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Jet-Propulsion of Subsonic Bodies with Jet Total-Head Equal to Free Stream's

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JET-PROPULSION OF SUBSONIC BODIES WITH JET TOTAL-HEAD EQUAL TO FREE STREAM'S *

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Abstract

Jet-propulsion of a subsonic axisymmetric 2.72:1 body has been achieved in a low-speed 8' x 10' wind-tunnel at a volume Reynolds Number of two millions *with a stern jet total-head equal to free-stream's* and therefore with 100% propulsive efficiency. The jet exit velocity was 33% lower than free-stream's and the jet exit static-pressure was over half the stagnation value.

The aerodynamic basis for this milestone was provided by the integrated/body pressure-distribution/boundary-layer control/stern jet-propulsion/design concept.

Large excess thrusts have been also generated with higher jet flows, with an incremental propulsive efficiency up to 81.5%. A propulsion power *reduction of 50% has been achieved with the inte-*grated self-propelled wind-tunnel model, as compared to the best conventional streamlined bodies with wake stern propellers, at the same volume Reynolds *Number.*

Nomenclature

$C_D = \frac{F}{\frac{1}{2}\rho U_0^2 V^{0.66}}$	Drag coefficient
C_{DW}	Wake drag coefficient
C_{DM}	Momentum drag coefficient
$C_T = \frac{T}{\frac{1}{2}\rho U_0^2 V^{0.66}}$	Thrust coefficient
$CQ = \frac{Q}{U_0 V^{0.66}}$	Suction flow coefficient
CQ_5	Suction flow coefficient measured @ Station 5
$CH_{12} = \frac{\Delta H_{12}}{q}$	Total-pressure differential coefficient between Stations 1 and 2
$CH_{25} = \frac{\Delta H_{25}}{q}$	Total-pressure differential coefficient between Stations 2 and 5
$CHP_{25} = CQ_5 \times CH_{25}$	Fan air power coefficient between Stations 2 and 5
C_P	Static pressure coefficient
C_{P5}	Static pressure coefficient @ jet discharge (Station 5)
ΔC_{P16}	Static pressure differential coefficient across suction slot (Stations 1 and 6)
D	Maximum body diameter
D_5	Jet diameter @ Station 5
$f = \frac{L}{D}$	Fineness ratio
F	Axial drag force
H_5	Jet total-pressure @ Station 5
ΔH_{12}	Total-pressure differential between Stations 1 and 2
ΔH_{25}	Total-pressure differential between Stations 2 and 5
L_0	Length of configuration 0
L_1	Length of configuration 1
$q = \frac{1}{2}\rho U_0^2$	Free-stream dynamic pressure
Q	*Suction flow*
Q_5	Suction flow measured @ Station 5
r	Body radius at axial location x
$R_L = \frac{U_0 L}{\nu}$	Length Reynolds Number
$R_V = \frac{U_0 V^{0.33}}{\nu}$	Volume Reynolds Number
T	*Axial thrust force*
U_0	Free-stream velocity
U_1	Velocity @ Station 1 upstream of suction slot
U_5	Jet velocity @ Station 5
U_6	Velocity @ Station 6 downstream of suction slot
V	Body useful volume
x	Axial distance from body's nose
θ	Boundary-layer momentum thickness
ν	Kinematic viscosity of free-stream flow
ρ	Mass density of free-stream flow

Introduction

Jet-propulsion of a body in subsonic flight is a classical problem in aerodynamics, which is still begging for complete solution. As it was pointed out by Prof. E. S. Taylor,[1] many erroneous ideas of propulsion by jet reaction were prevalent as late as the 1920s. It was well known at that time that a fireboat directing its streams of water at a fire would gradually move away from the fire target. Eminent professors of engineering were heard to scoff at this observation, saying that "you can't push on a rope." Such statement, of course, reflects a profound ignorance of the jet-propulsion problem. Goddard, at about this time, found it necessary to demonstrate that his rockets generated

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thrust even when fired in a vacuum; it was apparently difficult at that time to conceive of something propelling itself without some medium or body to push on. The idea of a device pushing on a medium which was being discarded was understood by only a few at that time; now it is part of the popular knowledge, after leading man into space.

The next phase of the jet-propulsion problem was started in 1953 by Kuchemann and Weber[2] with the following statement: "Another line of propulsion development may be the extreme application of boundary-layer suction, which uses air from the boundary-layer...and restores it to full free-stream energy, instead of producing a thrust force to overcome the drag associated with the boundary-layer wake." A further step was taken by Goldschmied[3] in 1966 with the presentation of the integrated/body pressure-distribution/boundary-layer control/stern jet propulsion/concept and of preliminary wind-tunnel test data only of body pressure-distribution/boundary-layer control/integration. The integrated aerodynamic design concept was verified by a wind-tunnel test program in 1981 at the David W. Taylor Naval Ship R&D Center with a self-propelled test model; the experimental results were reported by Goldschmied[4] in 1982, showing that propulsion power reductions of 50% were achieved, as compared to the best conventional streamlined bodies with wake stern propellers at the same volume Reynolds Number.

