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BOUNDARY LAYER CONTROL FOR AIRSHIPS

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ABSTRACT: This paper summarizes an investigation of the aerodynamic principle of boundary layer control for non-rigid LTA craft initiated under the Office of Naval Research, Contract NOnr1412(00)LI. The project included a wind tunnel test on a BLC body of revolution at zero angle of attack. Theoretical analysis is shown to be in excellent agreement with the test data. Methods are evolved for predicting the boundary layer development on a body of revolution and the suction pumping and propulsive power requirements. These methods are used to predict the performance characteristics of a full-scale airship. The analysis indicates that propulsive power reductions of 15 to 25 percent and endurance improvements of 20 to 40 percent may be realized in employing boundary-layer control to non-rigid airships.

INTRODUCTION

The investigation of the application of boundary-layer control to non-rigid LTA craft was initiated by Goodyear Aerospace Corporation in March, 1954 under Office of Naval Research Contract NOnr1412(00)LI. The project stretched over a 3 1/2 year period primarily because of a 20-month delay during which all effort was suspended while awaiting the availability of the 7' x 10' transonic wind tunnel at NSRDC (then called the David Taylor Model Basin). The scope of the study included the evaluation of the drag characteristics of an airship hull which employed either suction slots or an auxiliary air foil as a means of preventing turbulent boundary layer separation. The drag results were predicted by theoretical methods presented in References 1 and 3. Comparative drag values were obtained for one body configuration in the wind tunnel tests reported in Ref. 2.

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BOUNDARY LAYER CONTROL

This discussion of boundary layer control will be limited to bodies of revolution with flow at high Reynolds numbers. Therefore, turbulent flows are assumed. With fluid flow about a body the friction occurring on the forward portion consumes much of the initial energy of the fluid adjacent to the body. The fluid so affected is termed the boundary layer. When this relatively low energy fluid reaches the stern, the fluid is confronted with an unavoidable region of increasing surface pressures due to the increasing static pressure of the fluid external to the boundary layer being impressed upon it. If the rate of pressure increase is relatively large, the boundary layer fluid will not contain sufficient energy to flow against such a high "back pressure," so to speak. This then results in considerable thickening of the boundary layer with possible flow separation.

Although it is possible to design a body of revolution having a favorable pressure gradient over essentially the entire length of the body, generally such a body must have a relatively blunt after end. This design produces a correspondingly adverse pressure gradient that tends to cause boundary-layer separation and consequent drag losses.

This problem can be approached passively by lengthening the body (increasing the fineness ratio) thereby reducing the adverse pressure gradient and delaying boundary layer thickening so that the area affected by the reduced pressure is small and hence tend to reduce the pressure drag. For bodies of constant volume, however, an increase in fineness ratio is accompanied by an increase in friction drag due to the consequent increase in surface area. Altering the pressure drag by varying the fineness ratio gives rise to a change in friction drag of opposite and approximately equal magnitude for the common airship fineness ratios. When the pressure drag is efficiently reduced, accompanied by a lower fineness ratio, the total drag can be significantly reduced as illustrated in Figure 1.

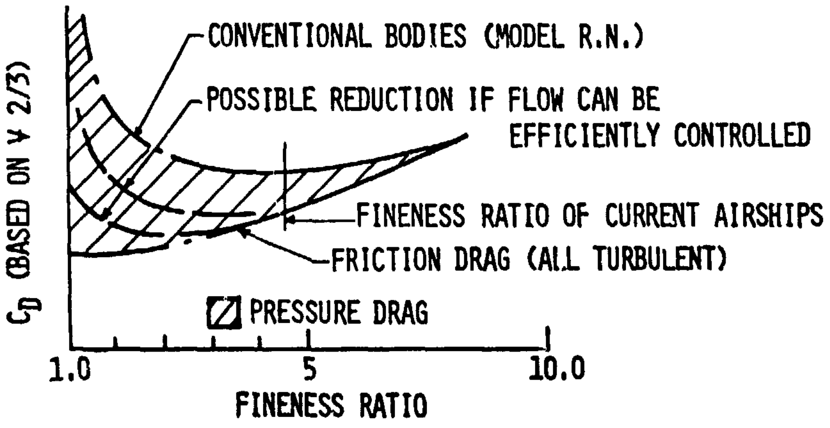

Figure 1
Pressure Drag Versus Fineness Ratio

However, through proper body-contour design, the adverse gradient can be located at one longitudinal body station or for a short longitudinal body station or for a short longitudinal distance to produce a favorable pressure gradient extending to the 100-percent body station. By applying the air-flow suction at this longitudinal body station (or area of velocity and pressure discontinuity), energy will be supplied to stabilize the boundary layer and prevent air-flow separation. A drag economy can be realized if the reduction in the external drag of the body is greater than the equivalent suction drag.

