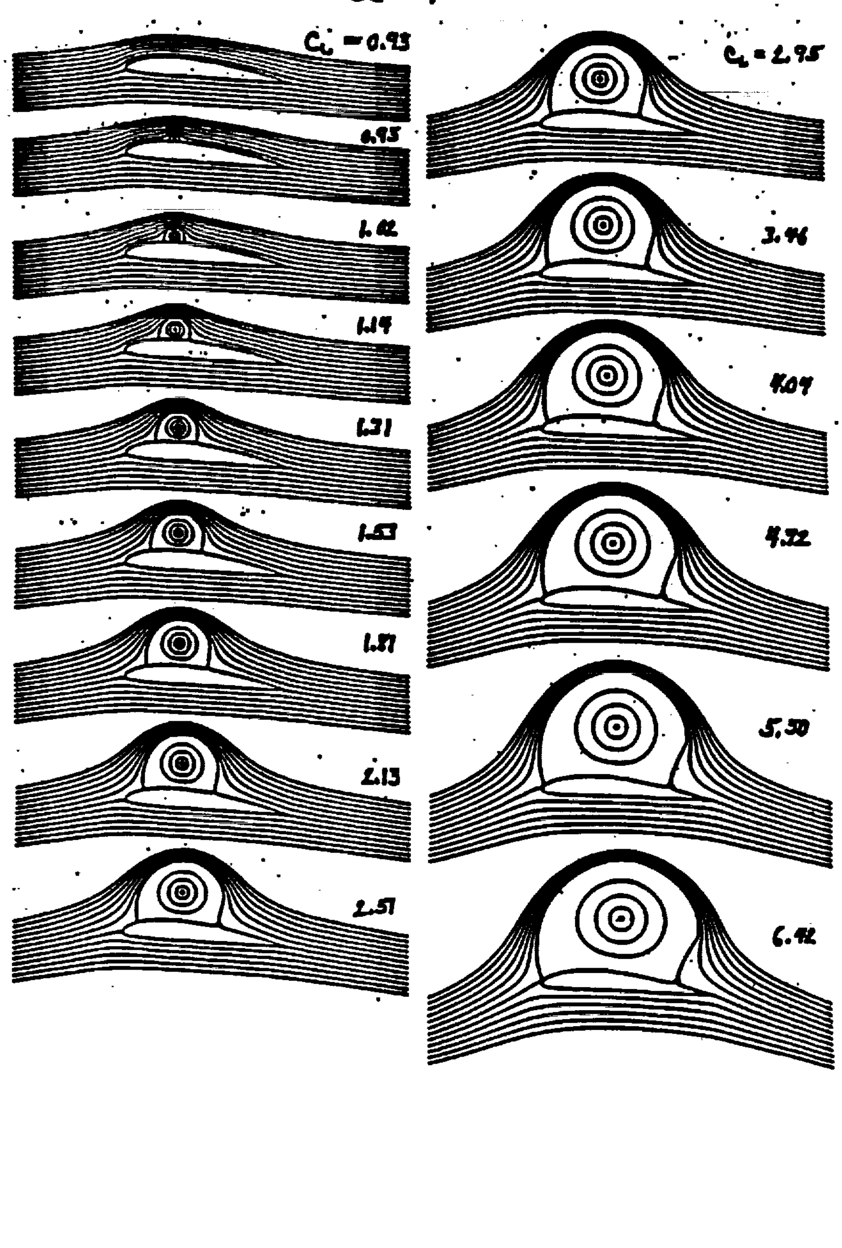
b. Rear fence just large enough to reduce $\dot m$ to zero. $h_1/c = 0, h_2/c = 0.114$; $x_{ps} = -0.165$, $y_{ps} = +0.332$, $\Gamma/cU_\infty = -1.886$, $\Gamma_s/cU_\infty = +0.998$, $\dot m/cU_\infty = 0.0$; $C_L = 1.777$, $C_D = 0.0$.