It is the purpose of this brief paper to focus on some significant aspects of the extensive 1981 test program, i.e. on the fact that jet-propulsion was conclusively achieved with jet total-head equal to free-stream's.

Despite the obvious significance of these experimental achievements, it has been the author's experience that an analogous situation to the 1920s is prevailing in the 1980s; it is apparently very difficult today to conceive of something propelling itself with jet total-heads no greater than free-stream's.

Aerodynamic System

The aerodynamic system approach is used to analyze the problem and then to attempt the synthesis of an optimum solution. A functional block diagram is shown in Fig. 1: it is a sensitive, complex and interacting closed-loop system with several feedback paths and interesting dynamic characteristics.

Photos of the wind-tunnel installation of the two test models are given in Figs. 2 and 3; Fig. 2 shows the model with the open stern jet (Configuration 00) while Fig. 3 shows Configuration 01, which differs only in the addition of a short slender tailboom in the jet discharge.

Figure 4 presents the layout of the suction/propulsion flow path in the aftbody of the test model, from Station 1 (end of forebody), to Station 2 (entrance to fan inlet plenum), to Station 3 (fan inlet plenum), to Station 4 (fan discharge plenum) and finally to Station 5 (jet discharge). It can be noted that the fan should have been installed at Station 5, if funds had been available for the design and fabrication of a miniature 3.25" dia. NACA axial compressor stage; instead a commercially available 2-stage fan was used in the most practical manner.

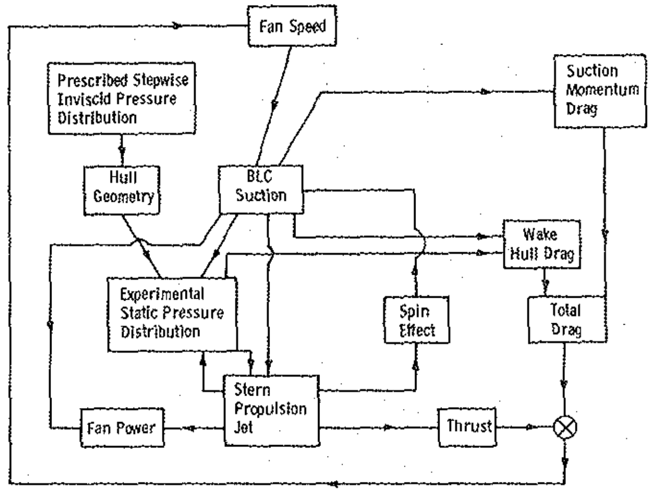


Fig. 1 Functional block diagram of integrated /body pressure-distribution/boundary-layer control/stern jet propulsion/ aerodynamic system.

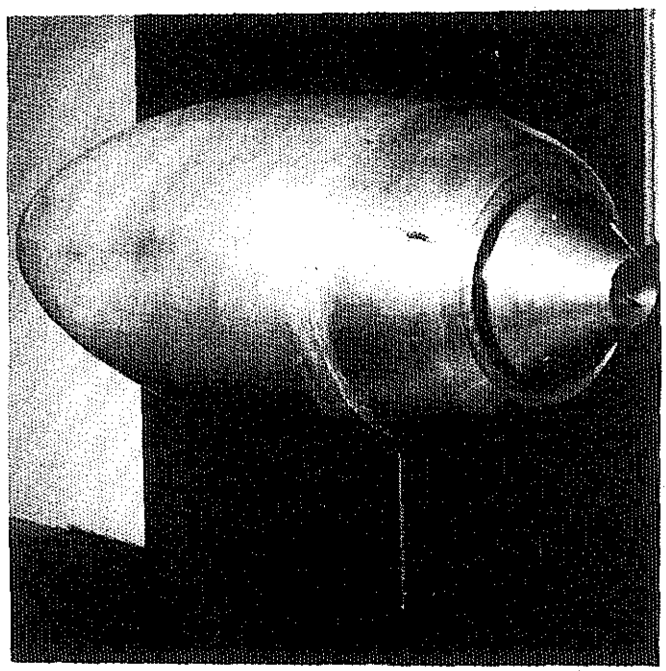


Fig. 2 Photo of wind-tunnel installation of integrated test model with open jet (Conf. 00).

