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EFFECT OF TURBULENT JET MIXING ON THE STATIC LIFT PERFORMANCE O--ETC(U)
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EFFECT OF TURBULENT JET MIXING ON THE STATIC LIFT PERFORMANCE OF A POWER-AUGMENTED-RAM WING

by

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DTNSRDC ASED-389

September 1977

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
BETHESDA MARYLAND 20084

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
(14) DTNSRDC/ASED-389 ✓

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
(6) EFFECT OF TURBULENT JET MIXING ON THE STATIC LIFT PERFORMANCE OF A POWER AUGMENTED RAM WING

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
(10) William J. H. Smithey, Basil S. Papadales, Jr. and Harvey R. Chaplin

8. CONTRACT OR GRANT NUMBER(s)
(16) SSH15

9. PERFORMING ORGANIZATION NAME AND ADDRESS
David W. Taylor Naval Ship R&D Center
Bethesda, Maryland 20084 ✓

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Program Element 63534N
(17) Task Area SSH15002
Work Unit 1612-008

11. CONTROLLING OFFICE NAME AND ADDRESS
Commander
David W. Taylor Naval Ship R&D Center
Bethesda, Maryland 20084

12. REPORT DATE
(11) Sep[redacted] 1977

13. NUMBER OF PAGES
17

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
(12) 18p.

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Ground Effect
Ram Wing
Powered Lift
Power Augmented Ram Wing
Turbulent Jet Mixing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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S/N 0102-LF-014-6601

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

387 695

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D_r	Drag per unit span
h	Height of wing bottom surface above ground plane
L	Lift per unit span
M	Momentum of the flow
P	Absolute pressure
P_a	Ambient pressure
P_c	Pressure difference at the chord
Q	Mass flux of the flow
q	Dynamic pressure
r	Radial coordinate for the axisymmetric jet
t	Thickness of the stream
$\bar{t}$	Average stream thickness at the wing leading edge
U	Flow velocity
x,y	Coordinate dimensions
β	Angle of the flow over the wing
η	Turbulent jet profile similarity parameter
θ	Angle of the jet
ρ	Density of the fluid
σ	Empirical constant

Subscripts

o	Flow condition at the jet origin
1	Flow condition approaching the wing
2	Flow condition at the flap trailing edge
3	Flow condition over top of wing
4	Condition of reverse flow from ground reaction
5	Flow condition under the wing
A	Flow associated with the axisymmetric jet
AIR	Flow in free air
S	Flow associated with the stagnation streamline
SURFACE	Flow along ground plane

Special Symbols

$( )'$	Indicates dimension along a streamline
$(\bar{\ })$	indicates average values

ABSTRACT

Calculation procedures are developed using axisymmetric and two-dimensional turbulent jet theory for predicting the static lift performance of a two-dimensional power-augmented-ram wing. The resulting lift prediction is found to be in good agreement with experimental data.

ADMINISTRATIVE INFORMATION

This investigation was authorized and funded by the Naval Air Development Center under Project SSH15, Program Element 63534N, and Work Unit 1-1612-008.

INTRODUCTION

The static lift and drag performance problem for a two-dimensional power-augmented-ram wing has been solved using incompressible potential flow theory.[1,2] However, to obtain good lift correlation with three-dimensional experimental data,[*] it has been necessary to extend the potential flow theory by including the effect of turbulent jet mixing. The turbulent mixing theory is used to calculate an equivalent potential flow under the wing so that the formulas developed from potential theory may be used to calculate lift and drag.

DEVELOPMENT

In Figure 1, the two dimensional jet is shown reacting with the ground at ambient pressure P_a to provide momentum M_1 flowing toward the

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[1] Gallington, R.W., "Sudden Deceleration of a Free Jet at the Entrance of a Channel," DTNSRDC Departmental Report ASED 350 (Jan 1976).

[2] Gallington, R. W. and H. R. Chaplin, "Theory of Power Augmented Ram Lift at Zero Forward Speed," DTNSRDC Departmental Report ASED 365 (Feb 1976).

