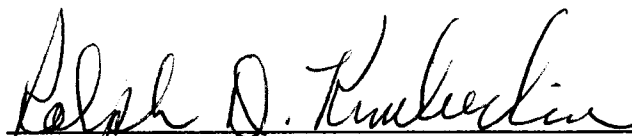


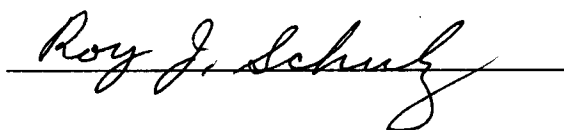
To the Graduate Council:

I am submitting herewith a thesis written by Melagne Timothée Yed entitled "Aerodynamic Performance of the Winged Helicopter Applying Upper Surface Blowing". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.



Dr. Ralph D. Kimberlin, Major Professor

We have read this thesis
and recommend its acceptance



Accepted for the Council



Associate Vice Chancellor
and Dean of the Graduate School

**AERODYNAMIC PERFORMANCE OF THE WINGED
HELICOPTER APPLYING UPPER SURFACE BLOWING**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Melagne Timothée Yed

May 1996

DEDICATION

This thesis is dedicated to

my Father,

Reverend Niagne Alphonse Essoh

and my Mother,

Mrs. You Blandine Agnimel Essoh

who have always privileged moral and religious values in overcoming life challenges.

ACKNOWLEDGMENT

I am very much grateful to my major professor, Dr. Ralph D. Kimberlin, who ignited my interest in powered-lift technology. I would like to emphasize his availability and his motivating guidance and patience without which this work would not have been possible.

I am also sincerely thankful to my other two committee members, Dr. Frank G. Collins and Dr. Roy J. Schulz, for their close attention to my academic progress, and particularly to the realization of this thesis.

ABSTRACT

Powered-lift technology applied to vertical takeoff and landing aircraft can generate high lift coefficients. The determination of how this high lift capability can be utilized to improve rotary-wing aircraft performance, and thereby unload the rotor, is obtained by estimating the amount of additional lift produced, as well as the effect of the powered-lift technique on rotor speed.

This thesis discusses the particular case of the winged helicopter applying upper-surface-blowing technology. A theoretical approach, supported by actual wind tunnel test results, is used to investigate the helicopter vertical drag compensation.

Furthermore, mathematical relations and plots are generated to illustrate the effect of flap deflection angle on additional lift, and also the effect of angle of attack on rotor speed at different settings of the blowing coefficient and the flap deflection angle.

Finally, this thesis shows how the upper-surface-blowing technique can also be utilized to improve the propulsive capability of the helicopter.

TABLE OF CONTENTS

CHAPTER		PAGE
1	INTRODUCTION	1
1.1	Concept of the Winged Helicopter	1
1.2	Concept of the Upper Surface Blowing (USB) and Recent Progress	2
2	DESCRIPTION OF THE WINGED HELICOPTER	5
2.1	Configuration of the Baseline Helicopter	5
2.2	Configuration of the Hypothetical Winged Helicopter	6
2.3	Description of the Blowing Engines	7
3	HOVER OUT OF GROUND EFFECT (OGE)	9
3.1	Fuselage Download OGE	9
3.2	Wing and Stabilizer Download OGE	12
3.3	USB Engines Download OGE	13
4	HOVER IN GROUND EFFECT (IGE)	14
4.1	Fuselage Download IGE	14
4.2	Wing, Stabilizer, and USB Engines Download IGE	15
4.3	Sample Computation	16
5	VERTICAL DRAG ALLEVIATION	19
5.1	Total Lift Generated by Blowing	19
5.2	Determination of the Lift Increase	20
5.3	Sample Computation	21
6	AERODYNAMIC PERFORMANCE	23
6.1	Methodology	23
6.2	Determination of the Lift Curve	24
6.3	Determination of the Maximum Lift Possible	27
6.3.1	Maximum Lift Possible	28
6.3.2	Maximum Lift Coefficient	28

7	ROTOR SPEED IN USB REGIME	31
7.1	Rotor Average Lift Coefficient	32
7.2	Rotor Speed in USB Operation	33
8	CONCLUSION AND RECOMMENDATIONS	35
	LIST OF REFERENCES	37
	APPENDIX	40
	VITA	71

LIST OF TABLES

TABLE	PAGE
1. Configuration of the BELL 222B Helicopter	41
2. Configuration of the Wing	42
3. Specifications of the Blowing Engines	43
4. Fuselage Download Computation	44
5. Wing Download Sample Computation	45
6. Stabilizer Download Computation	46
7. Blowing Engines Download Computation	47
8. Summary of the Aircraft Components Download	48
9. Aircraft Components Height Above the Ground and k_g Factor	48
10. Variation of $\Delta C_{L_{\max}}$ with respect to C_j	49
11. Effect of Blowing on Blade Tip Velocity	50

LIST OF FIGURES

FIGURE	PAGE
1. Examples of Powered-Lift Concepts	51
2. Upper Surface Blown Flap Concept	52
3. The BELL 222B Helicopter	53
4. Hypothetical Winged Helicopter	54
5. Winged Helicopter Maneuver Capability	55
6. Fuselage Segments Stations	56
7. Hover Downwash Velocity Distribution	57
8. Hypothetical Helicopter Vertical Drag Coefficients	58
9. Typical Helicopter Fuselage Section Vertical Drag Coefficients	59
10. Effect of Wing Aspect Ratio on C_{D_v}	60
11. Thrust Variation in Ground Effect at Constant Power	61
12. Effect of Ground Proximity on Hover Download Correction Factor, k_g	62
13. Additional Lift vs. Flap Deflection Angle	63
14. Change in Maximum Lift Coefficient vs. Angle of Attack	64
15. Blade Tip Speed vs. Angle of Attack	67
16. Blade element concept	70

LIST OF SYMBOLS AND ABBREVIATIONS

LATIN SYMBOLS

A	Wing aspect ratio
b	Number of rotor blades
B_0	Fourier coefficient for angle of attack
c	Wing chord, m
$\bar{c}$	Wing mean aerodynamic chord, m
C_{D_v}	Vertical drag coefficient
C_j	Two-dimensional blowing coefficient
C_J	Three-dimensional blowing coefficient
C_ℓ	Two-dimensional lift coefficient
C_L	Three-dimensional lift coefficient
C_{ℓ_α}	Two-dimensional lift curve slope
$C_{L_{\max}}$	Maximum three-dimensional lift coefficient
$\Delta C_{L_{c_j}}$	Change in lift coefficient due to blowing alone
$\Delta C_{L_{\delta, c_j}}$	Change in lift coefficient due to blowing and flap deflection
$\Delta C_{L_{\max}}$	Change in maximum lift coefficient between the basic airfoil and the case with blowing
D	Main rotor diameter, m

D_0	Fourier coefficient for flap deflection
ΔD_v	Incremental vertical drag, N
F	Blowing engine thrust, N
$G(A, C_j)$	Correcting factor for aspect ratio and blowing
H	Component height above ground, m
J	Blowing jet momentum or thrust at blowing nozzle, N
k_g	Correction factor to compute in-ground-effect vertical drag
L	Lift, N
$\dot{m}_j$	Mass flow at the blowing nozzle, $kg \cdot s^{-1}$
q	Free stream dynamic pressure, $N \cdot m^{-2}$
R	Main rotor radius, m
$\bar{r}$	Unit radius defined on rotor blade
S	Wing reference area, m^2
S_j	Blown portion of the wing reference area, m^2
t	Airfoil thickness, m
T	Main rotor thrust, N
V_j	Mean velocity of jet efflux, $m \cdot s^{-1}$
V_t	Main rotor blade tip velocity, $m \cdot s^{-1}$
W	Aircraft gross weight, N

GREEK SYMBOLS

α	Angle of attack, <i>rad</i>
α_{zL}	Angle of attack for zero lift, <i>rad</i>
δ or δ_F	Flap deflection angle, <i>rad</i>
θ	Partial span flap correction factor
ρ	Air density, $kg \cdot m^{-3}$
ν	Fuselage cutout correction factor, or downwash velocity, $m \cdot s^{-1}$
ζ	Distance from forward edge of the main rotor disk, <i>m</i>
χ	Correction factor for flap chord-to-wing chord ratio
Ω	Rotor angular velocity, $rad \cdot s^{-1}$

ABBREVIATIONS

CTOL	Conventional Takeoff and Landing
CTOSL	Conventional Takeoff and Short Landing
IGE	In Ground Effect
MAC	Mean Aerodynamic Chord
OGE	Out of Ground Effect
STOL	Short Takeoff and Landing
USB	Upper Surface Blowing
VSTOL	Vertical and Short Takeoff and Landing
VTOL	Vertical Takeoff and Landing

Chapter 1

Introduction

1.1 Concept of the Winged Helicopter

The concept of a helicopter with wings has been the concern of many aircraft designers in recent years. Today, the question as whether any benefits could be obtained from adding a lifting wing to a conventional helicopter, is no longer asked. As it is known, a typical disadvantage of the conventional helicopter is that the lifting capacity of the rotor on the retreating side of the rotor disk limits the maximum speed of the aircraft in forward flight. Reference [1] describes an experimental X-Wing model helicopter which even uses a stoppable rotor. Normally, during hover and low-speed flight, the rotor blades rotate as

they would on a conventional helicopter. However, during high-speed flight, the blades would be stopped and arranged in an X-configuration to improve the forward flight speed of the aircraft.

At first glance, a wing on a helicopter may indeed appear as a redundant and useless feature. On the contrary, although a penalty may be paid in the overall download, the addition of a wing is one way to improve the aerodynamics of the helicopter.

The study presented herein will examine the special case of the winged helicopter using an Upper Surface Blowing (USB) concept as a means to achieve the high lift coefficients required for Vertical Takeoff and Landing (VTOL) aircraft operation.

1.2 Concept of Upper Surface Blowing (USB) and Recent Progress

Upper Surface Blowing is a powered-lift concept in which the entire jet efflux from the blowing engines is directed at the wing upper surface. The jet exhaust becomes attached to the wing upper surface and follows the deflected trailing-edge flap through the Coanda effect. Actually, beside the conventional airfoils and flap systems, powered-lift technology is used to produce additional lift. The technology can be accomplished in various ways. Either the aircraft jet exhaust is turned downward in order to generate a vertical thrust, or, in the case of USB, pressurized air is directed over airfoil, flaps, and/or trailing edge nozzles to create additional lift through super circulation. Various powered lift methods are presented in Figure 1¹.

¹ All figures and tables are collected in the appendix

Over the past several years, USB research work has been conducted with satisfactory results.

In 1974, as reported by Leonard Roberts and Wallace Deckert in RECENT PROGRESS IN VSTOL TECHNOLOGY [2], NASA initiated the Quiet Short-Haul Research Aircraft (QSRA) Program in which a modified Buffalo aircraft was used. The aircraft was equipped with four high-bypass-ratio turbine engines. The engine efflux was directed over the upper surface of the wing and over a large Coanda flap, Figure 2, thereby generating additional wing circulation and lift. In 1978, the Boeing company, under contract to NASA, completed the design of the QSRA aircraft equipped with the new wing propulsion system. With a wing span of 73 ft, an aspect ratio of 9.0, and a 15-degree sweep angle, the aircraft was delivered to Ames Research Center to be tested.

The flight test conclusions reported in [2] include:

1. A maximum lift coefficient of 11 was achieved in flight with USB flaps set at 50° and at thrust-to-weight ratio of 0.38.
2. An operating lift coefficient of about 5.5, with wide operating margins ($\Delta\alpha = 20^\circ$ and one engine inoperative), can be obtained.
3. An approximate 30% reduction in takeoff and landing distances can be accomplished at a conventional aircraft thrust-to-weight ratio and wing loading.
4. A powered-lift USB aircraft is not difficult to fly and generally has better handling qualities and performance characteristics than a comparable conventional aircraft.

Actual progress in powered-lift technology has been the achievement of laborious ground and flight research work and, as such, may seem slow. Yet, the level of satisfaction and knowledge acquired has considerably improved over the last decade. High lift coefficients can be generated while protection against gusts, cross winds, and engine failure is also improved. However, tradeoffs of some parameters of merit such as payload, range, and fuel consumption remain, which means that a powered-lift aircraft may be successfully used in a CTOL mode, CTOSL mode, or STOL mode without compromise to the aircraft design.

The hypothetical baseline helicopter used in the present work is the BELL 222B helicopter. A wing with a reference area of 101 ft^2 and an aspect ratio of 4 will be added to the fuselage. Two small turbofan engines of high bypass ratios will be mounted, one on top of and ahead of each wing to provide the blowing. Then, an analytical approach, supported by existing wind tunnel data and flight test results, will be used to predict the aerodynamics of the hypothetical winged helicopter employing USB.

Chapter 2

Description of the Winged Helicopter

2.1 Configuration of the Baseline Helicopter

To make this study as realistic as possible, an existing aircraft, namely the BELL 222B helicopter with a main rotor diameter of 42 ft, has been selected as the baseline helicopter. The detailed description of the configuration, and a three-view drawing of the aircraft are presented in Table 1, and Figure 3, respectively.

2.2 Configuration of the Hypothetical Winged Helicopter

As stated earlier in the introduction, a 350-lb wing will be attached to the pure helicopter, Table 2, causing the total empty weight of the aircraft to increase to 5,279 lb. A descriptive layout of the helicopter with wing is pictured in Figure 4, with a 1-to-91 scale ratio. The wing with a reference area of 101 ft^2 was selected to provide 2-g banked turn maneuver capability, at airspeed from 100 to 170 knots at 4,000 ft/95°F, Figure 5. A low-wing arrangement is adopted to keep the aircraft aerodynamically clean and so the wing can be incorporated into the landing gear sponson.

Full-span 44-percent chord single-slotted Coanda flaps will be provided. The use of a Coanda flap will induce more wing circulation and lift, especially during hover and low speeds by blowing.

The selection of an aspect ratio as low as 4, and a taper ratio of 0.5 is made to reduce wing zero-lift drag, and aircraft structural weight.

The use of a 1/4-chord sweep angle as low as 3° will improve the lifting capacity of the wing during maneuvers.

The aerodynamics of the airfoil selected for the wing, namely the 65A-618 section [3], are:

1. Low profile drag at trim C_l , ($C_d = 0.007$ at $C_l = 0.4$)
2. High $C_{l_{\max}}$, ($C_{l_{\max}} = 1.5$)

3. Gentle trailing edge stall characteristics
4. High lift curve slope, ($C_{l_\alpha} = 0.114$ per degree)
5. Sufficient maximum thickness, (12%), and favorable chordwise thickness distribution for structural efficiency and low weight.