Vortex trapped on Clark Y airfoil (NACA 4412); $\alpha = 0.1$.

In order to obtain a data set of solutions that can be used to study the characteristics of airfoils with trapped vortices, a sequence of $\dot{m} = 0$ cases were calculated for the flow over an NACA 4412 (or Clark Y) airfoil at angles of attack from $\alpha = -4^o$ through $\alpha = +12^o$ in increments of 2^o. Since the streamlines for the various solutions do not change very much, only the solutions for $\alpha = +4^o$ are presented on this slide. The various solutions differ from one another in that the size of the trapped-vortex bubble increases gradually from zero to a size that nearly covers the entire upper surface of the airfoil. It could be imagined that the sequence of figures represents a streamwise cross-section of the flow field as the wing is changed from its cruise configuration (i.e., no vortex) to the vortex-bubble size (and lift) needed for landing. Conversely, when the aircraft takes off, the fences are first deployed so as to develop the size of trapped-vortex needed for high lift. As the aircraft becomes airborne and increases its flight velocity, the fences are changed so that the vortex bubble shrinks in size progressively until the cruise configuration is achieved.

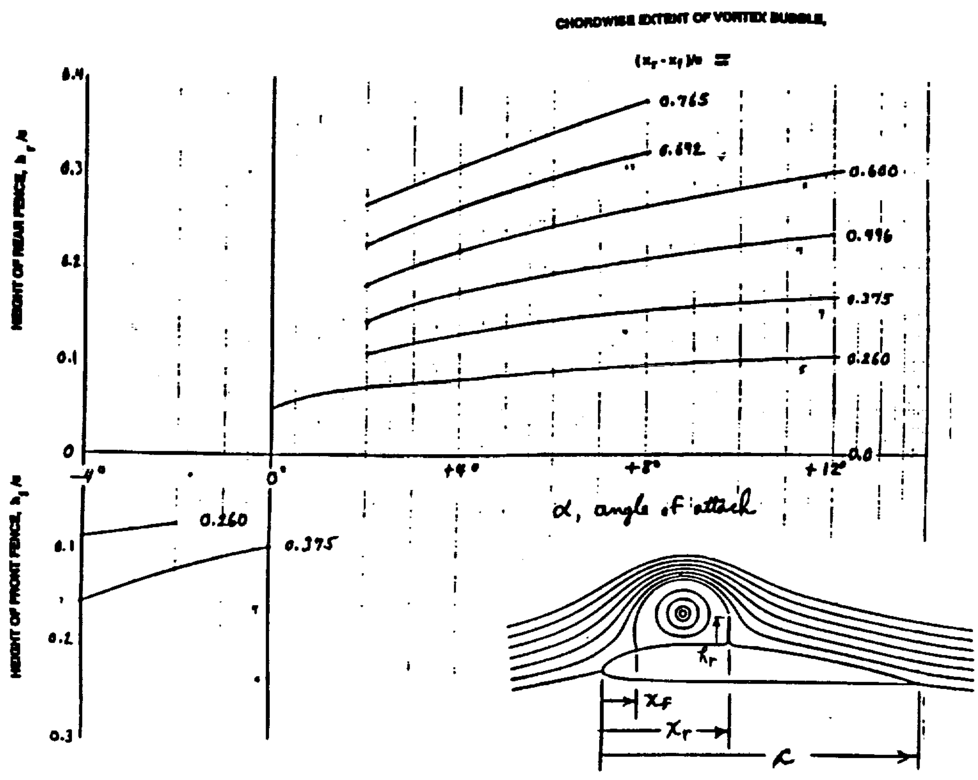
STREAMLINE PLOTS FOR RANGE OF VORTEX VORTEX BUBBLE SIZES

$\alpha = 4°$



The various characteristics of the trapped-vortex airfoils are now presented. The first parameter illustrated is the height of the flat fences used to bring about the $\dot{m} = 0$ condition. The parameters that are used to define the chordwise extent of the vortex bubble are shown in the inset figure. The chordwise beginning or front of the bubble, x_f, is taken as the intersection of the bubble or fence surface with the upper surface of the airfoil. Similarly, the rear or downstream end of the vortex bubble, x_r, is defined as the point where the bubble surface intersects the surface of the airfoil. It is noted that a flat fence length of about $0.1c$ is required in order to obtain a vortex bubble that covers 26% of the airfoil. A flat fence length of about $0.2c$ produces a vortex bubble that covers about half of the airfoil surface. This figure and the previous one clearly show that the size of the vortex bubble is largely controlled by the spacing between the front and rear fences. The height of the fences that are flat and do not conform to the shape of the vortex bubble govern the magnitude of the source or sink needed for equilibrium and are used to make $\dot{m} = 0$. Conforming fence portions of a certain length will likely also be necessary in practice to produce the shear layer needed for the development of the vortex and to control the physical limits of the vortex bubble. The present study does not include a study of the size of conforming fences that are needed.

