BOEING COMPUTER SERVICES
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ASSET/HYDROFOIL

ADVANCED SURFACE SHIP EVALUATION TOOL

HYDROFOIL SHIP PROGRAM

MODULE USER MANUALS

VOLUME 4B

Boeing Computer Services Company
P.O. Box 24346
Seattle, Washington 98124-0346

Prepared for the Costing and Design Systems Office, Code 1204 of the David W. Taylor Naval Ship Research and Development Center under Contract N00267-85-D-0041.

Version 2.0
April 1986

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BOEING COMPUTER SERVICES
A Division of The Boeing Company

ASSET/HYDROFOIL

ADVANCED SURFACE SHIP EVALUATION TOOL

HYDROFOIL SHIP PROGRAM

USER MANUAL

FOILBORNE HYDRODYNAMIC MODULE

Boeing Computer Services Company
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Version 2.0
April 1986

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REV. SYM.

REVISIONS

REV. SYM.	DESCRIPTION	DATE	AUTHORS
0.0	Original text was written for HANDE user and theory manuals.	June 1977	K.R. Meldahl
1.1	Documentation to describe graphic output capability was added to HANDE user manual.	Oct. 1978	M.D. Devine
2.0	HANDE user manual and theory manual were combined into a single ASSET/HYDROFOIL user manual. ASSET documentation standards were enforced.	Apr. 1986	M.D. Devine

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1.0 INTRODUCTION

The Foilborne Hydrodynamic Module is one of the modules which constitutes the ASSET/HYDROFOIL synthesis process. Its primary purpose is to compute: 1) the foilborne drag at input design speed and design weight, 2) the foilborne drag at input range speed and at 50% fuel load, 3) the takeoff hump drag and corresponding speed, and 4) if requested, the waterjet propulsion system inlet duct area required for takeoff. The pertinent parameters calculated in the module are passed to the other modules via the current model. With the exception of the waterjet inlet duct sizing, the Foilborne Hydrodynamic Module does not modify foil/strut assembly geometric parameters, and its only output is the foilborne and takeoff drags and corresponding takeoff speed.

Although this module is designed for integrated operation within the synthesis loop, it is capable of independent operation if desired; however, during independent operation, it must be recognized that in order to compute consistent drags, proper geometric input data will be required for both the hull and foil/strut assembly. All this input data enters the module through the current model. It should be noted that the exclusion of interfacing parameters during independent operation may lead to erroneous conclusions.

The Foilborne Hydrodynamic Module calculates the total foil system lift and drag and hull drag for takeoff calculations from the input geometry and operating conditions data. The foil/strut hydrodynamic calculations are based on methods described in References [1] thru [7] and the hull drag calculations are based on methods described in References [8] thru [10]. Modifications and additions to the referenced methods were required in order to integrate it into the module, although the basic calculation forms were not altered. A moment balance and lift summation have been incorporated in the Foilborne Hydrodynamic Module such that the moment about the ship center of gravity (CG) is zero and the summation of all vertical lifts equals total weight.

The calculation of hull resistance for takeoff calculations is based on the methods developed for the Hullborne Hydrodynamic Module. This coupling of the Foilborne

Hydrodynamic Module and the Hullborne Hydrodynamic Module drag estimation procedures was done to provide both a consistent drag estimate between the modules and to use a consistent geometric definition. Both modules use essentially the same input data. The approach, summary of input, description of output, explanation of diagnostic messages, theory, and examples of use of the Foilborne Hydrodynamic Module are given in the following sections.

2.0 APPROACH

The Foilborne Hydrodynamic Module is one of the modules which constitute the synthesis process. Its primary purpose is to compute: 1) foilborne drag at both design speed and range speed, and 2) takeoff hump drag and the corresponding speed at the hump drag point. In addition, the module can calculate a waterjet propulsion system inlet duct size required for takeoff. In order to properly compute drags, a complete set of geometry is required for the foil assembly and hull. With the exception of the waterjet inlet duct sizing, the Foilborne Hydrodynamic Module does not modify foil assembly geometric parameters, and its only output is foilborne and takeoff drag, and takeoff speed.

The two main computational functions performed by this module may be outlined as follows:

1. The foil assembly hydrodynamic calculations for the foilborne condition include the total foil assembly steady state lift and drag from input geometry and operating condition data. The estimation of these components is accomplished by utilizing a simple calculation technique to approximate a static equilibrium condition for external forces and moment. A detailed discussion of this group is considered in Section 5.

2. The takeoff hydrodynamic calculations include the takeoff hump drag and the corresponding speed at the hump drag. The estimation of the takeoff drag is accomplished by utilizing the static equilibrium calculation technique of the foil assembly hydrodynamic calculations. Included in the calculation is the contribution of the hull forces and moment. A minimum takeoff drag at a fixed speed is obtained in terms of two independent operating parameters. Takeoff speed is incremented until a hump drag value is found or the craft can achieve foilborne operation. If requested, the data generated from the takeoff calculation is used to calculate the maximum required waterjet inlet area.

Takeoff calculations are discussed in Section 6. Various limitations pertaining to calculation of foil assembly hydrodynamics and takeoff hydrodynamics are described in Section 7.

A macro flow chart of the Foilborne Hydrodynamic Module is shown in Figure 2.0-1.