2.3 Description of the Blowing Engines

To provide upper surface blowing, two engines have been selected. Each engine is a William-Rolls FJ44 two-shaft subsonic turbofan [4], Table 3. With a bypass ratio of 3.28 and a maximum takeoff thrust of 1,900 lb, each engine is expected to produce the amount of blowing necessary to achieve the high lift performance. With a total weight of 894 lb, the two USB engines increase the empty and dry weight of the aircraft to 6,173 lb. The maximum takeoff weight increases as well to allow the same or greater useful load. The specifications of the blowing engines are summarized in Table 3. These engines have been selected partly because of their low specific fuel consumption, especially during sea-level and takeoff operations, to cut down on fuel weight. Being two turbofans with mixed exhaust flows, the engines will generate less noise than they would if they had separate exhaust streams. They will provide, in addition, a propulsive force equivalent to the horizontal component of their total thrust. Furthermore, each engine will be enclosed in a D-shaped nozzle nacelle. The purpose of the "D" nozzle is to deflect and spread the

engines efflux over the wing. As shown in Figure 2, engines and nacelles will be mounted on top of and at about one foot ahead of the wing aerodynamic center. In addition to the nozzles, appropriate ducting of the engines exhausts will be done in order to allow the blowing to cover a wider wing surface.

Chapter 3

Hover out of Ground Effect (OGE)

3.1 Fuselage Download OGE

The hover performance calculations are based on the computation procedure presented by Stepniewski and Keys in their book **ROTARY-WING AERODYNAMICS** [3]. In general, the procedure consists of comparing the helicopter shaft power required with the engine installed power available. It expresses the main and tail rotors power required as a function of main rotor thrust, which will then be scaled for download effects to obtain gross weight. The total thrust T required by the main rotor in hover is equal to the gross weight W plus the vertical drag, or download D_v acting on the fuselage, that

is,

$$T = W + D_v \quad (1)$$

Wind tunnel test data for fuselage vertical drag coefficients and downwash velocity distributions, or analytical computations, if test results are lacking, will be used to predict the download. As described in [3], the fuselage is divided into a finite number of segments,

Figure 6. Then, the drag increment for each segment is computed as

$$\Delta D_{v_n} = \int_{\zeta_n}^{\zeta_{n+1}} C_{D_{v_n}} \frac{1}{2} \rho v^2 w_n d\zeta \quad (2)$$

where

ΔD_{v_n} = incremental download of segment n to $n + 1$

$C_{D_{v_n}}$ = fuselage segment vertical drag coefficient

ρ = air density

v = downwash velocity acting on $w_n d\zeta$

w_n = average segment width

ζ = distance from the forward edge of the rotor disk to segment n ,
measured along the fuselage centerline

The quantities $C_{D_{v_n}}$ and w_n are assumed to be constant for a given segment. Hence, (2)

becomes

$$\Delta D_{v_n} = \frac{1}{2} C_{D_{v_n}} \rho w_n \int_{\zeta_n}^{\zeta_{n+1}} v^2 d\zeta \quad (3)$$

Also, from momentum theory, the main rotor total thrust is given by

$$T = 2\rho\pi R^2 v_{id}^2 \quad (4)$$

where

R = main rotor radius

v_{id} = ideal downwash velocity

Dividing (3) by (4) gives the dimensionless download expression

$$\frac{\Delta D_{V_n}}{T} = \frac{C_{D_{V_n}} w_n}{4\pi R} \int_{\zeta_n}^{\zeta_{n+1}} \frac{1}{R} \left(\frac{v}{v_{id}} \right)^2 d\zeta \quad (5)$$

or

$$\frac{\Delta D_{V_n}}{T} = \frac{C_{D_{V_n}} w_n}{4\pi R} \int_{(\zeta/R)_n}^{(\zeta/R)_{n+1}} \left(\frac{v}{v_{id}} \right)^2 d\left(\frac{\zeta}{R} \right) \quad (6)$$

where the terms $\frac{\Delta D_{V_n}}{T}$ and $\frac{\zeta}{R}$ are defined as percentages. The term

$$\int_{(\zeta/R)_n}^{(\zeta/R)_{n+1}} \left(\frac{v}{v_{id}} \right)^2 d\left(\frac{\zeta}{R} \right)$$

in (6) is equal to the area under the plot of $\left(\frac{v}{v_{id}} \right)^2$ versus $\frac{\zeta}{R}$ between stations n and

$n + 1$ as shown in Figure 7. Introducing the variable k_{V_n} from [3], as

$$k_{V_n} = \int_0^{(\zeta/R)_n} \left(\frac{v}{v_{id}} \right)^2 d\left(\frac{\zeta}{R} \right)$$

then (6) becomes

$$\frac{\Delta D_{V_n}}{T} = \frac{C_{D_{V_n}} w_n}{4\pi R} (k_{V_{n+1}} - k_{V_n}) \quad (7)$$

In the illustration of the fuselage download derivation exposed in Table 4, the fuselage has been divided into eight segments, Figure 6. The drag coefficient $C_{D_{v_n}}$ for the cross-section shape of each segment is obtained from Figure 8. These coefficients are based on wind tunnel pressure and force measurements obtained on numerous fuselage shapes. Drag coefficients for other fuselage section shapes are illustrated in Figure 7.

Now, knowing both the drag coefficient and the downwash velocity, the incremental download for each fuselage segment can be computed. The downwash profile used for the computations are shown in Figure 9. The profile is a plot of velocity ratios $\frac{v}{v_{id}}$, $\left(\frac{v}{v_{id}}\right)^2$, and k_v values as a function of distance from the forward tip of the rotor disk in percent radius $\frac{\zeta}{R}$.

3.2 Wing and Stabilizer Download OGE

To obtain the wing and the stabilizer download, the technique described in the case of the fuselage is once more applied. Equations (2) through (7), as well as the downwash profiles of Figure 8 are also used. The only difference is that the radial stations are now measured along the wing or stabilizer span. Sample computation is provided in Tables 5 and 6 where the vertical drag coefficients are obtained from Figure 10, [3].

Adding a wing to the helicopter fuselage will obviously increase the overall

download of the aircraft. However, it will be shown in a later chapter how flap deflection and use of the blowing engines during hover can literally alter the helicopter total download, and even produce an additional upload.

3.3 USB Engines Download OGE

Following the fuselage method, the download due to the presence of the blowing engines during hover is computed and shown in Table 7. Again, all equations and existing velocity profiles previously described have been used.

Finally, the total download of the entire aircraft with flaps deflected 80° is calculated and summarized in Table 8 where the terms $\frac{D_v}{W}$ and $\frac{D_v}{T}$ are related by the equation

$$\frac{D_v}{W} = \frac{D_v}{T} \left(1 - \frac{D_v}{T} \right) \quad (8)$$

The total download is shown to be 5.57% of the aircraft gross weight, which is 2.23% more than that of the baseline helicopter without wings.

Chapter 4

Hover in Ground Effect (IGE)

4.1 Fuselage Download IGE

In hover IGE, the power to thrust relationship depends substantially on the height of the helicopter above the ground. Lacking a less complicated mathematical approach to the problem, available flight test measurements from [3] and Figure 11 are used to account for the ratio of thrust IGE as a function of the relative height H_r of the rotor disk above the ground. Also, another empirical correction factor is applied to take into account the reduction in vertical drag due to the use of the thrust ratio to determine in-ground-effect hover capability. Actually, the reduction in IGE download is caused by interference effects

between the lower surface of the fuselage and the ground. The pressure on the bottom of the fuselage does indeed increase due to higher static pressure in the surrounding downwash area. The correction factor k_g , defined as

$$k_g = \frac{D_{V_{IGE}}}{D_{V_{OGE}}} \quad (9)$$

is derived from rotor test data as a function of average distance H_f between the fuselage lower surface and the ground, and the rotor diameter D , Figure 12.

4.2 Wing, Stabilizer, and USB Engines Download IGE

Test data for a winged helicopter are not available; yet, the same figures obtained for the fuselage case can be used for a good estimate of wing, stabilizer, and blowing engines download IGE.

The total download factor k_{g_i} for the combined fuselage plus wing, stabilizer, and USB engines is:

$$k_{g_i} = \frac{\left[\left(\frac{D_v}{W} \right)_f + \left(\frac{D_v}{W} \right)_w + \left(\frac{D_v}{W} \right)_s + \left(\frac{D_v}{W} \right)_{usb} \right]_{IGE}}{\left[\left(\frac{D_v}{W} \right)_f + \left(\frac{D_v}{W} \right)_w + \left(\frac{D_v}{W} \right)_s + \left(\frac{D_v}{W} \right)_{usb} \right]_{OGE}} \quad (10)$$

where the subscripts “ f ”, “ w ”, “ s ”, and “ usb ” stand for fuselage, wing, stabilizer, and USB engines, respectively. Finally, the factor k_{g_i} is used to determine the gross weight

ratio $\frac{W_{IGE}}{W_{OGE}}$, using the thrust ratio $\frac{T_{IGE}}{T_{OGE}}$ obtained from Figure 12. The next section shows

a sample calculation of IGE download.

4.3 Sample Computation of IGE Downloads

Assuming a wheel height of 5 ft above the ground, the fuselage, wing, and USB engines download correction factors can be obtained, Figure 12, along with the thrust ratio as a function of rotor height, Figure 11. The numbers are presented in Table 9. Now, the components IGE download can be calculated:

$$\left(\frac{D_v}{W}\right)_{f,IGE} = k_{g_f} \left(\frac{D_v}{W}\right)_{f,OGE} = 0.09 \times 2.46 = 0.2214\%$$

$$\left(\frac{D_v}{W}\right)_{w,IGE} = k_{g_w} \left(\frac{D_v}{W}\right)_{w,OGE} = 0.125 \times 2.16 = 0.27\%$$

$$\left(\frac{D_v}{W}\right)_{s,IGE} = k_g \left(\frac{D_v}{W}\right)_{s,OGE} = 0.270 \times 0.88 = 0.2376\%$$

$$\left(\frac{D_v}{W}\right)_{usb,IGE} = k_{g_{usb}} \left(\frac{D_v}{W}\right)_{usb,OGE} = 0.125 \times 0.07 = 0.0088\%$$

hence, the helicopter overall IGE download would be

$$\left(\frac{D_v}{W}\right)_{IGE} = 0.2214 + 0.270 + 0.2376 + 0.0088 = 0.737\%$$

and the total download factor is

$$k_{s_i} = \frac{\left(\frac{D_v}{W}\right)_{IGE}}{\left(\frac{D_v}{W}\right)_{OGE}} = \frac{0.737}{5.57} = 0.13232$$

To compute the weight ratio, note that (1), that is,

$$T = W + D_v$$

can be rewritten as

$$T = W \left(1 + \frac{D_v}{W} \right) \quad (11)$$

so that

$$\frac{T_{IGE}}{T_{OGE}} = \frac{W_{IGE}}{W_{OGE}} \cdot \frac{1 + \left(\frac{D_v}{W}\right)_{IGE}}{1 + \left(\frac{D_v}{W}\right)_{OGE}} \quad (12)$$

However

$$\left(\frac{D_v}{W}\right)_{IGE} = k_{s_i} \left(\frac{D_v}{W}\right)_{OGE}$$

Therefore

$$\frac{T_{IGE}}{T_{OGE}} = \frac{W_{IGE}}{W_{OGE}} \cdot \frac{1 + k_{s_i} \left(\frac{D_v}{W}\right)_{OGE}}{1 + \left(\frac{D_v}{W}\right)_{OGE}} \quad (13)$$

which solves for the weight ratio:

$$\frac{W_{IGE}}{W_{OGE}} = \frac{T_{IGE}}{T_{OGE}} \cdot \frac{1 + \left(\frac{D_v}{W}\right)_{OGE}}{1 + k_{s_i} \left(\frac{D_v}{W}\right)_{OGE}} \quad (14)$$

$$\frac{W_{IGE}}{W_{OGE}} = 1.10 \times \frac{1 + 0.0557}{1 + (0.13232 \times 0.0557)} = 1.15277$$

Hence, the IGE gross weight capability of the hypothetical helicopter at 5-ft wheel height is about 15% higher than that of OGE, assuming constant power available, [3]. Later in chapter 5, the weight ratio will be used in the determination of the lift increase induced by blowing.

Chapter 5

Vertical Drag Alleviation

This chapter will now discuss how the total vertical drag of the helicopter can be alleviated by deflecting the flaps and running the blowing engines.

5.1 Total Lift Generated by Blowing

During takeoff and hover, the flaps will be deflected by δ_F degrees, causing the thrust $\vec{F}$ of each blowing engine to deflect the same angle with respect to the horizontal. So, the thrust $\vec{F}$ can be decomposed into its vertical component, the lifting part,

$$T_1 = F \sin \delta_F \tag{15}$$

and its horizontal component, the propulsive part,

$$T_2 = F \cos \delta_f \quad (16)$$

Therefore, the two blowing engines would induce a total lift L_T equal in magnitude to their combined thrust-induced lift forces, that is,

$$L_T = 2F \sin \delta_f \quad (17)$$

5.2 Determination of the Lift Increase

The increase in lift or additional lift ΔL created by the USB engines is computed by subtracting the helicopter total vertical drag D_v from the total lift L_T generated:

$$\Delta L = 2F \sin \delta_f - D_v \quad (18)$$

Note from (17) that for a zero-degree flap deflection, no lift can be obtained from the blowing, and the helicopter is subject to both its weight and vertical drag; which implies that the rotor alone would have to carry the entire load of the aircraft. On the other hand, a 90° flap deflection would lead to the ideal case where the increase in lift is maximum, that is,

$$\Delta L_{\max} = 2F - D_v \quad (19)$$

Naturally, this particular case is somewhat difficult to realize in USB powered lift. However, values of δ_f ranging between 20° and 70° will still give satisfactory results as will be shown in the following section.

5.3 Sample Computation of the Lift Increase

As specified in Table 1, the maximum takeoff weight of the baseline helicopter is 8,250 lb. But, due to the additional weight introduced by the wing and the blowing engines, an overall maximum takeoff weight of 10,000 lb will be assumed. The total thrust produced by both USB engines is

$$2F = 2 \times 1900 = 3800lb$$

The total download out of ground effect is

$$D_{V_{OGE}} = \left(\frac{D_v}{W} \right)_{OGE} \cdot W_{OGE}$$

and in ground effect is

$$D_{V_{IGE}} = \left(\frac{D_v}{W} \right)_{IGE} \cdot W_{IGE}$$

where

$$W_{OGE} \approx W = 10000lb$$

Using the weight ratio obtained in the previous chapter, it follows that

$$W_{IGE} = \frac{W_{IGE}}{W_{OGE}} \cdot W_{OGE} = 1.15277 \times 10000 = 11528lb$$

hence

$$D_{V_{OGE}} = \frac{5.57}{100} \times 10000 = 557lb$$

and

$$D_{V_{IGE}} = \frac{0.737}{100} \times 11528 = 85lb$$

Thus, from (18),

$$\Delta L_{OGE} = 3800 \sin \delta_F - 557$$

and

$$\Delta L_{IGE} = 3800 \sin \delta_F - 85$$

where

$$\Delta L_{OGE} = \text{lift increase OGE}$$

$$\Delta L_{IGE} = \text{lift increase IGE}$$

The lift increase ΔL versus flap deflection angle δ_F is plotted in Figure 13. For δ_F ranging from 20° to 70° , the aircraft gains an additional lift of about 2,250 lb.