Configuration Selection:

The first decision to be made in the selection of a boundary-layer control airship configuration was the suction system. The distributed type suction systems made up of many perforations or slots were discarded as not feasible for the non-rigid airship application. Thus the single slot system was chosen and it remained to choose an airfoil shape. The available selection could be categorized in two groups - the conventional airfoil and the Griffith type airfoil. The Griffith shape has several advantages for BLC applications. Although designed for laminar flow, it possesses the favorable pressure gradients necessary to any type of boundary layer control. The localized adverse pressure gradient is compatible with the single slot control system. Also, the slot location is well aft for the lower fineness ratios. The Griffith type airfoil was therefore chosen. The specific contour used in the study was a 34 percent thick Lighthill shape. This was selected on the basis of the potential flow characteristics as determined by a series of electrostatic tank tests. The selected airfoil shape and velocity distribution are shown in Figure 2. As can be seen the adverse flow region is quite local between $X/\ell = 1.6$ and 1.7. This shape was used in the theoretical drag estimates, the wind tunnel test and the full-scale performance studies.

Drag Estimates and Wind-Tunnel Tests:

A method of calculation was evolved to predict skin friction, equivalent suction drag, and propulsive efficiency of this type of airship hull. Local skin-friction coefficient values were determined for the forward stagnation region, the laminar boundary-layer region under a favorable pressure gradient before the suction slot, and the turbulent boundary-layer region under a favorable pressure gradient behind the suction slot.

Equivalent suction drag was based on the mean total-head loss in the boundary-layer suction flow at the slot entry. This did not include duct losses since such losses can be evaluated only after the preliminary design of a specific ducting system. Hence, the suction drag was evaluated for an idealized system where duct losses were small compared with boundary-layer losses.

The wind-tunnel tests were carried out in the 7' x 10' transonic tunnel. The Reynolds number was varied from 4.4×16^6 to 10^7. Due to the model size restriction and the relatively high test Reynolds numbers, a powered model with force measurements was not possible and therefore drag quantities were determined from the momentum deficit in the wake. Artificial stimulation at 10 percent of the model length