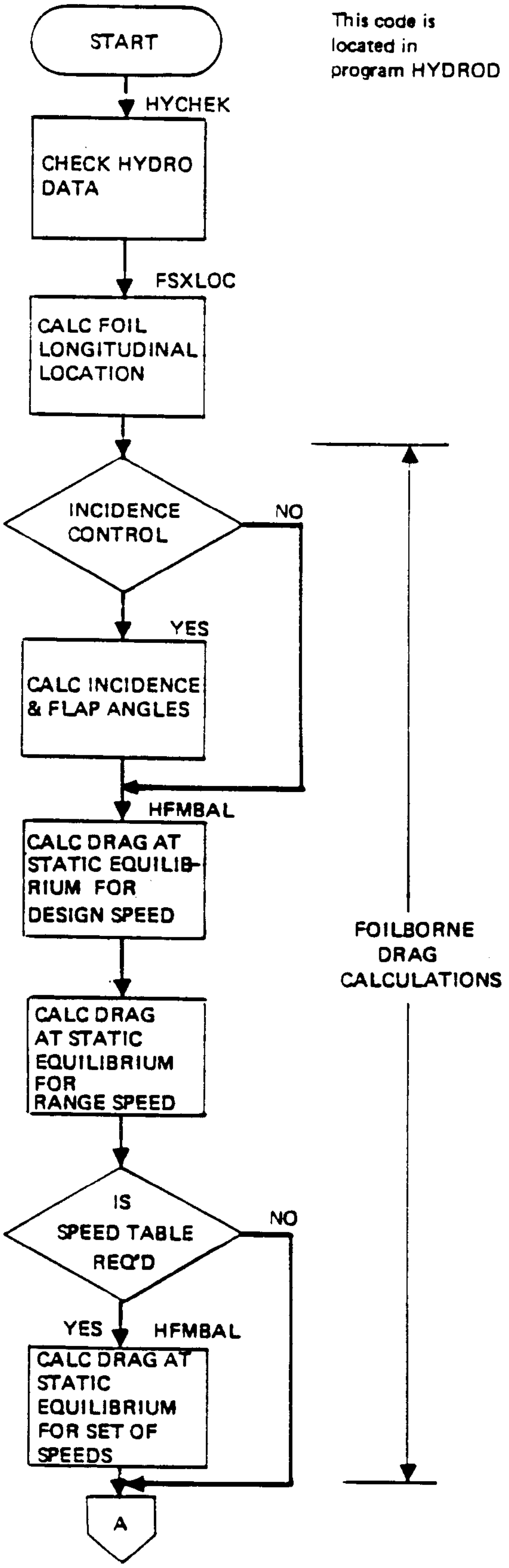


FIGURE 2.0-1 MODULE MACRO FLOW DIAGRAM

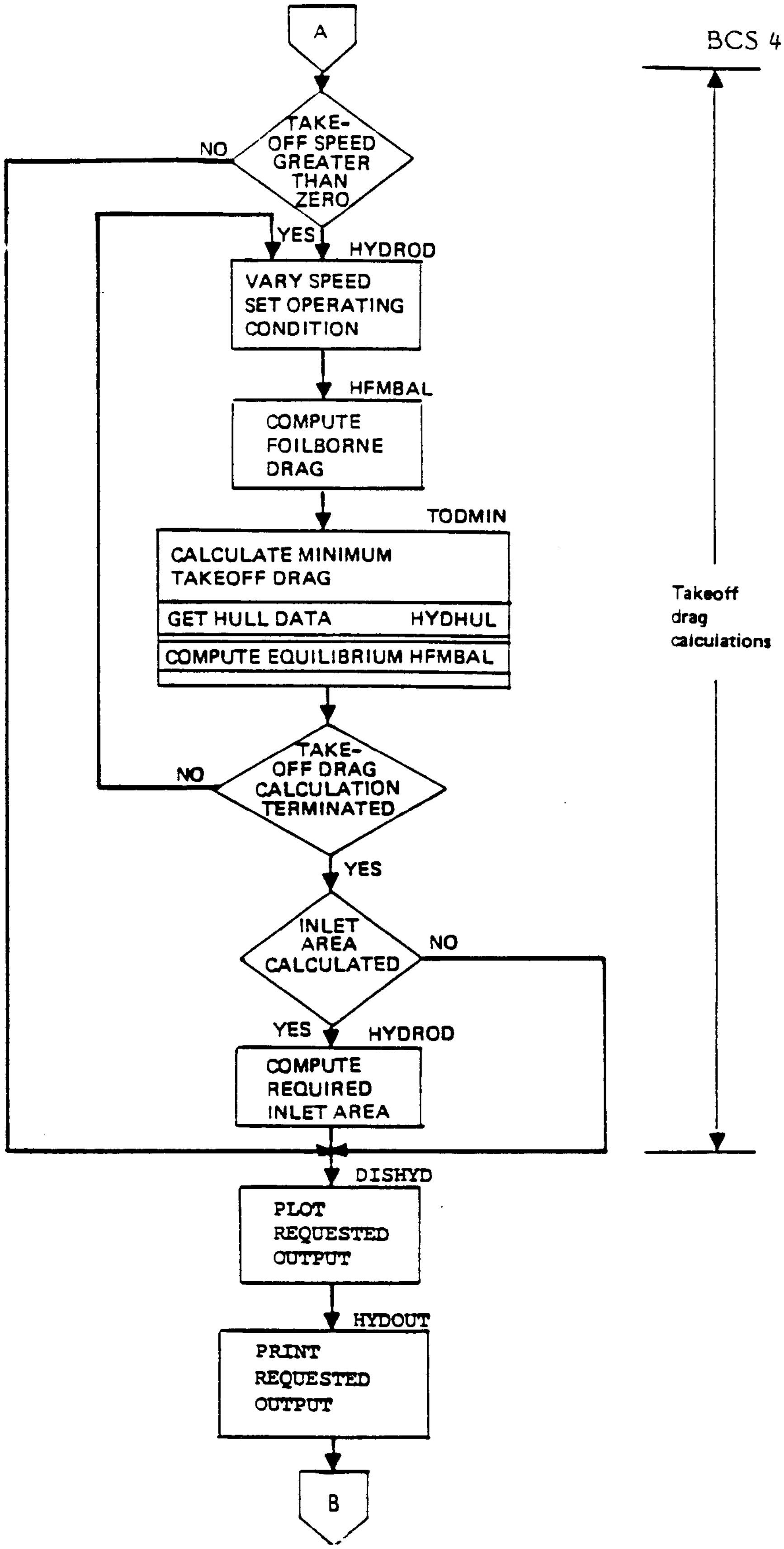


FIGURE 2.0-1 MODULE MACRO FLOW DIAGRAM (CONT'D)

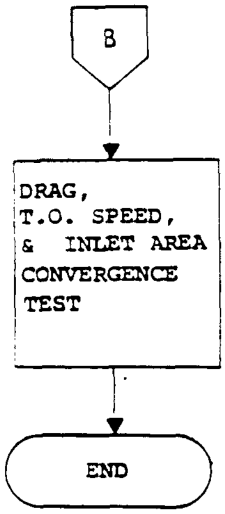


FIGURE 2.0-1 MODULE MACRO FLOW DIAGRAM (CONT'D)

3.0 INPUT

All input data for the Foilborne Hydrodynamic Module are extracted from the current model by the executive program. The parameters that are listed in Table 3.0-1 are required as input by the Foilborne Hydrodynamic Module.

TABLE 3.0-1
MODULE INPUT FROM CURRENT MODEL

DEFAULT	PARAMETER NAME	ARRAY SIZE	UNITS ENGLISH	UNITS METRIC
	SHIP REQ			
	MISSION			
	FB SPEED REQ		KT	KT
	FB RANGE SPEED REQ		KT	KT
	HB SPEED REQ		KT	KT
	HB RANGE SPEED REQ		KT	KT
	FB HEIGHT		FT	M
	HULL			
	HULL OFFSETS			
	STATION ARRAY	(15X1)	FT	M
	HALF BEAM ARRAY	(15X9)	FT	M
	WATERLINE ARRAY	(15X9)	FT	M
	CHINE LOC ARRAY	(15X1)	RATIO	RATIO
	FB PROPULSION			
	FB ENGINE			
	FB PROP TYPE IND			
	DESIGN TO MARGIN			
	FB GEARBOX			
	FB LWR GBX DIA		FT	M
	FB WATERJET			
	FB DUCT SIZE IND			
	FB JET VEL RATIO			
	FB DUCT IN AREA		FT2	M2
	FB PROPELLER			
	FB PROPELLER DIA		FT	M
	FB PROPELLER CHAR			
	FB HUB/DIA RATIO			
	HB PROPULSION			
	HB ENGINE			
	HB PROP TYPE IND			
	FWD FOIL/STRUT			
	FWD FOIL GEOMETRY			
	FWD F/S CONCEPT IND			
	FWD DESIGN CL			
	FWD FOIL BUOYANCY		LTON	MTON
	FWD FOIL ROOT CHORD		FT	M
	FWD FOIL TIP CHORD		FT	M
	FWD OB FOIL SWEEP		DEG	DEG
	FWD CEN FOIL SEMISPN		FT	M
	FWD OB FOIL SEMISPN		FT	M
	FWD FOIL ROOT T/C			
	FWD FOIL TIP T/C			
	FWD CEN FOIL ANHED		DEG	DEG
	FWD OB FOIL ANHED		DEG	DEG
	FWD CEN FLP SPN RATIO			
	FWD OB FLP SPN RATIO			

TABLE 3.0-1

MODULE INPUT FROM CURRENT MODEL (Continued)

