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A REVIEW OF TILT ROTOR DOWNLOAD RESEARCH

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ABSTRACT

Experimental and theoretical research on the forces on a wing immersed in the wake of a hovering rotor is reviewed, with emphasis on the tilt rotor download problem. The basic features of the rotor/wing flow field on a tilt rotor aircraft are described. The effect of important geometric and operational parameters on the wing download is assessed. The magnitude of the download for typical tilt rotor configurations is reviewed, and advanced concepts for download reduction are described. Recommendations are presented for the direction of future research efforts.

NOMENCLATURE

A_R	= rotor disc area, πR^2, m^2
A_W	= projected wing area below rotor disc, including reduction in area caused by flap deflection, m^2
C_T	= rotor thrust coefficient, $T/\rho A_R(\Omega R)^2$
c_d	= wing sectional drag coefficient
c_F	= flap chord, m
c_W	= wing chord with undeflected flap, m
D	= wing download, N
h	= vertical distance between rotor and ground, m
R	= rotor radius, m
r	= radial station, m
T	= rotor thrust, N
z	= vertical distance between rotor and wing, m
δ_F	= flap deflection, deg
ρ	= air density, kg/m^3
Ω	= rotor rotation rate, rad/sec

INTRODUCTION

In hover, the wing of a tilt rotor aircraft is immersed in the wake of the rotors. The downwash from the rotors impacting on the wing causes a vertical drag force on the wing, called download. The download on a tilt rotor wing can be as large as 10-15% of the total rotor thrust.[1-4] The download is a penalty associated with the tilt rotor configuration that causes a substantial reduction in the vehicle payload. For example, if the payload is 25% of the aircraft gross weight, and the download is 10% of the rotor thrust, then elimination of the download would result in a 40% increase in the payload. Clearly, it is very important to minimize the download in order to achieve good hover performance with a tilt rotor aircraft.

The potential for the wing download to cause a significant reduction in tilt rotor hover performance was recognized very early. In 1949 a Technical Note was published by the RAE describing an experiment to measure the effect of a horizontal wing surface under a hovering rotor.[5] This investigation was motivated by "Future development...of 'convertible' aircraft which employ both rotary and conventional fixed wings."

Since that time a wide range of experimental and theoretical investigations have been conducted to further examine the rotor/wing interaction problem. Much of the early work was focused on the compound helicopter configuration, where the rotor axis is at the center on the wing. Helicopters typically have less uniform downwash distributions than tilt rotors. Research specifically directed at the tilt rotor configuration began in earnest with the development of the XV-15 tilt rotor research aircraft. As the advantages of the tilt rotor configuration became evident, and the development of the V-22 aircraft was initiated, increased emphasis has been placed on the download problem.

The objective of this paper is to review the experimental and theoretical research that has been performed to date that is relevant to the tilt rotor download problem. The basic features of the rotor/wing flow field will be described. The effect of important geometrical and operational parameters will be summarized, drawing on the entire body of available information. The download of typical tilt rotor configurations will be reviewed, and advanced concepts for download reduction will be described. Recommendations will be provided for the directions of future research efforts.

EXPERIMENTAL INVESTIGATIONS

The flow over a wing immersed in the wake of a hovering rotor is 3-dimensional and unsteady, with regions of massive separation, and with rotor tip vortices directly impacting on the upper surface of the wing. Because of this complexity, analysis of this flow field is extremely difficult. Consequently, most of the research that has been performed on rotor/wing aerodynamic interactions has been experimental.

The experimental research has concentrated on six main areas: experiments to visualize and understand the nature of the flow about the wing; the effect on download of variations in the wing geometry; the effect of the location and orientation of the rotor relative to the wing; the effect of operational parameters (such as ground effect); measurements of the download of actual tilt rotor configurations; and advanced concepts for download reduction.

Throughout this paper, in the figures and in the discussion, download is normalized by dividing by the rotor thrust. Thus, the term "download" is used to indicate the nondimensional quantity D/T.

Description of the Flow Field

Much has been learned about the nature of the flow around the wing of a tilt rotor aircraft in hover. Recent experiments have used tufts on the wing surface, smoke flow visualization and wing surface pressure measurements to provide an understanding of the aerodynamic environment around the wing. In particular, Refs. 1, 4, and 6 have provided good descriptions of the flow field around a tilt rotor wing in hover.

Figure 1 shows the most significant features of the rotor/wing flowfield. The wing is immersed in the wake of the rotor, which is an unsteady flow field with regions of concentrated vorticity (tip vortices). These tip vortices impact directly on the upper surface of the wing. The mean velocities in the wake vary as a function of the nondimensional radial station, r/R. Wing surface pressure data reveal a large region of stagnated flow on the upper surface of the wing, and completely separated flow on the lower surface of the wing along the entire wing span.

Visualization of the flow on the upper surface of the wing using tufts and smoke has shown that the flow near the wing tip is predominantly in a chordwise direction. There exists a small amount of spanwise flow at the extreme tip of the wing, where the flow "spills" over the wing tip. Near the root of the wing, the flow is predominantly spanwise, with the mid-span region of the wing gradually transitioning from chordwise to spanwise flow.

At the centerline of the aircraft the spanwise flow from both wings meets and turns upward in a fountain. Some of the fountain flow is reingested by the rotors, forming a standing vortex above the wing near the aircraft centerline. Experimental measurements (discussed in detail later) indicate that the fountain accounts for 15-20% of the total download.

Because of the complexity and expense of a dual-rotor model, many researchers have used an image plane to simulate the presence of a second rotor and wing. However, the fountain flow is a free jet, whose behavior should be expected to be different from that of the shear layer that forms on an image plane. A detailed assessment of the differences between the dual-rotor and the rotor-plus-image-plane approaches needs to be performed.

Effect of Wing Geometry on Download

Many aspects of the wing geometry have been found to have a significant effect on the wing download; including the wing chord, wing flap deflection, leading edge devices, etc. There are constraints placed on the wing design in order to achieve good overall vehicle performance, and this limits the ability of the designer to optimize the wing geometry for minimum download. However, a discussion of these constraints and tradeoffs is beyond the scope of this paper.

Wing Chord. Clearly, the wing download can be expected to increase as the wing chord increases. However, there is little experimental data to quantify this relationship for the tilt rotor configuration, since many of the rotor/wing interaction experiments have focused on the compound helicopter configuration, with the rotor axis at the center of the wing. For data acquired with the compound helicopter configuration to be relevant for the tilt rotor problem, it is essential that the wing span be held constant as the chord is varied. This is because the downwash distribution in the wake of a hovering rotor is highly nonuniform, with much higher downwash velocities near the tip of the rotor than near the root of the blades. This is especially true for the low-twist, low-disc-loading helicopter rotors that were used in the early experiments on rotor/wing interactions. Modern tilt rotor designs have a much more uniform downwash distribution.[7]

The only data available on the effect of wing chord on download were obtained by McKee and Naeseth.[8] In this experiment two different flat plates were tested. The plates were rectangular, with spans equal to the rotor diameter, and chords of 0.167 and 0.333 R. The rotor was an untwisted model rotor with a radius of 0.914 m. The plates were tested at a variety of distances from the rotor, ranging from 0.10 to 1.33 R. Also, the lateral distance from the rotor axis to the center of the plates was varied from 0 to 2.2 R, so that configurations representative of compound helicopters (rotor axis at the center of wing) and of tilt rotor aircraft (rotor axis at tip of wing) were tested, with many intermediate cases. Unfortunately, there was no second rotor or image plane in their test, and the fountain flow of an actual tilt rotor aircraft was therefore not modeled.

Using data from Ref. 8, Fig. 2 shows the download measured with the large chord wing divided by the download measured with the small chord wing, plotted as a function of the distance between the rotor and wing, z/R. Data obtained for the compound helicopter configuration is shown along with data obtained for the tilt rotor configuration. Since the large chord wing has twice the chord of the small chord wing, the download ratio plotted would be exactly 2 if the relationship between wing chord and download were linear. The figure shows that if the distance between the rotor and wing is greater than 0.3 R (0.4 R is typical), doubling the chord of the tilt rotor wing causes an increase in the download of only 60-80%. This is probably caused by 3-dimensional flow effects at the tip of the wing. The fact that there was no nacelle at the tip of the wing (as there would be on an actual tilt rotor aircraft) will increase the tendency for the flow to "spill" over the wing tip, thereby reducing the download in the tip region. This effect would tend to make the download in the tip region less sensitive to variations in the wing chord. The compound helicopter configuration shows a gradual decline in the download ratio as the distance between the rotor and wing increases, but the download ratio is always higher than for the tilt rotor configuration.

Wing Taper. It has been shown in Refs. 1 and 4 that the outboard half of the wing on a tilt rotor aircraft produces more download per unit span than the inboard half of the wing. This effect was not caused by a nonuniform downwash distribution, since the rotor in question produced a remarkably uniform downwash distribution. Therefore, it would be expected that a tapered wing with the same total area as an untapered wing would produce less download than the untapered wing. Unfortunately, no experimental data have been published to confirm or disprove this hypothesis.

Wing Sweep. As described earlier, the fountain that forms at the centerline of a tilt rotor aircraft results from lateral flows along the upper surface of the left and right wings meeting at the aircraft centerline and turning upward. This fountain contributes to the total download. The magnitude of the download caused by the fountain has not been directly measured. However, by comparing the download measured with and without an image plane installed (with the rotor axis at the tip of the wing), an estimate of the download caused by the fountain can be obtained. Felker and Light[9] performed such a test, and their data indicates that the fountain accounts for 15-20% of the total download.

The flow along the upper surface of a tilt rotor wing is in a radial direction near the wing root. The lateral component of this radial flow would be reduced if the wing were swept, since the lateral component is equal to the radial flow times the cosine of the sweep angle. The momentum, and download, of the fountain should be reduced if the lateral flow along the upper surface of the wing was reduced. Therefore, it should be expected that wing sweep, either forward or aft, would reduce the download. However, the reduction in the download would not be significant unless the sweep angle was large, because the lateral component of the radial flow velocity is proportional to the cosine of the wing sweep angle. Also, this effect will only reduce the download caused by the fountain, which only accounts for 15-20% of the total download. As with wing taper, no experimental data have been published to confirm or disprove this hypothesis.

Wing Dihedral. Increasing the wing dihedral angle may tend to increase the amount of lateral flow along the upper surface of the wing, and thereby increase the download caused by the fountain. Conversely, anhedral may tend to reduce the download caused by the fountain. No experimental data on the effect of dihedral on download have been published.