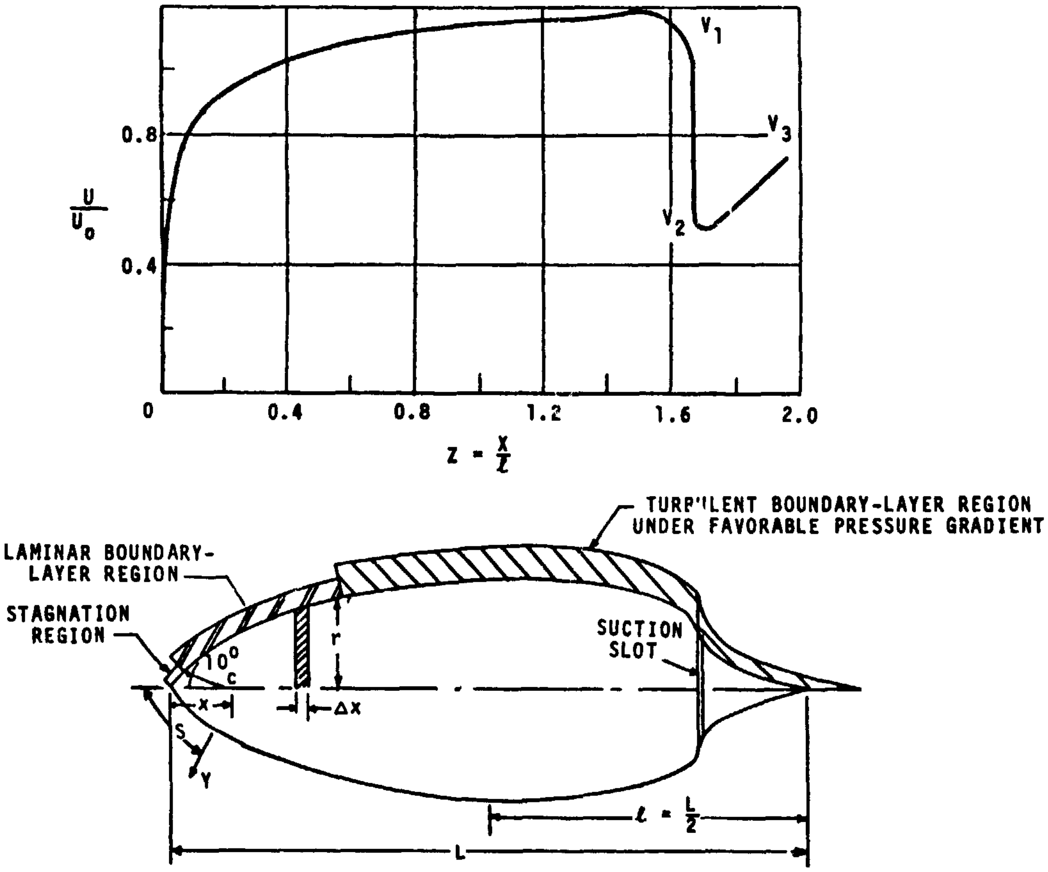

Figure 2
Favorable Velocity Distribution and Corresponding
Regions over a Boundary-Layer-Controlled Airship

was utilized to obtain turbulent flow. The final test consisted of one BLC configuration at zero angle of attack with the sole objective being whether or not the theory predicted the reduction in drag realistically. A model of ZP2G-1 airship hull was also tested under the same environment to ensure a true comparison of drag change between the conventional and BLC airships. The actual comparison of the experimental and test data is shown in Figure 3. The drag coefficients of the body are plotted versus the suction quantity coefficient. The plots shown are for a Reynolds number of 4.2×10^6. The wake drag and suction drag are plotted separately. They are then added together and plotted as total drag. The experimental data is presented in the same manner. It can be seen that good agreement exists between the theoretical and experimental work. This agreement is further borne out by the pressure distribution. The measured pressure coefficients are plotted with the theoretical values in Figure 4 for a Reynolds number of 10×10^6.