DEFAULT	PARAMETER NAME	ARRAY SIZE	UNITS ENGLISH	UNITS METRIC
	FWD FOIL AFT BOX LOC		RATIO	RATIO
	FWD STRUT GEOMETRY			
	FWD CEN STRUT IND			
	FWD OB STRUT IND			
	FWD STRUT X/LBP		RATIO	RATIO
	FWD STRUT BUOYANCY		LTON/FT	MTON/M
	FWD CEN STRUT LENGTH		FT	M
	FWD OB STRUT LENGTH		FT	M
	FWD CEN STRUT UP T/C			
	FWD CEN STRUT LR T/C			
	FWD OB STRUT UP T/C			
	FWD OB STRUT LR T/C			
	FWD OB STRUT SPLAY		DEG	DEG
	FWD POD GEOMETRY			
	FWD CEN POD NOSE L/W		RATIO	RATIO
	FWD OB POD NOSE L/W		RATIO	RATIO
	FWD CEN POD TAIL L/W		RATIO	RATIO
	FWD OB POD TAIL L/W		RATIO	RATIO
	FWD POD BUOYANCY		LTON	MTON
	FWD HYDRODYNAMICS			
	FWD CONTROL IND			
	FWD FOIL SUBMERGE		FT	M
	FOIL LOADING FRAC			
*	FB DRAG FACTOR			
	PWR/CNT STRUT/POD			
	PWR POD POS IND			
	PWR STRUT/FOIL CHORD		RATIO	RATIO
	PWR STRUT TAPER		RATIO	RATIO
	CNT STRUT/FOIL CHORD		RATIO	RATIO
	CONTROL POD W/THICK		RATIO	RATIO
	AFT FOIL/STRUT			
	AFT FOIL GEOMETRY			
	AFT F/S CONCEPT IND			
	AFT DESIGN CL			
	AFT FOIL BUOYANCY		LTON	MTON
	AFT FOIL ROOT CHORD		FT	M
	AFT FOIL TIP CHORD		FT	M
	AFT OB FOIL SWEEP		DEG	DEG
	AFT CEN FOIL SEMISPN		FT	M
	AFT OB FOIL SEMISPN		FT	M
	AFT FOIL ROOT T/C			
	AFT FOIL TIP T/C			
	AFT CEN FOIL ANHED		DEG	DEG
	AFT OB FOIL ANHED		DEG	DEG
	AFT CEN FLP SPN RATIO			
	AFT OB FLP SPN RATIO			
	AFT FOIL AFT BOX LOC		RATIO	RATIO

TABLE 3.0-1

MODULE INPUT FROM CURRENT MODEL (Continued)

DEFAULT	PARAMETER NAME	ARRAY SIZE	UNITS ENGLISH	UNITS METRIC
	AFT STRUT GEOMETRY			
	AFT CEN STRUT IND			
	AFT OB STRUT IND			
	AFT STRUT BUOYANCY		LTON/FT	MTON/M
	AFT CEN STRUT LENGTH		FT	M
	AFT OB STRUT LENGTH		FT	M
	AFT CEN STRUT UP T/C			
	AFT CEN STRUT LR T/C			
	AFT OB STRUT UP T/C			
	AFT OB STRUT LR T/C			
	AFT OB STRUT SPLAY		DEG	DEG
	AFT POD GEOMETRY			
	AFT CEN POD NOSE L/W			
	AFT OB POD NOSE L/W			
	AFT CEN POD TAIL L/W			
	AFT OB POD TAIL L/W			
	AFT POD BUOYANCY		LTON	MTON
	AFT HYDRODYNAMICS			
	AFT CONTROL IND			
	AFT FOIL SUBMERGE		FT	M
	HB HYDRODYNAMIC FACTORS			
	FOIL POS IND			
	HB DRAG		LBF	N
	HB RANGE DRAG		LBF	N
	HB DRAG FACTOR			
	WEIGHT FACTORS			
	CG INPUT IND			
	USABLE FUEL WT		LTON	MTON
	FULL LOAD WT		LTON	MTON
	FULL LOAD CG ARRAY	(2X1)	RATIO	RATIO

4.0 OUTPUT

4.1 CURRENT MODEL

A list of the parameters output to the current model by the module is given in Table 4.1-1.

4.2 GRAPHIC OUTPUT

Two graphic displays can be generated by the Foilborne Hydrodynamic Module. The title of each display and the corresponding display number is shown in Table 4.2-1.

4.2.1 Display No. 1 - Foilborne Drag Versus Speed

Graphic display number one is a plot of the speed-drag data contained in printed report number four (see Section 4.3.4). The executive command SET, GRAPHICS is used to select the graphics output. After construction, the graphic plot will remain on the display screen until the RETURN key on the user terminal is depressed. Following depression of the RETURN key, the graphics output is erased and module execution is continued. An example of graphic display number one is shown in Figure 4.2-1.

4.2.2 Display No. 2 - Foilborne Drag Plus Factor Versus Speed

Graphic display number two is a plot of the speed-drag (+ factor) data contained in printed report number four (see Section 4.3.4). The executive command SET, GRAPHICS is used to select the graphics output. After construction, the graphic plot will remain on the display screen until the RETURN key on the user terminal is depressed. Following depression of the RETURN key, the graphics output is erased and module execution is continued. An example of graphic display number two is shown in Figure 4.2-2.

TABLE 4.1-1

MODULE OUTPUT TO CURRENT MODEL

DEFAULT	PARAMETER NAME	ARRAY SIZE	UNITS ENGLISH	UNITS METRIC
	SHIP REQ			
	MISSION			
	TO SPEED		KT	KT
	FWD FOIL/STRUT			
	FWD HYDRODYNAMICS			
	FB DRAG		LBF	N
	TO DRAG		LBF	N
	FB RANGE DRAG		LBF	N

TABLE 4.2-1
MENU OF GRAPHIC OUTPUT DISPLAYS

Display #	Title
1	Foilborne Drag vs. Speed
2	Foilborne Drag Plus Factor vs. Speed