In conclusion, not only will the use of the blowing engines eliminate the vertical drag, but it will also generate an upload which would enhance the lifting capacity of the helicopter.

Furthermore, the blowing engines will induce a net gain in thrust equivalent to the horizontal component of their total thrust and thereby improve the overall propulsive performance of the aircraft. As it can be seen from (16), for very small flap deflection angles, the net gain in thrust, and consequently the forward flight speed of the helicopter, increase significantly.

Chapter 6

Aerodynamic Performance

6.1 Methodology

The prediction of the aerodynamic characteristics of the winged helicopter employing USB is based on the method discussed by Williams, Butler, and Wood in their work **THE AERODYNAMICS OF JET FLAPS** [5]. Based on flat plate theory, the method had undergone some modifications to account for airfoil camber effect. Such modifications have been summarized by Dr. Ralph D. Kimberlin in his dissertation **A CONCEPTUAL DESIGN METHOD FOR AIRCRAFT APPLYING UPPER SURFACE BLOWING** [6].

6.2 Determination of the Lift Curve

As presented in [6], the two-dimension lift coefficient C_ℓ of the airfoil with USB, at an angle of attack α and a flap-deflection angle δ is given by

$$C_\ell = \left(\frac{\partial C_\ell}{\partial \delta} \right) \delta + \left(\frac{\partial C_\ell}{\partial \alpha} \right) \alpha \quad (20)$$

where the partial derivatives $\frac{\partial C_\ell}{\partial \delta}$ and $\frac{\partial C_\ell}{\partial \alpha}$ are defined as

$$\frac{\partial C_\ell}{\partial \delta} = \left[4\pi C_j \left(1.0 + 0.151 C_j^{\frac{1}{2}} + 0.139 C_j \right) \right]^{\frac{1}{2}} \quad (21)$$

$$\frac{\partial C_\ell}{\partial \alpha} = \left(\frac{\partial C_\ell}{\partial \alpha} \right)' \left[1.0 + 0.151 C_j^{\frac{1}{2}} + 0.219 C_j \right] \quad (22)$$

The term $\left(\frac{\partial C_\ell}{\partial \alpha} \right)'$ in (22) is the two-dimensional lift curve slope of the actual airfoil

without blowing, and the term

$$C_j = C_j \frac{S}{S_j} \quad (23)$$

is the mean two-dimensional blowing coefficient, with

S = total wing reference area

S_j = reference area of the blown portion of the wing.

The term

$$C_j = \frac{J}{qS}$$

is the three-dimensional blowing coefficient where

$$J = \dot{m}_j V_j$$

denotes the momentum of the blowing nozzle efflux per unit time with

$$\dot{m}_j = \text{mass flow rate at the blowing nozzle}$$

$$V_j = \text{mean velocity of the jet efflux}$$

$$S = \text{wing reference area}$$

Hence, the section lift coefficient becomes

$$C_\ell = \left[4\pi C_j \left(1.0 + 0.151C_j^{\frac{1}{2}} + 0.139C_j \right) \right]^{\frac{1}{2}} \delta + \left(\frac{\partial C_\ell}{\partial \alpha} \right)' \left[1.0 + 0.151C_j^{\frac{1}{2}} + 0.219C_j \right] \alpha \quad (24)$$

To obtain the three-dimensional lift coefficient C_L , a correction factor, $G(A, C_j)$, is applied to the two-dimensional lift coefficient, and defined in [6] as

$$G(A, C_j) = \frac{A + \frac{2C_j}{\pi}}{A + 2 + 0.604C_j^{\frac{1}{2}} + 0.876C_j} \quad (25)$$

where A is the aspect ratio of the wing. Furthermore, two additional factors, θ and v are introduced to account for fuselage cutout [6]. These factors are:

$$\theta = \frac{S_j}{S} \quad (26)$$

and

$$v = \frac{\theta \left(\frac{\partial C_\ell}{\partial \alpha} \right) + (1 - \theta) \left(\frac{\partial C_\ell}{\partial \alpha} \right)_{C_j=0}}{\frac{\partial C_\ell}{\partial \alpha}} \quad (27)$$

Finally, the overall lift coefficient as computed in [6], becomes

$$C_L = G(A, C_j) \left[\left(1 + \frac{t}{c} \right) \left[\theta \left(\frac{\partial C_\ell}{\partial \delta} \right) \cdot \delta + v \left(\frac{\partial C_\ell}{\partial \alpha} \right) \cdot (\alpha - \alpha_{zL}) \right] \right] - \frac{t}{c} C_j [\delta + (\alpha - \alpha_{zL})] \quad (28)$$

where

$$\frac{t}{c} = \text{airfoil thickness-to-chord ratio}$$

$$\alpha_{zL} = \text{zero-lift angle of attack}$$

The term $(\alpha - \alpha_{zL})$ is used in (28) to account for airfoil camber. From the data provided for the wing airfoil section, it follows that

$$\left(\frac{\partial C_\ell}{\partial \alpha} \right)' = C_{\ell_\alpha} = 0.114 \text{ deg}^{-1} = 6.7036 \text{ rad}^{-1}$$

and

$$\frac{t}{c} = \left(\frac{t}{c} \right)_{\max} = 0.12$$

Also, as suggested by Raymer in AIRCRAFT DESIGN: A CONCEPTUAL APPROACH [7], the negative zero-lift angle of attack, in degrees, can be approximated to the airfoil percent camber; thus

$$\alpha_{zL} = -0.12^\circ = -0.002094 \text{ rad}$$

6.3 Determination of the Maximum Lift Coefficient

Not only will the maximum lift coefficient of the airfoil using USB depend on a large number of parameters such as

- Thickness-to-Chord Ratio,
- Camber
- Reynolds Number, R_e
- Surface Roughness
- Leading Edge Radius
- Deflection of High Lift Devices
- Aspect Ratio, A

but it will also depend on

- Blowing Coefficient, C_j
- Blowing Nozzle Aspect Ratio
- Position of USB Nozzle with respect to Wing Surface.

However, to avoid the complexity created by so many parameters, historical data will be used in the attempt to estimate the maximum lift coefficient [6].

6.3.1 Maximum Lift Possible

Different authors, such as McCormick [8], Helmbold [9], and Davenport [10], have proposed various methods to determine the maximum lift possible for an aircraft applying upper surface blowing. Their results have been summarized in [6] where the maximum lift possible is shown to be

$$C_{L\max} = 1.9A \quad (29)$$

Therefore, with an aspect ratio of 4, the theoretical $C_{L\max}$ of the winged helicopter with USB would be about 7.6.

6.3.2 Maximum Lift Coefficient

Using the results of Spence [11] and Perry [12] shown in [6], the maximum lift coefficient of the blown airfoil is:

$$C_{L\max} = C_{L\max_{C_J=0}} + \Delta C_{L\max} \quad (30)$$

where

$C_{L\max_{C_J=0}}$ = maximum lift coefficient of the unblown airfoil

and

$\Delta C_{L\max}$ = change in maximum lift coefficient between the basic airfoil with flap deflected, and the case with blowing, and defined in [6] as

$$\Delta C_{L \max} = \frac{1}{2} \left(\Delta C_{L_{\delta, c_j}} + \frac{1}{2} \Delta C_{L_{c_j}} \right) \quad (31)$$

with

$\Delta C_{L_{\delta, c_j}}$ = change in C_L due to blowing and flap deflection

$\Delta C_{L_{c_j}}$ = change in C_L due to blowing alone

$\Delta C_{L_{\delta, c_j}}$ and $\Delta C_{L_{c_j}}$ are given by the equations

$$\Delta C_{L_{\delta, c_j}} = 4\pi \left[B_0 \alpha + \left(\frac{\chi}{\pi} + D_0 \right) \delta \right] \quad (32)$$

and

$$\Delta C_{L_{c_j}} = 4\pi (B_0 \alpha + D_0 \delta) \quad (33)$$

where the Fourier coefficients B_0 and D_0 are given by:

$$B_0 = 0.0755 C_j^{\frac{1}{2}} + 0.109 C_j \quad (34)$$

and

$$D_0 = \frac{\left(\frac{\partial C_l}{\partial \delta} \right) - 4\chi}{4\pi} \quad (35)$$

with

$$\chi = 2 \sin^{-1} \left(\frac{c_f}{c} \right) \quad (36)$$

the term $\frac{c_f}{c}$ being the flap-to-wing chord ratio.

It can be seen from Table 10 and Figure 14 that the change in maximum lift coefficient

$\Delta C_{L\max}$ increases with the blowing coefficient C_j .

Chapter 7

Rotor Speed in USB Regime

The primary objective for applying the USB powered-lift concept to the winged helicopter is to enhance the lifting capacity of the aircraft and, thereby, unload the rotor. The present chapter will describe how the application of USB technique affects rotor speed.

7.1 Rotor Average Lift Coefficient

As demonstrated in [3], the thrust dT of a blade element $cRd\bar{r}$ located at $r = R\bar{r}$ along the rotor blade, Figure 17, is equal, within the validity of small angle assumptions, to the lift dL of the blade element, that is,

$$dT = dL = \frac{1}{2} \rho bc R C_l V_t^2 \bar{r}^2 d\bar{r} \quad (37)$$

where C_l is the average lift coefficient of the blade element and $\bar{r}$ and $d\bar{r}$ are as defined in Figure 17. For a rectangular blade with a constant chord c , the rotor solidity can be expressed as

$$\sigma = \frac{bcR}{\pi R^2}$$

Hence

$$bcR = \sigma \pi R^2$$

Substituting for bcR in (37) gives:

$$dT = \frac{1}{2} \rho \sigma \pi R^2 C_l V_t^2 \bar{r}^2 d\bar{r} \quad (38)$$

Assuming that C_l is constant along the total radius R , (38) can be integrated from $\bar{r} = 0$ to $\bar{r} = 1.0$, that is,

$$\int dT = \frac{1}{2} \rho \sigma \pi R^2 C_l V_t^2 \int_0^1 \bar{r}^2 d\bar{r} \quad (39)$$

to give

$$T = \frac{1}{6} \rho \sigma \pi R^2 C_t V_t^2 \quad (40)$$

and solve for the rotor average section lift coefficient without blowing:

$$C_t = \frac{6T}{\sigma \pi R^2 \rho V_t^2} \quad (41)$$

where

T = rotor total thrust

V_t = rotor blade tip velocity

7.2 Rotor Speed in USB Operation

Practically, to determine how the application of the USB method affects rotor speed, one would run the blowing engines at various blowing coefficient settings and flap deflection angles, and record the resulting variations in rotor speed for a helicopter in steady level flight. On the other hand, the analytical way to investigate this issue is to develop a mathematical relationship between the blade tip velocity V_t and the blowing coefficient C_j . Such a relationship can be derived by setting the section lift coefficient induced by blowing (24) equal to the rotor average section lift coefficient without blowing (41), that is,

$$\frac{6T}{\sigma \pi R^2 \rho V_t^2} = \left[4\pi C_j \left(1.0 + 0.151 C_j^{\frac{1}{2}} + 0.139 C_j \right) \right]^{\frac{1}{2}} \delta + \left(\frac{\partial C_t}{\partial \alpha} \right)' \left[1.0 + 0.151 C_j^{\frac{1}{2}} + 0.219 C_j \right] \alpha \quad (42)$$

It follows from (42) that:

$$V_t = \left[\frac{6T}{\sigma\pi R^2 \rho \left[\left[4\pi C_j \left(1.0 + 0.151C_j^{\frac{1}{2}} + 0.139C_j \right) \right]^{\frac{1}{2}} \delta + \left(\frac{\partial C_t}{\partial \alpha} \right)' \left[1.0 + 0.151C_j^{\frac{1}{2}} + 0.219C_j \right] \alpha \right]} \right]^{\frac{1}{2}} \quad (43)$$

where the main rotor thrust T can be substituted with the helicopter gross weight W .

The angular velocity Ω of the rotor can also be obtained as

$$\Omega = \frac{V_t}{R} \quad (44)$$

Obviously, equations (43) and (44) show that the rotor speed Ω is a decreasing function of the blowing coefficient C_j at given settings of the angle of attack α , and the flap deflection angle δ . They clearly suggest that with enough blowing, the rotor of the helicopter can be driven at significantly low speeds but still allow the wing to carry most of the aircraft load, and thereby, unload the rotor. This result is presented in Tables 10 and 11, and Figures 14 and 15.

The benefits of reduced tip or rotational velocity of the rotor are reduced loading, avoidance of transonic flow speeds at the rotor tip, and therefore, much less noise. It follows from such results that the use of upper surface blowing technology seems very beneficial to the operation of the aircraft.

Chapter 8

Conclusion and recommendations

This thesis has presented a theoretical study of the application of USB powered-lift technology to the winged helicopter. The study has shown how the technique could effectively be used to eliminate the vertical drag induced by the rotor. In addition, it has demonstrated that at relatively high blowing coefficients, the rotor speed could be significantly reduced while the lifting capacity of the wings would still be improved, allowing them to carry the entire load of the aircraft. Furthermore, not only could the use of USB technology provide additional lift, but it could also generate additional thrust, and thereby enhance the propulsive capacity of the helicopter, especially during forward flight when flap deflection is minimized. Also, at lower rotor speeds, this helicopter is expected

to be very much quieter. Such results strongly suggest that the winged helicopter applying upper surface blowing is faster and aerodynamically superior to an equivalent conventional helicopter, which means significant military and civilian implications for advanced helicopter technology.

Nonetheless, additional work remains. This thesis has essentially exposed a theoretical approach of the topic discussed. As such, it has yet to be completed by a comparative experimental analysis using the mathematical guidelines developed herein.

A method to reduce fuel consumption must be elaborated. One way could be the use of the primary engine(s) with an appropriate ducting, instead of two auxiliary engines, to provide the blowing.

Furthermore, a study of the stability and control of the helicopter must be investigated. Such a study is necessary since rotor flapping increases at lower rotor speeds, and therefore alter the stability of the aircraft.

Finally, for military and civilian purposes, such as quiet takeoff and landing capabilities, a method to predict the overall noise level of the helicopter needs to be developed.