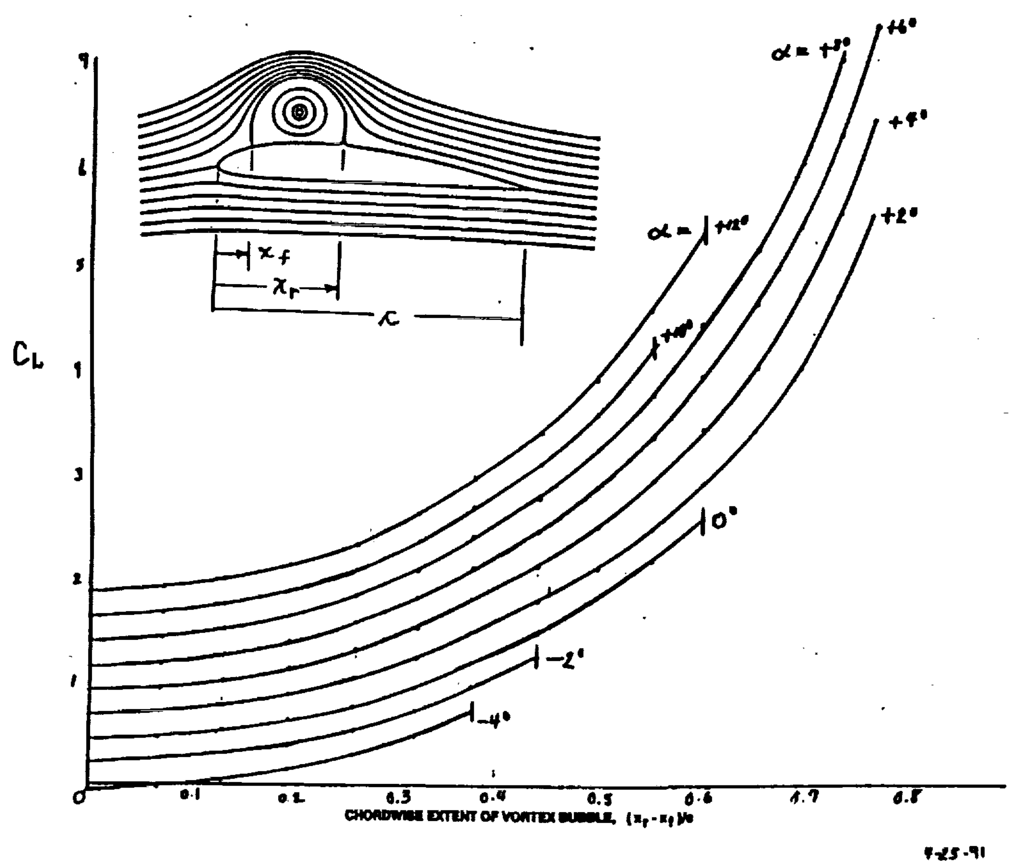
LENGTH OF FENCES REQUIRED FOR ZERO SOURCE STRENGTH



The lift coefficient developed by the various trapped- vortex configurations is presented on this slide for the range of vortex bubble sizes that were studied. It is noted that the lift increases slowly at first as the size of the vortex bubble increases from zero. At the larger vortex sizes, the lift changes rapidly with the size of the vortex bubble. Also to be noted is that not all of the curves end at the large vortex bubble sizes. The computations indicate that it is not possible to find an equilibrium point for $\dot{m} = 0$ in certain cases. Although a physical reason for the solution failure was not found, it