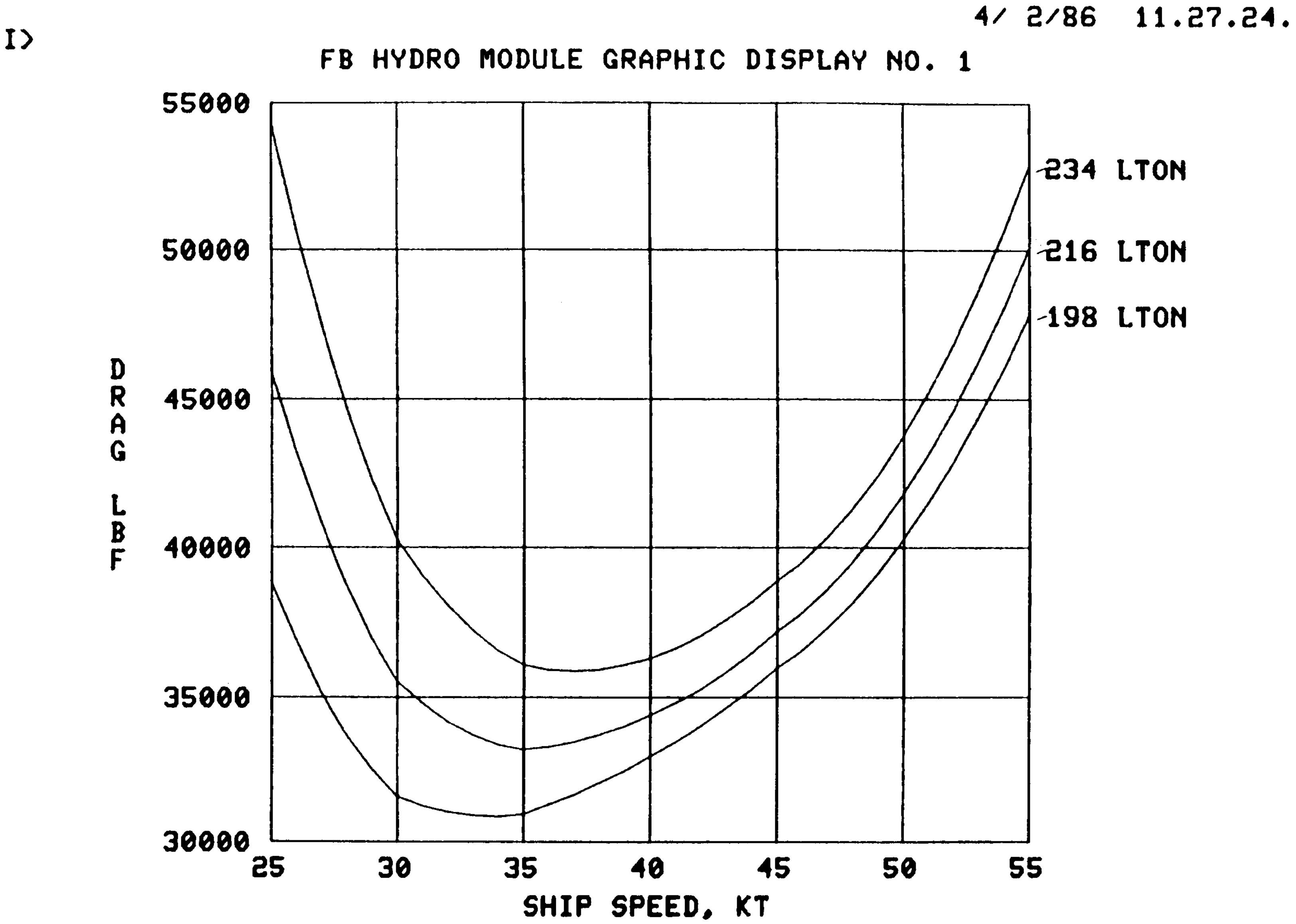


FIGURE 4.2-1 GRAPHIC DISPLAY NO. 1 - FOILBORNE DRAG VS. SPEED

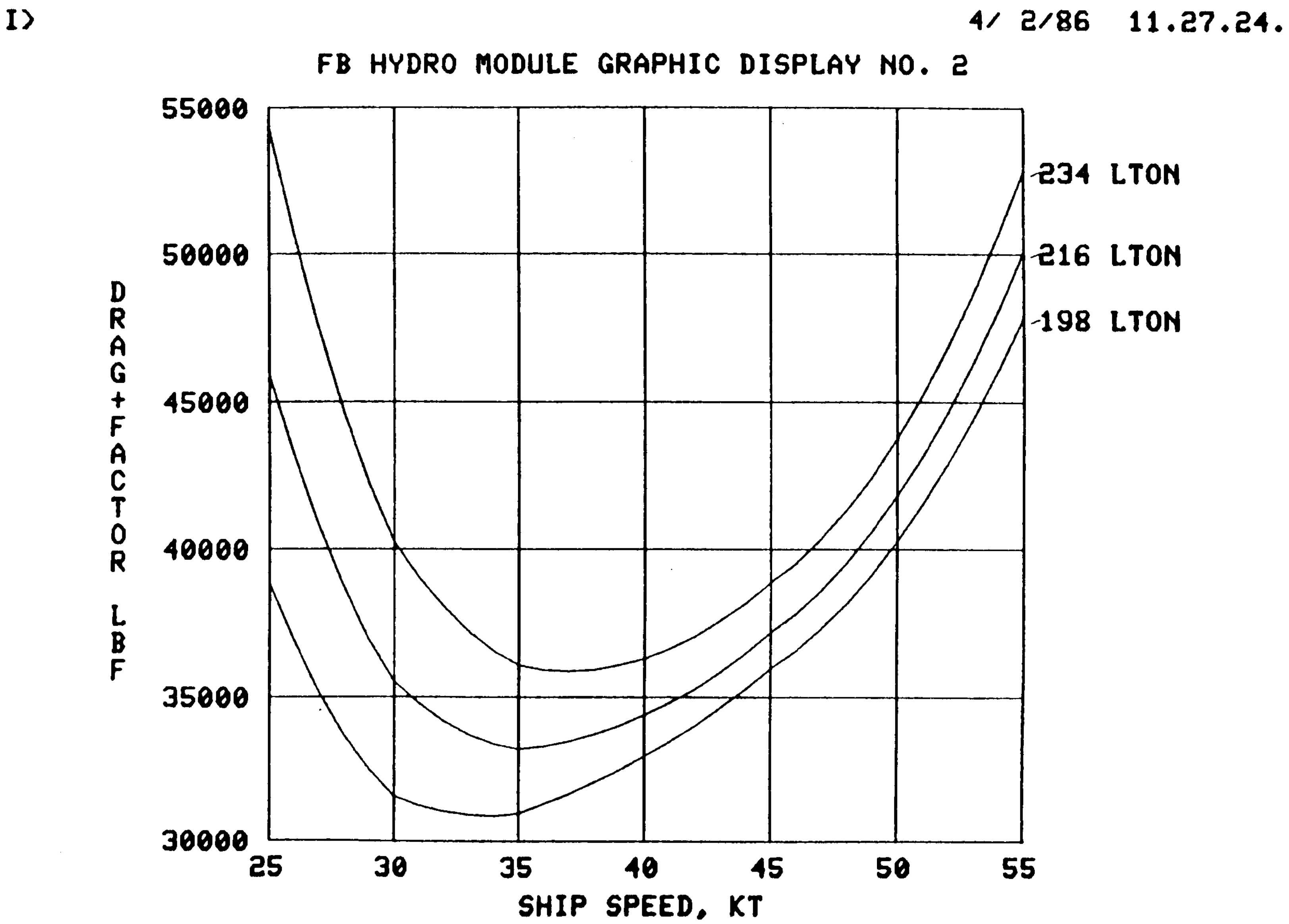


FIGURE 4.2-2 GRAPHIC DISPLAY NO. 2 - FOILBORNE DRAG PLUS FACTOR VS. SPEED

4.3 PRINTED OUTPUT

Five printed reports can be generated by the Foilborne Hydrodynamic Module. The title of each report and the corresponding report number is listed in Table 4.3-1.

Printed output is controlled via the SET,ONLINE and SET,OFFLINE executive commands. Samples of these outputs are presented in the following sections.

4.3.1 Report No. 1 - Summary

A typical summary is illustrated in Figure 4.3-1. This summary is printed by default when this module is used independently and no output is requested. The summary is also printed whenever specifically requested.

The type of foilborne propulsion system is printed for reference. If the foilborne propulsion system is waterjet and if the Foilborne Hydrodynamic Module has calculated the required inlet area, the computed inlet duct area is then printed. For a fixed duct area no printout is provided. The condition for which drags are printed out are as follows: foilborne design speed, foilborne range speed, takeoff hump speed and drag. The following weights are used for the calculation: for design speeds and takeoff the full load weight is used while for range speeds only one-half of the usable fuel weight is included. The nominal drags are shown for all conditions. A foilborne drag factor, FB DRAG FACTOR, multiplies both the foilborne design and range calculation drag and the resultant values are passed to the current model. This factor allows the user to modify the output drag values calculated by the Foilborne Hydrodynamic Module before it is passed to the current model. The nominal drag for takeoff is passed to the current model without any multiplication of a margin. The takeoff drag multiplied by the design takeoff margin, DESIGN TO MARGIN, is provided for reference only.