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LIST OF REFERENCES

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APPENDIX

Table 1. Configuration of the BELL 222B Helicopter

Item	Value	
<u>WEIGHTS</u>		
Empty	4,929 lb	
Maximum T.O.	8,250 lb	
Fuel capacity	1,275 lb	
<u>ENGINES</u>		
Type	Lycoming 750C-2	
Number	2	
Max. T.O. rating	1,470 hp	
Max. usable power	1,088 hp	
<u>ROTOR PARAMETERS</u>	<u>MAIN ROTOR</u>	<u>TAIL ROTOR</u>
Radius, R (ft)	21	3.45
Chord, c (ft)	2.167	0.8
Solidity, σ	0.0657	0.1476
# of blades	2	2
Tip speed, $R\Omega$ (ft.s ⁻¹)	765	671
Twist, θ_1 (deg)	-10.74	0
Hinge offset ratio, e/R	--	--
Airfoil	FX 71-H-080	BHT 10.9 FC
Collective range (deg)	11.7 ± 9	-1.7 to 25
Longitudinal cyclic range (deg)	-13 to +15	--
Lateral cyclic range (deg)	±9	--
Polar moment of inertia, J (slug.ft ²)	1,664	1.0

Source: Raymond W. Prouty, "Helicopter Performance, Stability, and Control", Robert E. Krieger Publishing Company, Inc., Malabar, FL, October, 1986

Table 2. Configuration of the Wing

Item	Value
Wing unit	3.5 lb.ft ⁻²
Reference area, S	101 ft ²
Span	20 ft
Airfoil section	65A-618
M.A.C., $\bar{c}$	4.20 ft
Aerodynamic center @ $\frac{1}{4}\bar{c}$	
Aspect ratio, A	4
Taper ratio, $\frac{c_t}{c_r}$	0.5
Chord @ centerline, c	5.5 ft
Tip chord, c_t	2.7 ft
Coanda flap	single-slotted, 44%chord, 100%span

Source: W. Z. Stepniewski, and C. N. Keys, "Rotary-Wing Aerodynamics", Dover Publications, Inc., Mineole, NY, 1979.

Table 3. Specifications of the Blowing Engines

Item	Specification	
Type	Williams-Rolls FJ44 two-shaft turbofan	
Number	2	
<u>Fan:</u>	Single-stage wide-chord axial Bypass ratio 3.28	
<u>Compressor:</u>	Single-stage axial on LP shaft Single-stage centrifugal on HP shaft	
<u>Nozzle:</u>	Full-length fan duct. Common core and fan exhaust	
<u>Dimensions:</u>		
Length	1,024 mm	3.4 ft
Max diameter	602 mm	2 ft
<u>Weight, dry</u>	203 kg	447 lbm
<u>Performance ratings</u>		
T-O, S/L to 22°C	8.45 kN	1,900 lbf
Max continuous (36,000 ft; Mach 0.7)	2.25 kN	506 lbf
<u>Specific fuel consumption</u>		
T-O, S/L	13.45 mg.N ⁻¹ .S ⁻¹	0.475 lbm/h/lbf
Max continuous(as above)	21.47 mg.N ⁻¹ .S ⁻¹	0.758 lbm/h/lbf

Source: Jane's, "All the World's Aircraft, Eighty-Fifth Edition", Jane's Information

Group Inc., Alexandria, VA, 1994-95, p. 761.

Table 4. Fuselage Download Computation

STEP	A	B	E	F	H	J	L	P	Q
ITEM	ζ (ft)	$\frac{\zeta}{R}$ (%)	k_{V_n}	$k_{V_{n+1}}$	Δk_{V_n}	$C_{D_{V_n}}$	w_n (ft)	$\frac{C_{D_{V_n}} w_n}{4\pi R}$	$\frac{\Delta D_{V_n}}{T}$ (%)
PROCEDURE		$\frac{A}{21}$	<i>Fig. 7</i>		$F - E$	<i>Fig. 8</i>	<i>segment width</i>	$\frac{J \cdot L}{84\pi}$	$H \cdot P$
SEGMENT n									
cockpit									
1-2	8	38.1	87	140	53	0.5	2.41	0.00457	0.24
cabin									
2-3	11	52.4	140	185	45	0.4	4.48	0.00679	0.31
aft-cabin									
3-4	13.8	65.7	185	200	15	0.4	5.17	0.00784	0.12
nacelle									
4-a	20.7	98.6	200	205	5	1.2	4.48	0.02037	0.10
a-5	24.1	114.8	205	250	45	1.2	4.83	0.02196	0.99
aft-body									
5-6	30.3	144.3	250	280	30	0.5	3.28	0.00621	0.19
tailboom									
6-b	32.5	154.8	280	365	85	0.5	2.46	0.00466	0.40
b-7	36.6	174.3	365	410	45	0.5	1.94	0.00368	0.17
7	42.0	200	410	—	—	—	—	—	—
								$\frac{D_v}{T} = 2.52\%$	

Table 5. Wing Download Sample Computation ($\delta_F = 80^\circ$)

STEP	A	B	E	F	H	J	L	P	Q
ITEM	ζ (ft)	$\frac{\zeta}{R}$ (%)	k_{V_n}	$k_{V_{n+1}}$	Δk_{V_n}	$C_{D_{V_n}}$	w_n (ft)	$\frac{C_{D_{V_n}} w_n}{4\pi R}$	$\frac{\Delta D_{V_n}}{T}$ (%)
PROCEDURE		$\frac{A}{21}$	Fig. 7		$F - E$	Fig. 10	segment width	$\frac{J \cdot L}{84\pi}$	$2 \cdot H \cdot P$
SEGMENT n									
1. wing tip	10.95	54.14	135	197.5	62.5	1.50	2.78	0.01580	1.98
2. wing root	15.83	75.38	197.5	205	7.5	1.10	3.75	0.01563	0.23
3. fuselage centerline	21.0	100	205	—	—	—	—	—	—

$$\frac{D_v}{T} = 2.21\%$$

Table 6. Stabilizer Download Computation

STEP	A	B	E	F	H	J	L	P	Q
ITEM	ζ (ft)	$\frac{\zeta}{R}$ (%)	k_{V_n}	$k_{V_{n+1}}$	Δk_{V_n}	$C_{D_{V_n}}$	w_n (ft)	$\frac{C_{D_{V_n}} w_n}{4\pi R}$	$\frac{\Delta D_{V_n}}{T}$ (%)
PROCEDURE		$\frac{A}{21}$	Fig. 7		$F - E$	Fig. 10	segment width	$\frac{J \cdot L}{84\pi}$	$2 \cdot H \cdot P$
SEGMENT n									
1. tip	8.33	39.67	95	165	70	0.67	2.2	0.00559	0.78
2. root	12.5	59.52	165	175	10	0.67	2.2	0.00559	0.11
3. fuselage centerline	13.33	63.48	175	—	—	—	—	—	—

$$\frac{D_v}{T} = 0.89\%$$

Table 7. Blowing Engines Download Computation

STEP	A	B	E	F	H	J	L	P	Q
ITEM	ζ (ft)	$\frac{\zeta}{R}$ (%)	k_{V_n}	$k_{V_{n+1}}$	Δk_{V_n}	$C_{D_{V_n}}$	w_n (ft)	$\frac{C_{D_{V_n}} w_n}{4\pi R}$	$\frac{\Delta D_{V_n}}{T}$ (%)
PROCEDURE		$\frac{A}{21}$	<i>Fig. 7</i>		$F - E$	<i>Fig. 9</i>	<i>segment width</i>	$\frac{J \cdot L}{84\pi}$	$2 \cdot H \cdot P$
NACELLE									
1. inlet	17.0	81.0	198	200	2	0.65	2	0.004926	0.02
2. body	18.6	88.6	200	205	5	0.65	2	0.004926	0.05
3. exit	20.3	96.7	205	—	—	—	—	—	—

$$\frac{D_v}{T} = 0.07\%$$

Table 8. Summary of the Aircraft Components Download

Component	Fuselage	Wing	Stabilizer	USB engines	Total aircraft
$\frac{D_v}{T}(\%)$	2.52	2.21	0.89	0.07	5.69
$\frac{D_v}{W}(\%)$	2.46	2.16	0.88	0.07	5.57

Table 9. Aircraft Components Height above the Ground and k_g Factor

Component	Fuselage	Wing	Stabilizer	USB engines	Rotor
Height H	6	7	10	7	16
Ratio $\frac{H}{D}$	0.14	0.17	0.24	0.17	0.38
Factor k_g	0.09	0.125	0.270	0.125	$\frac{T_{IGE}}{T_{OGE}} = 1.10$

Calculation of the $\Delta C_{L\max}$ of the Blown Wing

For all computations, it will be assumed that the blowing covers half of the wing reference area. Hence,

$$C_j = C_j \frac{S}{S_j} = 2C_j$$

Using equations (21) and (32–36), the variation of $\Delta C_{L\max}$ with respect to C_j can be calculated and plotted in Table 9 and Figure 16.

Table 10. Variation of $\Delta C_{L\max}$ with respect to C_j

α (deg)	$\Delta C_{L\max}$		
0	0.51	2.30	3.85
5	0.64	2.51	4.12
10	0.78	2.72	4.39
15	0.92	2.93	4.66
20	1.06	3.15	4.92
25	1.20	3.36	5.19
30	1.34	3.57	5.46
C_j	0.45	0.75	1.0
δ (deg)	15	45	60

Effect of Blowing on Rotor Speed

Constants used:

$$\rho = 1.225 \text{ kg} \cdot \text{m}^{-3}$$

$$R = 21 \text{ ft} = 6.4 \text{ m}$$

$$\sigma = 0.0657$$

$$T = W = 10,000 \text{ lb} = 44,482.2 \text{ N}$$

$$\left(\frac{\partial C_t}{\partial \alpha} \right)' = 6.7036 \text{ rad}^{-1}$$

Table 11. Effect of Blowing on Blade Tip Velocity

α (deg)	$V_t (\text{m} \cdot \text{s}^{-1})$		
0	161.2	80.0	63.39
5	120.46	72.43	59.10
10	100.33	66.67	55.57
15	87.78	62.10	52.61
20	79.00	58.35	50.1
25	72.42	55.21	47.87
30	67.25	52.53	45.94
C_j	0.45	0.75	1.0
δ (deg)	15	45	60

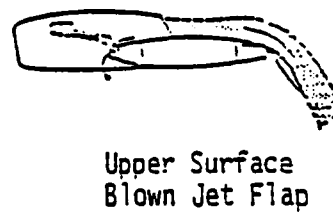
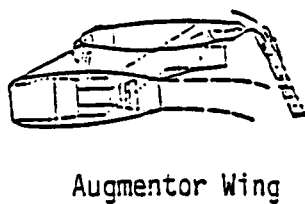
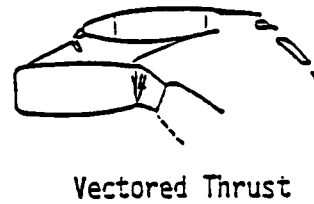
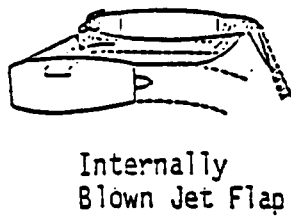
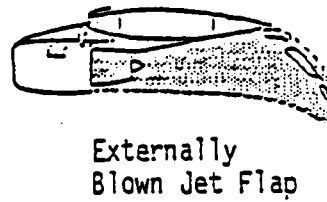
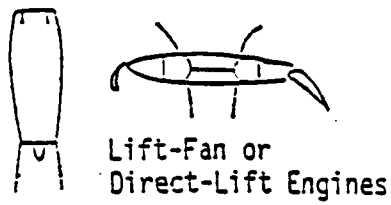


Figure 1. Examples of Powered-Lift Concepts

Source: Peter U. Solies, "A Study of the Flow Field about an Upper Surface Blown Wing and its Effect on Longitudinal Static Stability of a Small Jet Aircraft", Ph. D Dissertation, The University of Tennessee Space Institute, Tullahoma, TN, 1985.

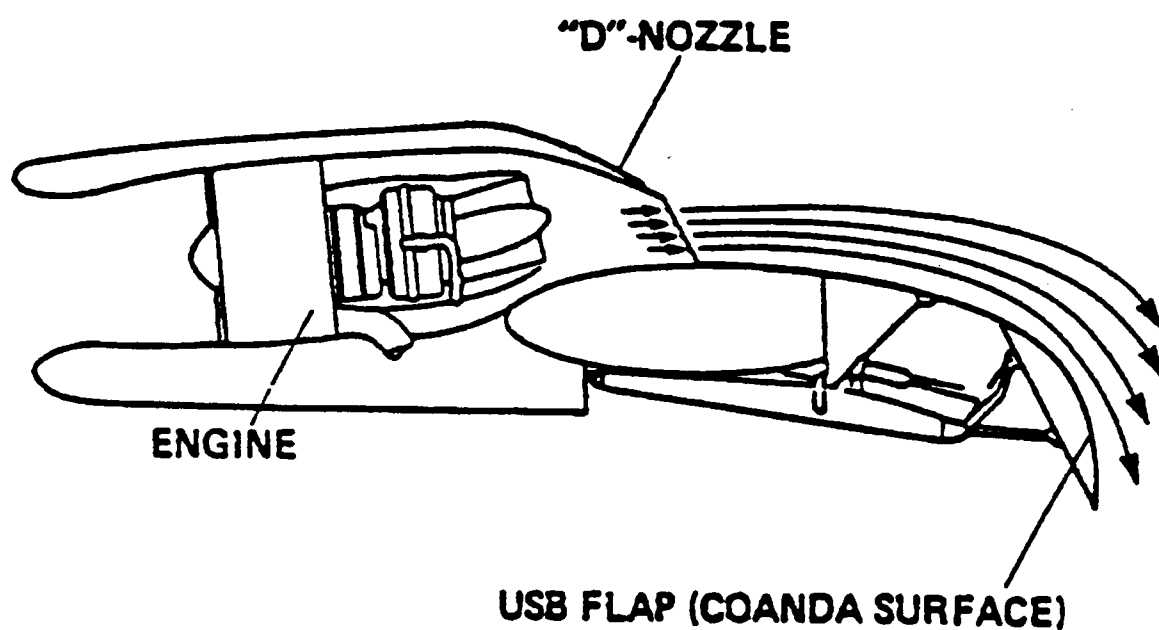


Figure 2. Upper Surface Blown Flap Concept

Source: Leonard Robert and Wallace Deckert, "Recent Progress in VSTOL Technology", NASA Technical Memorandum 84238, August, 1982.

