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REDUCTION OF TILT ROTOR DOWNLOAD USING CIRCULATION CONTROL

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ABSTRACT

The effect of boundary-layer control blowing on the download of a wing in the wake of a hovering rotor was measured in a small-scale experiment. The objective was to evaluate the potential of boundary-layer control blowing for reducing tilt-rotor download. Variations were made in rotor thrust coefficient, blowing pressure ratio, and blowing slot height. The effect of these parameter variations on the wing download and wing surface pressures is presented. The boundary-layer control blowing caused reductions in the wing download of 25 to 55%.

NOMENCLATURE

A — rotor disc area, πR^2, m^2

C_T — rotor thrust coefficient, $T/\rho A V_{tip}^2$

c — wing chord, m

DL — wing download, N

h — blowing slot height, m

P — pressure, N/m^2

P_{atm} — atmospheric pressure, N/m^2

P_p — blowing slot plenum pressure, N/m^2

δP — differential pressure, $P-P_{atm}$, N/m^2

R	rotor radius, m
T	rotor thrust, N
x	wing chordwise location, m
z	distance between rotor and wing, m
ρ	air density, kg/m^3

INTRODUCTION

The hover performance of tilt-rotor aircraft is reduced by the adverse aerodynamic interference on the wing caused by the rotor wake. The wing is immersed in the rotor downwash, and this results in a vertical drag, or "download," on the wing. This download can be as large as 15% of the total rotor thrust (refs. 1 and 2). If this download could be reduced or eliminated, the hover performance of tilt-rotor aircraft could be significantly improved. Since the payload of a tilt rotor is typically 25 to 30% of the aircraft's gross weight, small changes in the wing download can have a large effect on the size of the payload. Some previous investigations of wing download in hover are reported in references 3-7.

Flow visualization studies have shown that the rotor wake separates from the wing at the leading and trailing edges. The separated flow below the wing has a lower pressure than the flow on the top of the wing, and a download results. If a means could be found to reduce or eliminate the flow separation, the pressure below the wing would be increased, and the download would be reduced.

It may be possible to delay or eliminate the flow separation at the wing leading and trailing edges with boundary-layer control technology. The wing used in this investigation had slots for upper-surface boundary-layer control blowing at the wing leading and trailing edges. The jets of air from these slots should remain attached to the airfoil surface because of the Coanda effect. If this high-energy boundary layer, caused by the blowing, delays or prevents the rotor downwash from separating from the wing leading and trailing edges, then the download will be reduced.

The dynamic pressure in the rotor wake is comparable to the disc loading of the aircraft, and is much lower than the free-stream dynamic pressure for typical circulation-control airfoil applications. Therefore, low mass flows will be required to achieve the required blowing momentum coefficients. Thus, the weight of the air supply system, and the power required to drive it, will be small compared to typical circulation-control systems. A net vehicle performance gain will be achieved if the reduction in download is greater than the weight of the air supply system plus the reduction in rotor thrust caused by the power lost to the air supply system.

This paper describes an experimental investigation into the reduction of wing download obtained with leading- and trailing-edge upper-surface blowing. Measurements were made of wing download, wing surface pressures, and boundary-layer control blowing pressure ratio. The effect on the wing download of rotor-thrust coefficient, blowing slot height, and blowing pressure ratio is presented.

DESCRIPTION OF TEST APPARATUS

The test was conducted at the Ames Outdoor Aerodynamic Research Facility, which consists of a 30-m square concrete pad, a below-ground-level frame for attaching model support struts, and an underground control room with a complete data acquisition system. The facility is remotely located from other buildings so that there is no aerodynamic interference (other than with the ground).

The rotor was a 0.16-scale model of the Sikorsky S-76 rotor system (fig. 1). The blades were dynamically and geometrically similar to Sikorsky S-76 blades, except that the model blades had rectangular tips instead of swept-tapered tips. Rotor system characteristics are summarized in table 1. The rotor plane was 2.86 rotor radii above the ground.

