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Power Requirements for Distributed Suction for Increasing Maximum Lift

By

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7th September, 1948

Summary

This paper considers the power requirements for distributed suction. It appears that they are low for take-off and landing; no estimates can be made for the case of high-speed manoeuvres until tests have been made under the conditions of compressible flow.

Introduction

Suction through a porous surface is known[1,2,3,4] to be a powerful method of boundary-layer control for the purpose of obtaining high lift coefficients. The suction quantities required are small, but considerable energy-losses may occur when the sucked air passes through the porous material.

This paper is concerned with the power economy of this method of boundary-layer control.

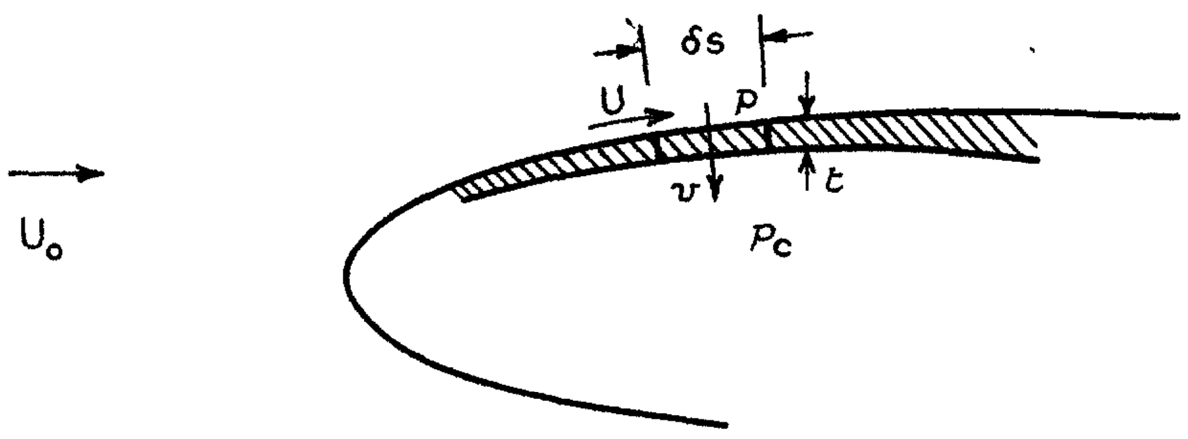
Definitions and Notation

Let $v(s)$ denote the mean velocity through the element δs of aerofoil surface. If κ is the resistance coefficient of the material the pressure p_c on the inner surface is given by

$$p - p_c = \kappa v t$$

where t is the thickness of the sheet.

FIG./



The suction pump is assumed to restore the total head of the sucked air to that of the free stream (H_o), discharging it with a velocity relative to the aeroplane which is equal and opposite to the forward speed of the aircraft relative to the ground (U_o), so that there is neither a sink drag nor a jet thrust. Neglecting losses in the ducting between the porous sheet and the suction pump, and assuming v to be small, the power required per unit span of a two-dimensional aerofoil is

$$P = \frac{1}{\eta_p} \int (H_o - p_c)\, v\, ds$$

where η_p is the efficiency of the pump. If η_a is the efficiency of the propulsive system of the aircraft, and c the aerofoil chord, the pump power can conveniently be expressed as an equivalent drag coefficient,

$$C_{Dp} = \frac{\eta_a P}{\frac{1}{2}\rho c U_o^3} .$$

In/

In the rest of this paper it will be assumed that $\eta_p = \eta_a$, so that

$$C_{Dp} = \int \frac{H_o - p_c}{\frac{1}{2}\rho U_o^2} \frac{v}{U_o} d\left(\frac{s}{c}\right)$$

$$= \int \left(\frac{H_o - p}{\frac{1}{2}\rho U_o^2} + \frac{p - p_c}{\frac{1}{2}\rho U_o^2} \right) \frac{v}{U_o} d\left(\frac{s}{c}\right).$$

Note that for jet propulsion η_a is low and likely to be less than η_p.