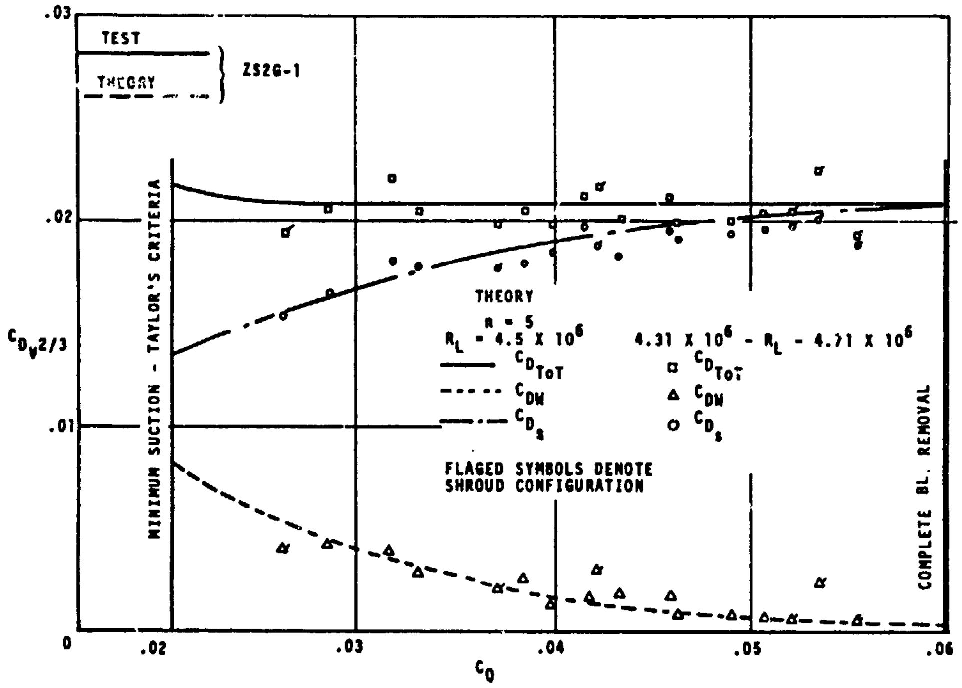

Figure 3
Test & Theoretical Drag Comparison
BLC Model - $R_L = 4.5 \times 10^6$

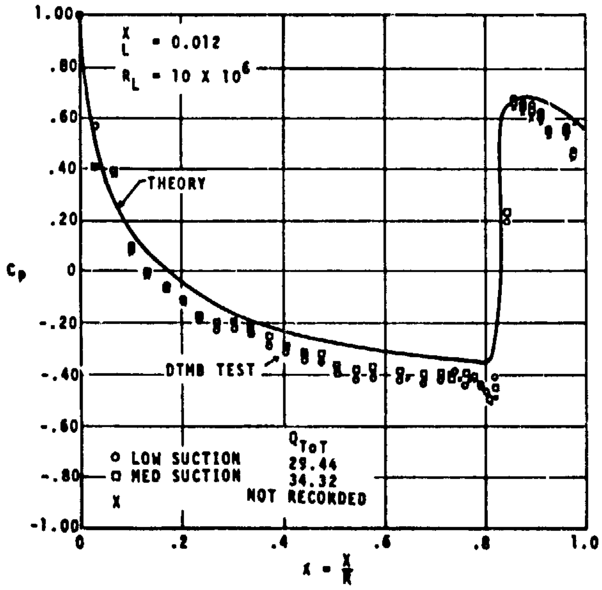

Figure 4
Pressure Distribution Comparison Test
and Theoretical BLC Body

The drag of the BLC airship at all Reynolds Numbers and slot widths, as determined from the rake, were in excellent agreement with the theoretically predicted values. The ideal suction drag also indicated close agreement although theory appears to be somewhat greater than the measured values. Other comparisons of BLC test parameters with theory also showed excellent agreement. These preliminary tests validated the drag reduction predicted by theory. The tests not only showed this excellent agreement with theory, but also demonstrated this agreement over a sufficient range of Reynolds Numbers to give credence to full-scale theoretical estimates.

Comparison of Full Scale Performance

In order to compare the performance of a BLC airship with that of a conventional (ZP2N) airship, a preliminary design was required in order to consider the impact of all the features associated with each type that had a bearing on drag besides the hull drag alone. The scope of this program does not permit comparing airship sizes and the associated power requirements based on missions but does compare mission capability based on an airship size of one million (10^6) cubic feet. Figure 5 compares the total power requirements for the two configurations. A 10 percent reduction in component drag for the BLC configuration can be attributed primarily to the fact that outriggers, nacelles and empennage cables (fins are cantilevered) are not required.

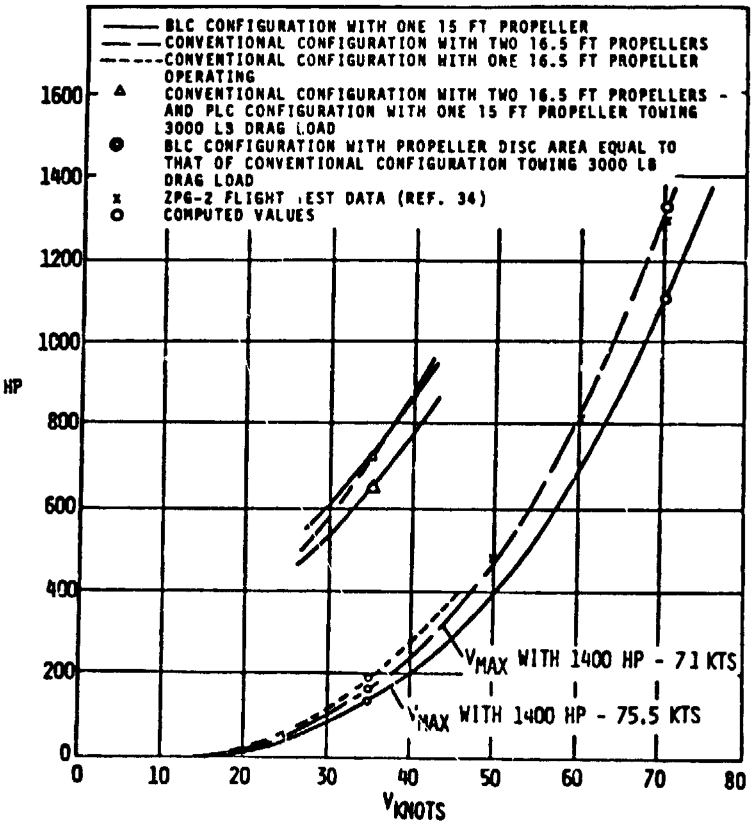

Figure 5
Horsepower Requirements vs Flight Velocity
For BLC & Conventional Airships V = 10^6

When considering various operational conditions such as single engine cruise (normal conventional airship operation) with the corresponding differences in SFC and propeller efficiencies, the BLC airship would offer an endurance improvement of between 20 and 40 percent at most operating velocities. With a propeller comparable in size to those used on conventional airships, the improvement in endurance for ASW towing would be 10 percent when the tow drag is 3000 pounds or 25 percent if the tow load was 100 pounds.

A complete evaluation of the advantages of a BLC airship must encompass many factors including a comparison of the general operational characteristics of each configuration and the weight allowable for fuel. Although such an evaluation was beyond the scope of this study, it is of interest to briefly discuss some of the major BLC operational characteristics as they differ from the conventional airship's characteristics.