The rotor was installed on the Ames rotor test rig (RTR). A six-component, internal strain-gage balance was used to measure steady-state rotor forces and moments. Three single-axis load cells were installed between the RTR and its support stand to provide redundant measurements of the rotor thrust.

The rotor was operated with the rotor thrust down, and the wake of the rotor traveled up into the wing. The wing was mounted upside down on a model support system and balance to allow unobstructed flow between the rotor and the wing. Throughout this paper, references to the upper and lower surfaces of the wing refer to the normal upper and lower surfaces of the wing, and not the test setup (fig. 1). A sketch of the rotor and wing installation is provided in fig. 2. All of the data presented in this paper were obtained with the rotor axis at the center of the wing, and the wing fully immersed in the rotor wake. Thus the test configuration simulated the chordwise flow over the wing of a tilt-rotor aircraft, but did not simulate the spanwise flow or "fountain effect." The distance between the rotor and wing was 0.4 rotor radii throughout the test. This distance is representative of the XV-15 and V-22 tilt-rotor aircraft.

The wing used in this test had an airfoil section (fig. 3) similar to those used on an X-wing aircraft. The airfoil was symmetric about the half-chord line and had 5% camber. Airfoil coordinates from the leading edge to the mid-chord are presented in table 2. The wing had blowing slots at both the leading and trailing edges. The airflow through the slots was varied by either changing the slot height or by changing the air pressure in the two wing plenums. These plenums, one for the leading edge and one for the trailing edge, allowed the effect of differential blowing on the wing download to be tested. Wing forces and moments were measured using a six-component, internal strain-gage task balance. The wing was instrumented wing at the leading and trailing edges. The asymmetry in the pressure distribution is probably caused by the swirl in the rotor wake, which is from the wing leading edge to the wing trailing edge at this wing station.

By comparing the data obtained with the upper-surface blowing on (fig. 7(b)) with that obtained with the blowing off (fig. 7(a)), the aerodynamic phenomena responsible for the reduction in download can be determined. The region of stagnated flow exists on the upper surface of the wing whether the blowing is on or off; however, this region is smaller when the blowing is on. In fact, there is a large region of negative pressure on the wing upper surface near the leading edge when the blowing is on. This negative pressure region extends well aft of the location of the blowing slot, which is located at 2.7% of the wing chord. This indicates that the blowing jet has locally entrained the rotor downwash, thereby reducing the size of the region of stagnated flow on the wing upper surface. The large region of negative pressure on the upper surface of the wing does not exist at the wing trailing edge. This phenomenon was probably caused by the asymmetry induced by the swirl velocity in the rotor wake.

The upper-surface blowing was originally intended to reduce the download by delaying or preventing the rotor wake from separating from the wing leading and trailing edges. The degree to which the blowing has accomplished this objective can be evaluated by comparing the pressures on the wing lower surface when the blowing is on and off. Figure 7 shows that the pressure on the lower surface of the wing was only slightly less negative when the blowing was on than when it was off. Thus, the use of boundary-layer control blowing has not proven very successful in preventing the rotor downwash from separating from the wing leading and trailing edges.

The magnitude of the reduction in download caused by the negative pressure on the upper surface and the increase in pressure on the lower surface was found by integrating the wing surface pressure data. The result was that the negative pressure on the upper surface of the wing was responsible for about two-thirds of the total reduction in download, and the increased pressure on the lower surface caused about one-third of the total reduction in download.

The pressure distribution on the wing when the blowing was off reveals that the attempt to reduce the download by preventing flow separation at the wing leading and trailing edges may have been misguided. About two-thirds of the download is caused by the large region of stagnated flow on the upper surface of the wing, and relatively little download is caused by the negative pressure on the lower surface (caused by flow separation). It seems unlikely that the pressure on the lower surface of the wing could be increased above atmospheric, so the potential for substantially reducing the download by increasing the lower surface pressure for this configuration is small. There is clearly more potential for reducing the download by minimizing the size of the stagnated flow region on the upper surface of the wing. The fact that the boundary-layer control blowing caused a substantial reduction in the pressure on the upper surface of the wing well aft of the blowing slot probably accounts for most of the download reduction caused by the blowing. This may explain why the download was sensitive to the velocity of the blowing jet, and not to the momentum of the jet or the ratio of blowing jet velocity to rotor downwash velocity.