TABLE 4.3-1
MENU OF PRINTED OUTPUT REPORTS

Report #	Report Title
1	Summary
2	Foilborne Foil/Strut Data
3	Foil/Strut Geometry Data
4	Speed/Drag Matrix Data
5	Takeoff Data

```
  ASSET/HYDROFOIL VERSION 2.0 - FB HYDRO MODULE -  3/31/86 09.22.58.

PRINTED REPORT NO. 1 - SUMMARY

 FB PROP TYPE-WATERJET
 FB DUCT SIZE-CALC
 NUMBER OF DUCTS               2.
 AREA/DUCT, FT2             2.207

CONDITION        SPEED,KT    WT,LTON      DRAG,LBF  DRAG+FACTOR,LBF
FB DESIGN          45.0       235.0        38878.         38878.
FB RANGE           44.0       216.8        36493.         36493.
TO DESIGN          25.0       235.0        46223.         57779.
```

FIGURE 4.3-1 REPORT NO. 1 - SUMMARY

4.3.2 Report No. 2 - Foilborne Foil/Strut Data

Typical foilborne foil/strut drag-lift summary data output is shown on Figure 4.3-2 and is obtained when the print control is set to two. The data shown is for nominal drags and does not include the foilborne drag margin.

4.3.3 Report No. 3 - Foil/Strut Geometry Data

Typical foil/strut geometry summary data output is shown on Figure 4.3-3 and is obtained when the print control is set to three. The data shown is that geometry used by the Foilborne Hydrodynamic Module to calculate the foil system hydrodynamics.

4.3.4 Report No. 4 - Speed-Drag Matrix Data

Typical foilborne speed-drag matrix summary data output is shown on Figure 4.3-4 and is obtained when the print control is set to four. The data shown is for a variation of speed from 25 knots to 55 knots at a five knot increment and a weight variation of full fuel load, 50% fuel load and zero fuel load. The Drag+Factor column is as explained in Section 4.3.1.

4.3.5 Report No. 5 - Takeoff Data

Typical takeoff summary data output is shown on Figure 4.3-5 and is obtained when the print control is set to five. The required waterjet duct area is shown as a function of speed if waterjet duct area is to be calculated. The largest area calculated is then passed to the current model.

```
PRINTED REPORT NO. 2 - FOILBORNE FOIL/STRUT DATA

                   DESIGN SPEED CONDITION I RANGE SPEED CONDITION
                   SPEED  =   45.0 KNOTS  I SPEED  =   44.0 KNOTS
                   WEIGHT =  235.0 LTON   I WEIGHT =  216.8 LTON
                   PITCH  =   0.00 DEG    I PITCH  =   0.15 DEG
                   LCG    =  67.84 FT     I LCG    =  67.84 FT
                   VCG    =   8.14 FT     I VCG    =   8.14 FT

                      FORWARD    AFT      I   FORWARD    AFT
                      FOIL       FOIL     I   FOIL       FOIL

FOIL SUBMERGENCE, FT    4.00       5.50   I     4.00       5.74
FOIL INCIDENCE, DEG     2.61       1.87   I     2.61       1.87
FLAP DEFLECTION, DEG    0.45       0.44   I    -0.09      -0.27
FOIL X LOCATION, FT     7.71      97.72   I     7.71      97.72
FOIL DRAGS, LBF                           I
 PROFILE               5504.     11187.   I    5171.     10674.
 INDUCED               3526.      4934.   I    3083.      4247.
 TOTAL                 9030.     16121.   I    8253.     14921.
STRUT DRAGS, LBF                          I
 PROFILE                609.      1454.   I     584.      1528.
 SPRAY                  677.      3402.   I     647.      3287.
 WAVE                     9.        89.   I       9.        93.
 TOTAL                 1295.      4945.   I    1240.      4909.
POD DRAGS, LBF                            I
 PROFILE               1028.      3470.   I     985.      3326.
 WAVE                     1.         4.   I       1.         4.
 TOTAL                 1029.      3474.   I     987.      3330.

TOTAL DRAGS, LBF      11354.     24540.   I   10480.     23160.

FOIL LIFT, LTON                           I
 DYNAMIC               79.97     148.19   I    73.52     136.51
 BUOYANCY               1.08       2.67   I     1.08       2.67
 TOTAL                 81.05     150.86   I    74.59     139.17
STRUT LIFT, LTON                          I
 BUOYANCY               0.22       0.54   I     0.22       0.56
POD LIFT, LTON                            I
 BUOYANCY               0.73       1.89   I     0.73       1.89

TOTAL LIFT, LTON       81.95     153.00   I    75.49     141.34
F/S_LIFT/DRAG RATIO    16.17      13.97   I    16.14      13.67
DYN LOADING, LBF/FT2  1270.9     1097.4   I   1168.3     1010.9

AIR DRAG, LBF          2984.              I    2853.

SHIP DRAG, LBF        38878.              I   36493.
SHIP WEIGHT/DRAG       13.54              I    13.31
```

FIGURE 4.3-2 REPORT NO. 2 - FOILBORNE FOIL/STRUT DATA

```
PRINTED REPORT NO. 3 - FOIL/STRUT GEOMETRY DATA
                        FORWARD SYSTEM      I      AFT SYSTEM
FOIL/STRUT CONCEPT            T             I         PI
LIFT CONTROL TYPE            FLAP           I         FLAP
FOIL GEOMETRY          TOTAL  CENTER  OUTBRD  I  TOTAL  CENTER  OUTBRD
 DESIGN CL             0.200                 I  0.200
 ASPECT RATIO           5.50                 I   7.50
 AREA, FT2            140.95    0.00  140.95  I 302.48  168.47  134.01
 SPAN, FT              27.84    0.00   13.92  I  47.63   13.26   10.55
 CHORD, FT                      7.79    2.34  I           6.35    6.35
 THICKNESS RATIO               0.065   0.065  I          0.065   0.065
 ANHEDRAL, DEG                  0.00    0.00  I          12.00   12.00
 FLAP CHORD RATIO               0.00    0.27  I           0.27    0.27
 FLAP SPAN RATIO                0.00    0.95  I           0.75    0.94
 SWEEP, DEG                            11.04  I                   0.00
STRUT GEOMETRY          CENTER      OUTBRD    I  CENTER      OUTBRD
 STRUT TYPE            STEERABLE              I              POWER
 LENGTH, FT              18.22        0.00    I   0.00       19.03
 SPLAY ANGLE, DEG         0.00        0.00    I   0.00        3.90
FOIL INTERSECTION                             I
 CHORD, FT                5.58        0.00    I   0.00        8.17
 THICKNESS RATIO         0.100       0.000    I  0.000       0.100
POD INTERSECTION                              I
 CHORD, FT                5.58        0.00    I   0.00        8.54
 THICKNESS RATIO         0.105       0.000    I  0.000       0.112
TOP OF STRUT                                  I
 CHORD, FT                5.58        0.00    I   0.00       10.52
 THICKNESS RATIO         0.200       0.000    I  0.000       0.162


POD GEOMETRY             CENTER      OUTBRD   I  CENTER      OUTBRD
 SHAPE                   ROUND          -     I    -       RECTANGLE
 POSITION                CL FOIL        -     I    -       ABOVE FOIL
 WIDTH, FT                 1.80       0.00    I   0.00          1.31
 HEIGHT, FT                1.80       0.00    I   0.00          2.99
 FOREBODY LNGTH, FT        3.16       0.00    I   0.00          2.56
 MIDBODY LNGTH, FT         5.58       0.00    I   0.00          8.17
 AFTERBODY LNGTH, FT       4.35       0.00    I   0.00          4.52
```