*Reported informally by F. H. Krause and R. W. Gallington ("Static Performance of a Power Augmented Ram Wing," DTNSRDC ASED TM-16-76-76, May 1976).

ram wing with height h, chord C, and flap height t_2. Conserving horizontal momentum in the ground reaction

$$M_1 = M_o \cos\theta + M_4 \qquad (1)$$

But if total scalar momentum is conserved in the reaction, $M_4 = M_o - M_1$. Thus from equation (1)

$$M_1/M_o = (1 + \cos\theta)/2 \qquad (2)$$

With a turbulent jet, it is assumed that the velocity profile is "frozen" during the ground reaction and this same result is obtained.

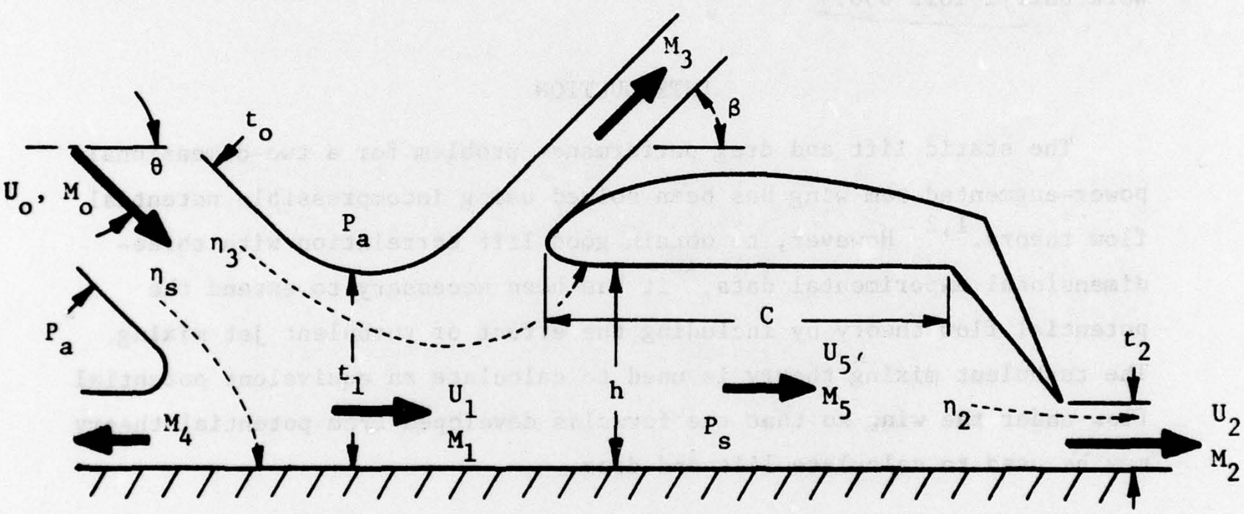

Figure 1 - Momentum Flux Model

When the duct flow under the wing is filled, part of the flow will go over the wing at angle β. Assuming the flow under the wing is thoroughly mixed so that the pressure and velocity are uniform, one may write a horizontal momentum balance

$$P_c h = (P_5 - P_a)h = M_1 - M_3 \cos\beta - \rho U_5^2 h \qquad (3)$$

Assuming U_2 is uniform, one may write a horizontal momentum balance under the wing and along the flap

$$P_c h = U_2^2 t_2 - U_5^2 h + D_r \qquad (4)$$

where D_r is drag due to the flap, $D_r = \int_{t_2}^{h} (P-P_a)dy$.