Future investigations of download reduction using this concept should investigate blowing slot locations on the upper surface of the wing that are farther from the leading or trailing edge than the 2.7% of chord that was tested here. It may be possible to increase the size of the negative pressure region on the wing upper surface caused by the blowing, and thereby obtain further reductions in the download.

CONCLUSIONS

A small-scale experiment was performed to evaluate the potential of upper-surface blowing for reducing the download on tilt-rotor aircraft. The test results have provided new insight into the mechanisms of wing download, and quantitative data on the effect of the upper-surface blowing on the wing download. Specific conclusions are:

1. Wing download is reduced by upper-surface blowing. The reduction in download ranged from 54% at low rotor-thrust coefficients to 25% at high rotor-thrust coefficients.

2. The blowing slot height has little effect on the download.

3. Significant reductions in download are obtained with only one blowing slot operational.

4. The surface pressure data indicated that about two-thirds of the reduction in download with upper surface blowing is caused by suction on the upper surface of the wing, and one-third of the reduction in download is caused by increased pressure on the lower surface of the wing.

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TABLE 1.- Small-Scale Rotor Characteristics

Radius, m	1.067
Chord, m	0.0629
Airfoils	SC1095/SC1095R8
Number of blades	4
Twist	-10° linear
Solidity	0.0751

TABLE 2.- Wing Airfoil Coordinates

x/c	y/c
Outside of Upper Surface: Starting at Slot	
0.0319	0.0530
0.0531	0.0668
0.0710	0.0716
0.0905	0.0794
0.1115	0.0871
0.1528	0.1002
0.1930	0.1109
0.2306	0.1194
0.2702	0.1269
0.3114	0.1333
0.3727	0.1403
0.4358	0.1447
0.5000	0.1461
Inside of Upper Surface: Starting at Slot	
0.0319	0.0522
0.0505	0.0585
0.0700	0.0615
Outside of Lower Surface: Starting at Leading Edge	
0.0000	0.0000
0.0113	-0.0314
0.0204	-0.0404
0.0324	-0.0472
0.0404	-0.0498
0.0541	-0.0530
0.0748	-0.0558
0.0916	-0.0576
0.1157	-0.0597
0.1550	-0.0621
0.1905	-0.0635
0.2358	-0.0647
0.2918	-0.0656
0.3507	-0.0661
0.4202	-0.0663
0.5000	-0.0664

TABLE 2.- Continued

x/c	y/c
Inside of Lower Surface: Starting at Leading Edge	
0.0000	0.0000
0.0112	0.0340
0.0218	0.0444
0.0324	0.0501
0.0401	0.0518
0.0507	0.0518
0.0613	0.0489
0.0736	0.0379
0.0802	0.0303
0.0934	0.0153

Table 3. Small-Scale Wing Characteristics

Span, m	1.60 m
Chord, m	0.447 m
Thickness/chord	0.2125
Twist, deg	0
Dihedral, deg	0
Camber/chord	0.05
Slot locations, x/c	0.027, 0.973
Leading edge radius, % chord	5.25
Locations of pressure taps, % semispan	13, 27, 53, 80, 93