A particular inviscid pressure distribution is prescribed, with a favorable forebody pressure-gradient (increasing velocity) from the nose to the suction slot @ 85% length, a stepwise pressure rise at the slot location, followed by another favorable aftbody pressure-gradient from the slot location to the trailing edge. This pressure distribution is shown in Fig. 5, together with experimental points with and without boundary-layer control by slot suction. It can be readily seen that the stepwise pressure distribution can only be achieved with a suction slot to provide adequate boundary-layer

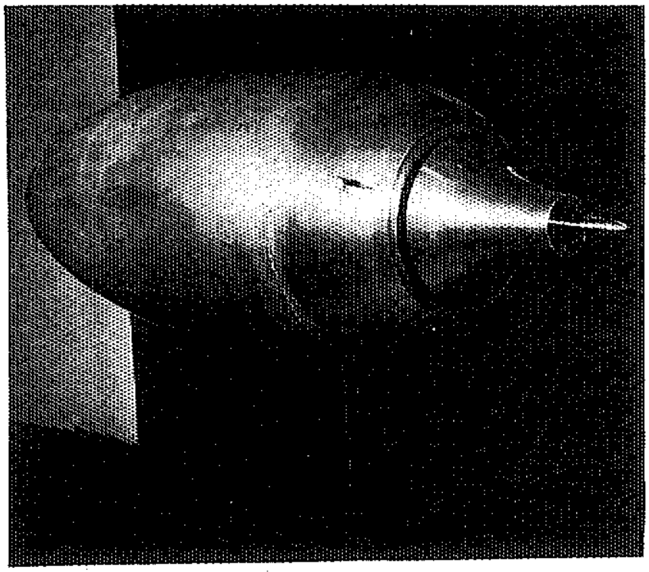


Fig. 3 Photo of wind-tunnel installation of integrated test model with tailboom (Conf. 01).

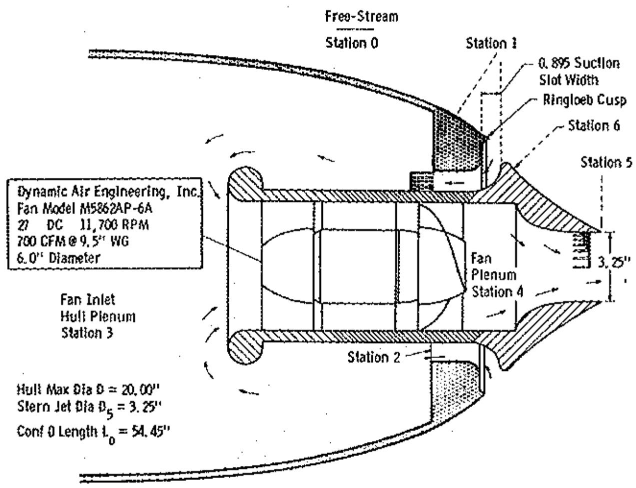


Fig. 4 Layout of Conf. 00: Aftbody with suction slot, fan and stert jet.

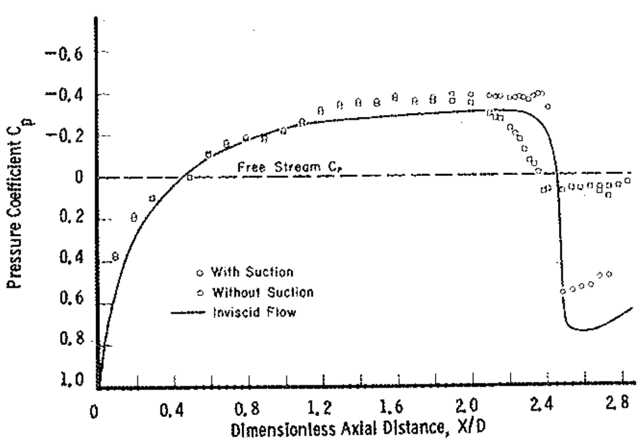


Fig. 5 Stepwise pressure distribution: inviscid and experimental with and without boundary-layer control suction.

control; this is the meaning of /Body Pressure Distribution/Boundary-Layer Control/Integration.

The significant advantages of this procedure are not obvious at first glance and they were not recognized by Griffith who first suggested stepwise pressure-distributions to maximize laminar flow on two-dimensional airfoils. These advantages, however, can be made quite clear by comparing the axial growth of the boundary-layer momentum thickness θ for the test body and for two bodies with optimum tails (without boundary-layer control) as developed and presented by Smith, Stokes and Lee.[5]

The Smith, Stokes and Lee optimum tails are designed to yield the Stratford zero skin-friction pressure-distribution on the aftbody, also starting @ 85% length. These aftbodies yield the fastest possible pressure recovery without any form of boundary-layer control and thus provide an important reference point. Figure 2 of Ref. 5 is reproduced as Fig. 6: it is quite evident that there occurs a quite dramatic rise of the momentum thickness θ over the aftbodies, from the θ_0 values at the start of the adverse pressure gradient.