FIGURE 4.3-3 REPORT NO. 3 - FOIL/STRUT GEOMETRY DATA

```
PRINTED REPORT NO. 4 - SPEED-DRAG MATRIX DATA

 SPEED,KT   WT,LTON   PITCH,DEG   DRAG,LBF DRAG+FACTOR,LBF
   25.0      235.0       2.99      54276.      54276.
   30.0      235.0       2.25      40246.      40246.
   35.0      235.0       1.50      36068.      36068.
   40.0      235.0       0.75      36303.      36303.
   45.0      235.0       0.00      38876.      38876.
   50.0      235.0      -0.75      43737.      43737.
   55.0      235.0      -1.50      52782.      52782.
   25.0      216.8       2.99      45978.      45978.
   30.0      216.8       2.25      35537.      35537.
   35.0      216.8       1.50      33188.      33188.
   40.0      216.8       0.75      34365.      34365.
   45.0      216.8       0.00      37158.      37158.
   50.0      216.8      -0.75      41779.      41779.
   55.0      216.8      -1.50      50036.      50036.
   25.0      198.7       2.99      38891.      38891.
   30.0      198.7       2.25      31602.      31602.
   35.0      198.7       1.50      30978.      30978.
   40.0      198.7       0.75      32948.      32948.
   45.0      198.7       0.00      35964.      35964.
   50.0      198.7      -0.75      40256.      40256.
   55.0      198.7      -1.50      47839.      47839.
```

FIGURE 4.3-4 REPORT NO. 4 - SPEED-DRAG MATRIX DATA

```
PRINTED REPORT NO. 5 - TAKEOFF DATA

SPEED FOILBORNE TAKEOFF    FOIL      HULL   HULL LIFT PITCH DRAFT WJ DUCT
 KT    DRAG,LBF DRAG,LBF DRAG,LBF DRAG,LBF    LTON     DEG   AP,FT   FT2
 13.0  244686.   18224.     5191.   13033.     211.5  -0.15  6.06  1.585
 16.0  171911.   29205.     8092.   21113.     193.8  -0.02  5.89  1.919
 19.0  120713.   37742.    14421.   23321.     153.4   0.51  5.56  2.106
 22.0   63065.   41763.    21465.   20298.     110.4   1.36  5.52  2.156
 25.0   46630.   46223.    33860.   11956.      39.3   3.31  6.28  2.207
```

FIGURE 4.3-5 REPORT NO. 5 - TAKEOFF DATA

4.4 DIAGNOSTIC MESSAGES

If certain data input errors are encountered during Foilborne Hydrodynamic Module execution, a diagnostic message will be printed to inform the user. Other than the input data parameters listed below, no checks are made in the input foil/strut data because it is assumed that the required data was checked by other modules. When fatal errors associated with diagnostic messages are encountered, calculations are terminated and control is returned to the user for appropriate action.

The following input parameters are examined for missing data, i.e., numeric values greater than or equal to 10^{36}. For each one found, a diagnostic message is printed showing the parameter name and that it is a fatal error which caused termination of the Foilborne Hydrodynamic Module execution.

FWD DESIGN CL
AFT DESIGN CL
FWD FOIL SUBMERGE
AFT FOIL SUBMERGE
FB SPEED REQ
FB LWR GBX DIA (if a propeller foilborne propulsion system is used)
FB DUCT IN AREA (if a waterjet foilborne propulsion system is used)
STATION ARRAY

A special test is made on the center of gravity array, FULL LOAD CG ARRAY. If either the longitudinal center of gravity ratio (the first element in the array) is outside the range 0.01 to 0.99 or if the vertical center of gravity ratio (the second element in the array) is outside the range -10 to +10, a fatal error message for missing data is printed.

The fatal error message for missing data is:

```
HYDRO MODULE **FATAL ERROR** MISSING DATA - parameter name
```

If the FB DRAG FACTOR is greater than or equal to 10^{36}, a warning diagnostic message is printed and its value is set to one. The warning message is:

> HYDRO MODULE **WARNING** FB DRAG FACTOR MISSING** SET TO 1**

If the FB RANGE SPEED REQ is greater than the FB SPEED REQ, a warning diagnostic message is printed and its value is set equal to the FB SPEED REQ. The warning message is:

> HYDRO MODULE **WARNING** RANGE SPEED REQ GREATER THAN FB SPEED REQ. RANGE SPEED REQ IS SET TO FB SPEED REQ.

If the TO SPEED is less than zero, a warning diagnostic is printed and program execution continues without the takeoff calculations. The warning message is:

> HYDRO MODULE **WARNING** TO SPEED SET AT LESS THAN ZERO - NO TAKEOFF CALCULATIONS WILL BE MADE.

5.0 THEORY: FOIL ASSEMBLY HYDRODYNAMICS

This section contains a discussion of the procedures used to estimate the hydrodynamic characteristics of the foil assembly. The procedure used to establish equilibrium operating conditions is presented in Section 5.1. The detailed equations for the lift and drag of the various foil assembly components are given in Sections 5.2 and 5.3.

5.1 EQUILIBRIUM OPERATING CONDITIONS

5.1.1 Calculation Sequence

The calculation of the steady state foilborne drag is initiated from the Foilborne Hydrodynamic Module "main" subroutine HYDROD. This subroutine: 1) checks critical input data for missing values, 2) sets additional foil assembly geometry and the operating conditions, 3) initiates the steady state drag calculations, and 4) passes the calculated drags to the current model and prints data according to the output menu. Each of the above items are discussed below.

Data Checking

Before initiation of drag calculations, checks for missing values are made in subroutine HYCHEK. Calculations are not made if the following items are not specified:

The forward and aft foil section design lift coefficients, FWD DESIGN CL and AFT DESIGN CL.

The forward and aft foil submergence, FWD FOIL SUBMERGE and AFT FOIL SUBMERGE.

The foilborne speed required, FB SPEED REQ.

The hull offset station array, STATION ARRAY. Only the first element is tested.

The foilborne lower gearbox diameter, FB LWR GBX DIA, is checked only if a propeller propulsion system is specified.

The foilborne duct inlet area, FB DUCT IN AREA, is checked only if a waterjet propulsion system is specified.

The foilborne range speed required, FB RANGE SPEED REQ, must not be greater than the foilborne speed required.

The foilborne drag factor, FB DRAG FACTOR, if not specified will be set equal to one.

In addition, the hullborne speed required, HB SPEED REQ, and hullborne range speed required, HB RANGE SPEED REQ, are checked. The hullborne hydrodynamic calculations will be bypassed if these parameters are not given. Foilborne calculations will be made, however.

Physical Constants

Several physical constants are set as follows:

Acceleration due to gravity = $g = 32.174$ ft/sec^2
Water density = $\rho = 1.9905$ slugs/ft^3
Water temperature = $T_{OF} = 59$ degrees Fahrenheit
Wind speed for rough water calculations = 0 knots

Pitch Angle Schedule

For flap controlled hydrofoils, experience has shown that providing a pitch schedule at off design foilborne speeds reduces drag from a zero pitch attitude. The following linear function is assumed for the craft pitch angle if one or more foil assemblies are flap controlled. For all foilborne calculations the foward foil submergence (FWD FOIL SUBMERGE) is fixed at the input value.

$$\theta = \bar{\theta}\,\frac{(V - V_D)}{(\bar{V} - V_D)} \qquad (5.1\text{-}1)$$

$$\bar{\theta} = 57.3 \tan^{-1} \frac{\tfrac{1}{2}\text{ foilborne height}}{\text{longitudinal distance between foil assemblies}} \qquad (5.1\text{-}2)$$

where:

θ = pitch angle, deg

$\bar{\theta}$ = pitch angle at $\bar{V}$, deg. Equals the pitch angle which would bring the baseline at the aft strut to a foilborne height of one half the input foilborne height.