Further, by assuming the flow under the wing is one dimensional, one may write the energy equation

$$P_c h = \tfrac{1}{2}\rho U_2^2 h[1 - (U_5/U_2)^2] \qquad (5)$$

Using $(U_5/U_2) = (t_2/h)$ from continuity and $M_2 = \rho U_2^2 t_2$, Equation (5) becomes

$$P_c h = \tfrac{1}{2}M_2[h/t_2 - t_2/h] \qquad (6)$$

From Equation (4)

$$D_r = \tfrac{1}{2}M_2[h/t_2 + t_2/h - 2] \qquad (7)$$

The lift of the wing is $L \doteq P_c C$. Using Equations (6) and (7), one may form simplified dimensionless ratios for comparison with experimental data

$$\frac{Lh}{M_1 C} = \tfrac{1}{2}\frac{M_2}{M_1}[h/t_2 - t_2/h] \qquad (8)$$

$$\frac{D_r}{M_1} = \tfrac{1}{2}\frac{M_2}{M_1}[h/t_2 + t_2/h - 2] \qquad (9)$$

From Equations (8) and (9) it is clear that the flap position t_2 and the ratio t_2/h substantially control the lift and drag of the power-augmented-ram wing at zero airspeed. As long as t_2/h is small, the duct under the wing remains filled and some of the flow will be lost over the top of the wing as $M_3\cos\beta$, shown in Equation (3). As $(t_2/h) \rightarrow 1$ the duct may become underfilled and rapidly lose lift. This occurs when the jet is thin and has not entrained sufficient mass to stagnate near the leading edge and fill the duct. In effect, when the duct is underfilled, the jet streams under the wing at ambient pressure and practically no lift is generated. The effect of turbulent mixing is included by using a two dimensional turbulent jet velocity profile[3] to describe the flow from the jet origin to the wing. Using ( )' coordinates along and normal to the centerline,

$$U' = [3t_o U_o^2 \sigma/4x']^{\frac{1}{2}}[1 - \tanh^2\eta] \qquad (10)$$

$$\eta = \sigma y'/x' \qquad (11)$$

where σ is an empirical constant, $\sigma = 7.67$, and t_o is the thickness of the jet at its origin where it has uniform velocity $U'_o = U_o$. The normal component of velocity is neglected in these calculations. Since the stagnation streamline in the ambient pressure ground reaction will divide the flow into M_1 and M_4, one may use Equation (10) to write

$$M_1/M_o = (1/M_o)\int_{\eta_s}^{\infty} \rho U'^2 dy' = (3/4)[2/3 - \tanh\eta_s + (1/3)\tanh^3\eta_s] \qquad (12)$$

Substituting Equation (12) into (2)

$$3\tanh\eta_s - \tanh^3\eta_s + 2\cos\theta = 0 \qquad (13)$$

This equation may be easily solved numerically for $-1 \leq \tanh\eta_s \leq 0$, where $0 \geq \theta \geq -\pi/2$, by using the Newton-Raphson method with $3\tanh\eta_{s_1} = -2\cos\theta$ for the first approximation. Having solved for $\tanh\eta_s$, one may now

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[3] Schlichting, H., "Boundary Layer Theory," 4th ed., 1960, McGraw-Hill, New York, pp. 605-611.

write the equation for mass flux Q_1 flowing toward the wing.

$$Q_1/Q_o = (1/Q_o)\int_{\eta_s}^{\infty} \rho U' dy' = [3x'/4t_o\sigma]^{1/2}[1-\tanh\eta_s] \quad (14)$$

Similarly, one finds the total mass flux approaching the ground, i.e., immediately before the ground reaction so that $\tanh\eta_s = -1$, is given by

$$Q/Q_o = [3x'/t_o\sigma]^{1/2} = 0.6254[x'/t_o]^{1/2}$$

To obtain good correlation with the experimental data, it was necessary to assume that when $t_2/h \to 0$ the flow under the wing comes from the Q_1 flow with the highest energy, i.e., about $\eta = 0$ since from Equation (10) this is the maximum velocity available. When one considers that the actual flow toward the wing was generated by one, two or three fans during the experiment, where the flow expands to form a quasi-two-dimensional jet,[4] then it appears correct that the greater inertia of the flow about each core should cause the highest energy stream tubes to spread and form a sheet along the ground with lower energy flow displaced above in sheets of decreasing energy. Thus the momentum and mass flux of the quasi-two-dimensional jet, which is assumed for the ambient pressure momentum balance and for calculating the flow under the wing, should be equal to the momentum and mass flux calculated at the ground plane for the axi-symmetric turbulent jets from the fans.