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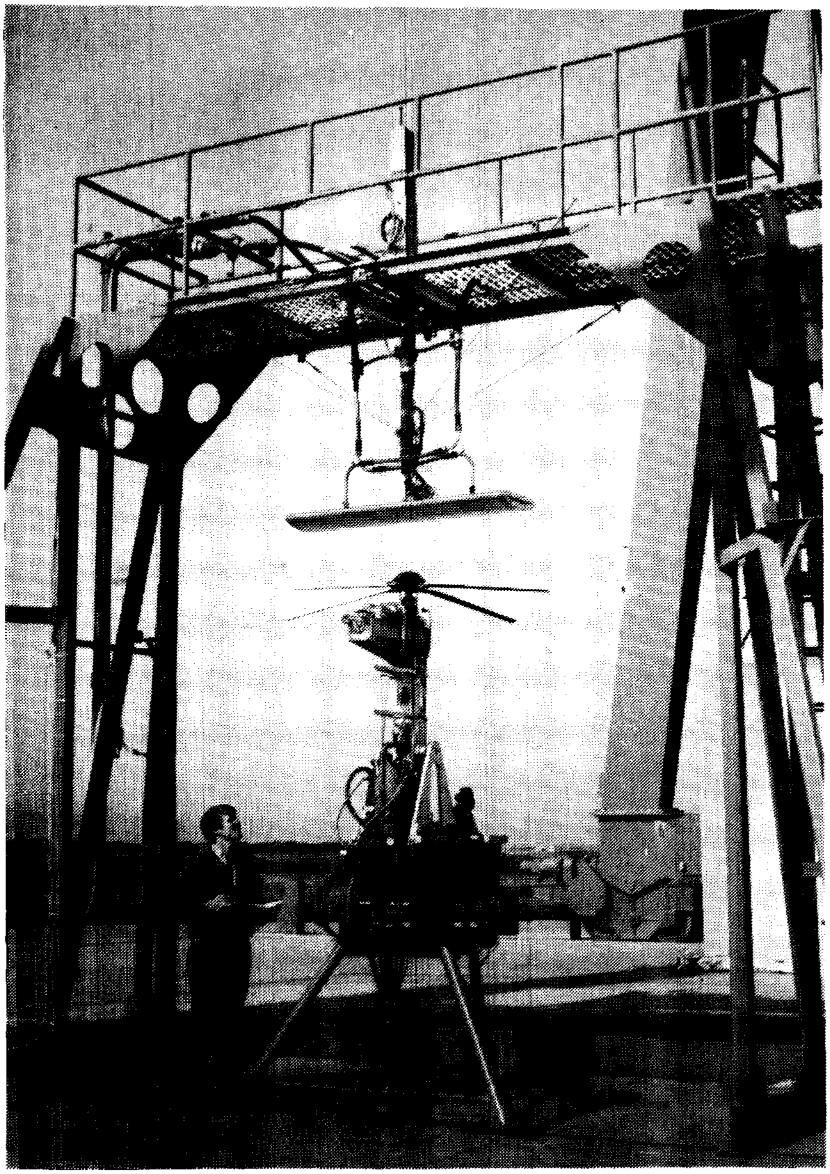

Figure 1.- NASA Ames Rotor Test Rig with circulation control wing.