(1) Static instability of an airship is due almost entirely to the hull and is a function of fineness ratio; C_{M_α} decreases with decreasing fineness ratio and consequently will require less in the way of a stabilizing system. As shown in Figure 6 the tail length is substantially the same and due to structural considerations the aspect ratio can be considerably greater.
(2) Low speed control is a prime consideration for airships and with the BLC airship it can, to a considerable degree, be obtained by vectoring the outlet air from the duct. This would have its greatest effect during a towing operation such as sonar array towing.

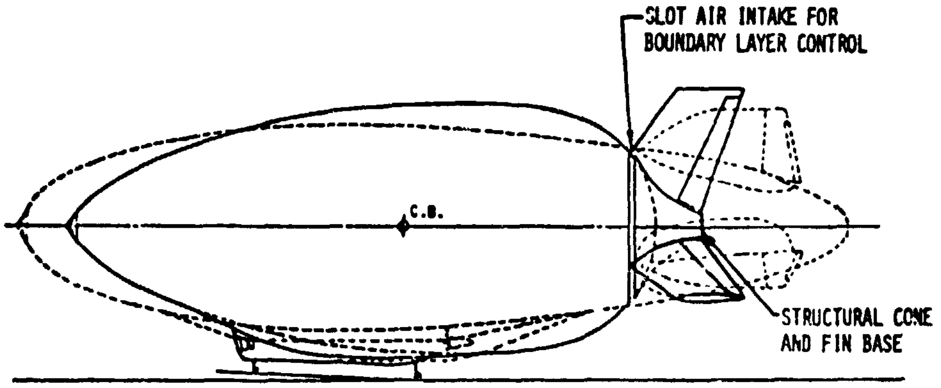

Figure 6
Comparison of BLC Airship with Conventional
For Equal Volume

(3) Propeller and engine noise interferes not only with crew comfort but also with the effectiveness of the mission equipment; sonar operations as an example. The BLC configuration is inherently conducive to quiet operation; the propeller is shrouded and the distance between the propulsion unit and the crew is considerably greater than is the case with the conventional design. The aft location of the BLC power plant also represents a noise reduction to the crew.
(4) Other advantages of the BLC configuration are in the areas of elimination of variable pitch protection from physical damage.

CONCLUSIONS

The findings of this limited investigation into the boundary-layer-control airship show sufficient increase in the airship performance to warrent further study. The following conclusions are offered:

(1) The NSRDC wind tunnel tests confirm the ability of the theoretical methods described in this report to predict the boundary layer control of a body of revolution at zero angle of attack.
(2) The theory confirmed by the NSRDC wind tunnel tests together with allowance for inlet and duct losses predicts that the bare hull power requirements for a full scale BLC airship hull of fineness ratio 3.0 at zero angle of attack can be expected to be 10 to 20 percent less than the power requirements of a conventional airship hull of equal volume.
(3) The differences in the components other than the hull associated with the two configurations, offers an additional 5 to 10 percent reduction in power requirements for the BLC non-rigid airship configuration.
(4) A BLC configuration of fineness ratio 3.0 can be expected to reduce the total propulsive power requirements of a conventional non-rigid airship of equal volume 15 to 25 percent.
(5) If both configurations have equal fuel quantities available, BLC can be expected to increase the endurance 20 to 40 percent.
(6) Indications exist that the fineness ratio of 3.0 selected for this investigation may not be optimum for a BLC airship.

The predicted theoretical increase in performance, together with the operational advantages, indicated a significant advance in airship design and led to the initiation of the BLC program. This program, although limited in scope, has confirmed the validity of the predicted performance improvement. To take full advantage of the results thus far and fully exploit the potential of the BLC configuration, this contractor recommends the following program to continued effort be initiated:

(1) To refine the merits and limitations of applying boundary-layer control to airships, the following investigations should be initiated:
a) Theoretical power requirement studies for bodies with fineness ratios less than 3.0 which necessitate further electrostatic tank testing.
b) Wind tunnel testing to determine the effect of angles of attack.
c) Preliminary design studies to define an operational configuration would, in conjunction with items (a) and (b) above, permit the selection of an optimum and practicable configuration.

(2) To obtain data for the design and fabrication of a BLC airship, a wind tunnel test of a self-powered model at reasonable, large Reynolds numbers should be conducted upon completion of Item 1 above.

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3. Horshe, M. L., Pake, F. A., and Wasson H. R., Air Investigation of a Boundary Layer Controlled Airship, GER 8399, Goodyear Aerospace Corporation, Akron, Ohio (15 October, 1957).