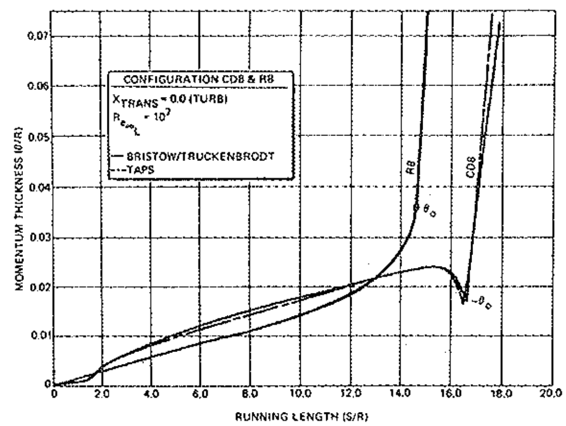


Fig. 2 Predictions of momentum thickness distribution for CD8 and R8 bodies.

Fig. 6 Reproduced from Ref. 5, "Optimum Tail Shapes for Bodies of Revolution," (1981).

On the other hand, the momentum thickness θ remains constant across the pressure step, if adequate boundary-layer control is applied, for the test body as shown by Fig. 11 of Ref. 3, which is reproduced here as Fig. 7. It is to be noted that, while θ_1 refers to Station 1 of Fig. 4, θ_2 refers to Station 6 of Fig. 4, i.e. the ratio $\theta_2/\theta_1 = 1.0$ expresses the lack of momentum-thickness change across the pressure step and the suction slot.

The avoidance of ~90% of the momentum-thickness growth (and concomitant wake drag) is the very important benefit offered by the optimum integration of body pressure distribution with boundary-layer control.

The wake drag of the integrated test body is compared to that of conventional streamlined bodies in Fig. 8; the XZS-2G data and the integrated BLC airship data are taken from Ref. 8 while the Model A and Model M data are taken from Ref. 7. It appears that the integrated test body's wake drag is

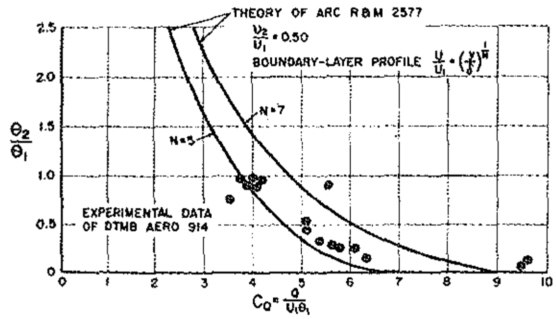


Fig. 11 Ratio of boundary-layer momentum thicknesses across boundary-layer control suction slot.

Fig. 7 Reproduced from Ref. 3, "Integrated Hull Design, Boundary-layer Control and Propulsion of Submerged Bodies," (1967).

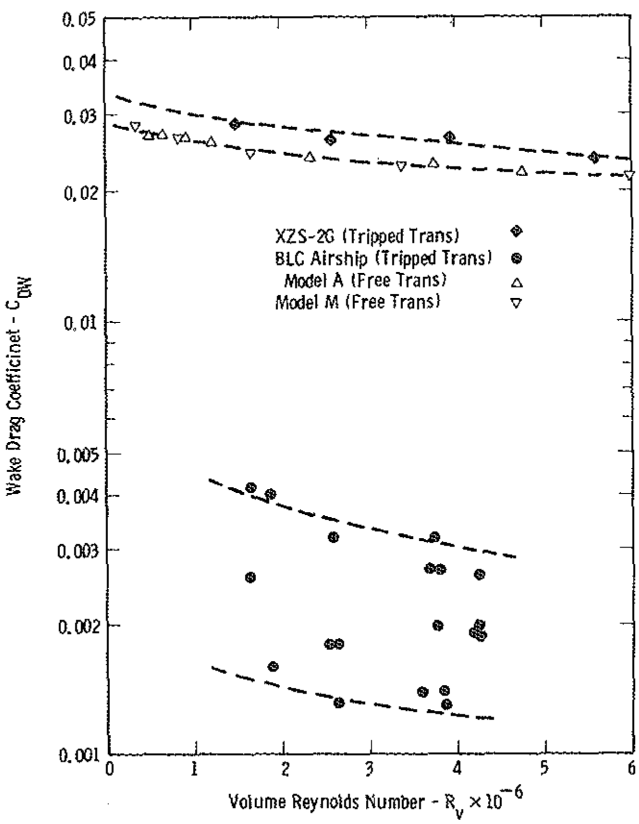


Fig. 8 Body's wake drag with integrated/body pressure-distribution/boundary-layer control/and with conventional streamlined bodies.

smaller by one order of magnitude, while the suction boundary-layer control function was strictly limited to maintaining constant momentum thickness, as shown in Fig. 7.