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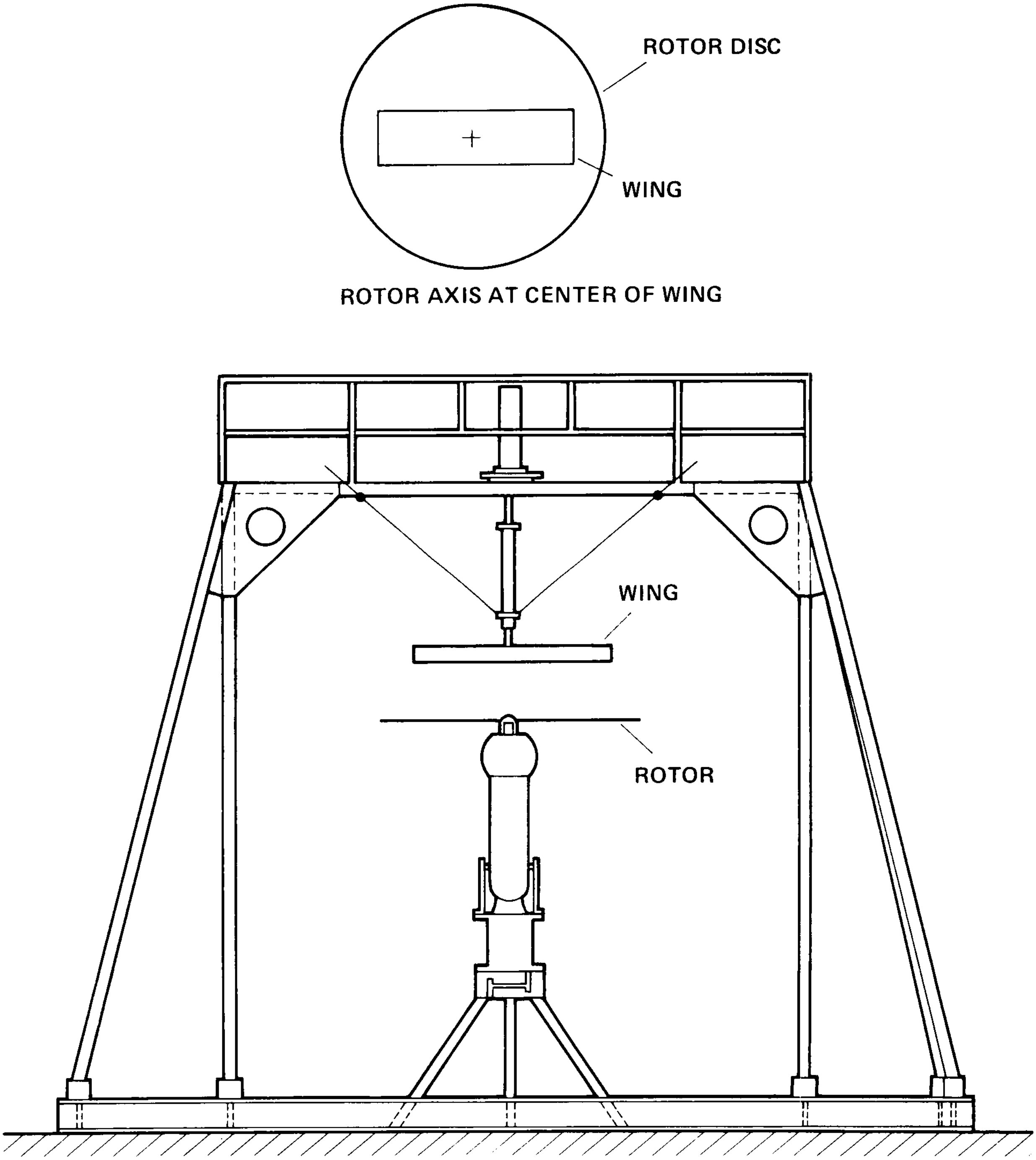


Figure 2.- Small-scale test configuration.