If there were no loss across the porous material, p_c would be equal to p, and C_{Dp} would assume the "ideal" value

$$C_{Dpi} = \int \frac{H_o - p}{\frac{1}{2}\rho U_o^2} \frac{v}{U_o} d\left(\frac{s}{c}\right)$$

$$= \int \left(\frac{U}{U_o}\right)^2 \frac{v}{U_o} d\left(\frac{s}{c}\right)$$

where U is the velocity at the edge of the boundary layer, assuming that the pressure is transmitted through the boundary layer without change.

When the resistance of the porous material is not negligible we must add to C_{Dpi} the "porous-resistivity" drag, namely

$$C_{Dpk} = \int \frac{p - p_c}{\frac{1}{2}\rho U_o^2} \frac{v}{U_o} d\left(\frac{s}{c}\right).$$

References 1 and 2 suggest that the normal velocity (v) needed at a given C_L to prevent laminar separation of the flow is determined by the parameter $(v/U_o)\sqrt{R}$; C_{Dpi} may therefore be expected to vary as $R^{-\frac{1}{2}}$.

Expressions when p_c is Constant over Portions of the Chord

If p_c and κt were constant over the whole of the chordwise extent of the porous surface, v would vary excessively* unless the resistance of the material were prohibitively high. It is probable,

however,/

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*and would be least where the external pressure p was least, i.e., in regions of peak velocity over the aerofoil surface, which is precisely where v would generally be required to be greatest.

however, that the suction chamber would be divided into several compartments for each of which p_c would be constant. Then

$$C_{Dp} = \Sigma \left[\frac{H_0 - p_c}{\frac{1}{2}\rho U_0^2} \int' \frac{v}{U_0} \, d\left(\frac{s}{c}\right) \right]$$

$$= \Sigma \frac{H_0 - p_c}{\frac{1}{2}\rho U_0^2} C_Q' ,$$

where $\int'$ denotes integration over each compartment and C_Q' the corresponding contribution to the total suction quantity coefficient (volume flow per unit span per unit time, divided by $U_0 c$), and the summation refers to the several compartments.

The condition for v to be constant is

$$\kappa t \propto p - p_c .$$

For a chosen value of p_c in each compartment, this condition can be satisfied by varying κ or t (or both).

Applications

The following numerical results relate to the 8% thick H.S.A. V section of References 2 and 3 at a lift coefficient of 1.5, with the porous surface extending from the front stagnation point to the 0.15c position on the upper surface, a distance of 0.21c measured along the arc. The velocity distribution over the surface was assumed to be that of potential flow; the suction velocity was assumed to be constant over the surface and to correspond to the experimental value (17) of $(v/U)\sqrt{R}$ which it is estimated would produce the lift coefficient of 1.5 at 15° inc. according to tests of a two-dimensional aerofoil in the N.P.L. 4 ft. No.2 tunnel[3]. As the extrapolation from the Reynolds numbers of the tests is so great, it should be emphasised that the assumption $v/U_0 \propto R^{-\frac{1}{2}}$ needs additional experimental verification. Moreover, in the absence of further experimental data, it has not been possible to make any allowance for scale effect on the comparative figures quoted for the performance of the aerofoil without suction. In the present state of knowledge, therefore, the numerical results here given indicate little more than the orders of magnitude to be expected.