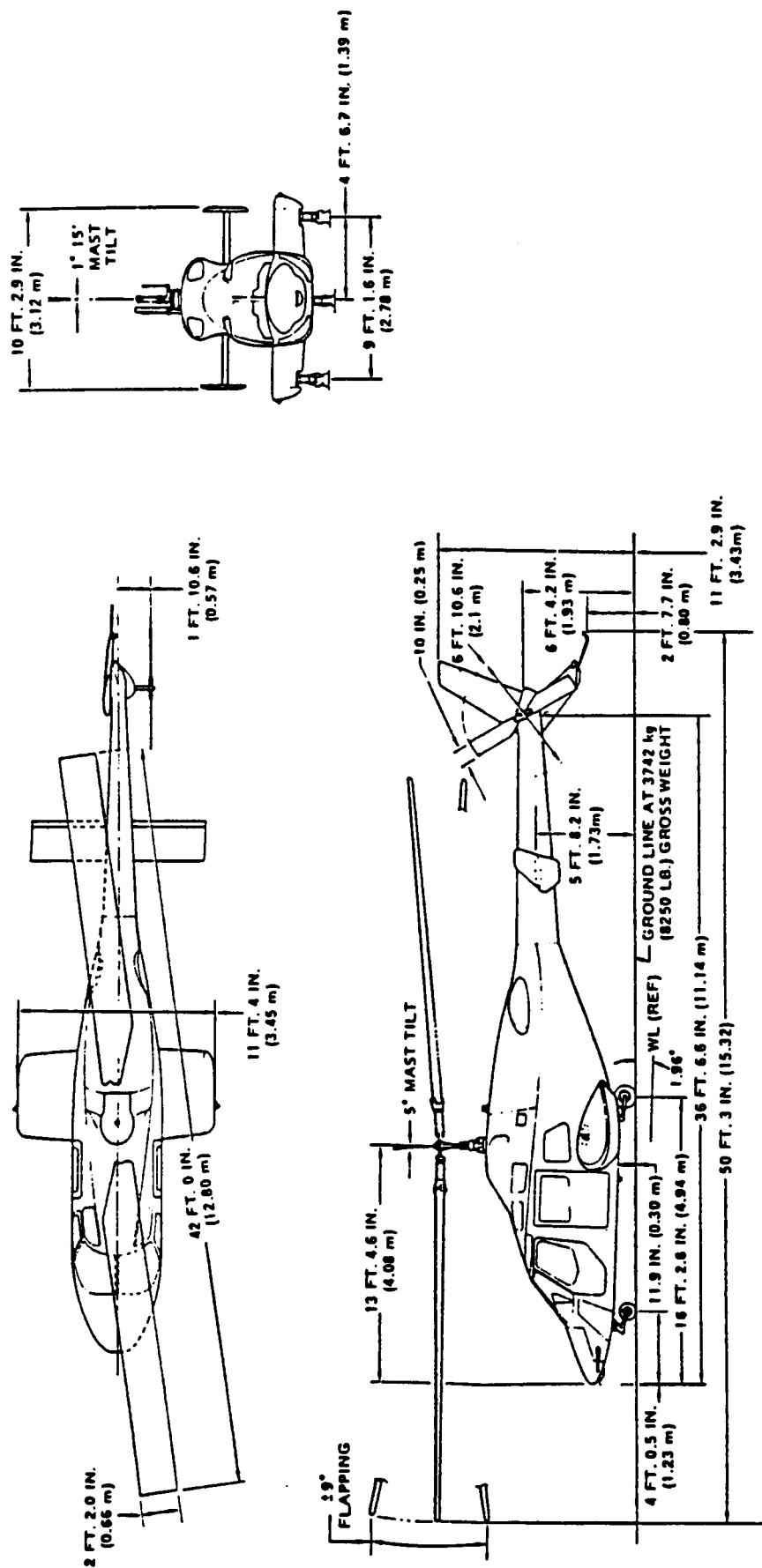


Figure 3. The BELL 222B Helicopter

Source: W. Z. Stepniewski and C. N. Keys, "Rotary-Wing Aerodynamics",
Dover Publications, Inc., Mineole, NY, 1979.