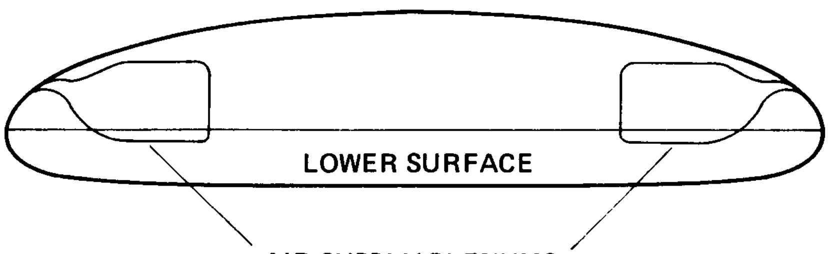
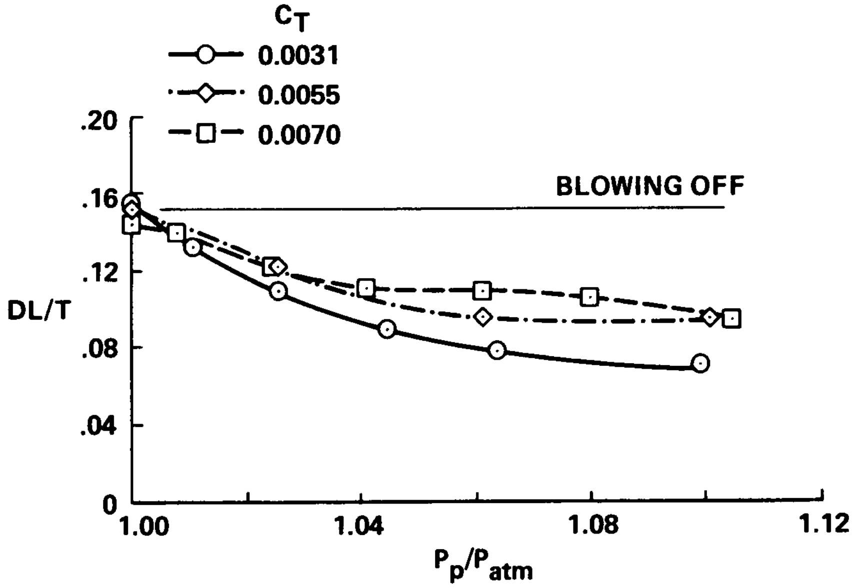
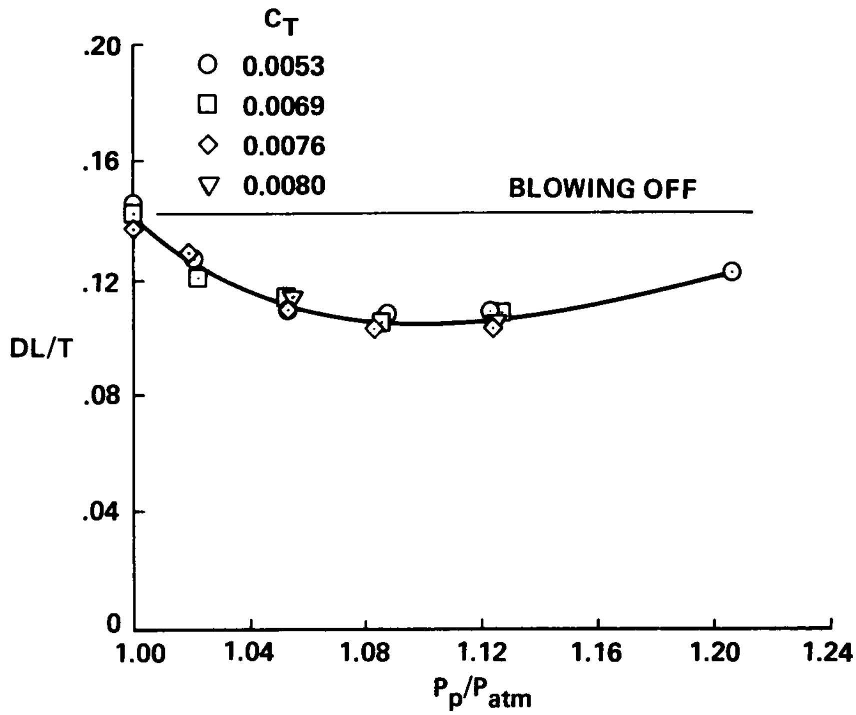


Figure 3.- Circulation control wing airfoil section.



(a) h/c = 0.0014.



(b) h/c = 0.0010.

Figure 4.- Effect of blowing pressure ratio on download.