Wing Airfoil Section. No experimental data have been published on the effect of the wing airfoil section on download. However, it should be expected that the shape of the wing leading edge, the wing thickness, and the wing camber would all have an effect on the download. A leading edge with a large radius of curvature should tend to delay flow separation at the leading edge, and reduce the size of the separated wake. Wing thickness and camber tend to make the wing airfoil look less like a flat plate and more like a circular cylinder or ellipse. A flat plate has a 2-dimensional drag coefficient near 2, and a circular cylinder has a drag coefficient near 1, while intermediate elliptic shapes have drag coefficients between 1 and 2.[10] Thus, camber and thickness should tend to reduce the download. Future experiments should quantify the effect of wing leading edge radius, camber, and thickness on download.

Wing Flaps. Wing flaps are a very effective device for reducing the download of a tilt rotor aircraft. Deflection of the flap reduces the download in two ways. First, deflecting the flap reduces the effective planform area of the wing. For example, the wing planform area is reduced 19% by deflecting a 25% chord plain flap 75°. Second, the 2-dimensional drag coefficient of the wing airfoil section at -90° angle of attack is reduced by deflecting the flap. Felker and Light[1] have shown that, for a 25% chord plain flap deflected 75°, about 2/3 of the download reduction associated with flap deflection is caused by the reduction in effective planform area, and 1/3 is caused by the reduction in wing drag coefficient. The amount of wing planform area reduction for a particular configuration, and the change in wing drag coefficient, is determined by the flap size, flap type (plain flap, slotted flap, etc.) and the flap deflection angle. Many researchers have examined the effect of wing flaps on download. These tests have ranged from a 2-dimensional wind tunnel test of various wing sections near -90° angle of attack,[11] to tests of small-scale models of varying degrees of complexity,[1,6,12] to analyses of XV-15 flight test data.[4,9]

Maisel, et al,[11] tested a number of wing airfoil sections at angles of attack near -90° in a 2-dimensional wind tunnel test. The baseline configuration was identical to the XV-15 aircraft wing section. Many other configurations were considered, with a variety of leading-edge devices, spoilers, and flaps. Figure 3 shows the effect of the flap angle on the wing sectional drag coefficient at -90° angle of attack for three different flap configurations. Plotted in the figure is the drag coefficient as a function of flap angle, divided by the drag coefficient at zero flap angle. All three configurations utilized a plain flap, with the chord of the flap (measured from flap leading edge to trailing edge) equal to 25, 30 and 35% of the wing chord. The data for the three configurations is qualitatively similar, with the drag coefficient decreasing as the flap angle increases until flow separation occurs on the upper surface of the flap, after which the drag increases with increasing flap angle. However, note that the minimum drag with the 35% chord flap is higher than the minimum observed with the 30% chord flap. This is contrary to what would be expected, since the larger chord flap reduces the effective chord of the airfoil section more than the short chord flap. The best configuration (30% chord flap deflected 75°) provided a 40% reduction in drag coefficient compared with the undeflected flap case. Also tested was a 30% chord flap with a modified upper surface. The modification provided a more rounded upper surface to the flap. The modified flap provided an additional drag reduction of about 10%, but with flow separation occurring at smaller flap angles than for the unmodified case.

The download of various small-scale models as a function of flap angle has been reported by Felker and Light,[1] McVeigh, et al,[6] and Marr, et al.[12] Felker and Light tested a wing with a 25% chord plain flap, a span of 1.5 R and a chord of 0.42 R. The rotor was a 1/6-scale model of a Sikorsky S-76 helicopter rotor, with -10° of twist and a radius of 1.07 m. Data were acquired both with the rotor axis at the center of the wing and with the rotor axis at the wing tip. McVeigh, et al,[6] tested a 0.15-scale model of the V-22. The V-22 wing had a 31% chord slotted flap, a wing chord of 0.44 R, and the rotors had -41° of twist, and a radius of 1.74 m. Marr, et al,[12] published data from tests of several small-scale tilt rotor models. The most interesting data were acquired in a test of a 1/4-scale semi-span model of an XV-3. This data is particularly useful because a wide range of flap angles were considered, and two different sizes of trailing edge flap were tested, with chords equal to 22 and 44% of the wing chord. The rotor rotation direction was from wing leading edge to wing trailing edge on all of these models. As will be seen later, the rotor rotation direction has a significant influence on the trends of download with flap angle.

Figure 4 shows the effect of the flap angle on the download measured in these small-scale tests. Plotted in the figure is the download as a function of the flap angle, divided by the download at zero flap angle. The data is qualitatively similar to the 2-dimensional drag data shown in Fig. 3, with the download decreasing with increasing flap angle until flow separation on the upper surface of the flap occurs, with the download increasing as the flap angle is increased further. Only the data of Ref. 6 have sufficiently small increments of flap angle to precisely define the flap angle for minimum download, which was 80° for that configuration. The reduction in download caused by the flaps ranged from 28% for the 22% chord flap XV-3 model to 57% for the 44% chord flap XV-3 model. The trend of decreasing download with increasing flap chord is further explored in Fig. 5. This figure shows the minimum download observed for each configuration, divided by the download with zero flap deflection, plotted as a function of flap size. For the 2-dimensional wind tunnel data an analogous ratios of c_d's was used. The XV-3 test provides the most reliable data for assessing the effect of flap size on download, since two different flap sizes were tested on the same model.

It can be very difficult to deduce the download of an actual aircraft, since niether the forces on the wing nor the rotor thrust are directly measured. However, if the rotor torque can be accurately measured, and the relationship between rotor torque and rotor power is known, then the download can be deduced. Additional corrections associated with the engine exhaust thrust, and the interference on the rotor caused by the wing and the other rotor must also be applied. Felker and Light,[9] and McVeigh,[4] have published data on the download of the XV-15 aircraft as a function of flap angle, and this data is shown in Fig. 6. As before, the download data have been normalized by the download at zero flap angle.

The XV-15 has a wing chord of 0.42 R, with a 25% chord plain flap, and the rotor has -36° of twist. The data shown in Fig. 6 agrees very well with the small-scale model data obtained with a 25% chord flap (Fig. 4). The flap angle for minimum download is not apparent, since the flaps on theXV-15 cannot be deflected far enough to find the angle for minimum download. However, it is clear that the wing flaps do provide a 30-40% reduction in the download over the available range.

Wing Leading Edge Devices. A number of leading edge devices have been proposed for reducing download. These are intended to reduce the download through the same mechanisms as flaps; reduction of effective planform area and reduction of drag coefficient. One of the most effective of these is the leading edge "umbrella" flap. The umbrella flap is formed by the upper and lower surfaces of the wing leading edge opening up by pivoting about the leading edge (Fig. 7). The chord of these flaps is typically 25% of the wing chord. In addition to the substantial reduction in wing planform area, the upper and lower surface flaps can be directed to reduce flow separation on the wing lower surface, reducing the download further. References 11 and 13 present data on 2-dimensional drag characteristics of wing sections with umbrella flaps, and their effect on the download measured in a small-scale test with a tilt rotor model, respectively. Reference 11 indicates that a 25% chord umbrella can reduce the drag coefficient of the airfoil section at -90° angle of attack by as much as 63%. Considerable effort was devoted to finding the optimum angles for the upper and lower halves of the umbrella to produce this large reduction in drag coefficient. The test of a small-scale tilt rotor model reported in Ref. 13 indicated that similar leading edge umbrellas reduced the download by about 30%. The download was not reduced as much as the drag coefficient reduction measured in the 2-dimensional wind tunnel test for several reasons. First, the model of Ref. 13 used umbrella flaps with a chord equal to 17% of the wing chord, instead of the 25% chord umbrella flaps used in the 2-dimensional wind tunnel test. Second, it is possible that the umbrella flap deflections were not optimum on the model test of Ref. 13. Finally, the umbrella flaps will have very little influence on the download caused by the fountain, and will therefore produce less download reduction than a comparison of 2-dimensional drag coefficients might indicate.

There are a number of drawbacks associated with the umbrella flaps. The large reduction in wing structural volume will have an adverse effect on wing stiffness, which will have a significant impact on the aircraft aeroelastic stability. Additional structural weight would be required to satisfy aeroelastic wing stiffness criteria. The reduction in wing volume would also provide less room for fuel. Finally, the umbrella flap can produce large forces in a chordwise direction, which implies high loads on the flaps themselves and significant changes in aircraft trim. For these reasons, umbrella flaps may not be a practical solution to the download problem.

Various other leading edge devices were also tested in the 2-dimensional wind tunnel test,[11] including upper- and lower-surface slats (Fig. 7). These provided reductions in drag coefficient ranging from 15 to

50%, with the configurations with a large slot between the leading edge device and the wing providing the lowest drag. These devices have practical implementation problems that are similar to those of the umbrella flaps, but to a lesser degree, since the reduction in wing structural volume is smaller.

Wing Spoilers. Maisel, et al,[11] also tested a number of configurations with wing spoilers on the upper surface of the airfoil. An example of a wing spoiler configuration is shown in Fig. 7. The chordwise location of the spoiler was varied from 53 to 67% of the airfoil chord, with a spoiler deflection of approximately 90°. The airfoil drag coefficient was not found to be very sensitive to spoiler location, and the spoiler provided a drag reduction of about 20%. No data has been published on the effect of spoilers on the download of an actual tilt rotor configuration.

Wing Fences. Wing fences have been proposed to turn the spanwise flow on the upper surface of a tilt rotor wing to a chordwise direction, and prevent the formation of the fountain at the aircraft centerline. A fence with a height of 11% of the wing chord, located on the upper surface of the wing at its junction with the fuselage, was tested in the large-scale V-22 rotor performance/wing download test.[2] Data acquired in this test indicates that the wing fence had a very small effect on the wing download, providing a reduction in download of about 6%. Tuft flow visualization observed during that test by the author indicated that the spanwise flow was not significantly turned by the fence, but merely "hopped the fence," forming a fountain at the centerline in the usual manner. Perhaps a higher fence, or one located further outboard on the wing, would be more effective than the one that was tested.

Effect on Download of Rotor Position and Orientation

The distance between the rotor and wing and the orientation of the rotor have been shown in many experiments to have a significant effect on the download. There are constraints on the distance from the rotor and wing. If the rotor is too close, there will not be adequate flapping clearance between the rotor and wing for maneuvers. If the distance is too great, the weight of the supporting structure increases. The rotor orientation is relatively unconstrained, with more freedom available to the aircraft designer to specify the lateral and longitudinal flapping angles of the rotor in hover, the nacelle angles, etc. These parameters can be selected to reduce the wing download.