The equations for the turbulent axisymmetric jet calculation are

$$U'_A = (3/4)^{1/2}\, \sigma_A U_o D/(4 + \eta_A^2)^2\, x'_A \quad (15)$$

$$\eta_A \Rightarrow \sigma_A r'/x'_A \quad (16)$$

---

[4]Knystautas, R., "The Turbulent Jet from a Series of Holes in Line," The Aeronautical Quarterly, Vol. XV (Feb 1964) pp. 1-28.

where D is the diameter of the jet at its origin where it has uniform velocity $U'_o = U_o$ and $\sigma_A = 15.174$. Again, the radial component of velocity is neglected. Forming the axisymmetric mass flux integral

$$Q_A/Q_o = (1/Q_o)\int_o^\infty 2\pi\rho U'_A r'dr' = 0.4566x'_A/D \qquad (17)$$

Since the pressure is ambient throughout the jet, $M_A = M_o = (\pi/4)\rho D^2 U_o^2$. From $Q/Q_o = 0.6254[x'/t_o]^{1/2}$ and Equation (17), the mass flux ratio is taken as 1 until $x'_A = 2.19D$ or $x' = 2.56t_o$. Beyond these critical values, the entrainment process increases mass flux until restricted by the ground. This can be seen in Figure (1), where the two-dimensional flow, M_1, can only entrain from above.

Using average values, $(\bar{\ })$,

$$(\bar{t}/t_o) = (Q/Q_o)^2/(M/M_o) \qquad (18)$$

is the thickness of the jet since $(Q/Q_o) = (U/U_o)(\bar{t}/t_o)$ and $(M/M_o) = (U/U_o)^2(\bar{t}/t_o)$. These average values, when properly formed, may be used to calculate the lift and drag ratios given by Equations (8) and (9), respectively. For a two-dimensional jet reaching the ground immediately ahead of the wing, the thickness will be

$$\bar{t} = 3x'/\sigma = 0.391x' \qquad (19)$$

Following Equations (13) and (11), the mass flux and momentum going over the wing will be

$$Q_3/Q_o = [3x'/4t_o\sigma]^{1/2}(1-\tanh\eta_3) \qquad (20)$$

$$M_3/M_o = [2 - 3\tanh\eta_3 + \tanh^3\eta_3]/4 \qquad (21)$$

Using this, the mass flux and momentum flowing under the wing may be readily found by subtracting

$$Q_2/Q_o = (U_2/U_o)(t_2/t_o) = (Q_1/Q_o) - (Q_3/Q_o) =$$

$$[3x'/4t_o\sigma]^{1/2}(\tanh\eta_3 - \tanh\eta_s) \tag{22}$$

$$M_2/M_o = (U_2/U_o)^2(t_2/t_o) =$$

$$[3\tanh\eta_3 - \tanh^3\eta_3 - 3\tanh\eta_s + \tanh^3\eta_s]/4 \tag{23}$$

Then, using Equations (19), (22) and (23) into (18)

$$t_2/\bar{t} = [\tanh\eta_3-\tanh\eta_s]^2/[3\tanh\eta_3-\tanh^3\eta_3-3\tanh\eta_s+\tanh^3\eta_s] \tag{24}$$

If the ratio of $h/\bar{t}$ is known

$$(t_2/h) = (t_2/\bar{t})/(h/\bar{t}) \tag{25}$$

may be used for calculating the lift and drag ratios of Equations (8) and (9). As mentioned earlier, the flow for small values of (t_2/h) should be calculated about $\eta = 0$; thus, Equation (24) is used for $\tanh\eta_3 \geq |\tanh\eta_s|$. Up to this condition, use

$$[Q_2/Q_o]^2 = [3x'/t_o\sigma]\tanh^2\eta_2 \tag{26}$$

and

$$M_2/M_o = [3\tanh\eta_2 - \tanh^3\eta_2]/2 \tag{27}$$

where $0 < \tanh\eta_2 < |\tanh\eta_s|$, to calculate $t_2/\bar{t}$.