seems reasonable that fence heights above certain values should not be possible solutions because the fences begin to interfere with the vortical flow field and cause it to become too distended in the vertical direction. An explanation or criterion for the fence lengths above which solutions can no longer be found was not found.

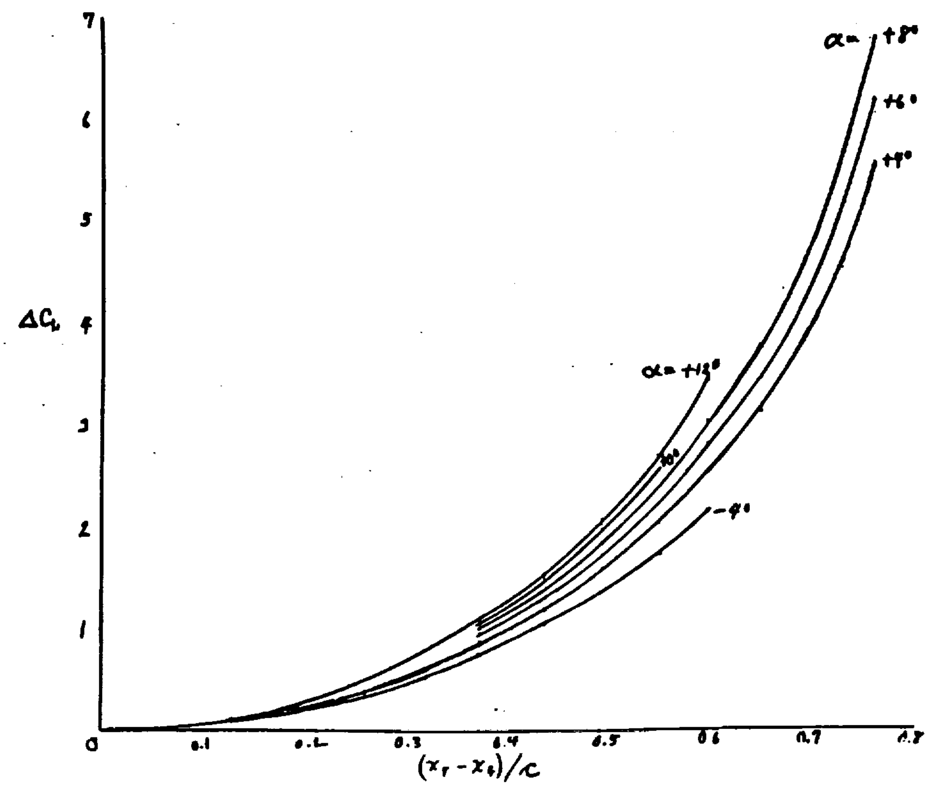
Even a casual look at the curves of lift as a function of bubble size suggests that the curves are about of the same shape and that they might possibly collapse to a single curve if the lift increment due to the trapped vortex is plotted as a function of the size of the vortex bubble, $(x_r - x_f)/c$. Those results are presented on the next slide.