Distance Between Rotor and Wing. The downwash velocity distribution in a rotor wake changes as the distance from the rotor increases. Near the rotor, the wake is unsteady in a periodic manner and has a nonuniform downwash distribution. As the distance from the rotor increases, the wake gradually evolves into a turbulent jet. The unsteadiness in the wake gradually loses its periodicity and becomes random, and the downwash velocity distribution becomes more uniform. In light of this changing flow environment it would not be surprising if the wing download exhibits a dependence on the distance between the rotor and wing.

Many researchers have examined the effect that the distance between the rotor and wing has on the wing download. Fail and Eyre[5] found no measurable effect of the distance between the rotor and wing for the two distances they examined (z/R = 0.33 and 0.67). Makofski and Menkick[14] tested a flat plate with a span equal to the rotor diameter (compound helicopter configuration), and a chord of 0.213 R. They examined distances between the rotor and wing ranging from 0.05 to 0.64 R. The rotor was a full-scale, untwisted rotor with a radius of 5.71 m. Felker and Light[9] examined both compound helicopter and tilt rotor configurations at small scale with the distance between the rotor and wing varied from 0.22 to 0.66. R. No second rotor or image plane was used to produce a fountain flow in the tilt rotor configuration.

Figure 8 shows the effect of the distance between the rotor and wing on download, using data from Refs. 5, 9, and 14. The download have been divided by the rotor thrust and the ratio of the wing area to rotor disc area to provide a common basis for comparison of the data. With the exception of the data obtained by Fail and Eyre, all the data is consistent, with the download gradually decreasing as the distance between the rotor and wing is increased. Fail and Eyre mounted their "wing" on the same balance system as the rotor, and the download was measured as a loss in rotor thrust. Their balance system may not have been sensitive enough to discern the small change in download that would be measured as the distance between the rotor and wing was increased from 0.33 to 0.67 R, since the download was only 5.5% of the total rotor thrust. As shown in Fig. 8, the distance between the rotor and wing can have a significant effect on the download. As the distance between the rotor and wing is increased from the minimum distance that would be practical on a tilt rotor aircraft (z/R = 0.25, limited for rotor/wing clearance requirements) to the maximum practical distance (z/R = 0.6, limited by unfavorable weight and aeroelastic stability effects), the download is decreased by 10%.

Lateral Flapping. Lateral flapping can affect the wing download in much the same way as wing dihedral, reducing or increasing the amount of spanwise flow on the wing, and the download created by the fountain. Outboard flapping (outboard side of rotor disc down) should increase the spanwise flow on the wing, and increase the amount of the wing immersed in the rotor wake, thereby increasing the download. Conversely, inboard flapping should reduce the download. Data have been acquired both in model-scale wind tunnel tests and in flight test on the effect of lateral flapping on download, but this data has not yet been published.

Longitudinal Flapping, Wing Incidence Angle, or Nacelle Angle. These three parameters are all essentially equivalent, changing the angle between the wing and the rotor disc in the longitudinal direction. Felker and Light[1] measured the effect of wing incidence angle on wing download in a small-scale test with the compound helicopter configuration. They found only a very weak influence of wing incidence angle on download with the wing flap undeflected. However, when the wing flap was deflected 60°, an 8° change in the wing incidence angle (leading edge up) reduced the download 10% (Fig. 9). Note that the flap angle where this effect was observed was not the flap angle for minimum download. At the minimum download flap angle, an increase in the wing incidence angle may cause the flow over the flap to separate, increasing the download. This would be more readily observed on a tilt rotor model, where the swirl velocity in the rotor wake is in the same direction for both wings. For the compound helicopter configuration tested, the swirl velocity has a different direction relative to the wing leading edge on each half of the wing and flow separation on the flap caused by excessive incidence angle would probably occur on one side of the wing before the other. On tilt rotor aircraft where the maximum wing flap setting is less than the setting for minimum download (e.g. XV-15, V-22), tilting the nacelles forward a few degrees provides a means of effectively reducing the download by as much as 10%.

Effect on Download of Operational Parameters

Ground Effect. Marr, et al,[12] published data from a number of tests of small-scale tilt rotor models. Data included in their report show the effect of height above the ground on download, for height-to-rotor radius ratios ranging from 0.6 to 4.2. Some of the data in Ref. 12 were taken from Ref. 15. Fradenburgh[16] presents download data for a flat plate beneath an untwisted model rotor, and his data are qualitatively similar to the data of Refs. 12 and 14. The data of Refs. 12, 15, and 16 are presented in Fig. 10, with the download data normalized by the download out of ground effect to account for differences in the model geometries. For height-to-radius ratios above 3, the download is essentially constant. This agrees well with the effect of the ground on helicopter rotor performance, which is generally considered to be negligible for height-to-radius ratios above 3. As the distance to the ground is decreased, the download is also decreased. At height-to-radius ratios ranging from 0.5 to 1.5 the download is reduced to zero, with further reductions in height resulting in negative download. The negative download probably results from the interaction of the rotor wakes with the ground. When the wakes from the rotors impact the ground they will flow radially along the surface of the ground. The two wakes will meet at the centerline of the aircraft and form a fountain in a manner that is analogous to what occurs on the upper surface of the wing. This fountain will impact on the bottom of the fuselage and the wing lower surfaces, resulting in a negative download. The formation of a fountain on the underside on an aircraft in ground effect is common to all VTOL aircraft that have more than one rotor or jet for lift.

Rotor Thrust Coefficient or Rotor Spanwise Load Distribution. As the rotor thrust coefficient on a twisted rotor is changed, the downwash distribution in the rotor wake is changed.[7] At low thrust coefficients the downwash velocities are relatively higher on the inboard areas of the wake, while at high thrust coefficients the outboard areas of the wake have the highest downwash velocities. Changes in the rotor design can also affect the downwash velocity distribution. For example, increases in blade twist or in taper will tend to increase the downwash velocities in the inboard areas of the rotor wake, and decrease the downwash velocities in the outboard regions of the wake. Because of the 3-dimensional nature of the flow over the wing, with predominantly chordwise flow near the wing tip and predominantly spanwise flow at the wing root, it should be expected that changes in the rotor downwash distribution will produce changes in the wing download.

References 1, 2, 4, 6, and 16 present data on the effect of the rotor thrust coefficient on download, and Ref. 12 presents download data acquired with various small-scale models having different blade twists (and, therefore, different spanwise loading distributions). All of the data indicate that the download decreases as the rotor thrust coefficient increases. For example, Refs. 1, 2, and 4 indicate that the download on the V-22 decreases by about 13% as the rotor thrust coefficient increases from 0.006 to 0.018. The data of Ref. 12 indicate that the download tends to be higher on models with higher rotor twist. This is consistent with the finding that increasing thrust coefficient decreases download, since both increasing thrust coefficient and decreasing twist tend to increase the downwash velocities in the outboard regions of the wake and decrease the downwash velocities in the inboard regions of the wake (compared with the mean downwash velocity).

Rotor Rotation Direction. Felker and Light,[1] and McVeigh, et al,[6] have examined the effect of rotor rotation direction on download. The direction of rotation used on the XV-15 and V-22 is for the blades to pass over the wing from the leading edge to the trailing edge in hover. Felker and Light found that reversing the direction of rotation reduced the download by 12-20%, depending on wing flap angle. In their investigation a relatively thin airfoil section was used on the wing (15%, the XV-15 and V-22 use 23% thick airfoils), along with a 1/6-scale Sikorsky S-76 helicopter rotor. A single rotor was used, with an image plane representing the second rotor and wing. Flap angles of 60° and 75° were tested with the rotation direction reversed. McVeigh, et al, examined the effect of rotor rotation direction on a 0.15-scale full-span, dual-rotor model of a V-22. The data of Ref. 6 are reproduced in Fig. 11. The figure shows that reversing the direction of rotation decreased the download for flap angles below 50°, but increased the download for flap angles between 50° and 85°. As the flap angle was increased past 85°, the download with reversed rotor rotation was again lower. The minimum download observed with both configurations was the same, with the flap angle for minimum download being 80° for the normal rotation direction and 95° (the largest flap deflection tested) with reversed rotation direction. As pointed out in Ref. 6, the configuration with reversed rotation direction should continue to show a reduction in download if the flap angle was increased past 95°, thereby achieving lower download than the normal rotation direction. At the present time the discrepancy between the results of Refs. 1 and 6 at moderate flap angles is not understood.

The complex effect that rotor rotation direction has on download at various flap angles is probably caused by the effect that the swirl velocities in the rotor wake have on separation at the wing leading edge and flap. The swirl velocity in the rotor wake follows the direction of rotor rotation. Thus, when the rotor blade passes over the wing from the wing leading edge to the trailing edge, the swirl will tend to delay leading edge separation, and make separation over the flap occur at lower flap angles. Conversely, reversed rotor rotation direction should tend to have a detrimental effect on leading edge separation, and delay flow separation over the flap to very high flap angles. These effects should be explored more fully in future experiments.

Rotor Tip Mach Number and Wing Reynolds Number. No experiments have been conducted where the Mach number and Reynolds number of the rotor/wing flow field have been independently varied. For example, McVeigh, et al,[6] tested a 0.15-scale V-22 model at two rotor tip speeds, 139 and 241 m/s. They found that the download was about 5% higher when the lower tip speed was used. In this experiment the rotor tip Mach number and the wing Reynolds number were both changed at the same time, and it is difficult to assess the effect that the Mach number and the Reynolds number had on the download. An argument was advanced in Ref. 12 that Reynolds number effects should make the download measured with small-scale models higher than would be obtained on full-scale flight vehicles, However, no substantial differences between small-scale and full-scale results have been observed by the author in this investigation. The highly unsteady and turbulent nature of the rotor wake and wing flow field make simple Reynolds number corrections based on steady, 2-dimensional wind tunnel tests difficult to justify.

Download of Complete Tilt Rotor Configurations

XV-15. As discussed earlier, it is very difficult to deduce the download of an actual aircraft, since niether the forces on the wing nor the rotor thrust are directly measured. However, if the rotor torque can be accurately measured, and the relationship between rotor torque and rotor power is known, then the download can be deduced. Additional corrections associated with the engine exhaust thrust, and the interference on the rotor caused by the wing and the other rotor must also be applied. Felker and Light,[9] and McVeigh,[4] have published data on the download of the XV-15 aircraft. Their data indicate that the download of the XV-15 with normal flap and flaperon deflections is about 11.5% of rotor thrust. The XV-15 flaps and flaperons are 25% chord plain flaps, and normal deflections are 45° for the flaperons and 60° for the flaps.