The correct estimate of $h/\bar{t}$, used in Equation (25), is essential for good correlation with the experimental lift data. Since the lift is calculated as if the ambient pressure ground reaction occurred immediately ahead of the wing leading edge, one must determine an equivalent total mass flux and resulting $\bar{t}$ for a two-dimensional jet which matches the conditions of the experiment. From Equations (17) and (18), and using $M/M_o = 1$ immediately before the ground reaction, one may write the equivalent $\bar{t}$ for axisymmetric jets with spacing b assuming $t_o = \pi D^2/4b$,

$$\bar{t} = \pi(0.4566x)^2/(4b) = 0.164x^2/b \qquad (28)$$

Similarly, for the two-dimensional jet one finds

$$\bar{t} = (0.6254)^2 x = 0.391x \qquad (29)$$

These two equations for free air mixing are plotted in Figure (2) to give a simplified model of the entrainment process. The value of $\pi D^2/4b$ for $\bar{t}_A$ corresponds to $Q/Q_o = 1$ and is taken constant until $x = 2.19D$ where the axisymmetric entrainment formula, Equation (28), starts to increase $\bar{t}$. From this point, $\bar{t}$ is given by Equation (28) until $x = 2.38b$ where the axisymmetric jets have spread into a quasi-two-dimensional jet and equation (29) must be used. If the jet reacts with the ground ahead of the wing, some of the free air entrainment will be inhibited during the ground reaction so that $\bar{t}_A$ will only contribute about 0.8 its calculated value. Similarly, the entrainment during the ground run must be taken at 0.5 its calculated value since the two-dimensional jet along the ground can only entrain from above.

With the estimate of $\bar{t}$ from Figure (2) and h from the geometry of the experiment, one may calculate t_2/h and M_2/M_0 for various values of η using Equations (18) and (22) through (27) and in turn calculate a plot of Lh/M_1C versus t_2/h from Equation (8). Note that equations