LIFT COEFFICIENT AS A FUNCTION OF VORTEX BUBBLE SIZE



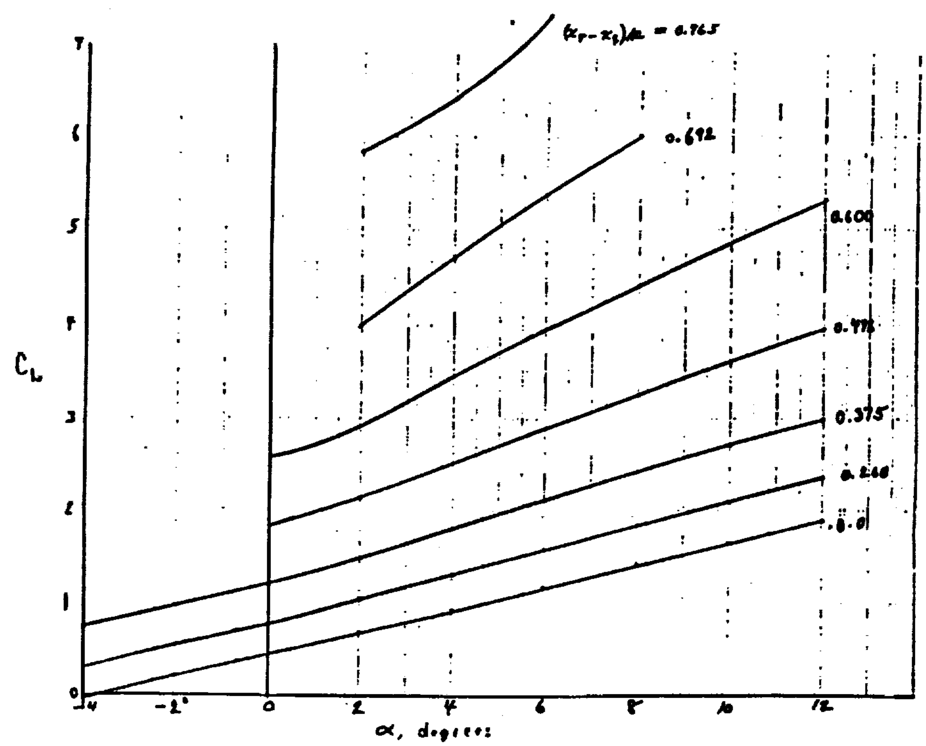
The data on the previous slide collapses to a single curve only for the smaller values of $(x_r - x_f)/c$. As the vortex bubble size increases the differences between the curves increases, even though the curves all have about the same shape. Manipulation of the various parameters might provide a better correlation of the data but was not tried.