V-22. The V-22 aircraft has not yet entered flight test, so no flight test data are available to allow calculation of download for this aircraft. The best estimate of the V-22 download can be found in Refs. 1, 2, and 4, which describe a 2/3-scale test of a V-22 rotor and wing, complete with a large image plane to simulate the presence of a second rotor and wing.

References 1 and 4 only present data obtained with the wing fence on. Since the current V-22 configuration does not employ a wing fence, the data of Ref. 2 should be used to estimate the V-22 download, since Ref. 2 presents data obtained with the wing fence off. These data indicate that the V-22 download is about 10% of the rotor thrust. The V-22 employs full-span, 31% chord slotted flaps, deflected 67°. The lower download of the V-22 (compared with the XV-15) is primarily attributable to the larger chord flaps used on the V-22, with a higher flap deflection. However, the V-22 has 5% more wing area beneath the rotor than the XV-15, and a more uniform downwash distribution at normal operational thrust coefficients (the XV-15 is more highly loaded at the blade tips). These factors would tend to increase the download on the V-22 compared to the XV-15, but are more than offset by the larger chord flap and higher flap deflection of the V-22.

Advanced Concepts for Download Reduction

Several advanced concepts have been proposed for reducing tilt rotor download. Very little experimental data are available to assess most of these proposals. There are most certainly many other novel ways to reduce tilt rotor download than those presented here, and this is a research area that is sure to see much activity, because of the substantial benefits associated with download reductions.

Upper Surface Blowing. Felker and Light[9] conducted an experiment to measure the download reduction obtained by using upper-surface blowing on the wing. They used an airfoil that was symmetric about the mid-chord, with tangential blowing slots located at 3% and 97% chord. The airfoil had no flaps, and was originally designed for use on X-wing rotors. The wing was tested in the wake of a 1/6-scale Sikorsky S-76 helicopter rotor, in the compound helicopter configuration. They examined a range of blowing slot heights and blowing pressure ratios, with blowing out both slots or only one slot. Substantial reductions in download were observed as the blowing pressure ratio was increased from 1 (blowing off) to 1.1. At the optimum slot height and blowing pressure ratio, the blowing reduced the download by about 35%. The intent of the blowing was to prevent flow separation at the airfoil leading and trailing edges. However, examination of the surface pressure data indicated that the main mechanism for download reduction was reduced pressure on the upper surface of the airfoil induced by the blowing. Flow separation was still occurring at the leading and trailing edges with the blowing on.

For an upper-surface blowing system to provide a net improvement in tilt rotor hover performance, the weight of the blowing system, and the power required to provide the blowing, must be smaller than the download reduction obtained with the system. Faye, et al,[17] performed an analysis of the weight and power penalties associated with the upper-surface blowing system. They found that net reductions in download of 10-15% could be obtained, even with the weight and power penalties included. This is a promising result, since the blowing configuration tested in Ref. 9

was certainly not optimum. Improved system performance will be obtained when the optimum blowing slot location has been found.

Rotating Cylinder. Drees,[18] described the use of a rotating cylinder at the junction of the wing and trailing edge flap to reduce the wing download. He describes a small-scale experiment where download reductions of approximately 25% were produced by the rotating shaft. The fact that an interconnect shaft already exists at this location on tilt rotor aircraft means that this concept could be implemented with only a small weight penalty. As noted in Ref. 18, the rotating shaft could also increase the wing's maximum lift coefficient, providing improvements in low speed performance as well.

Wing Tilt. Stroub,[19] has proposed that the wing of a tilt rotor aircraft be allowed to tilt relative to the fuselage independently of the rotors. While in hover, the wing would be tilted up so that the wing chord was parallel with the rotor axis, reducing the wing download to very low levels. As the transition to forward flight was made, the wing would begin to tilt forward. After sufficient flight speed was achieved for the wing to provide a substantial portion of the total lift the rotors could be tilted forward in the usual manner. Although this concept would result in the virtual elimination of wing download, it must be evaluated in light of the weight penalties associated with the wing tilt mechanism, including the weight of the actuators, and increased structural weight because of concentrated load paths between the wing and fuselage. However, it seems unlikely that these weight penalties could be nearly as large as the download (10% of the rotor thrust), and this concept has the potential to provide substantial increases in tilt rotor hover performance.

ANALYTICAL INVESTIGATIONS

Progress has been very slow in the prediction of download. This is primarily because of the complexity of the flow field in the rotor wake and over the wing. The rotor wake is a 3-dimensional, unsteady flow, with regions of concentrated vorticity (tip vortices). The flow over the wing is also 3-dimensional and unsteady, with massive separation, and with tip vortices directly impacting on the upper surface of the wing. This complex flow environment gives rise to very complex download phenomena, as was shown in the section describing the experimental results. Accurate computation of the details of such flows has been, and is currently, well beyond the state-of-the-art in aerodynamic prediction methodology. Because of this, various simplified analyses have been formulated for the download problem. These invariably view the rotor wake as a steady flow, with varying degrees of complexity for the wing model. The methods that have been described in the literature to date are summarized below.

Strip Theory

The first documented effort to calculate the airload on a wing immersed in a rotor wake was described by Makofski and Menkick.[14] They used a "strip theory," which took into account the rotor wake contraction. The wing planform area was divided into a series of strips, and the incremental download of each strip was found by multiplying the area of that strip by the dynamic pressure of the wake at that strip, and then multiplying by an appropriate drag coefficient. Thus, the total download was the sum of the incremental download for each strip. The dynamic pressure in the rotor wake was found from a uniform inflow momentum theory, with empirical corrections for wake contraction and blade root cutout. The drag coefficient was found from wind tunnel data for 3-dimensional flat plates.

This method produced reasonable predictions of the download on the flat plates that they tested. However, the method incorrectly predicted that the download on the plates would be reduced as the plates were moved closer to the wing. In Ref. 14, this error in the analysis was attributed to the effect of the unsteady pressures on the wing that coincided with the blade passage. Their method correctly predicted that the steady pressures on the wing would be reduced as the wing was moved closer to the wing, but was unable to calculate the effect of the unsteady pressures on the wing. It was shown in Ref. 14 that these unsteady pressures caused the total download to increase as the distance between the rotor and plate was reduced.

Strip theory is easy to implement and understand. The effect of the nonuniform rotor downwash distribution, although not considered in Ref. 14, can be included in a straightforward manner. It can be used with configurations having complex geometries, simply by using a sufficient number of strips to resolve that geometry, and an appropriate drag coefficient for each strip. For these reasons, strip theory has continued to be useful for estimating the download on wings and other bodies immersed in rotor wakes. A significant limitation of the theory is its inability to deal with 3-dimensional effects, such as the fountain flow at the centerline of a tilt rotor aircraft.

Conformal Transformation

Bramwell and Johnston,[20] developed a conformal transformation method for calculating the effect of a passing rotor blade on a body, and the effect of the body on the rotor blade. Their method had the advantage of being able to account for the inherent unsteadiness in the flow field. However, like all conformal transformation methods, it was a 2-dimensional analysis. Approximate corrections were developed for 3-dimensional effects. Many simplifying assumptions had to be made to allow for use of the conformal transformation technique. For example, when calculating the effect of a passing rotor blade on a solid body the blade is modeled as a single line vortex. The assumptions used were well justified in the context of their approach.

Examples of application of the method to a wide range of rotor/body interaction problems are provided in the report. The authors also correlate their predictions with experimental data, with mixed results. This methodology does not appear to have been used for the tilt rotor download problem at all. It certainly has the capability to provide estimates of unsteady flow effects on the wing, which addresses one of the most serious limitations of the more popular strip theory. It can be very difficult to use conformal transformation techniques for complex geometries, but perhaps the two approaches could be combined, drawing on the best features of both.

Panel Methods

Potential flow panel methods have demonstrated great versatility for calculating the aerodynamic characteristics of complex configurations. Some of these analyses can handle massively-separated flows, so long as the areas that are separated can be correctly specified by the user. Unsteadiness in the flow field can be modeled, but at a great computational cost. For the tilt rotor download problem, the lines of separation on the wing can be specified rather easily in most cases, with separation occurring at the leading and trailing edges of the wing. Thus, panel methods offer great potential for accurately calculating the rotor/wing flow field.

McCroskey, et al,[3] and Clark and McVeigh,[21] have applied panel methods to the tilt rotor download problem. McCroskey, et al, considered the problem of a 2-dimensional wing at -90° angle of attack. Their calculations were found to be in good agreement with experimental wind tunnel data.[3] Clark and McVeigh considered a full 3-dimensional tilt rotor aircraft. The rotor was modeled by a segmented actuator disc/momentum theory, with simple corrections to account for radial and azimuthal load variations. Thus, nonuniform rotor loading distributions could be included in the analysis, although they were time-averaged. The rotor wake was modeled by a series of free vortex lines emanating from the edges of the rotor disc, with their strength determined from the strength of the disc panels from which they originate. The panel method obviously allows for arbitrary wing geometries. The problem of close interactions between the rotor wake vortices and the wing panels was not addressed in Ref. 20. Very limited data is provided in the report on the results of hover calculations. What is shown appears to underestimate the wing download by about 20%. It is clear that the panel method approach has promise for the analysis of tilt rotor download.

Extension of the panel methods to correctly model the discrete vortex structure in the rotor wake, and the unsteady interaction of these vortices with the upper surface of the wing will be challenging. However, the analytical methodology and computational power to handle these challenges is becoming available, and unsteady panel methods with a detailed rotor wake model may be the best approach for calculating the detailed characteristics of the rotor/wing flow field.

Vortex Tracking Methods

McCroskey, et al,[3] used a vortex tracking method to calculate the flow about a 2-dimensional airfoil at -90° angle of attack. The vortex tracking method solved the 2-dimensional vorticity conservation equation in a Lagrangian formulation, with the vorticity field modeled by "particles" of vorticity that retained their strength and were convected with the flow field. The vortex particles were introduced along the walls of the airfoil at each time step, and their subsequent motion was calculated using a multistep time integration scheme. The boundary layer flow along the airfoil surface was computed using an integral boundary layer analysis, with the pressure gradient determined from a Biot-Savart calculation of the velocity field induced by the vortex particles. The separation points on the airfoil were calculated by the boundary layer analysis.