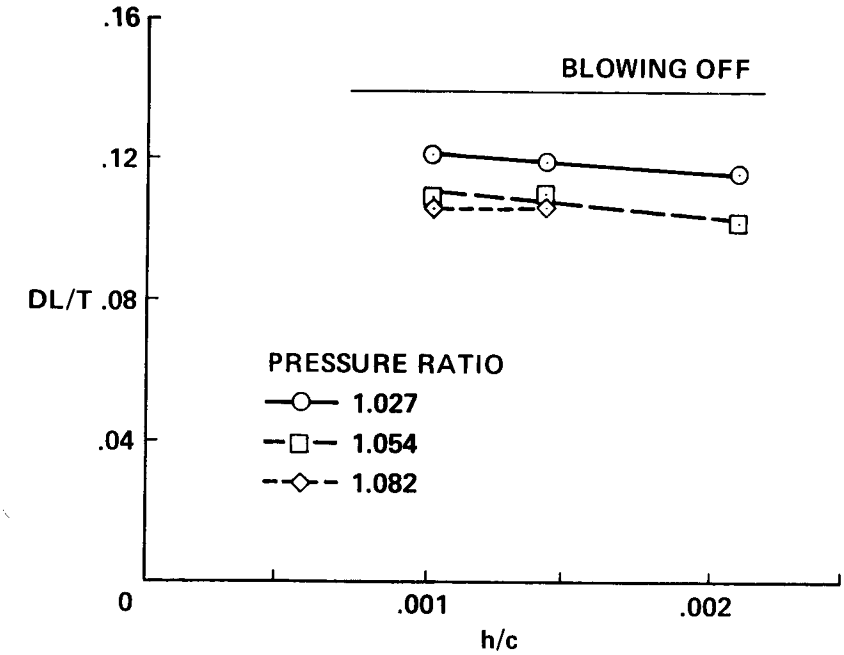


Figure 5.- Effect of blowing slot height on download.