The penalty, of course, is the momentum drag created by the boundary-layer flow ingestion, with the concomitant power requirements to create the counter-balancing thrust. It is obvious that suction requirements must be minimized, consistently with full aftbody flow attachment and system stability; the suction momentum drag is much larger than the wake drag, i.e. it demands the major portion of the thrust generation. The present work has developed a boundary-layer control system with three elements, which is superior to that of Ref. 3; the minimum suction flow coefficient CQ was reduced from CQ = 0.045 (average @ R_V = 1.726 x 10^6) to CQ = 0.015 (average @ R_V = 1.45 x 10^6), for transition tripped @ 10% length in both cases.

The three elements are the suction slot, the Ringloeb cusp at the slot leading-edge and the slender rear tailboom, as compared to only the suction slot with rounded leading-edge. The Ringloeb cusp alone as a passive BLC element was found to be effective in preventing aftbody flow separation, as presented by Goldschmied.[6]

The other consequence of boundary-layer control suction, in addition to creating momentum drag, is that it provides the mass flow for the generation of thrust through the axial impeller stage and the stern jet. The jet total-pressure required is dictated by the axial force balance of the vehicle; if the suction momentum drag is generated by the radially-inward ingestion of mass-flow into the body, destroying its axial momentum component, then, similarly, the thrust generation must start from this radially-inward flow with associated zero axial momentum.

It is no longer necessary to exceed free-stream total-head to generate any thrust: the jet total-head will be dictated by the required thrust and it may be no greater than free-stream's. This is the key point which has been demonstrated by the self-propelled test body.

Experimental Results

The test program reported by Goldschmied[4] was carried out in 1981 in the 8' x 10' Low-speed Wind-Tunnel of the David W. Taylor Naval Ship R&D Center. The original test model was fabricated in 1956 and the test program was reported by Cerreta;[8] the rebuilt test model retained only the 1956 forebody and was provided with a new suction slot with cusped leading-edge, with a new jet aftbody and with the propulsor fan, as shown in Fig. 4. The aluminum forebody was rather eroded and corroded by its 25 years life and was far from the polished gleaming surface of "laminar" bodies; it was simply cleaned and tested without addition of transition trips (roughness strips or wires) for Confs. 00 and 01.

The stern propulsion jet discharge at Station 5 (Fig. 4) was measured by 3 radial total-pressure rakes, as seen in the stern view photo of Fig. 9; the static pressure was measured by 3 wall static taps and 2 static probes; thus the jet mass-averaged mean total-pressure is quite reliable and accurate.

The jet Station 5 measurement must be taken when the test model is in equilibrium in the wind-tunnel, i.e. when the axial force is zero (zero drag/zero thrust). The axial force determination was made by integration of the wake rake data and by wind-tunnel balance force measurement on the supporting strut. The wake rake data are considered to be more reliable because of the crude calibration of the strut, which neglected the strut/body interaction as function of the slot suction.

Figure 10 shows the fan air power coefficient CHP_{25}, as measured from Station 2 to Station 5

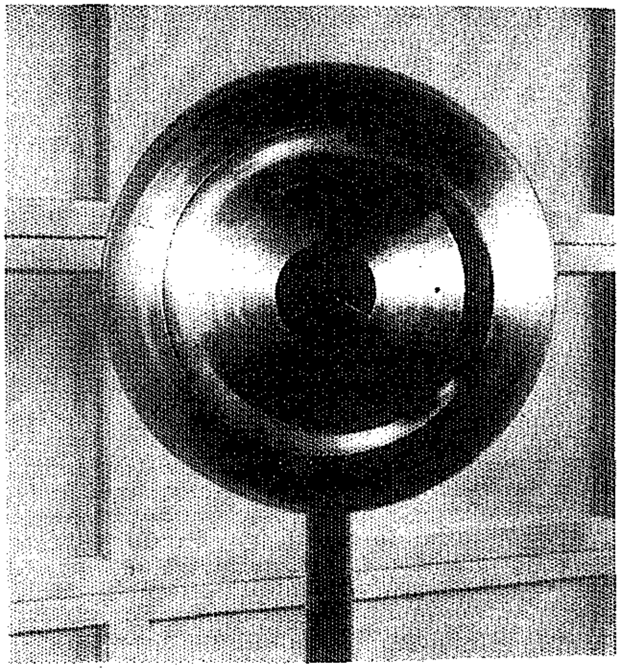


Fig. 9 Stern photo view of test model with open jet (Conf. 00), showing three radial total-pressure rakes.