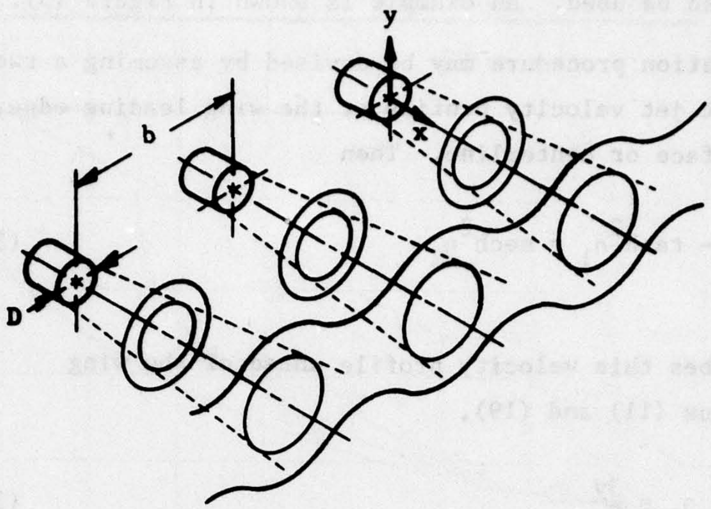


Figure 2a - Turbulent Mixing Model

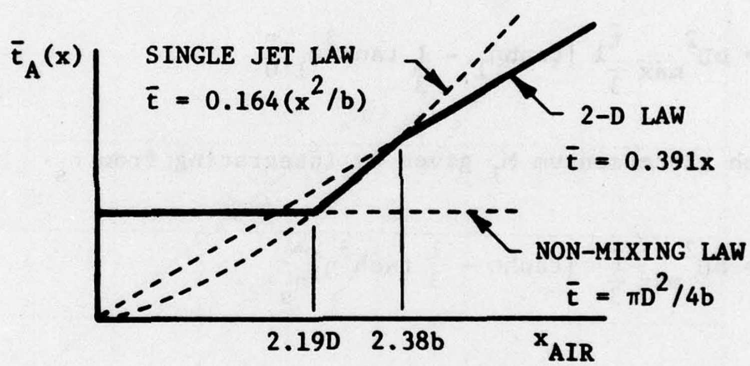


Figure 2b - In Free Air

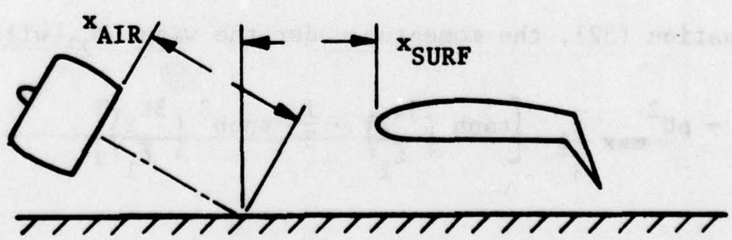


Figure 2c - In Ground Effect

Figure 2 - Summary of Turbulent Mixing

(2) and (13) must also be used. An example is shown in Figure (3).

A direct calculation procedure may be devised by assuming a two dimensional turbulent jet velocity profile at the wing leading edge, with U_{max} at the surface or centerline. Then

$$\frac{U}{U_{max}} = 1 - \tanh^2\eta_1 = \mathrm{sech}^2\eta_1 \qquad (30)$$

approximately describes this velocity profile ahead of the wing where, using Equations (11) and (19),

$$\eta_1 = \frac{3y}{\bar{t}_1} \qquad (31)$$

Using Equation (30), the momentum M_1 is

$$M_1 = \rho U^2_{max} \frac{\bar{t}_1}{3} \left[\tanh\eta_1 - \frac{1}{3}\tanh^3\eta_1\right]_0^\infty \qquad (32)$$

This must match the momentum M_1 given by integrating from η_s.

$$M_1 = \rho U^2_{max} \frac{\bar{t}}{3} \left[\tanh\eta - \frac{1}{3}\tanh^3\eta\right]_{\eta_s}^\infty \qquad (33)$$

Using Equation (13), one finds

$$\bar{t}_1 = (1 + \cos\,\theta)\,\bar{t} \qquad (34)$$

Following Equation (32), the momentum under the wing, M_2, will be

$$M_2 = \rho U^2_{max} \frac{\bar{t}_1}{3} \left[\tanh\left(\frac{3t_2}{\bar{t}_1}\right) - \frac{1}{3}\tanh^3\left(\frac{3t_2}{\bar{t}_1}\right)\right] \qquad (35)$$

Substituting these results in Equation (8)

$$\frac{Lh}{M_1 C} = \left[\tanh\left(\frac{4}{3}\ \frac{t_2}{h}\ a\right) - \frac{1}{3}\tanh^3\left(\frac{4}{3}\ \frac{t_2}{h}\ a\right)\right]\left[\frac{1 - \left(\frac{t_2}{h}\right)^2}{\left(\frac{4t_2}{3h}\right)}\right] \quad (36)$$

where

$$a = (9/4)h/(1 + \cos\ \Theta)\ \bar{t} \quad (37)$$

is a scaling factor when $\bar{t} \geq (9/4)\ t_0$.

If $\bar{t} < (9/4)\ t_0$, then

$$a = h/(1 + \cos\ \Theta)\ t_0 \quad (38)$$

should be used to avoid the nonmixing region shown in Figure (2b) and in turn avoid calculating a dynamic pressure at the wing greater than q_0. These results are summarized in Figures (3) and (4). Note that the drag plot in Figure (3) only uses one half the theoretical drag prediction. This is attributed to thrust recovery at the wing leading edge which is not considered in the flow model.