The suction chamber was assumed to comprise one or several compartments, the partitions being located so as to give minimum power requirements in each case. The pressure in each compartment was taken to be equal to the static pressure on the aerofoil surface at the point of highest velocity over the appropriate portion of the surface. This is equivalent to assuming that κt is zero at this point, its value elsewhere being determined by the condition for constant v. In two of the examples, corresponding compartments on either side of the middle were assumed to be interconnected and thus at the same pressure, as this would simplify the pumping arrangements. The results are as follows:-

(1)/

		$C_{Dp}\sqrt{R}$
(1)	Ideal Case ($p = p_c$ everywhere: zero porous resistivity)	15.3
(2)	One suction compartment	53.6
(3)	Three compartments most economically placed	25.4
(4)	" " " " " (1st and 3rd interconnected)	26.4
(5)	Five chambers most economically placed	21.3
(6)	" " " " " (1st and 5th, and 2nd and 4th interconnected)	22.5

The analysis of Case 5 is given below in full:-

<u>Case 5</u>

s/c	U/U_0	$(U/U_0)^2$	Length of Compartment	$(H_0 - p_c)/\frac{1}{2}\rho U_0^2 = (U/U_0)^2_{max.}$	$(U/U_0)^2_{max.} \times (s/c)$ Compartment
0	0	0			
			0.030	1	0.030
0.030	1.0	1.0			
			0.011	8.3	0.093
0.041	2.88	8.3			
(0.053	3.87	15.0)	0.0325	15	0.488
0.0735	2.67	7.15			
			0.0365	7.15	0.261
0.110	1.96	3.85			
			0.100	3.85	0.385
0.210	1.582	2.50			
					1.26

$$C_D\sqrt{R} = \frac{v_o}{U_o}\sqrt{R} \times 1.26$$

$$= 17 \times 1.26 = 21.3.$$

In order to prevent κt from falling to zero at one point in each compartment, the thickness of the porous material could be increased everywhere by a constant amount. For example, if in Case 5 we add a value of κt equal to the maximum attained in the compartment with the smallest external pressure variation, and hence with the thinnest wall, $C_D\sqrt{R}$ would only be increased to 26.1, i.e., by 16%.

Power Requirements for a Specific Aircraft

The aircraft data assumed are as follows:-

Aircraft weight	10,000 lb.
Wing area	250 sq. ft.
Wing loading	40 lb./sq. ft.
Mean chord	8 ft.

The lift coefficient of 1.5 corresponds to a landing speed of 102 m.p.h. (150 ft./sec.) at sea level, the Reynolds number (based on the mean wing chord) being 7.66×10^6. No attempt has been made to allow for three-dimensional effects, and the suction has been assumed to be applied along the whole of the span: the suction quantity is then 48 cu. ft./sec. (3.7 lb./sec.). The following table gives the estimated power requirements, subject to the assumptions stated above, for producing the assumed lift coefficient of 1.5 at 15° inc., at which the lift coefficient with zero suction was 0.7. (The maximum lift with zero suction was 0.87, and occurred at $10\frac{1}{2}°$ inc.)

		Horse Power
(1)	Ideal Case	10.0
(2)	One suction compartment	35.1
(4)	Three compartments, interconnected	17.3
(6)	Five compartments, interconnected	14.8

The suction head $(H_0 - p_c)$ to be produced by the pump is most in the compartment which covers the point of maximum velocity over the aerofoil surface. As κt has been assumed to be zero at this point, the required head is about 400 lb./sq. ft.

No estimates can be given for the power required to apply distributed suction to the nose of an aerofoil at very high speed until wind-tunnel tests have been carried out to discover the effect of suction on compressible flow and in the presence of shock waves.

Conclusions

For the aircraft assumed, the order of magnitude of the suction power requirements are 10 h.p. for the "ideal" case and 35 h.p. for a suction chamber which consists of a single compartment. These powers are estimated to produce a lift coefficient of 1.5 at 15° inc.; without suction the lift would have been 0.7 at the same incidence, or 0.87 at the stalling incidence ($10\frac{1}{2}°$).

The above numerical values are based on tests of a two-dimensional aerofoil at low Reynolds number, together with the assumption that $C_Q \propto R^{-\frac{1}{2}}$; this assumption needs further experimental verification. In the absence of further data, it has not been possible to allow for scale effect on the comparative figures quoted for the performance of the wing without suction.

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