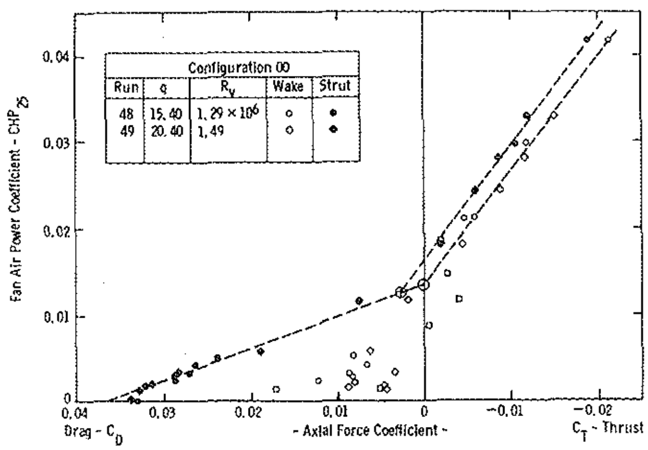


Fig. 10 Fan air power coefficient CHP_{25} vs axial force coefficient - Conf. 00.

(Fig. 4), plotted against the axial force coefficient for Conf. 00 with the open jet; to the left, there is the drag area, while to the right there is the thrust area. It can be seen that the wake rake points in the thrust area yield a very credible linear trend with its intersection of the equilibrium axis; the flow is attached on the aftbody and the wake is well ordered. On the other hand, in the drag area the aftbody flow is separated and the wake is unsteady and disordered; wake rake data are scattered and unreliable.

Figure 11 shows the fan air power coefficient CHP_{25}, as measured from Station 2 to Station 5 (Fig. 4) plotted against the axial force coefficient for Conf. 01 with the slender rear tailboom. Here the wake rake points appear well organized not only in the thrust area, as above, but also in the drag area. There is no uncertainty about the equilibrium point.

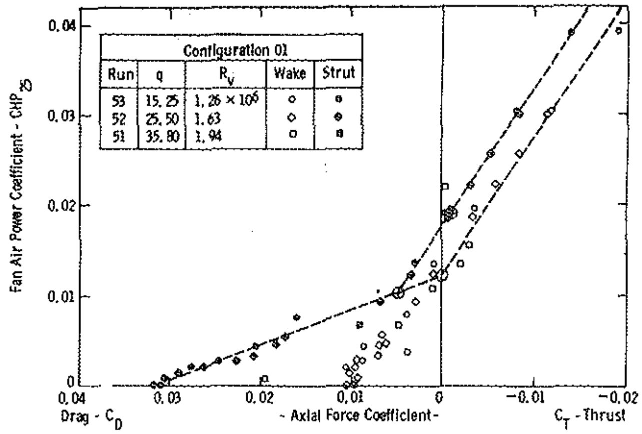


Fig. 11 Fan air power coefficient CHP_{25} vs axial force coefficient - Conf. 01.

The experimental results are tabulated below in terms of fan air power coefficient CHP_{25}, suction flow coefficient CQ_5 and total-pressure rise coefficient CH_{25}.

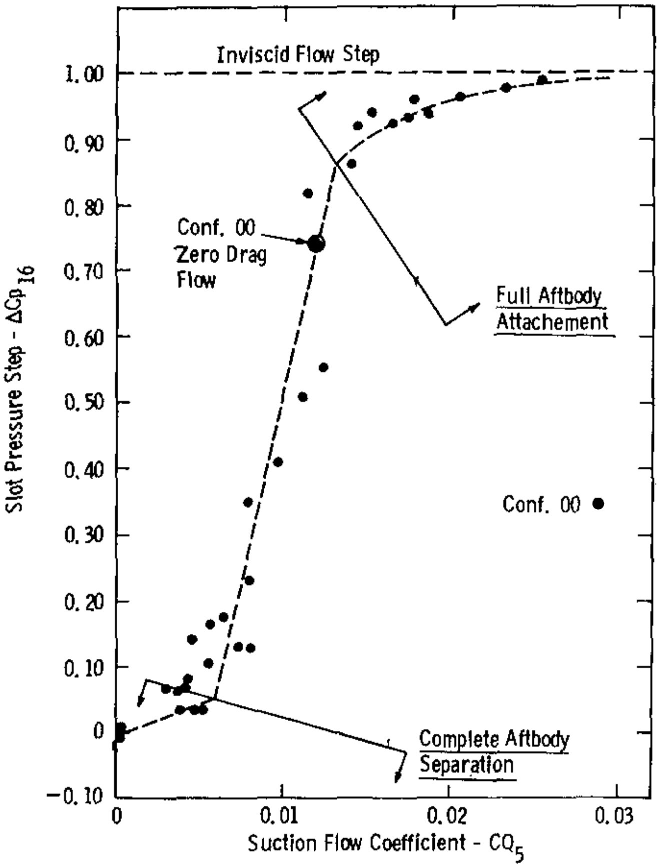
Experimental Data Tabulation

Conf.	Reynolds Number R_V	Fan Air Power Coeff. CHP_{25}	Flow Coeff. CQ_5	Total-Pressure Rise Coeff. CH_{25}
00	1.29 x 10	0.0144	0.0123	1.17
00	1.49	0.0134	0.0120	1.11
00	1.94	0.0130	0.0118	1.10
00	1.615 (Mean)	0.0135	0.0121	1.11
01	1.26	0.0148	0.0126	1.17
01	1.63	0.0136	0.0121	1.12
01	1.94	0.0120	0.0115	1.04
01	1.60 (Mean)	0.0124	0.0116	1.06