CONCLUSIONS

The static lift performance for a power-augmented-ram wing can be accurately predicted by using two-dimensional and axisymmetric turbulent jet theory to extend the existing potential flow analysis. The drag prediction using this theory is quite conservative and requires further investigation to obtain good correlation with experimental data.

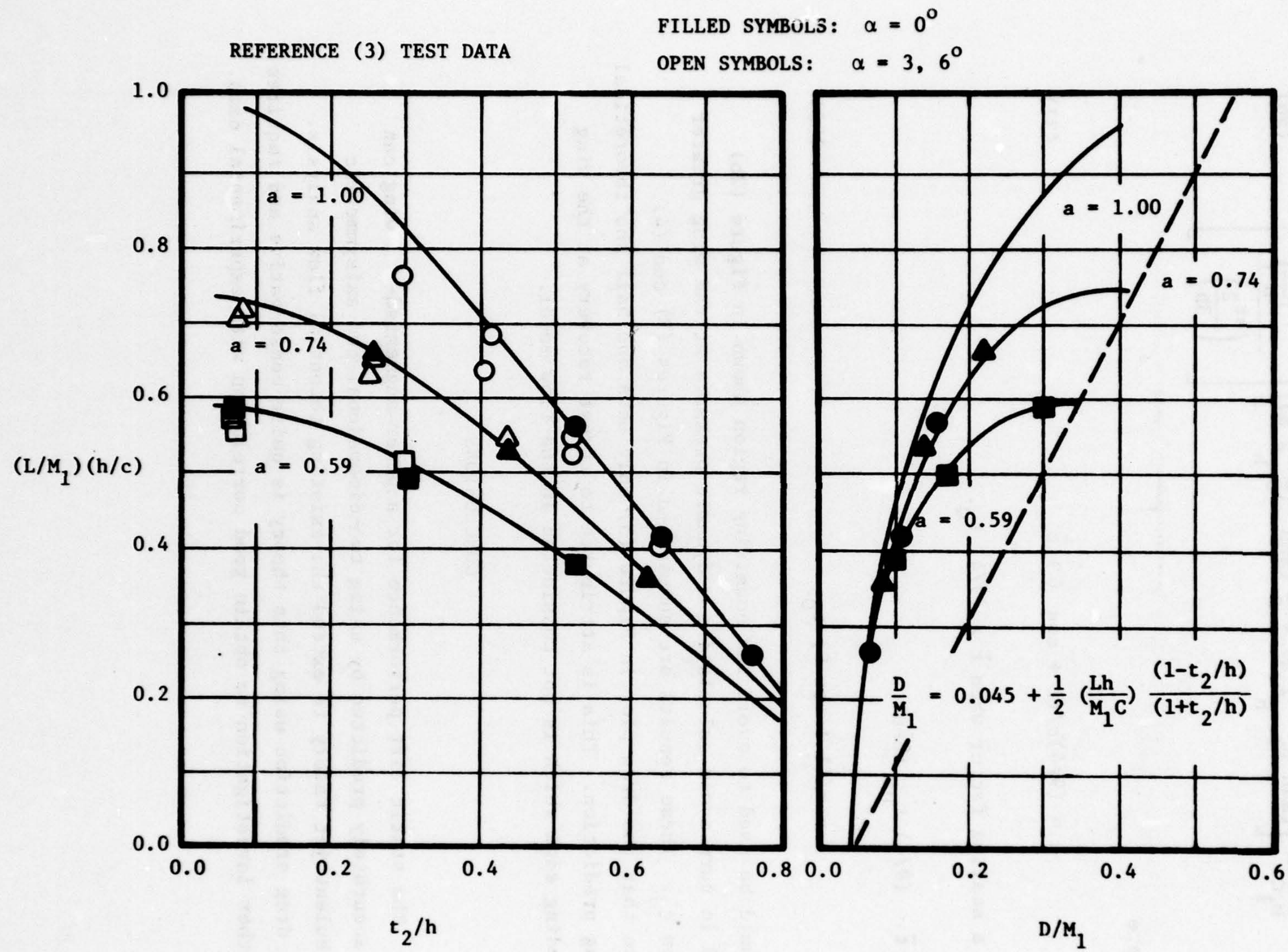
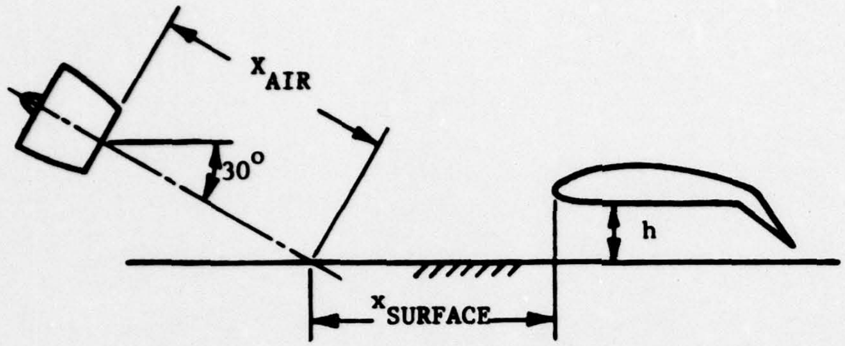