V_D = foilborne speed required (FB SPEED REQ), kt

V = foilborne speed at which drag calculation is being made, kt

$\bar{V}$ = foilborne speed at which $\bar{\theta}$ is defined, kt. A value of 28 knots is set in HYDROD. If the foilborne speed required is less than 28 knots, then $\bar{V}$ is set to one half of the foilborne speed required.

For an all incidence controlled craft, the pitch angle is fixed at zero degrees for all foilborne speeds.

Operating Conditions

The specific operating conditions for which foilborne drag calculations are made are as follows and are summarized in Table 5.1-1.

TABLE 5.1-1 FOILBORNE DRAG CALCULATION SUMMARY

CALCULATION	SPEED	OPERATING CONDITIONS USED WEIGHT	PITCH
1. Of Incidence Settings[1]	Foilborne Speed Required	60% fuel load	0
2. At Design Speed	Foilborne Speed Required	Full load	0
3. At Range Speed	Foilborne Range Speed Required	50% fuel load	Pitch function if flap control. Zero if incidence control.
4. Of Speed Table[2]	25 to 55 knots by 5 knots increments	0, 50%, 100% fuel load	Pitch function if flap control. Zero if incidence control.

[1] This calculation is bypassed for incidence controlled ships.

[2] An output control index of four (4) is required to obtain these data.

1. Incidence Set for Flap Control

If one or more foil assemblies uses a flap control, the foil incidence angle is fixed so that a zero flap deflection is obtained at the foilborne speed required for a zero pitch angle and at a fuel load of 60% of full fuel load.

For an all incidence control craft the calculation of incidence angle is bypassed.

2. Foilborne Speed Required (Design Speed)

The foilborne drag calculation at the foilborne speed required is done for a pitch angle of zero and a full fuel load. The calculated foilborne drag is multiplied by the input value of the foilborne drag factor (FB DRAG FACTOR) and is passed to the current model as the foilborne drag (FB DRAG).

3. Foilborne Range Speed Required

The foilborne drag calculation at the foilborne range speed required is done for a pitch angle given by the pitch angle schedule and a fuel load of 50% full fuel load. The calculated foilborne drag is multiplied by the input value of the foilborne drag factor (FB DRAG FACTOR) and is passed to the current model as the foilborne range drag (FB RANGE DRAG).

4. Speed Table

If printed report number four is selected, or if graphic displays number one or two are selected, a foilborne speed-weight matrix is developed. Speeds starting at 25 knots and going to 55 knots by 5 knot increments are used. Fuel loads of 0%, 50% and 100% full fuel load are used. A pitch angle given by the pitch angle functions is used if the assemblies are flap controlled; otherwise, a zero angle is assumed. The calculated foilborne drag is multiplied by the input value of the foilborne drag factor (FB DRAG FACTOR). The data produced for this speed-weight matrix are not output to the current model.

5.1.2 Steady State Equilibrium Calculations

In order for static equilibrium to exist, the summation of the external forces and moments must be zero. An approximate static balancing technique has been employed in subroutine HFMBAL to estimate the required control surface deflections for static equilibrium. Subroutine HFMBAL calls subroutine HFMCAL to provide estimates of the foil assembly lift, drag, and moment about the craft center of gravity. Two sets of force and moment data corresponding to two assumed values of control surface deflections are then used to develop two first order equations representing lift and moment. The approximate static balancing technique is based on the assumption that both the lift and moment are sufficiently linear with control surface deflection to use first order equations to represent these components.

Control surface deflection is assumed to be either a plain flap deflection for a flap control system or foil incidence changes for an incidence control system. The current control model does not allow both control methods to be used on a single foil assembly. The type of control system is set by the FWD CONTROL IND and AFT CONTROL IND parameters.

The first order equations for each foil assembly lift and moment about the craft center of gravity are of the form:

$$L = L_1 + ((L_2 - L_1)/\Delta)\phi \qquad (5.1\text{-}3)$$

$$M = M_1 + ((M_2 - M_1)/\Delta)\phi \qquad (5.1\text{-}4)$$

where:

L = foil assembly lift

L_1 = lift at the initial control deflection (θ_1)

L_2 = lift at the second control deflection (θ_2)

M = foil assembly moment

M_1 = moment at the initial control deflection (ϕ_1)

M_2 = moment at the second control deflection (ϕ_2)

Δ = control deflection increment ($\phi_2 - \phi_1$)

ϕ = variable control deflection

The following control surface deflections are used:

Value	Flap Control*	Incidence Control
Initial ϕ_1	0	0
Second ϕ_2	4 degrees	2 degrees

An independent set of equations is developed for each foil assembly in the form shown above. To approximate a static equilibrium condition a summation of lift and moment about the craft center of gravity is done. For foilborne calculations it is assumed that a thrust equal to drag condition exists. For takeoff calculations it is assumed that the thrust is equal to the drag times the input design takeoff margin. The design takeoff margin is the required thrust margin over drag available at takeoff. These conditions introduce additional moment terms which are included in the foil assembly moment. The equations for total lift and moment are:

$$W = L_f + L_a + L_{hull} \qquad (5.1\text{-}5)$$

$$0 = M_f + M_a + M_{hull} \qquad (5.1\text{-}6)$$

---

* For flap control systems the foil incidence angle must be determined by using the incidence control mode of subroutine HFMBAL.

where:

W	=	weight
L	=	lift
M	=	moment
a		denotes aft foil assembly
f		denotes forward foil assembly
hull		denotes hull

NOTE:

1) The foil assembly lift is composed of both dynamic lift and buoyancy components.

2) The lift and moment contributions due to the hull are used for takeoff calculations and are set to zero for all foilborne calculations.

3) The foil assembly moment is composed of all the lift and drag moment components including the following:

    a) The forward foil assembly moment includes the air drag moment component.

    b) The foil assembly which contains the foilborne propulsion system elements includes in its moment the contribution due to the thrust vector.

Substitution of the foil assembly lift and moment equations into the craft total lift and moment equations and then solving for the required forward and aft control surface deflections provides the following expressions:

$$\phi_f = \Big[(W - (L_{1_f} - L_{1_a} + L_{hull}))((M_{2_a} - M_{1_a})/\Delta_a) + ((L_{2_a} - L_{1_a})/\Delta_a)(M_{1_f} - M_{1_a} + M_{hull}) \Big] /DET \qquad (5.1\text{-}7)$$

$$\phi_a = \Big[-((L_{2_f} - L_{1_f})/\Delta_f)(M_{1_f} + M_{1_a} + M_{hull}) - (W - (L_{1_f} + L_{1_a} + L_{hull}))((M_{2_f} + M_{1_f})\Delta_f) \Big] /DET \qquad (5.1\text{-}8)$$

$$DET = ((L_{2_f} - L_{1_f})/\Delta_f)((M_{2_a} - M_{1_a})/\Delta_a) - ((L_{2_a} - L_{1_a})/\Delta_a)((M_{2_f} - M_{1_f})/\Delta_f) \qquad (5.1\text{-}9)$$

where:

ϕ_f = forward control surface deflection required for static equilibrium

ϕ_a = aft control surface deflection required for static equilibrium

The control deflections calculated are approximations due to the assumption of linear variation of lift and moment with control deflection. The errors associated with this approximation are small for realistic hydrofoil configurations. This approach affords a significant reduction in computer calculation time over a more precise iterative scheme. The linear approximation of lift does not allow consideration of nonlinear conditions such as stall, cavitation, or ventilation. It is assumed that if the operating condition occurs in such a region the foil configuration is not realistic.