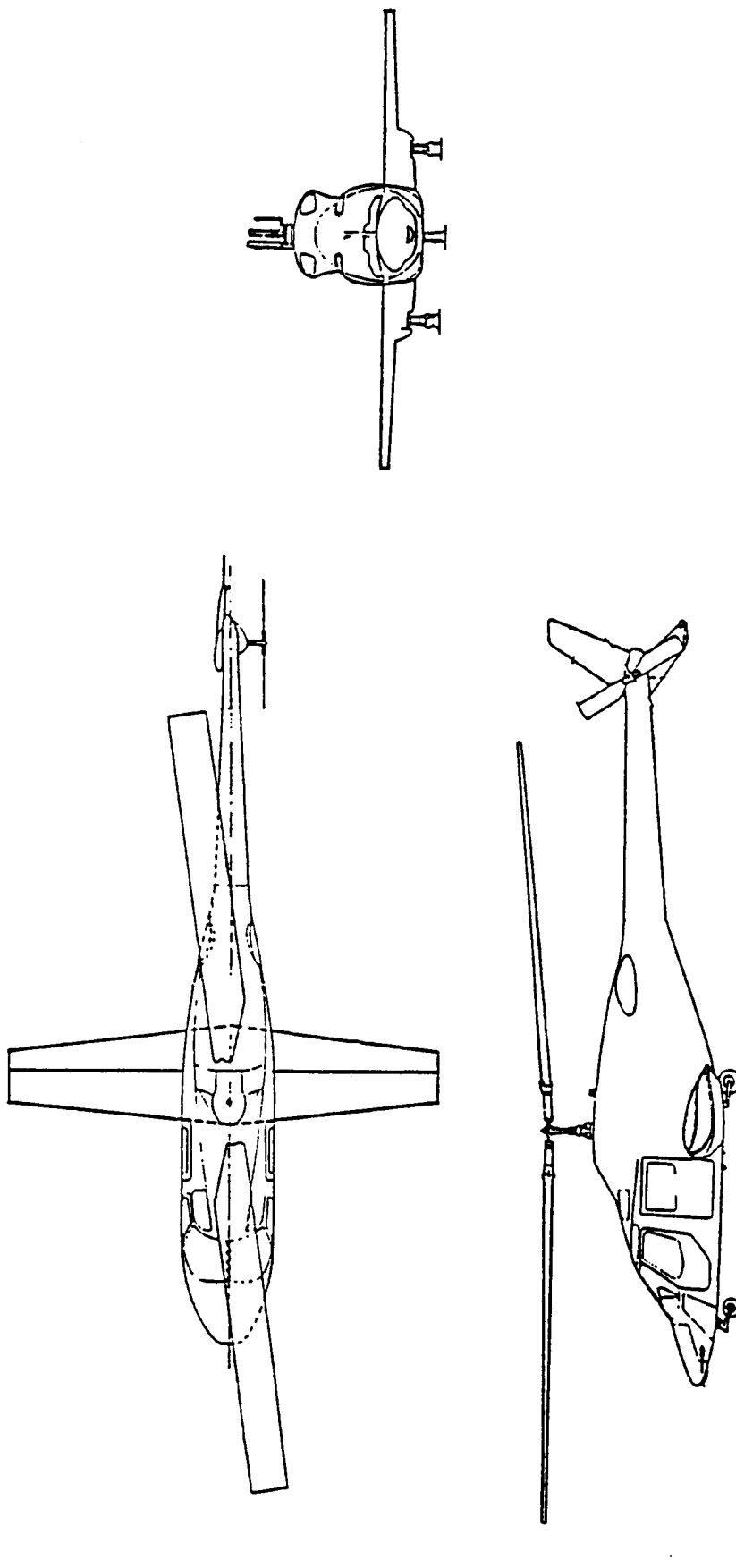


Figure 4. Hypothetical Winged Helicopter

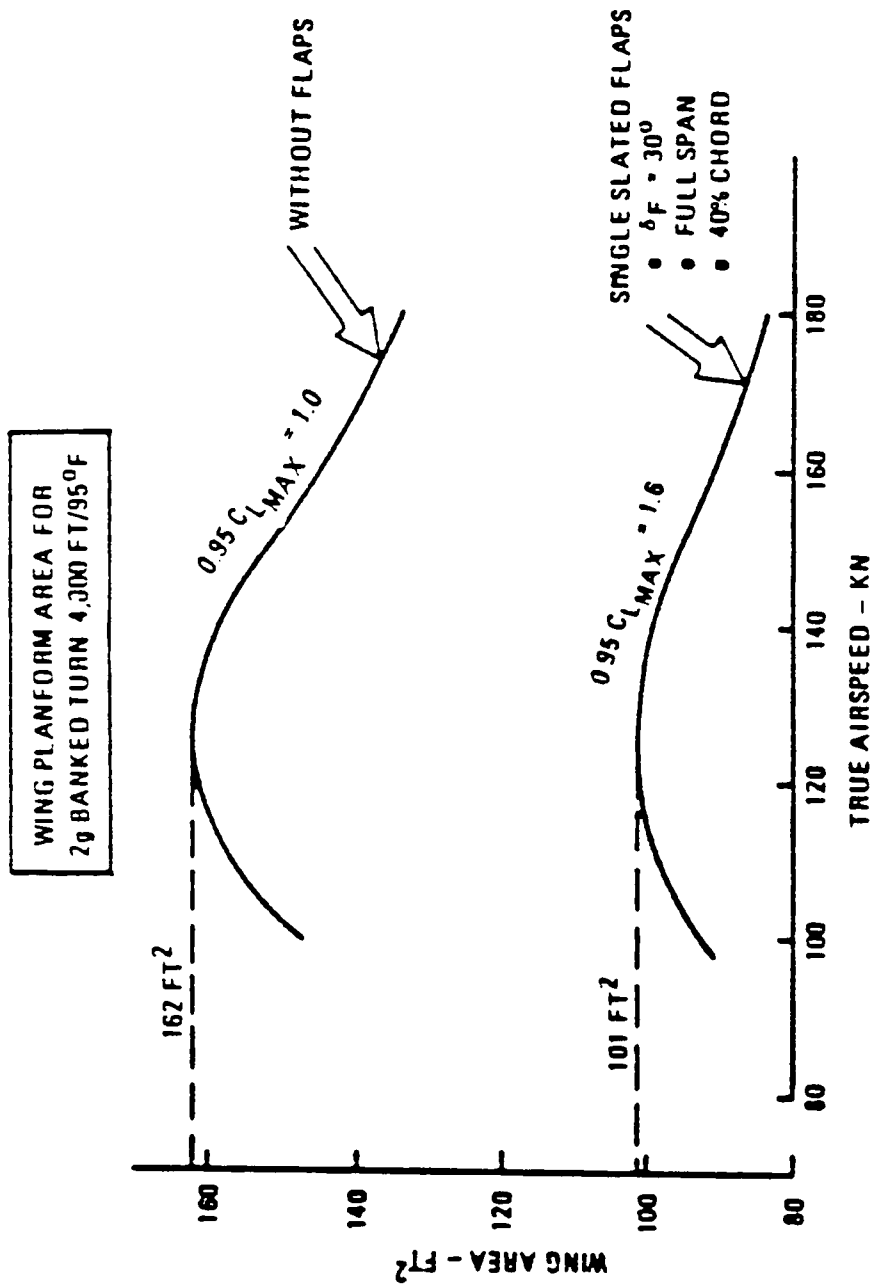


Figure 5. Winged Helicopter Maneuver Capability

Source: Stepniewski and Keys, 1979

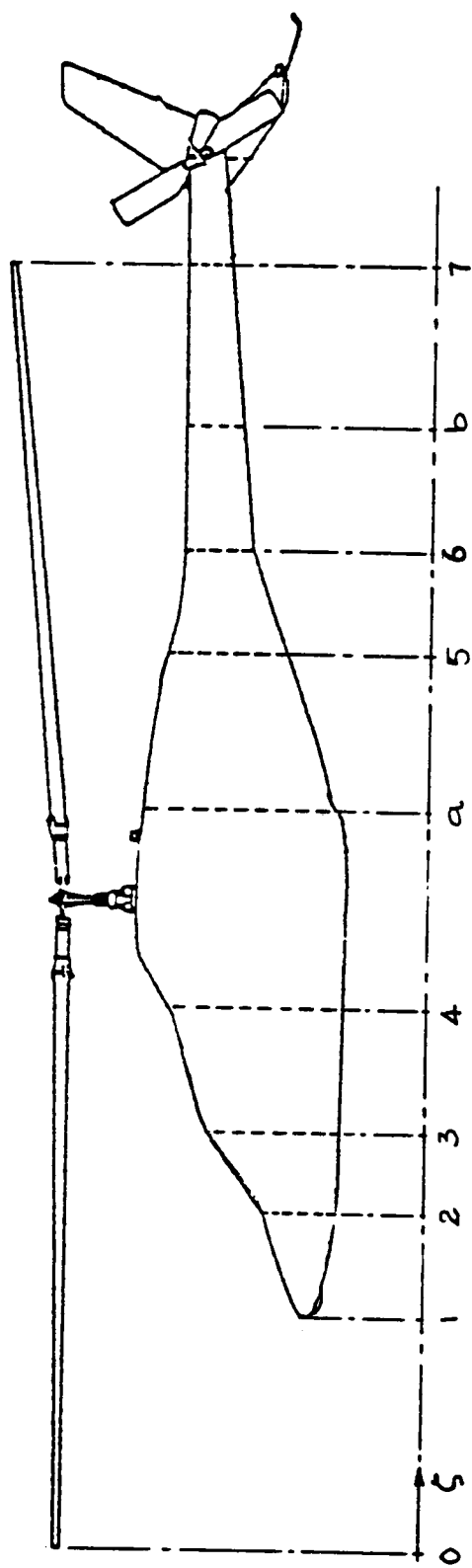


Figure 6. Fuselage Segments Stations

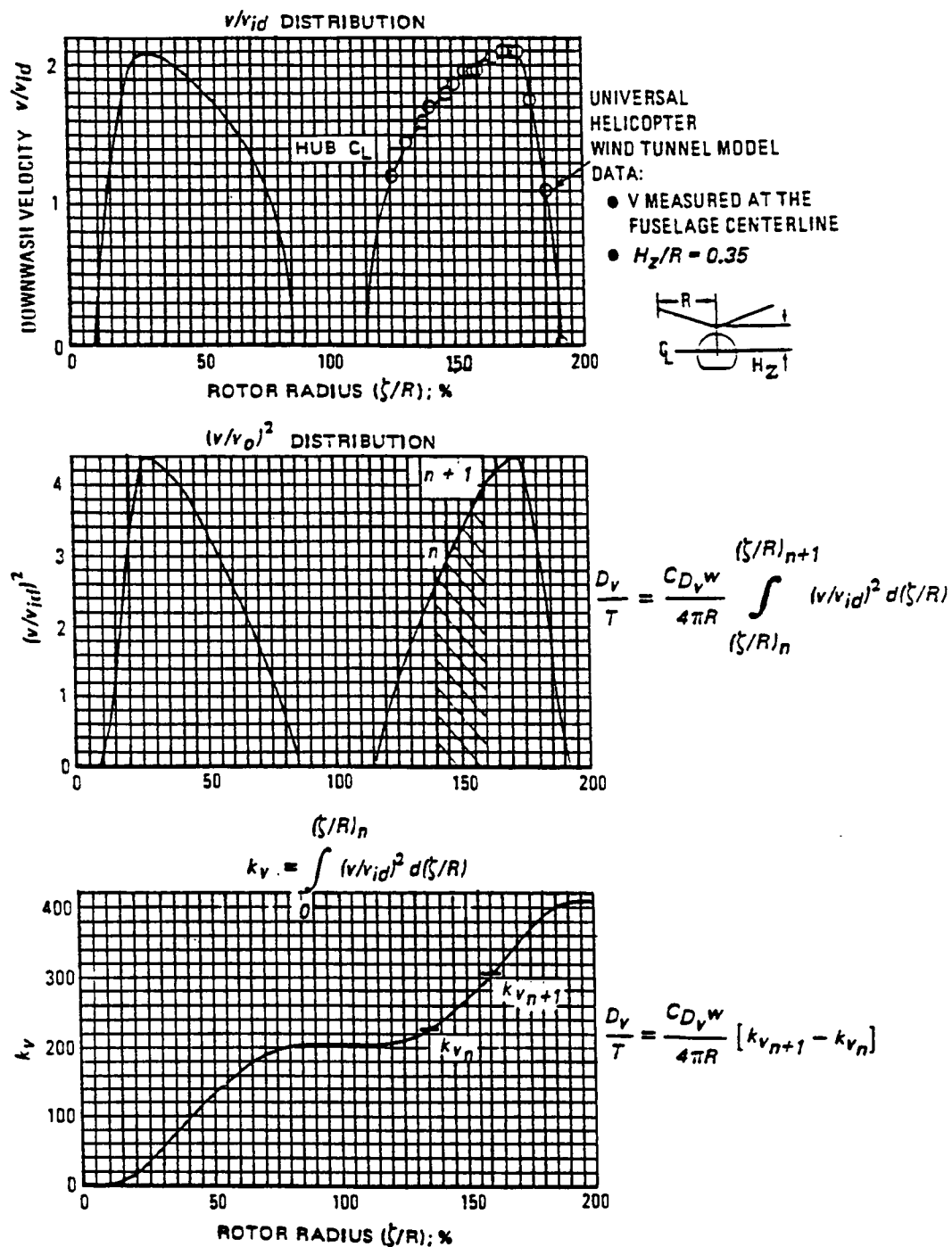
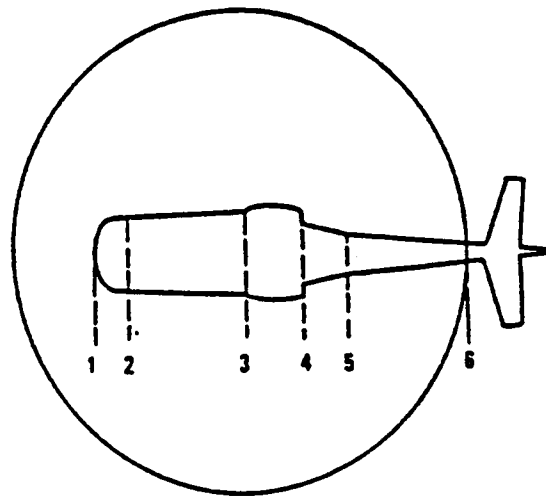


Figure 7. Hover Downwash Velocity Distribution

Source: Stepniewski and Keys, 1979.



SECTION	SHAPE	C_{D_v}
1-2 COCKPIT		0.5
2-3 CABIN		0.4
3-4 ENGINE NACELLE		1.2
4-5 AFTERBODY		0.5
5-6 TAIL CONE		0.5

Figure 8. Hypothetical Helicopter Vertical Drag Coefficients

Source: Stepniewski and Keys, 1979.

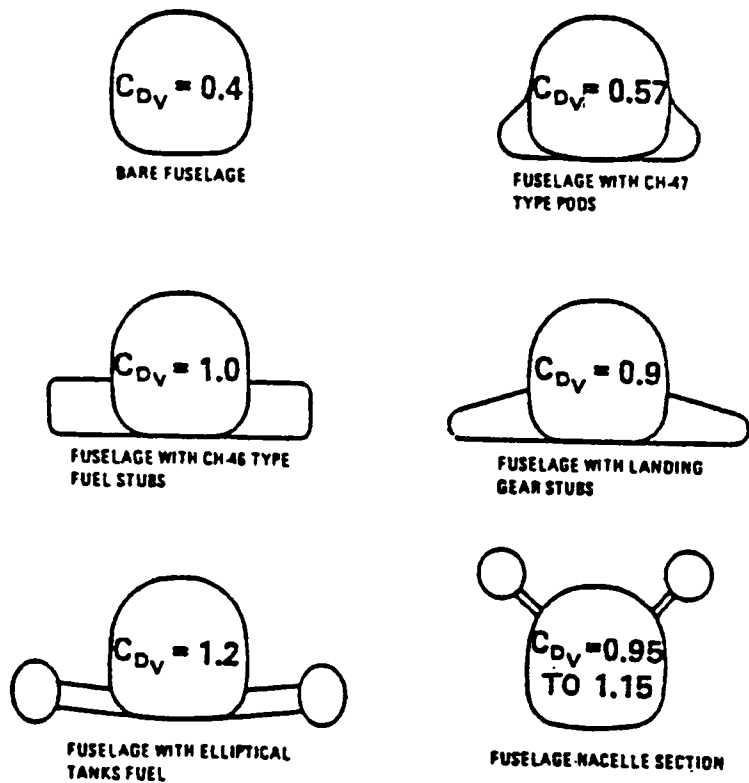


Figure 9. Typical Helicopter Fuselage Section Vertical Drag Coefficients

Source: Stepniewski and Keys, 1979.

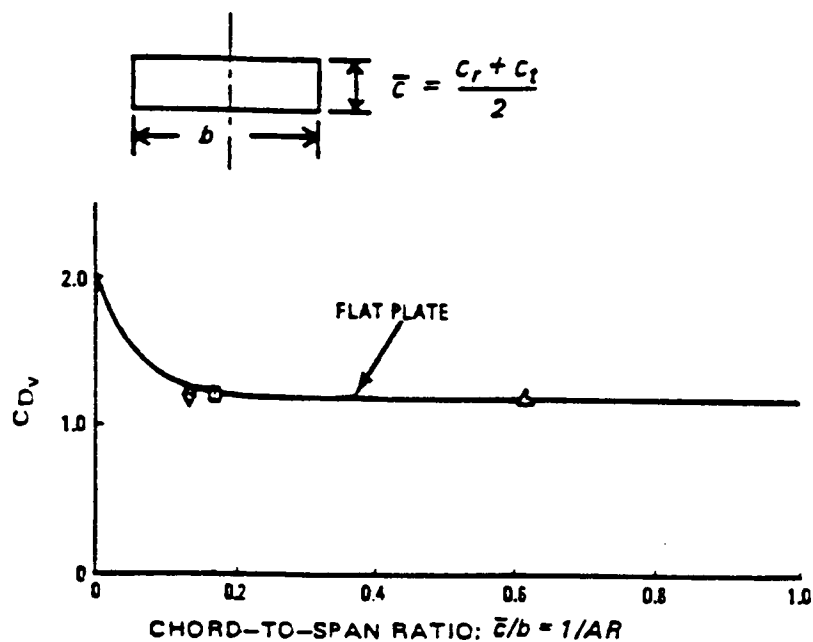


Figure 10. Effect of Wing Aspect Ratio on C_{Dv}

Source: Stepniewski and Keys, 1979.

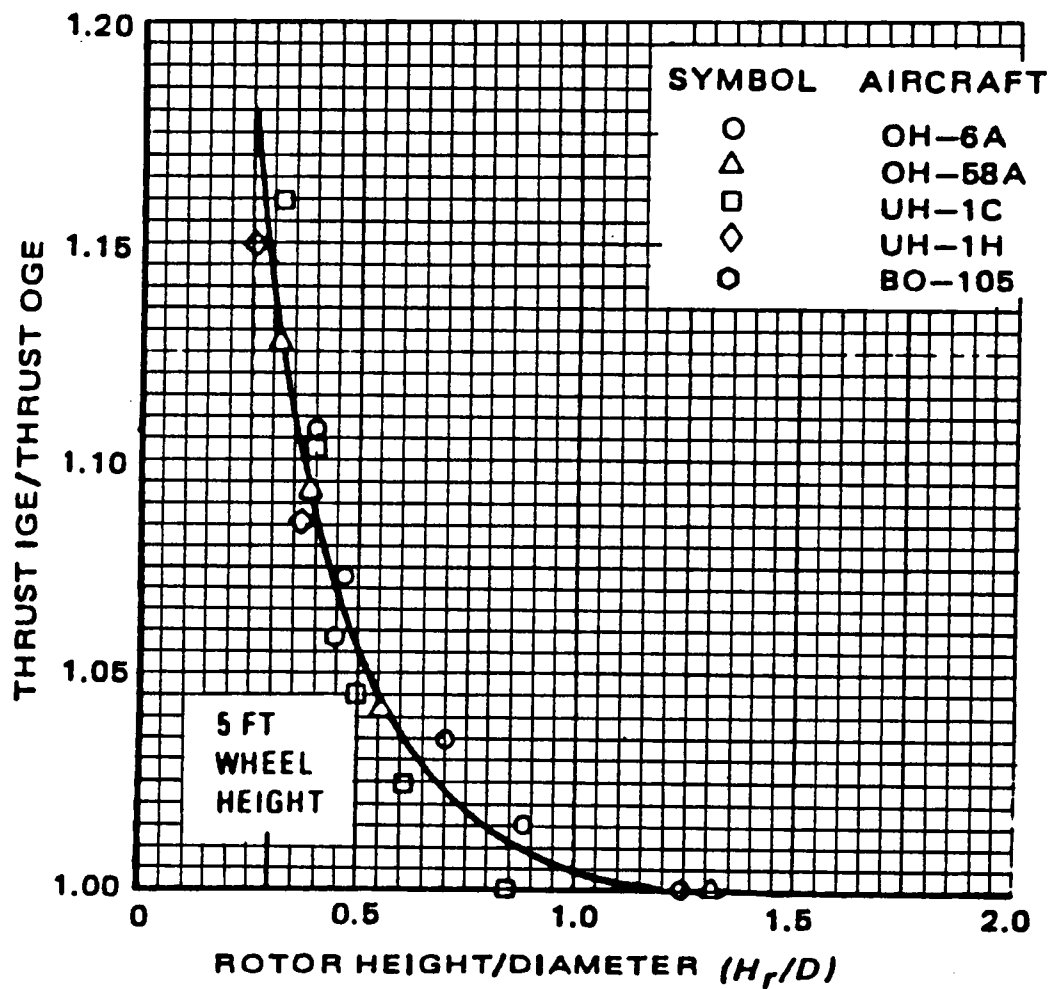


Figure 11. Thrust Variation in Ground Effect at Constant Power.

Source: Stepniewski and Keys, 1979.

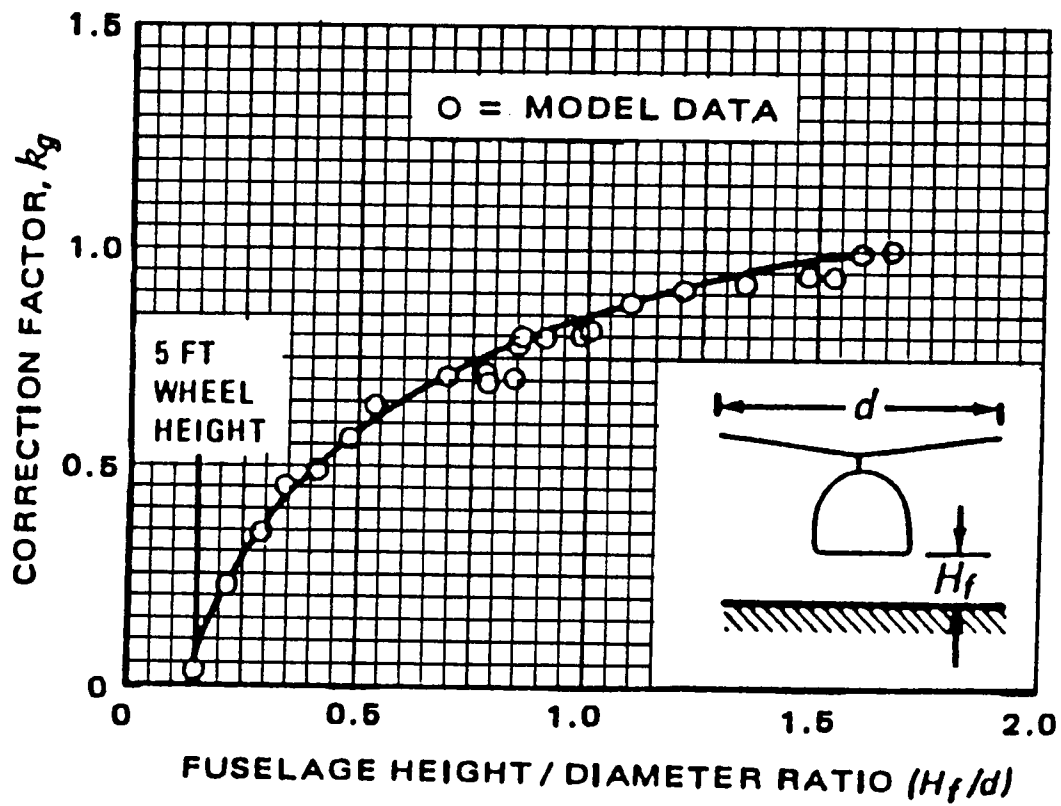


Figure 12. Effect of Ground Proximity on Hover Download Correction Factor, k_g

Source: Stepniewski and Keys, 1979.