Comparisons of the predicted airfoil drag coefficient with the data of Ref. 11 show fair results. The trends of drag coefficient with flap deflection were not well predicted, with the analysis failing to show the increase in drag coefficient that accompanies flap deflections high enough to result in flow separation over the flap. Also, the magnitude of the drag coefficient was typically in error by 10-20%. The method allows for unsteady flows, which is an advantage, and it should be possible to extend the approach to 3-dimensional flow fields and a realistic representation of the rotor wake. However, it would be prudent to identify the source of the poor 2-dimensional results before proceeding with these extensions.

Finite Difference Methods

Finite difference methods offer the promise of including viscous effects in the calculation, and can be used for complex configurations (if a way can ever be found to generate a good grid around a complex body). At the present time, the computational cost of these methods make them impractical for computations about a complete tilt rotor aircraft, or even the rotor/wing component alone. However, it is practical to calculate the flow about a 2-dimensional airfoil at -90° angle of attack. Unfortunately , it has not been demonstrated that the finite difference methods can handle massively separated flows, although they are probably no worse off in this respect than the panel methods. It is certain that much progress will occur in the capabilities of the finite difference methods, and they will soon be ready for application to the tilt rotor download problem.

CONCLUDING REMARKS

A review of 40 years of research on the problem of rotor/wing interactions in hover has been presented, with emphasis on tilt rotor download. A description of the rotor/wing flow field on tilt rotor aircraft provided the framework for understanding the complex behavior that has been observed in the experiments. The results of many diverse experiments have been unified, often providing a clear understanding of the effects of changes in the wing geometry, changes in the location and orientation of the rotor, and the effect of operational parameters. Areas in need of additional experimental data have been identified. The download of the two existing tilt rotor aircraft was reviewed, and advanced concepts for download reduction were described. Finally, a review of existing analytical tools was presented, and an enhanced panel method was identified as the method with the most near-term promise. Specific conclusions are as follows:

1. The effect of many parameters on download is well understood. For example, the effects of wing flap size and wing flap deflection have been thoroughly examined.

2. There are many other important parameters that remain to be investigated. For example, the effects of wing taper and sweep should be measured in future experiments.

3. Tilt rotor download can be reduced; both by changes in the rotor/wing geometry, and by use of advanced configurations.

4. Analytical predictions of download are in a very early stage of development, and are not yet reliable for aircraft design purposes.

ACKNOWLEDGEMENT

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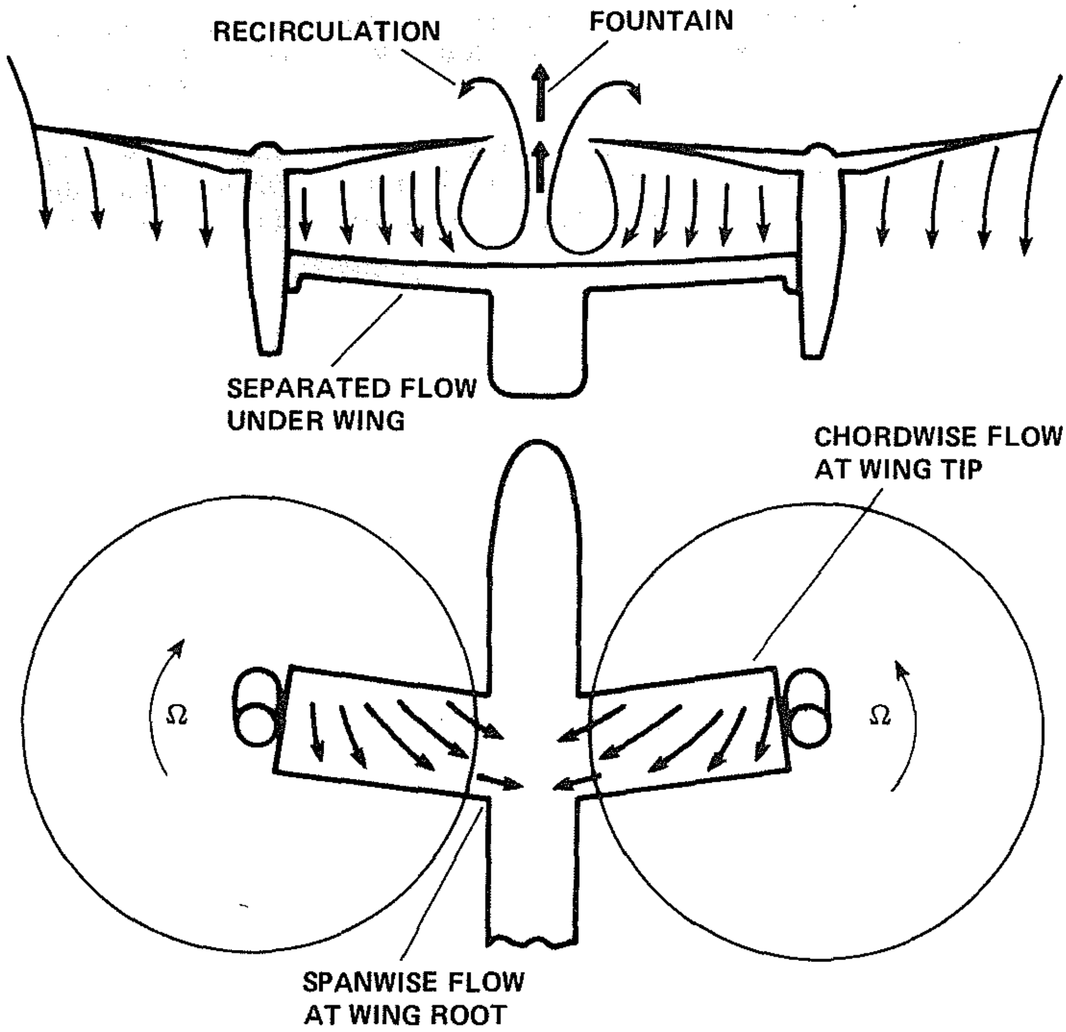

Figure 1. Schematic of rotor/wing flow field.

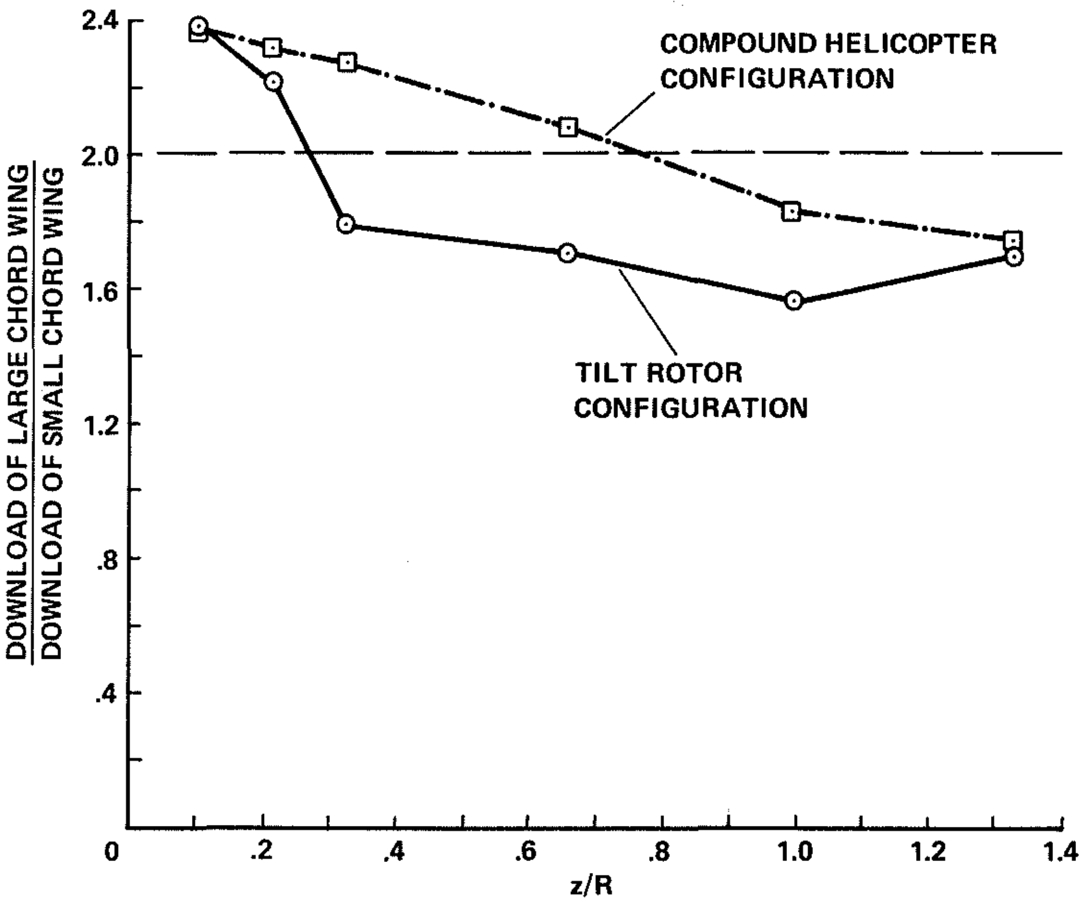

Figure 2. Effect of wing chord on download.