First of all, the fan air power coefficient CHP_{25} can be compared to the drag of two streamlined airship bodies as tested by Abbott[7] in a NACA wind-tunnel; at $R_V = 1.94 \times 10^6$, the free-transition Model A and Model M are practically equivalent with a drag coefficient $C_D = 0.0242$. If Conf. 01 is assessed against this value, the reduction is 50%. It can also be noted that large excess thrusts were generated in the test program. For Conf. 00 a maximum thrust coefficient of $C_T = 0.0433$ was recorded, with a fan air power increment (over equilibrium) of $\Delta CHP_{25} = 0.0559$ and an incremental propulsive efficiency of 77.4%. For Conf. 01 a maximum thrust coefficient of $C_T = 0.0430$ was recorded, with a fan air power increment (over equilibrium) of $\Delta CHP_{25} = 0.0527$ and an incremental propulsive efficiency of 81.5%.

The boundary-layer control performance and the match of the propulsion mass flow to the suction mass flow can be evaluated by consideration of Fig. 12 for Conf. 00 and of Fig. 13 for Conf. 01.

The slot pressure rise ΔCp_{16} is plotted against the suction coefficient CQ_5; in both figures it can be seen that a "Complete Aftbody Separation Boundary" and a "Full Aftbody Attachment Boundary" can be defined experimentally. The zero drag point is



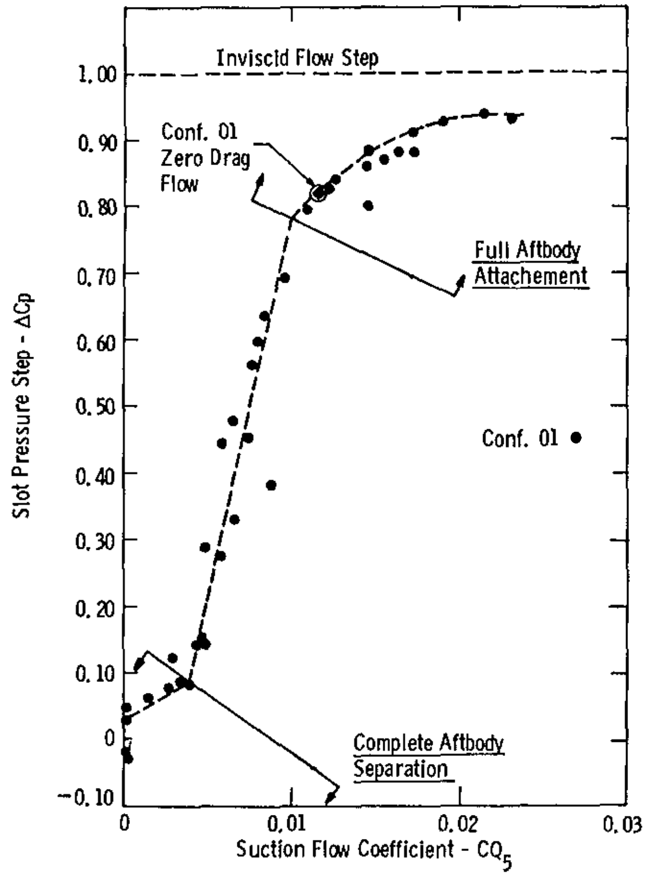


Fig. 12 Correlation of slot pressure-step ΔCp_{16} with suction flow coefficient CQ_5 - Conf. 00.

Fig. 13 Correlation of slot pressure-step ΔCp_{16} with suction flow coefficient CQ_5 - Conf. 01.

also marked in both figures; for Conf. 00 the zero drag flow is less than the minimum required for full aftbody attachment, i.e. there is a poor match between boundary-layer control and propulsion, while for Conf. 01 there is an excellent match since the zero drag flow is just higher than the minimum for full aftbody attachment. It remains to investigate the static-pressure as measured at Station 5 by the jet wall static taps.

The jet static-pressure coefficient Cp_5 is plotted against the slot pressure step ΔCp_{16} in Fig. 14 for Conf. 00 and in Fig. 15 for Conf. 01; the slot pressure step ΔCp_{16} was selected as the most significant measure of the boundary-layer control achievement.