INCREMENT IN LIFT COEFFICIENT DUE TO TRAPPED VORTEX



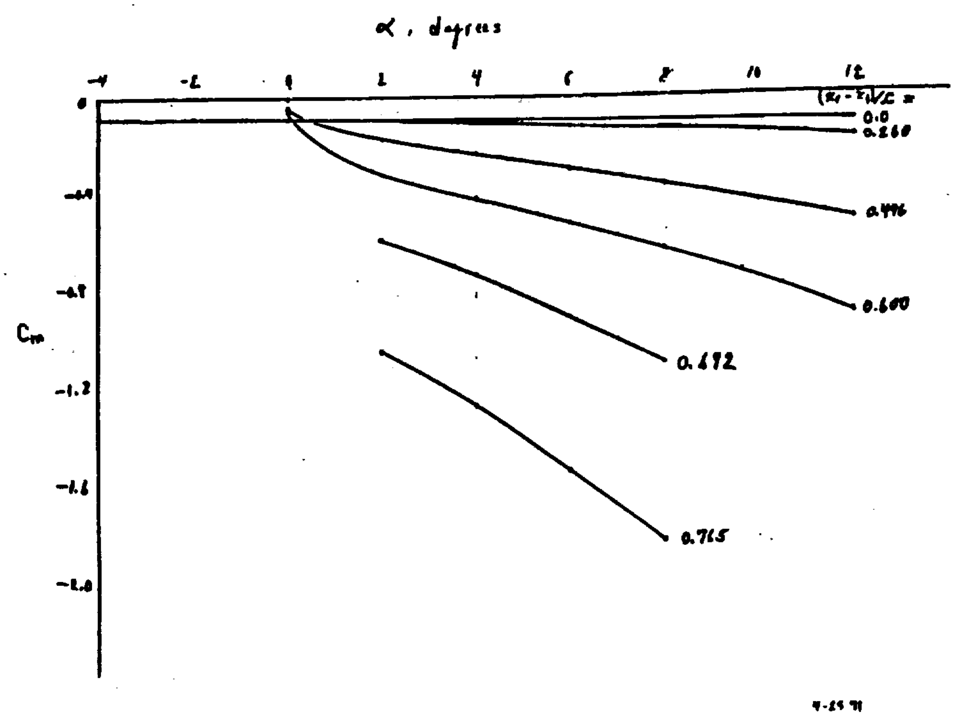
In order to demonstrate that the lift responds in the conventional way to angle of attack, this slide presents the lift produced as a function of angle of attack for various sizes of the trapped-vortex bubble. It is noted that the variation of lift with angle of attack for bubble sizes that are 60% or less of the chord are approximately linear with angle of attack. The slope of the lift curves increases with increasing size of the vortex bubble but not dramatically. These results indicate that trapped-vortex airfoils have a conventional response to angle of attack. The figure also provides an estimate of the reduction in angle of attack that can be achieved by adding a trapped vortex to the flow field over the airfoil. For example, addition of a trapped vortex that covers 26% of the airfoil, permits about a 4° reduction in angle of attack for a given section lift coefficient.

LIFT COEFFICIENT AS A FUNCTION OF ANGLE OF ATTACK



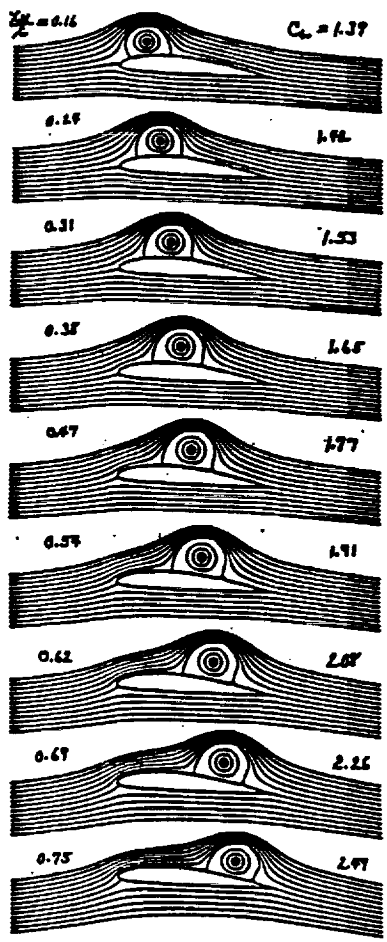
The pitching moment about the quarter-chord location is expected to vary greatly when the vortex bubble is large and moves aft. Even though an attempt was made to keep the center of the vortex bubble at about the same chordwise station, the pitching moment is seen to become quite large. Latitude is available, however, for placing the vortex bubble fore or aft on the airfoil to influence the pitching moment–see next slide.

PITCHING MOMENT COEFFICIENT VS. ANGLE OF ATTACK



In this particular sequence of trapped-vortex cases, the size of the trapped-vortex bubble is held approximately constant as the chordwise location of the bubble is move aft in a series of steps from a very forward location. The cases presented illustrate some of the latitude that is available for manipulating the characteristics of the airfoil.