Figure 3 - Lift and Drag Predictions

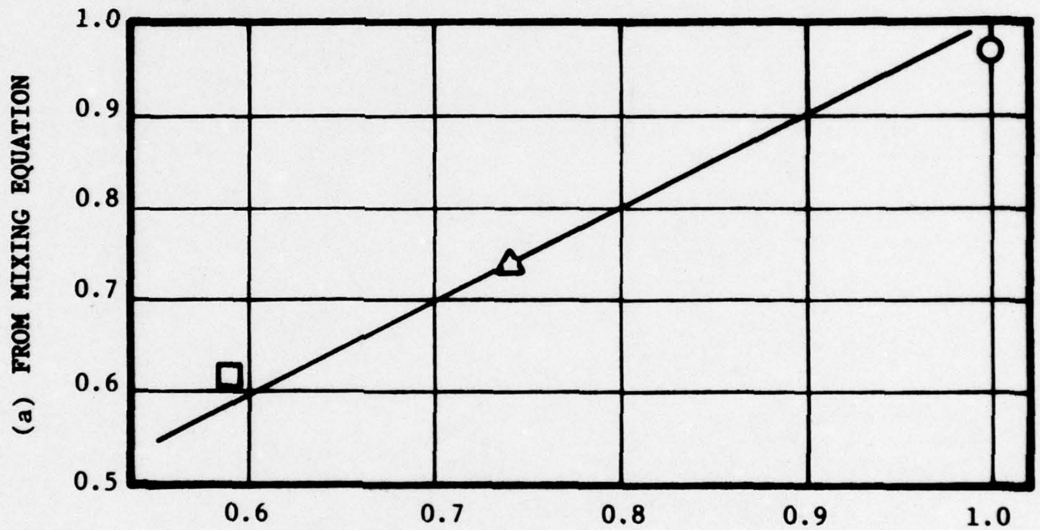


TEST CONDITIONS*

	h/C	$x_{AIR/C}$	$x_{SURFACE/C}$
□	0.083	0.542	0.302
△	0.104	0.583	0.267
○	0.162	0.700	0.165

C = 48.0 INCHES (122 CM)

*Reported informally by F. H. Krause and R. W. Gallington ("Static Performance of a Power-Augmented-Ram Wing," DTNSRDC ASED TM-16-76-76, May 1976).



(a) FOR BEST FIT FOR (L/M_1) (h/C) VERSUS (t_2/h)

Figure 4 - Comparison Between Theoretical/Experimental Results