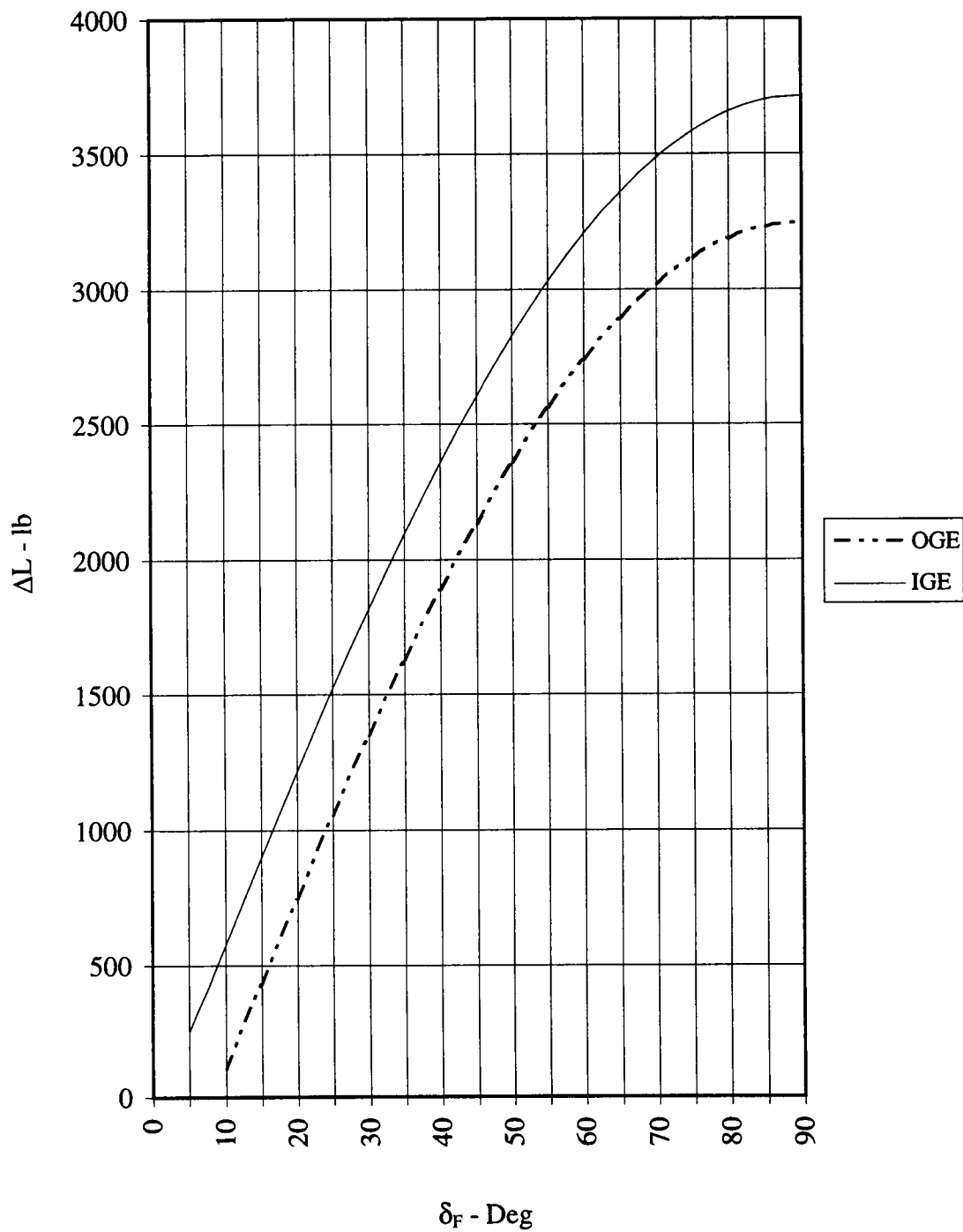


Figure 13. Additional Lift vs. Flap Deflection Angle

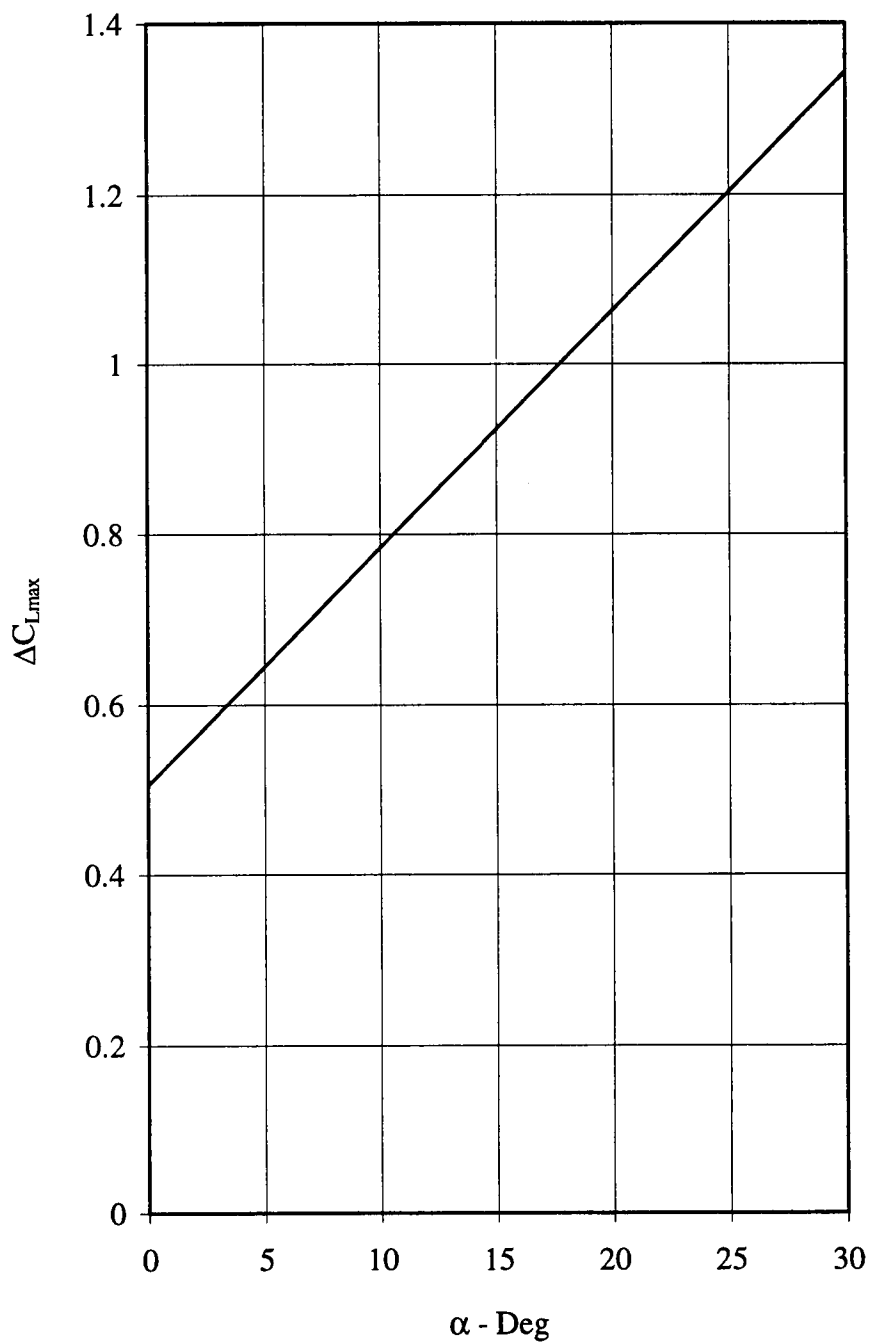


Figure 14. Change in Maximum Lift Coefficient vs. Angle of Attack
 $C_J = 0.45, \delta = 15^\circ$