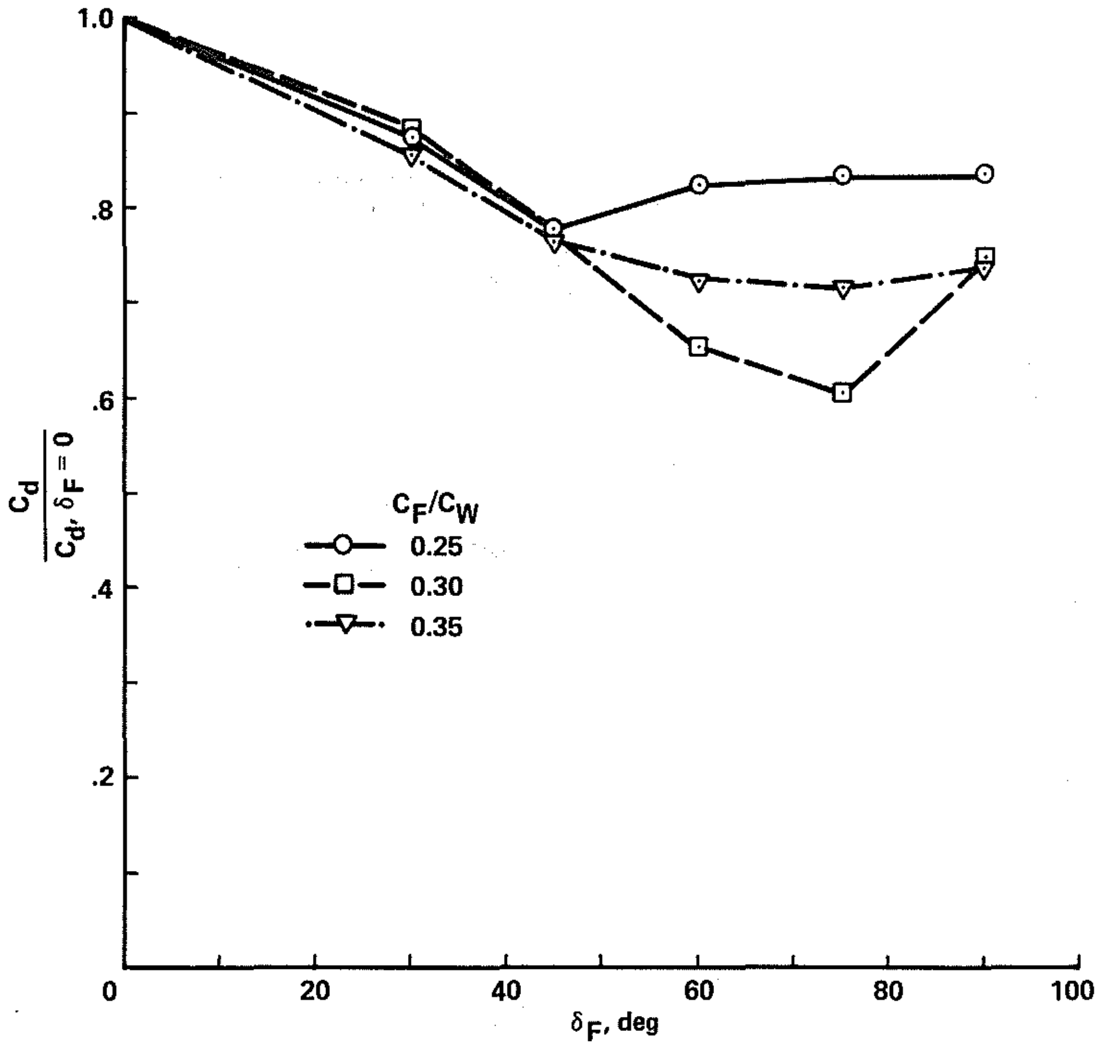

Figure 3. Effect of flap deflection on drag of various flapped airfoils at -90° angle of attack. Data from 2-dimensional wind tunnel test (Ref. 11).

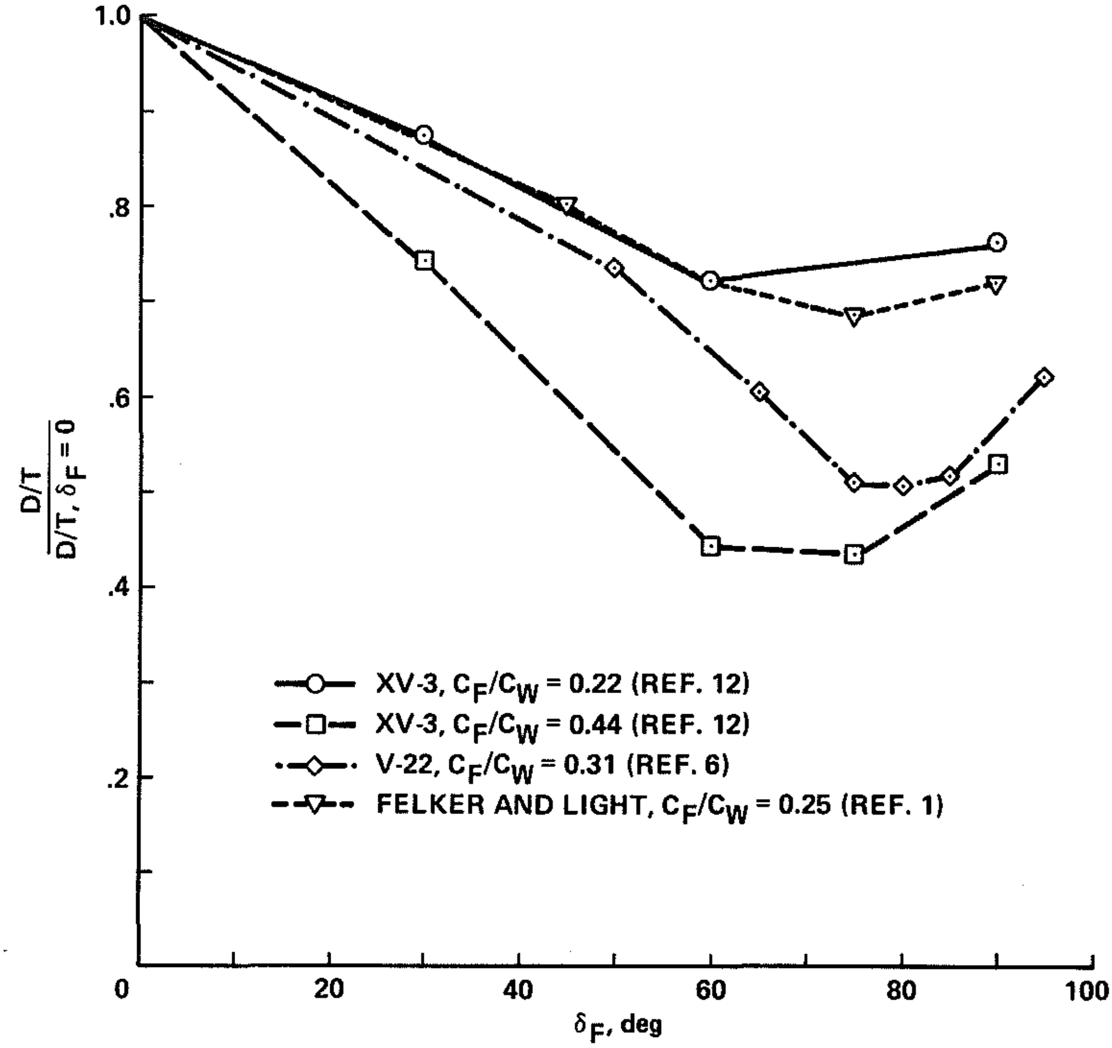

Figure 4. Effect of flap deflection on download. Data from small-scale wind tunnel tests.

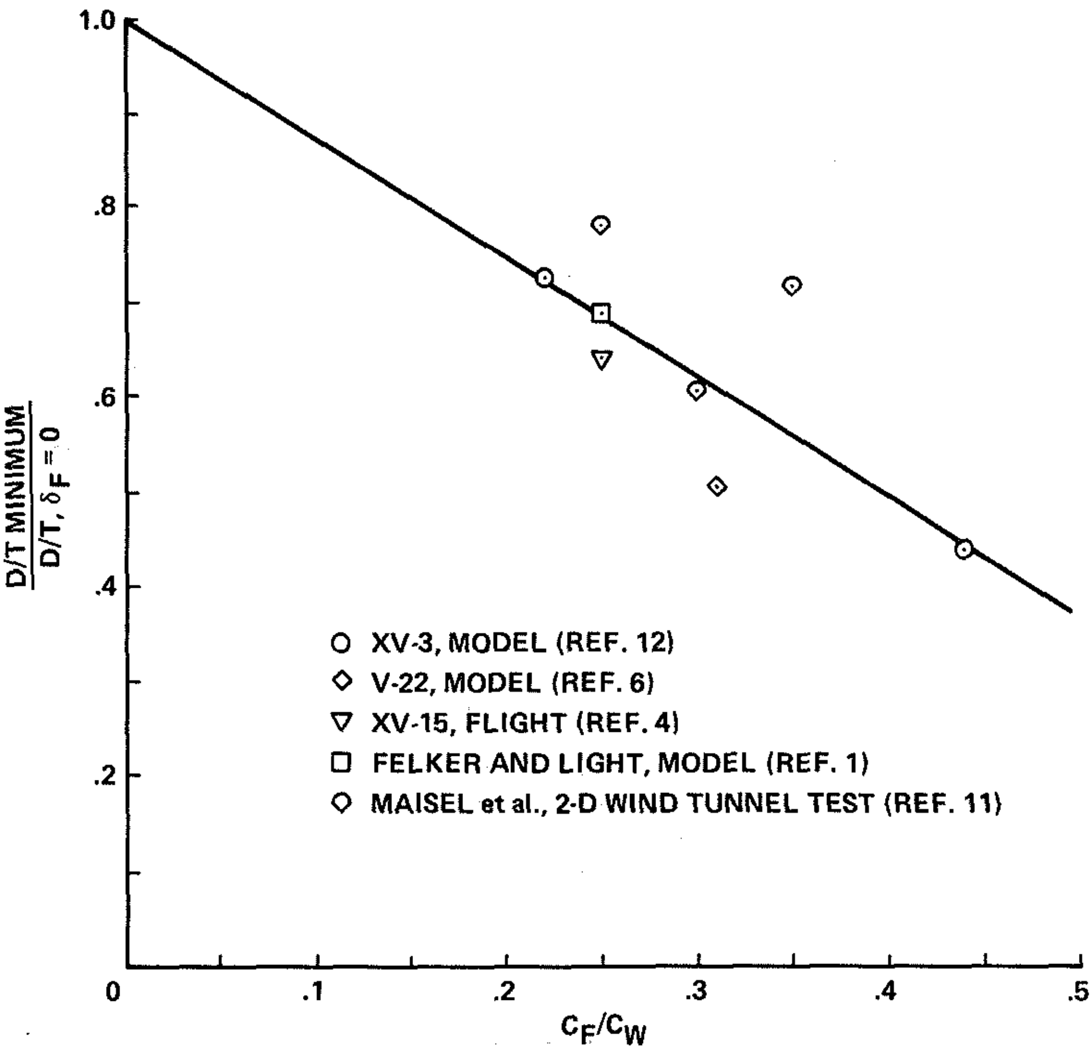

Figure 5. Effect of flap size on maximum flap download reduction.