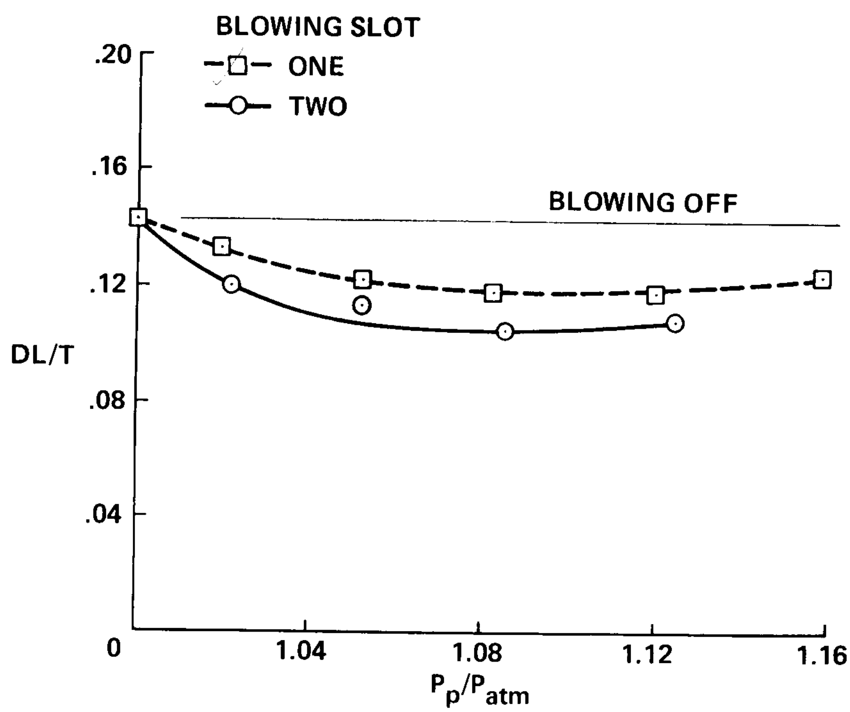
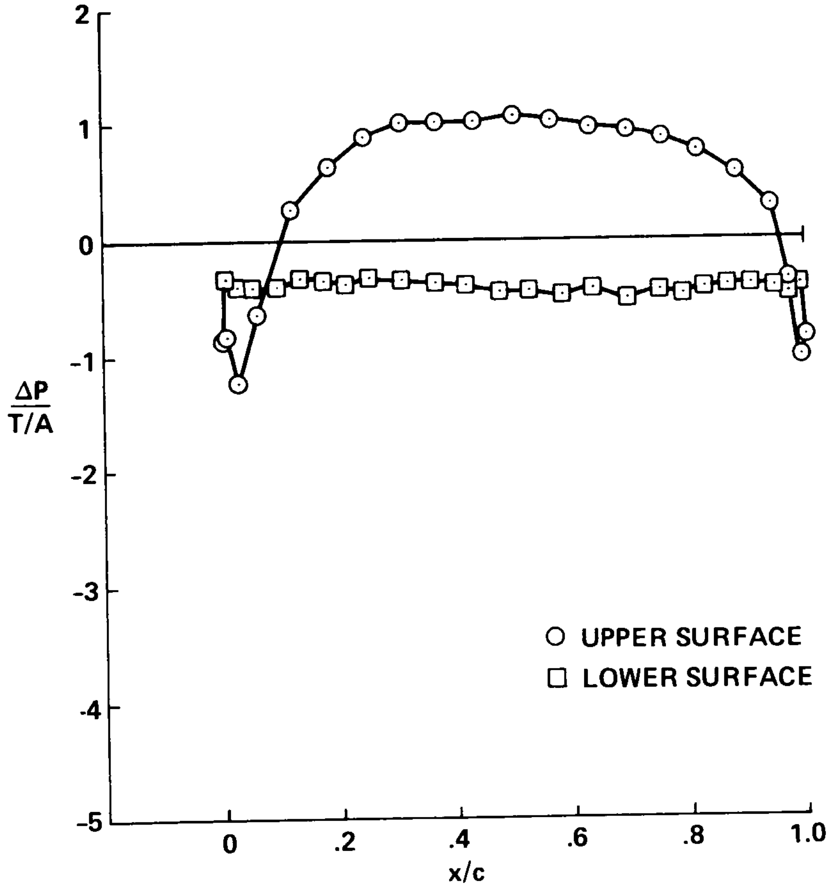
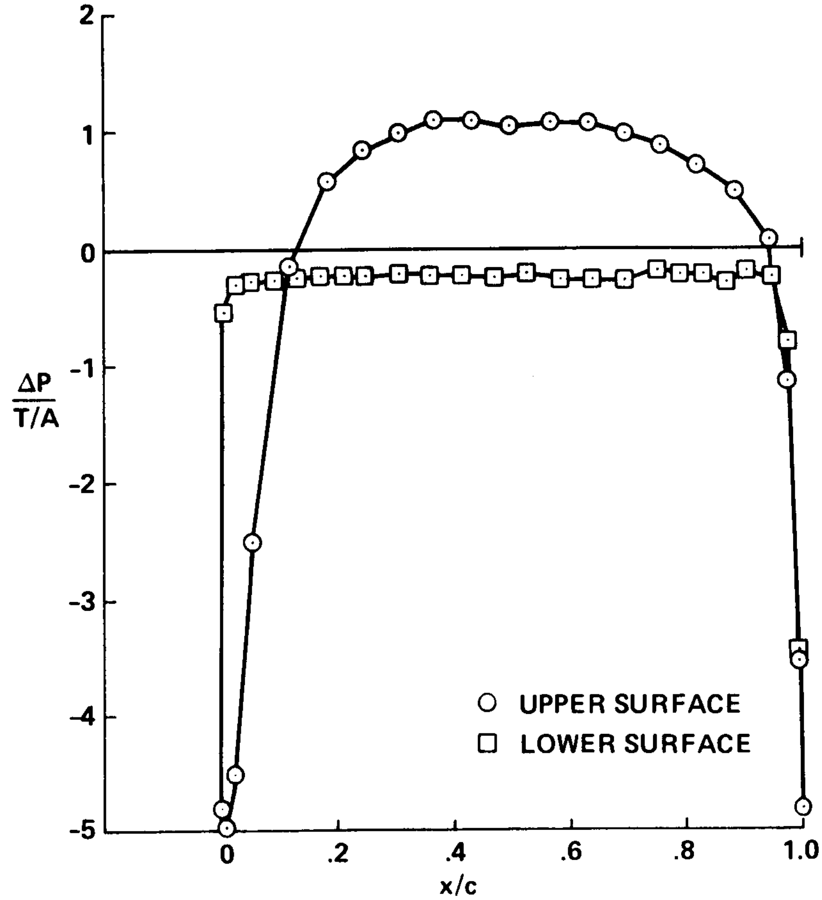


Figure 6.- Comparison of download with one and two blowing slots.



(a) blowing off, P_p/P_{atm} = 1.00.

Figure 7. Circulation control wing surface pressures.



(b) blowing on, P_p/P_{atm} = 1.09.

Figure 7. Concluded.