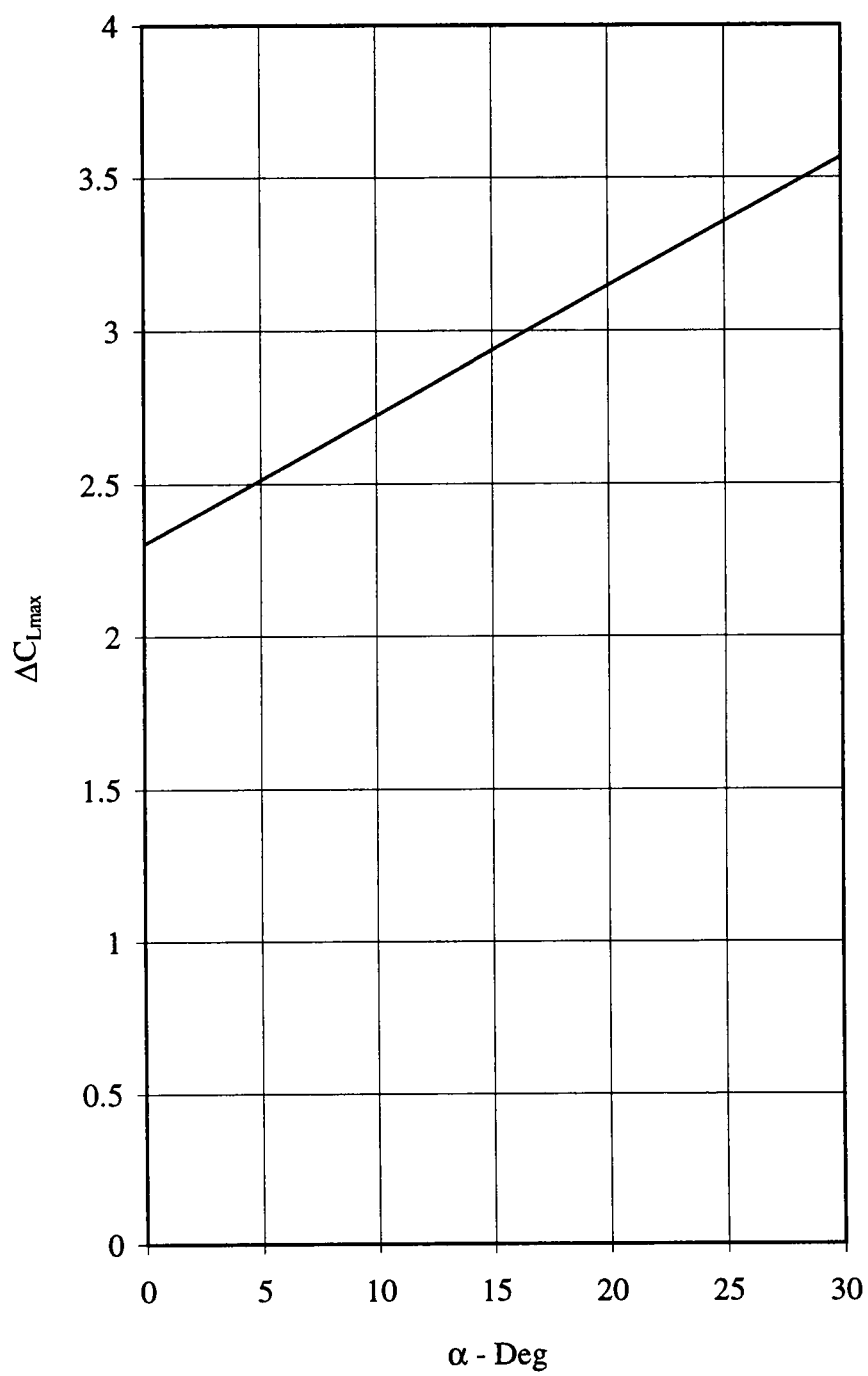


Figure 14 (continued). $C_I = 0.75$, $\delta = 45^\circ$

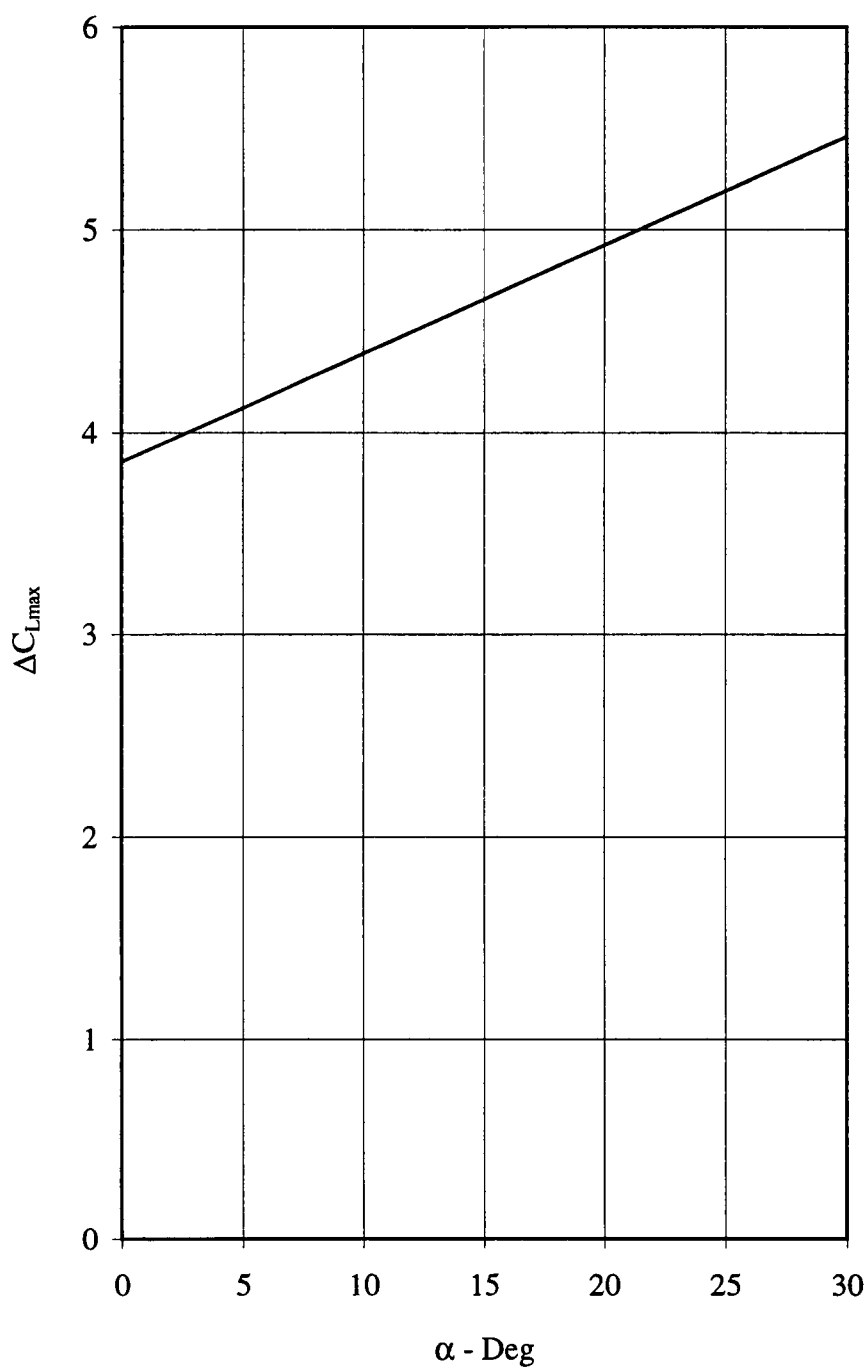


Figure 14 (continued). $C_J = 1.0$, $\delta = 60^\circ$

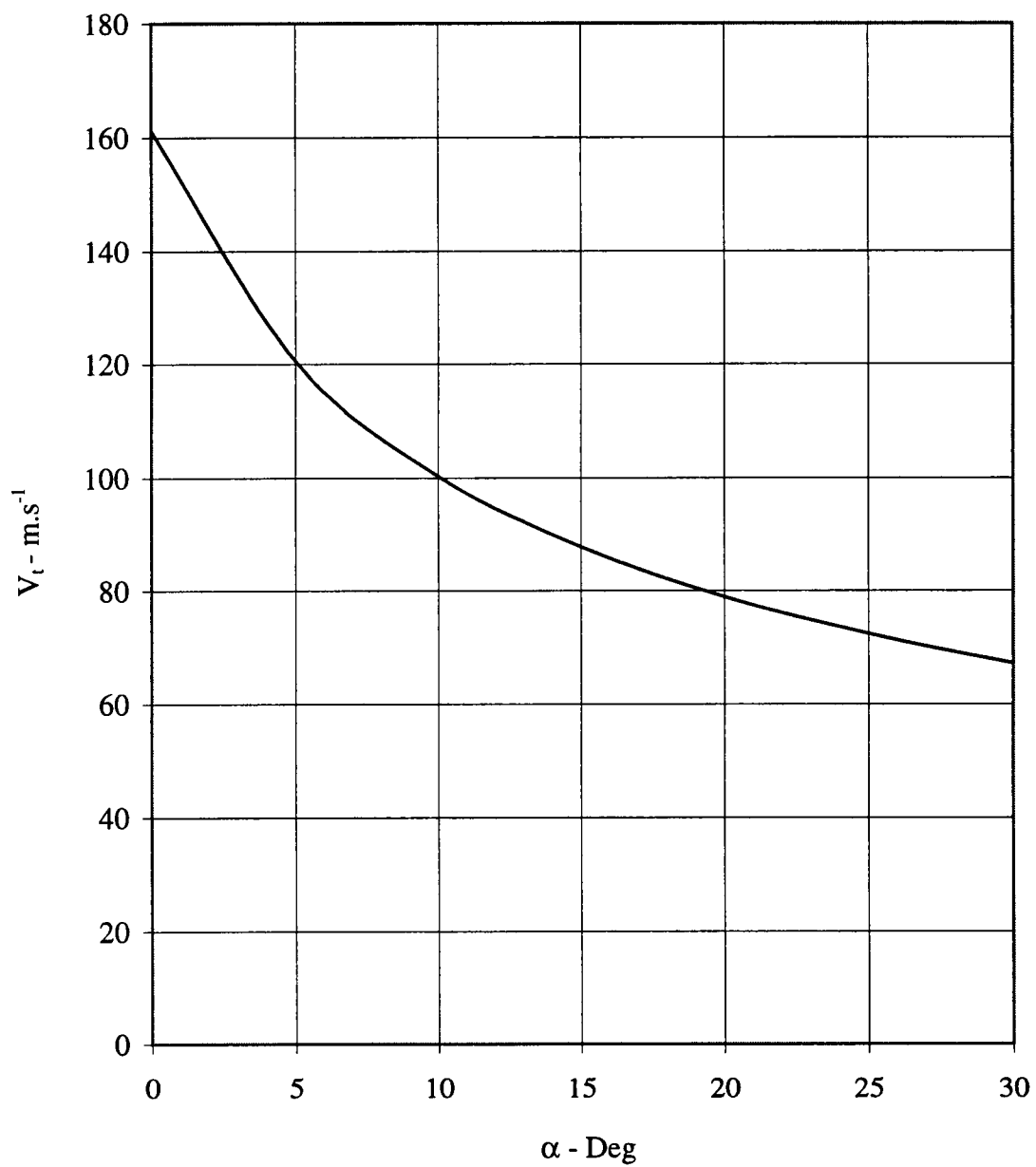


Figure 15. Blade Tip Speed vs. Angle of Attack
 $\delta = 15^\circ$, $C_l = 0.45$, $W = 10,000 \text{ lb}$

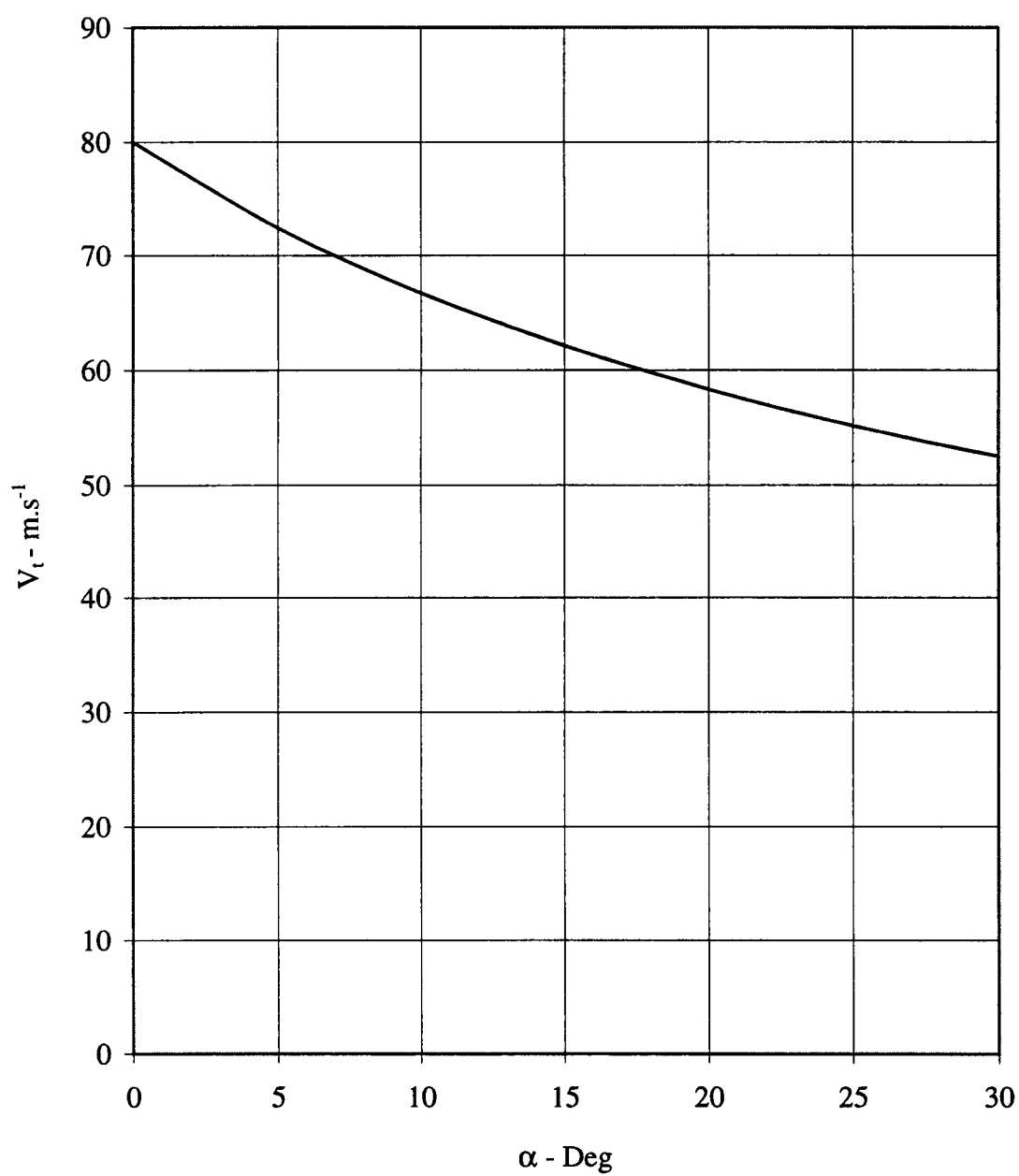


Figure 15 (continued). $\delta = 45^\circ$, $C_j = 0.75$, $W = 10,000$ lb

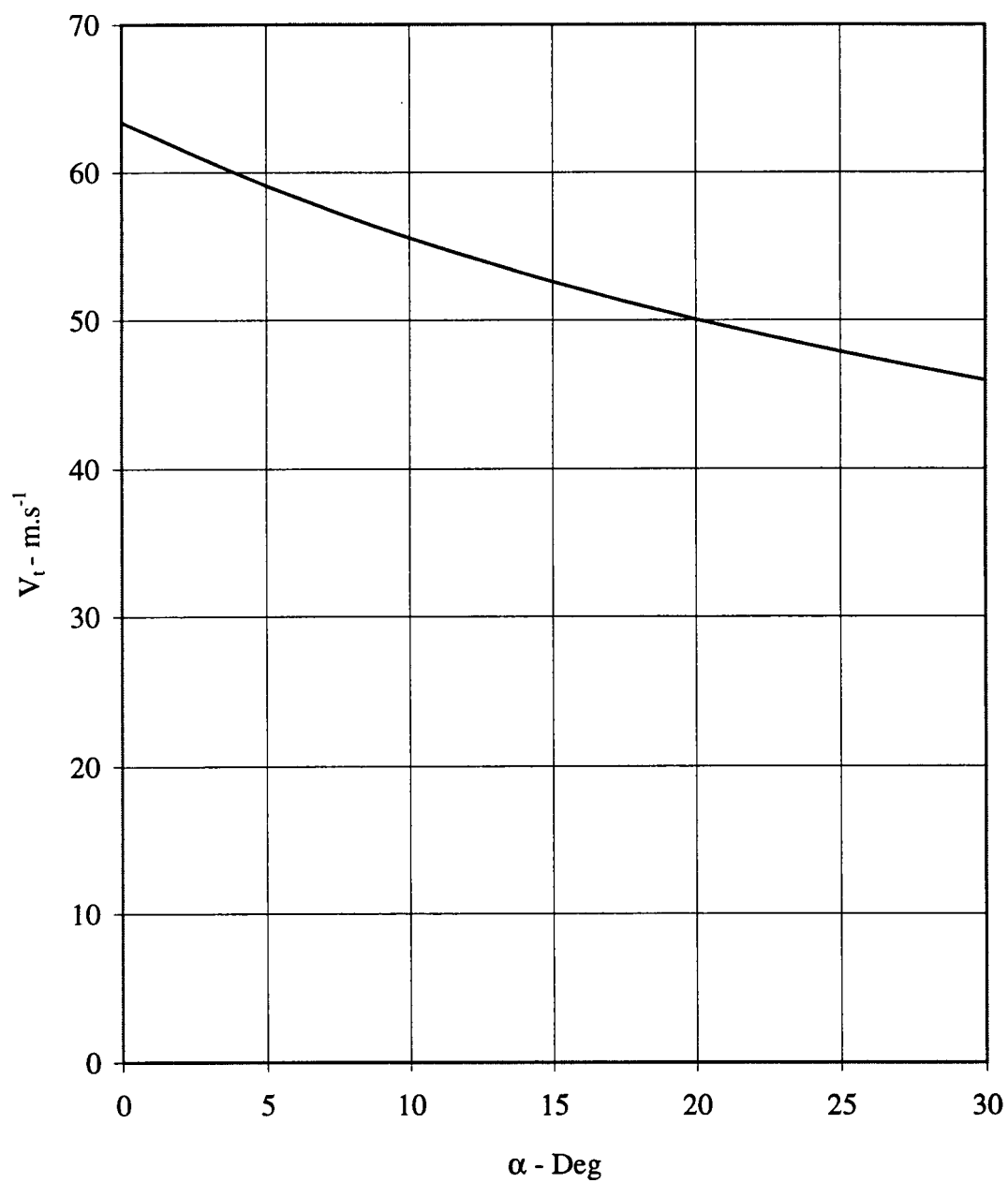
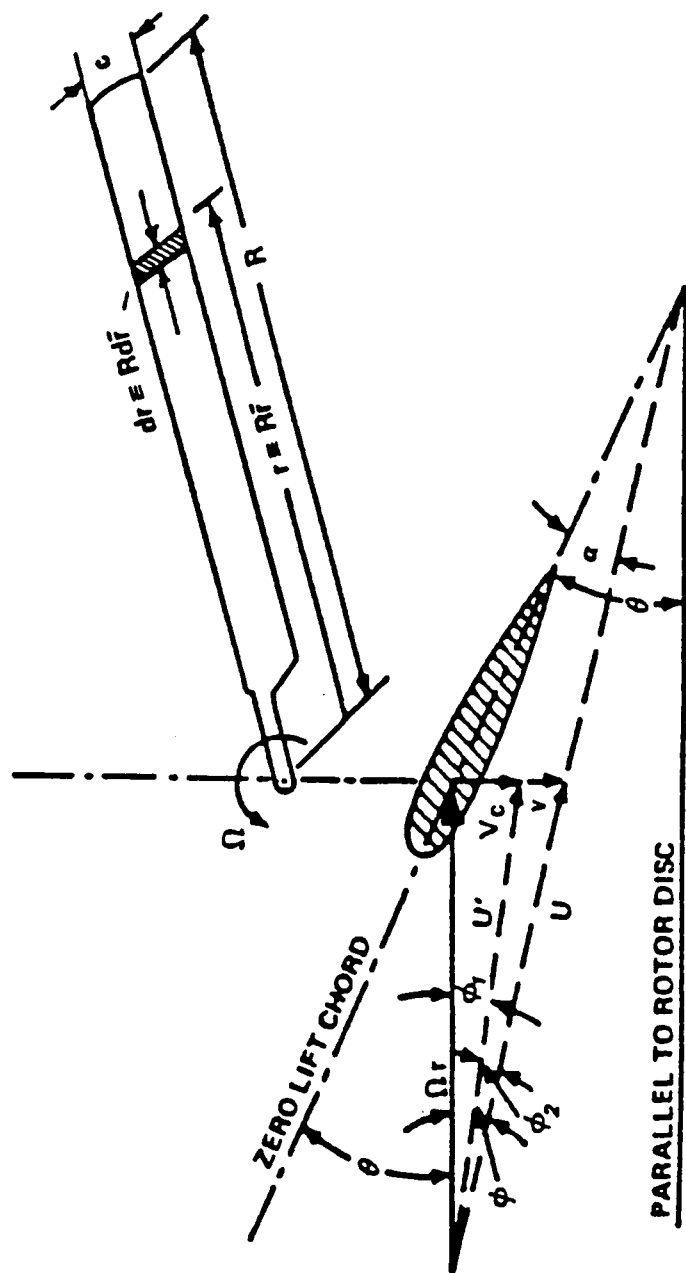


Figure 15 (continued). $\delta = 60^\circ$, $C_I = 1.0$, $W = 10,000$ lb



NOTE: THE BLADE ELEMENT IS SHOWN STATIONARY WHILE THE AIR FLOWS PAST IT

Figure 16. Blade Element Concept

Source: Stepniewski and Keys, 1979.

VITA

Melagne Timothée Yed was born on May 5, 1963, in Dabou, Côte d'Ivoire. He completed his elementary education in south Côte d'Ivoire schools, and graduated from Bingerville Modern High School in July 1984. He enrolled the National University of Abidjan, Côte d'Ivoire, in October 1984, and graduated four years later with a Bachelor of Science degree in Electro-mechanical Engineering. In October 1992, Melagne T. Yed was admitted at the University of Tennessee at Martin, Tennessee, as a post-baccalaureate student. Then, in August 1994, he enrolled the University of Tennessee Space Institute at Tullahoma, Tennessee. There, he earned his Master of Science degree in Aerospace Engineering in May 1996. Upon graduation, Melagne T. Yed has been offered a summer internship at International Telecommunication Satellite (INTELSAT) where he expects to improve his professional abilities.