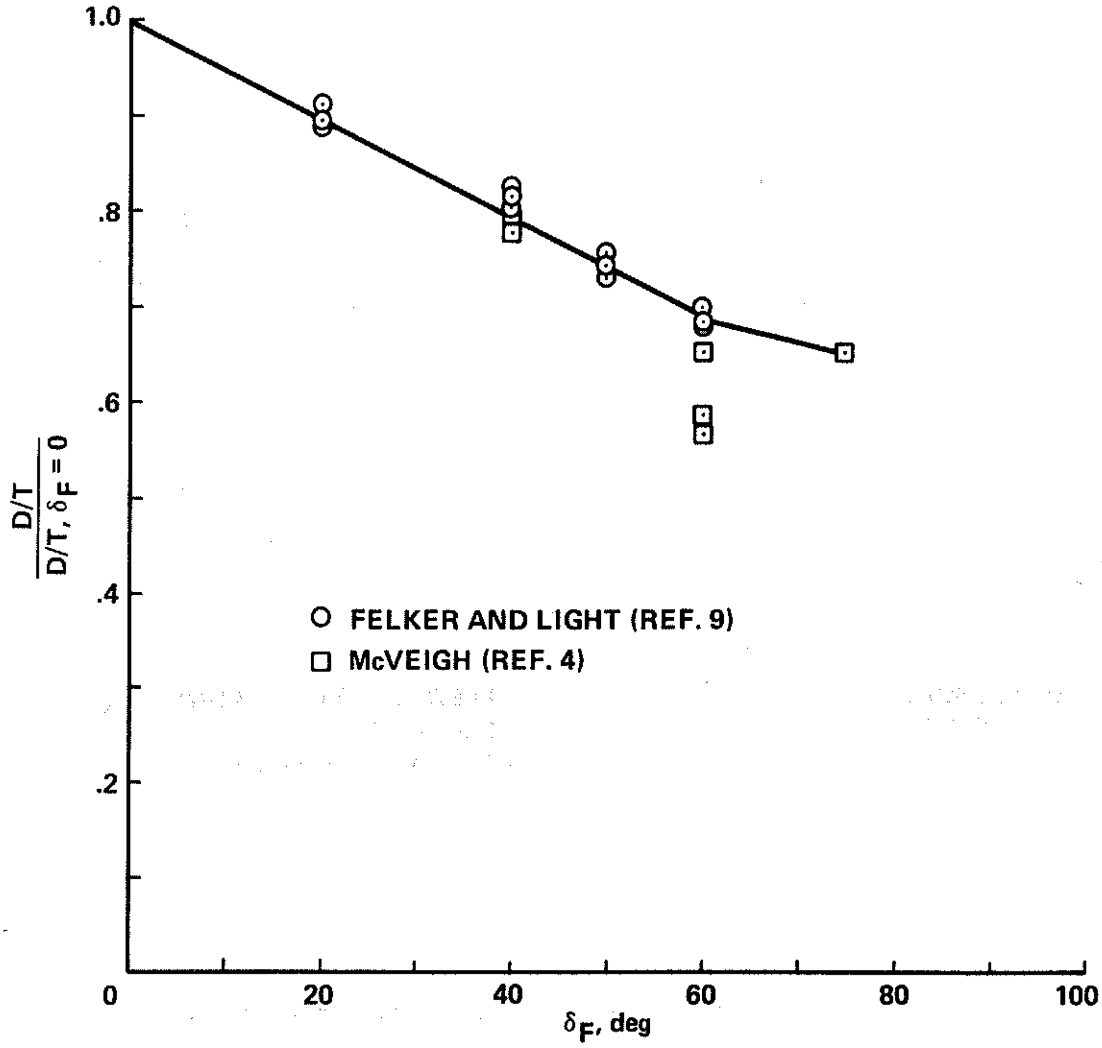

Figure 6. Effect of flap deflection of XV-15 aircraft download. Data from flight test.

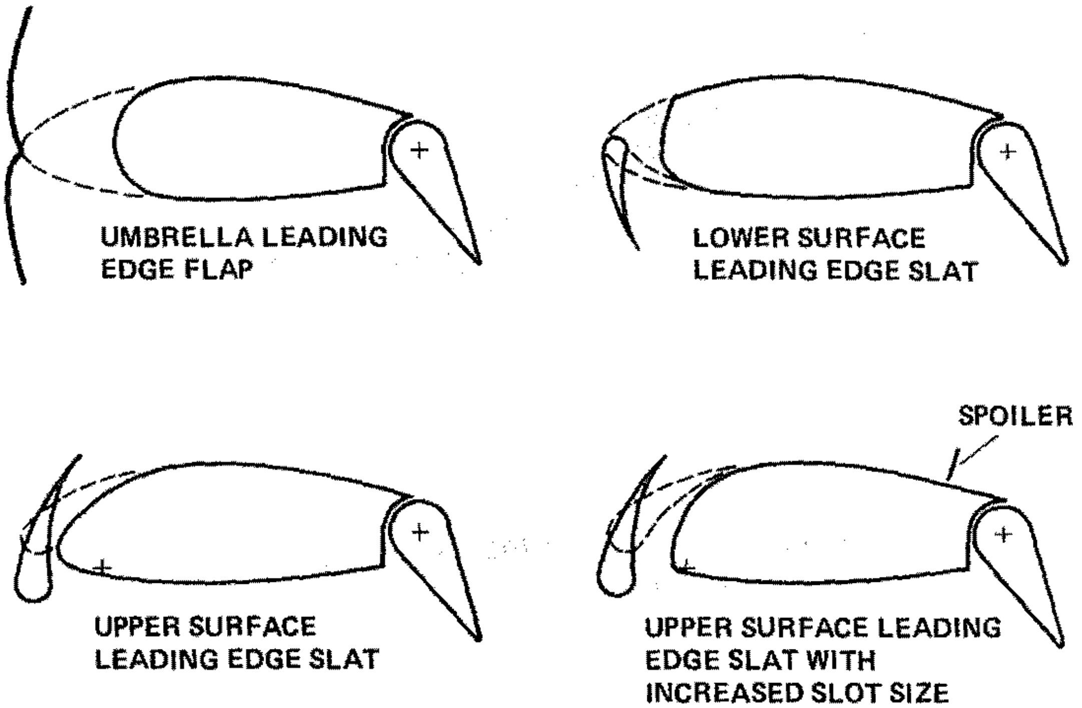

Figure 7. Typical leading-edge devices for download reduction (Ref. 11).

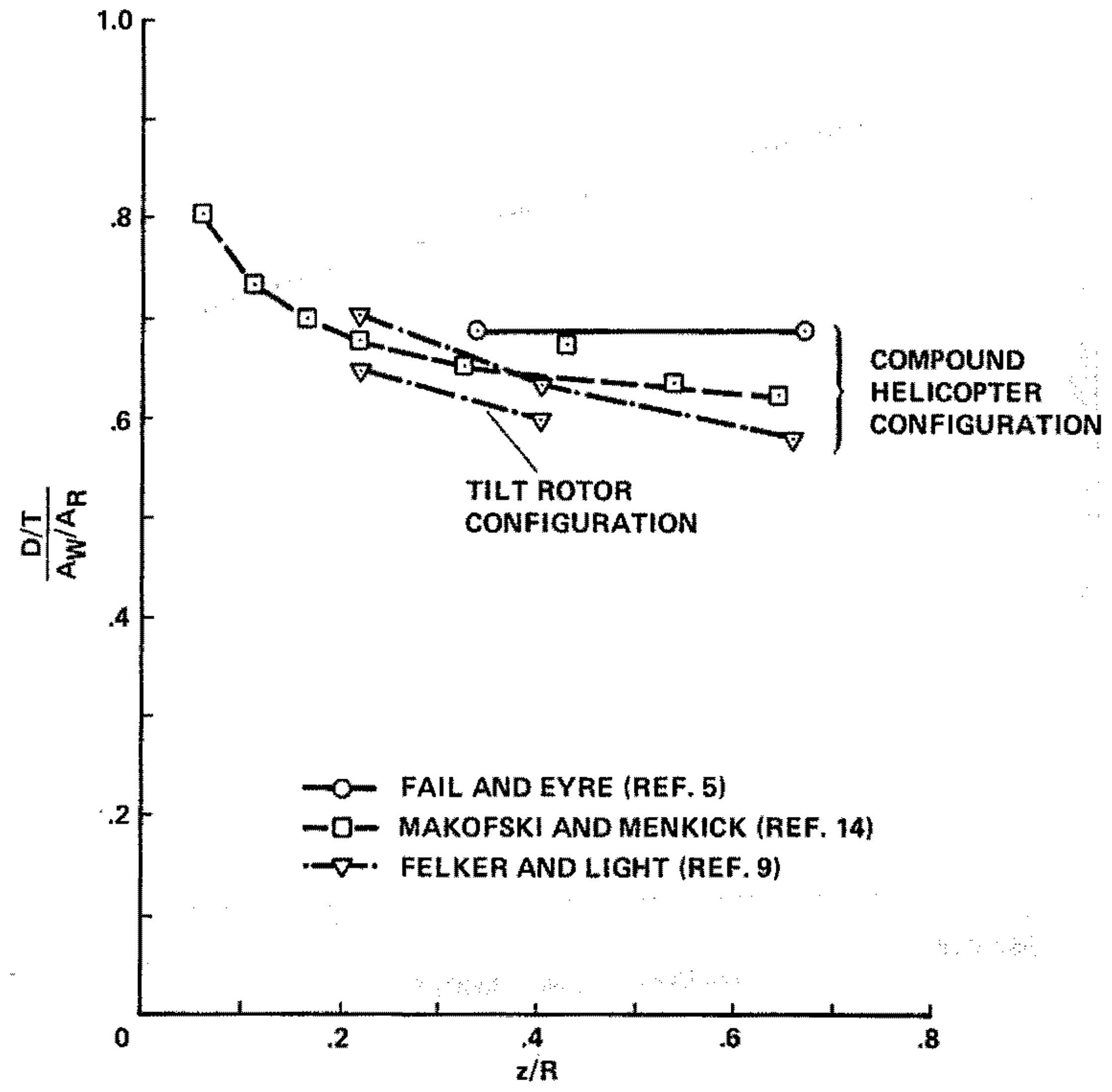

Figure 8. Effect of distance between rotor and wing on download.