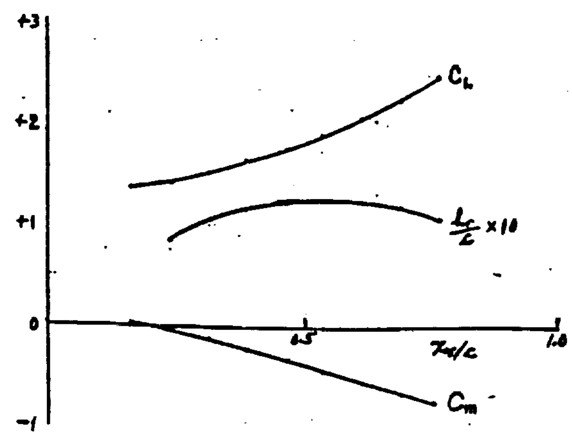
STREAMLINE PLOTS FOR RANGE OF CHORDWISE LOCATIONS OF VORTEX BUBBLE



$\alpha = 14°$

The characteristics of the trapped-vortex cases presented on the previous slide are summarized here. As expected, the pitching moment can be made as small as desired by moving the vortex bubble forward. The lift generated by the trapped vortex does decrease with the more forward location but not disastrously. The minimum height or length of the flat fences also changes a bit with the location of the trapped vortex but not by a large amount.

AIRFOIL CHARACTERISTICS FOR RANGE OF CHORDWISE LOCATIONS OF VORTEX BUBBLE



The foregoing slides provide an overview of the characteristics of one airfoil shape which has its lift enhanced by a trapped vortex flow field. Results for other airfoil shapes will differ in detail but will genenerally have much the same character. This information provides the beginning steps in the fulfillment of the objective of the research which is to find the necessary and sufficient conditions for vortex trapping. Not only should the vortex trapping be efficient and effective for two-dimensional (or airfoil) situations but also in the three-dimensional or wing situations. Furthermore, the trapped-vortex configurations should be efficient, easy to produce and maintain and not too onerous to implement on actual aircraft. With these guidelines for the research program, it is concluded from the investigation presented here that vortex trapping in two-dimensions is reaching a point of good understanding. More detailed studies not only with conformal mapping methods but also with other methods need to be carried out to fill out the characteristics of trapped-vortex airfoils. As noted in the items listed below, the most pertinent contributions of the present study to date include the introduction of a second fence to help control the characteristics of the trapped-vortex flow field. In particular, the use of fence curvature and height to bring about the equilibrium or zero velocity condition at the center of the vortex with negligible mass removal from the vortex core makes the trapped-vortex high-lift concept an efficient one. In this way the two-fence concept provides the necessary tools in two-dimensions at least for producing efficient easily formable high lift airfoils. The other conclusions listed below are essentially self explanatory. It should be remarked, however, that the steps from two- to three-dimensions will require some good ideas if the trapped-vortex flow fields are to be realized on real wings wherein only the local flow fields are used as the suction needed for evacuating the vortex core. The special suction orifices used in two dimensions will not then be needed. Encouragement is provided however, by the success achieved with the two-dimensional results and it is believed that comparable success can be achieved with three-dimensional configurations.

CONCLUSIONS

1. TWO DIMENSIONAL RESULTS INDICATE THAT TRAPPED VORTICES CAN PROVIDE LARGE AMOUNTS OF LIFT ENHANCEMENT.

2. AN UPSTREAM AND A DOWNSTREAM FENCE APPEAR TO BE NECESSARY PARTS OF THE TWO-DIMENSIONAL TRAPPING PROCESS.

3. FENCE HEIGHTS MUST BE ADJUSTED SO THAT SOURCE STRENGTH IS ZERO IN ORDER TO PROMOTE VORTEX FORMATION AND TO REDUCE DRAG.

4. ADDITIONAL DESIGN GUIDELINES WILL NO DOUBT BE NEEDED FOR VORTEX TRAPPING ON WINGS IN THE FULL THREE-DIMENSIONAL ENVIRONMENT.

Session XIII. Supersonic Laminar Flow Control

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