In Fig. 14 it can be seen that Conf. 00 reaches a $Cp_5 = 0.60$ at the "Full Aftbody Attachment Boundary" and that the data are quite scattered; the maximum static-pressure is well below $Cp_5 = 0.70$.

A different behavior can be observed in Fig. 15 for Conf. 01 with the tailboom: a static-pressure coefficient of $Cp_5 = 0.50$ is reached at the "Full Aftbody Attachment Boundary" but then there is a very sharp pressure rise to full stagnation values of $Cp_5 = 1.0$ for only a small increment of ΔCp_{16}. The tailboom is responsible for this difference; it serves to stabilize the flowfield closure behind the body so that the theoretical static-pressure recovery is actually achieved.

In conclusion, the total-pressure ratio of the jet over free-stream's and the velocity ratio of the jet over free-stream's are tabulated below from Station 5 measurements.

Jet Total-Pressure and Velocity Ratios

Conf.	Reynolds Number R_V	Flow Coeff. CQ	Velocity Ratio U_5/U_0	Total-Pressure Ratio H_5/q
00	1.29×10^6	0.0123	0.703	1.025
00	1.49	0.0120	0.686	0.990
00	1.94	0.0118	0.674	0.970
00	1.615 (Mean)	0.0121	0.692	1.005
01	1.26	0.0126	0.733	1.080
01	1.63	0.0121	0.704	1.025
01	1.94	0.0115	0.669	0.965
01	1.60 (Mean)	0.0116	0.675	0.980

There seems to be little doubt that the experimental evidence demonstrates that jet-propulsion has been achieved with jet total-pressure no greater than free-stream's.

Conclusions

Jet-propulsion of an axisymmetric 2.72:1 body at low subsonic velocities has been achieved in a wind-tunnel with jet total-pressure equal to free-

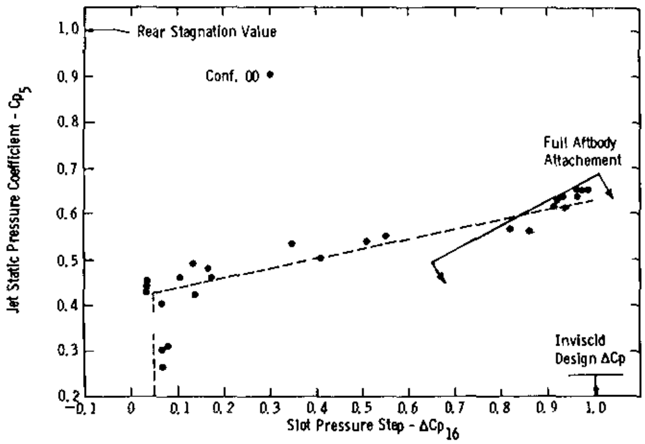


Fig. 14 Correlation of jet static-pressure coefficient C_{p5} with slot pressure-step ΔC_{p16} - Conf. 00.

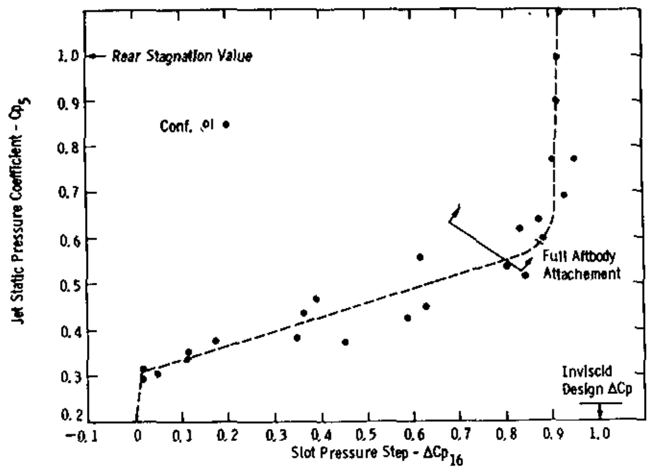


Fig. 15 Correlation of jet static-pressure coefficient C_{p5} with slot pressure-step ΔC_{p16} - Conf. 01.

stream's and with jet exit velocities 33% lower than free-stream's.

Full stagnation static-pressure recovery has been observed at the jet exit for boundary-layer control suction flows only slightly over the boundary of full aftbody attachment. Large excess thrusts have also been generated in the wind-tunnel up to $C_T = 0.043$, with incremental propulsive efficiency up to 81.5%.

A 50% propulsion power reduction has been achieved, as compared to the best conventional streamlined body with stern wake propeller at the same volume Reynolds Number.

It is to be hoped that this will usher in a new phase of aerodynamic system optimization research, leading to improved and much more efficient aircraft design.

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