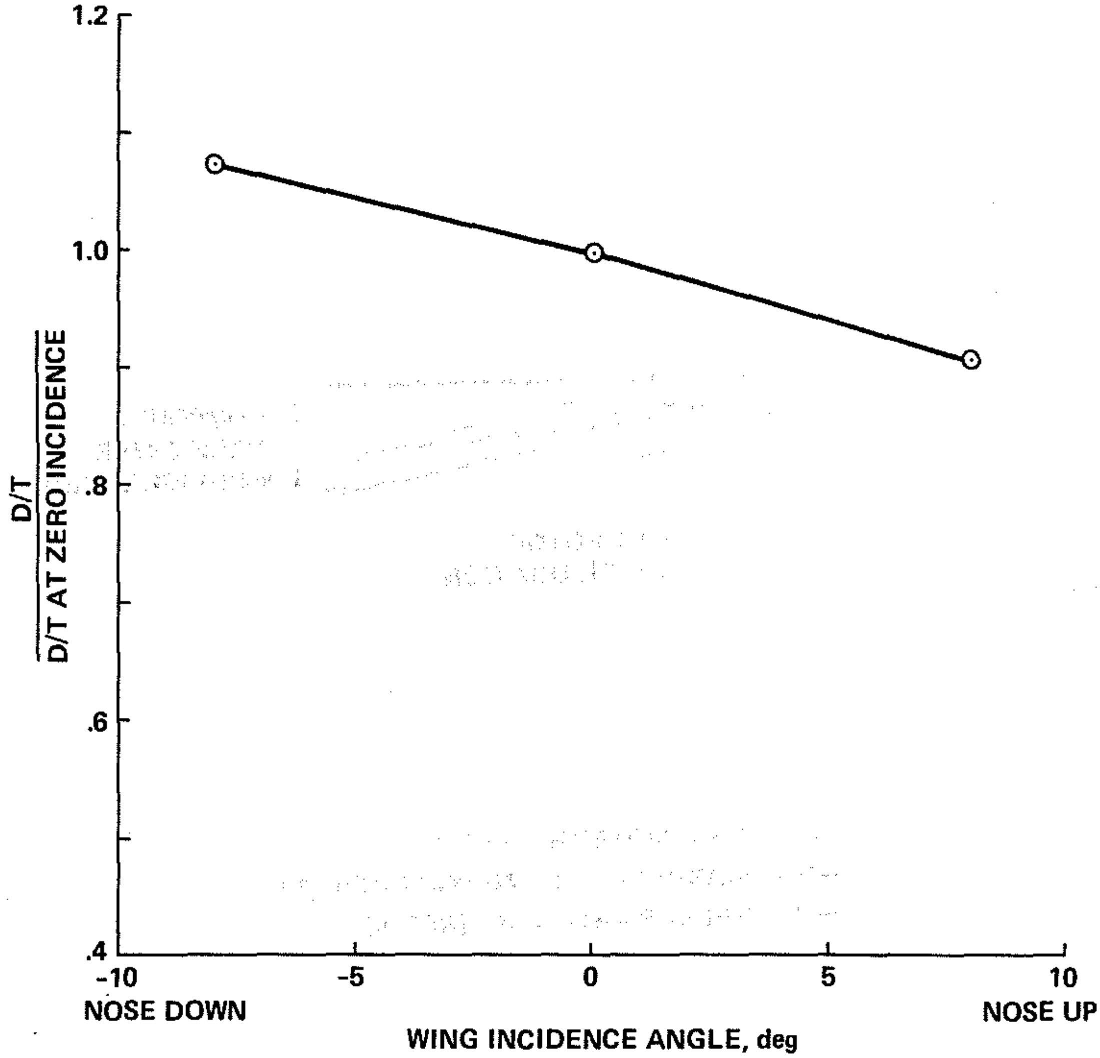

Figure 9. Effect of wing incidence angle on download. 60° flap deflection. Data from Ref. 1.

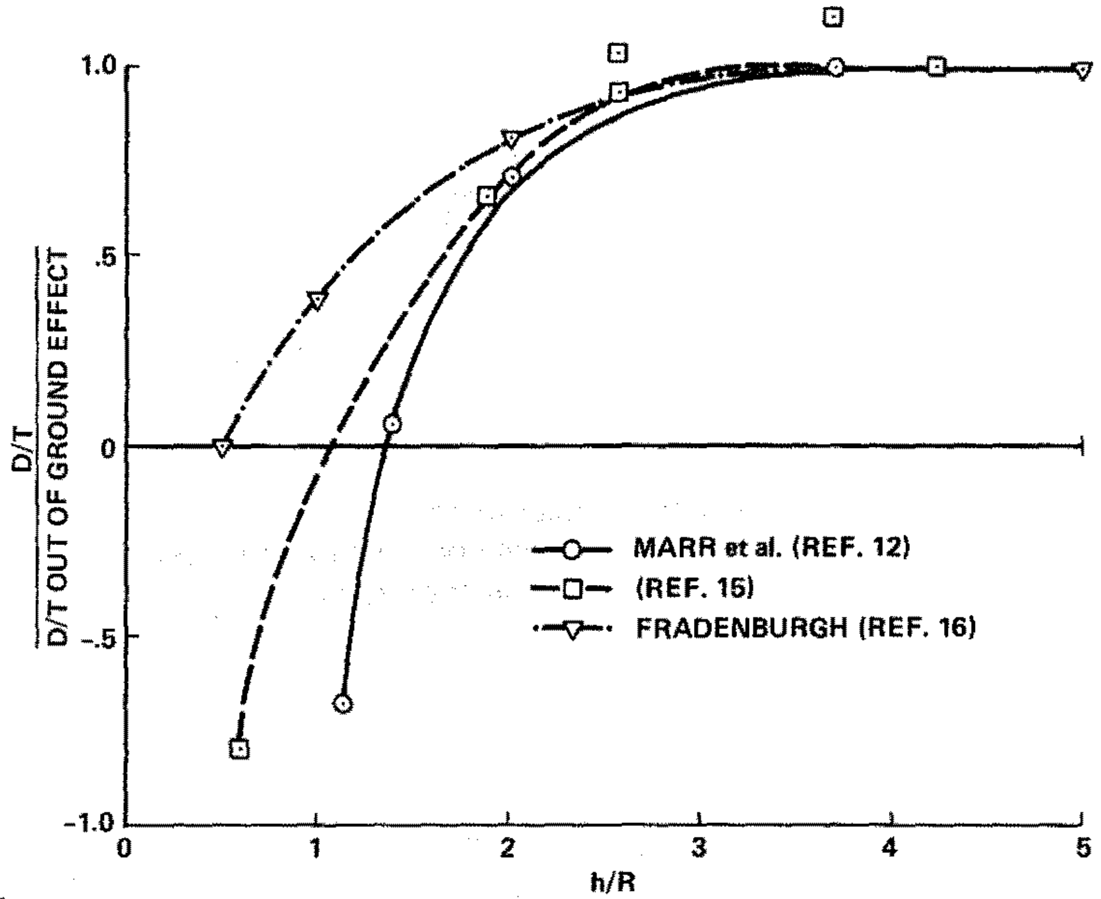

Figure 10. Effect of distance between rotor and ground on download.

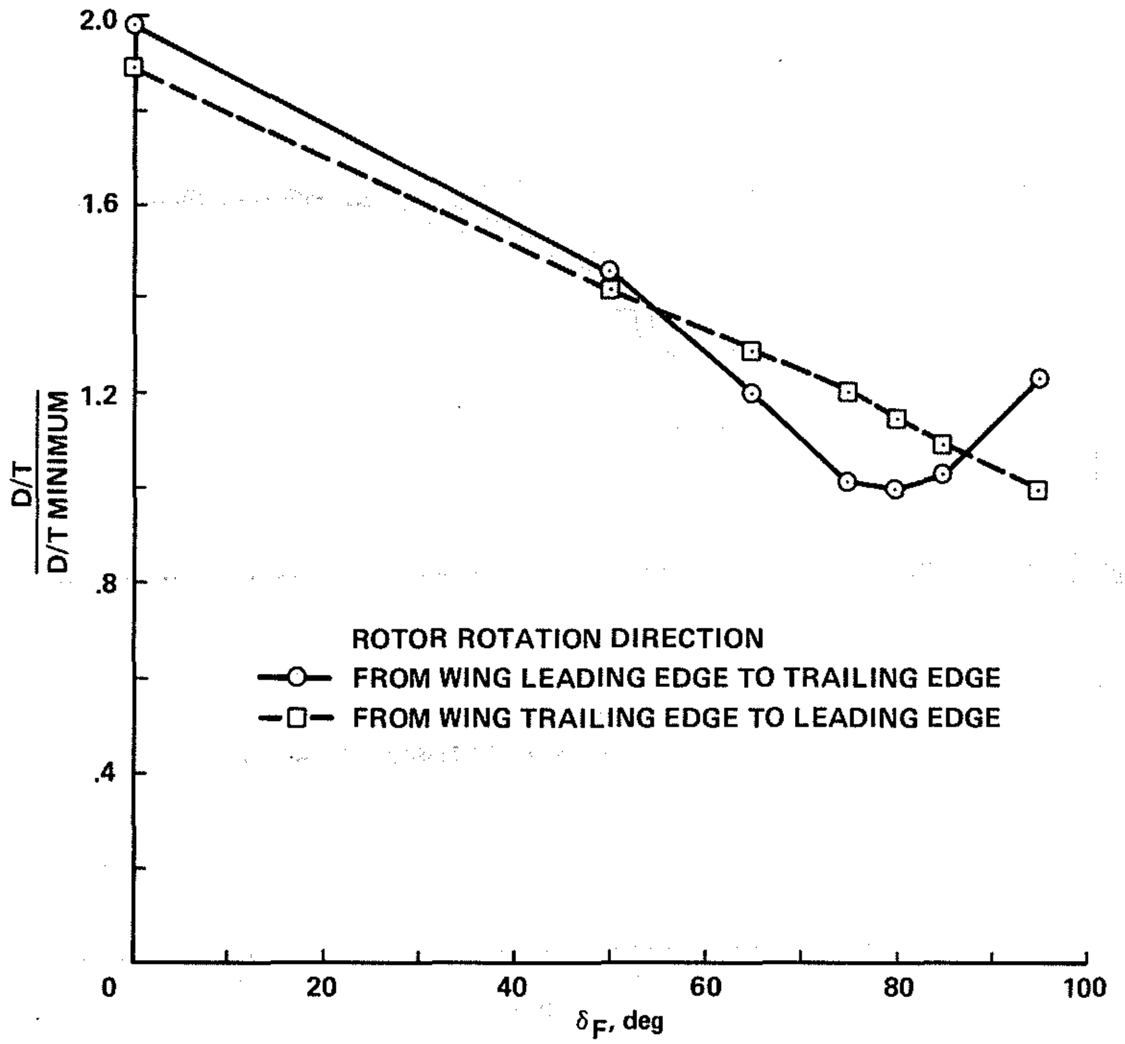

Figure 11. Effect of rotor rotation direction on download. Data from Ref. 6. Minimum download was equal in both cases.