The calculated forward and aft control surface deflections are used to compute the steady state static equilibrium foilborne drag and lift.

5.1.3 Foil Assembly Moment About Center of Gravity

The total foil assembly moment about the craft center of gravity is obtained by summing the individual moments contributed by the lift and drag components. A positive moment is defined as a bow up rotation.

The moment contributed by the lift components is defined as follows:

$$\begin{aligned} M_{L_{CG}} = {} & (L_{DL_{foil}} + L_{B_{foil}}) (X_{cg}-X_{foil}) \\ & + (L_{DL_{pod}} + L_{B_{pod}}) (X_{cg}-X_{pod}) \\ & + (L_{B_{strut}}) (X_{cg}-X_{strut}) \end{aligned} \tag{5.1-10}$$

where:

$M_{L_{CG}}$ = moment contributed by the lift components, ft-lton

L_B = buoyancy lift, lton

L_{DL} = dynamic lift, lton

X_{cg} = longitudinal location of craft center of gravity, ft

X_{foil} = longitudinal location of 50% foil root chord, ft

X_{pod} = pod longitudinal location of lift (assumed equal to the foil location X_{foil}), ft

X_{strut} = strut longitudinal location of lift (assumed equal to the foil location X_{foil}), ft

The moment contributed by the drag component is defined as follows:

$$M_{D_{cg}} = (\Sigma D_{strut_{spray}} + \Sigma D_{strut_{wave}})(\Delta Z_{strut\ spray}) + \Sigma(D_{strut_{profile}} \; \Delta Z_{strut\ profile}) + (\Sigma D_{pod_{profile}} + \Sigma D_{pod_{wave}}) \; (\Delta Z_{pod}) + (D_{foil} \, \Delta Z_{foil}) - M_{air} \qquad (5.1\text{-}11)$$

where:

$M_{D_{CG}}$ = moment contributed by the drag components, ft-lbf

$\Sigma D_{strut_{spray}}$ = summation of the foil assembly strut spray drag, lbf

$\Sigma D_{strut_{wave}}$ = summation of the foil assembly strut wave drag, lbf

$D_{strut_{profile}}$ = individual strut profile drag, lbf

$\Sigma D_{pod_{profile}}$ = summation of the foil assembly pod profile drag, lbf

$\Sigma D_{pod_{wave}}$ = summation of the foil assembly pod wave drag, lbf

D_{foil} = total foil assembly foil drag, lbf

$\Delta Z_{strut\ spray}$ = vertical distance from craft center of gravity to the strut actual waterline

$\Delta Z_{strut\ profile}$ = vertical distance from craft center of gravity to the strut actual waterline plus 60% of the strut wetted height. This assumes that the strut center of profile drag is located at 60% of the wetted strut height below the actual waterline.

ΔZ_{pod} = vertical distance from craft center of gravity to the assumed pod center of drag. It is assumed that the pod center of drag is at the foil chord plane (ΔZ_{foil}).

ΔZ_{foil} = vertical distance from craft center of gravity to the foil root chord plane.

M_{air} = contribution of air drag to the drag moment. This term is computed and added to only the forward foil assembly moment. It is not computed for any other foil assembly.

The contribution of the air drag to the drag moment is given by:

$$M_{air} = D_{air}\ \Delta Z_{air} \qquad (5.1\text{-}12)$$

where:

D_{air} = air drag which is estimated by an empirical function of the length between perpendiculars. A discussion of this term is given in Section 5.3-7.

ΔZ_{air} = vertical distance from craft center of gravity to an estimated vertical location of the center of air drag. The estimation of the center of air drag is by an empirical function of the length between perpendiculars and is discussed in Section 5.3-7.

The total moment about the craft center of gravity is given by:

$$M_{cg} = (M_{L_{cg}} - M_{D_{cg}})/2240 \qquad (5.1\text{-}13)$$

where:

M_{cg} = total moment about the craft center of gravity, ft-lton

5.1.4 Thrust Moment Corrections

For a static equilibrium condition to exist, the thrust force must be equal to drag. The moment due to the thrust vector must be considered for a correct moment balance.

A check is made for the type of strut in each foil assembly. Whichever foil assembly has a power strut, the estimated thrust moment about the craft center of gravity is added to that foil assembly moment about the center of gravity. The following forms are used to estimate the added thrust moment depending upon the type of foilborne propulsion system.

For the foilborne calculations, the thrust required is defined as:

$$\text{THRUST} = \text{TOTAL CRAFT FOILBORNE DRAG} \qquad (5.1\text{-}14)$$

For the takeoff calculations the thrust required is defined as

$$\text{THRUST} = \text{(TOTAL FOIL SYSTEM DRAG + HULL DRAG) (DESIGN TAKEOFF MARGIN)} \qquad (5.1\text{-}15)$$

where the total foil system drag is the estimated total drag for the foil assemblies at takeoff. The hull drag is the estimated hull drag at takeoff. The design takeoff margin is the ratio of thrust to drag required at takeoff.

The added thrust moment is calculated as indicated below for the two propulsion system types.

Propeller Foilborne Propulsion System

The thrust vector is assumed to be horizontal and acts at the foil chord plane. Thus the added moment is:

$$M_{thrust} = (\text{thrust})\,(Z_{thrust\ arm}) \qquad (5.1\text{-}16)$$

where:

M_{thrust} = moment due to thrust

$Z_{thrust\ arm}$ = vertical distance from foil chord plane to the craft center of gravity

Waterjet Foilborne Propulsion System

The gross thrust vector is assumed to be horizontal and acts at the baseline while the inlet momentum is assumed to be horizontal and acts at the foil chord plane. In order to estimate both the gross thrust and inlet momentum, an estimate of the waterjet flow must be made. The following expressions are used to estimate the waterjet flow and are programed in subroutine SIMPWJ.

1. At the foilborne speed required a jet area (vena-contracta) is calculated using the following expression:

$$A_{jet} = D/(\rho\, r_o\, (r_o - 1)\, V^2) \qquad (5.1\text{-}17)$$

$$r_o = V_{jet}/V \qquad (5.1\text{-}18)$$

where:

D = craft drag, lbf

ρ = water density, slugs/ft^3

r_o = jet velocity ratio at design speed

V_{jet} = jet velocity at vena-contracta, ft/sec

V = free stream velocity, ft/sec

The jet area calculated at the design speed is then used for all subsequent calculations of jet flow.

2. The jet flow is calculated using the following expression:

$$Q = (1.06)\,(A_{jet}V + ((A_{jet}V)^2 + 4(D)\,(A_{jet})/\rho\,)^{1/2})/2 \qquad (5.1\text{-}19)$$

where:

Q = the total theoretical jet flow with a 6% factor applied to account for nozzle losses, ft^3/sec

Using the estimated value of jet flow, the gross thrust and inlet momentum are respectively:

$$T_{gross} = \rho Q V_{jet} = \rho Q^2/A_{jet} \qquad (5.1\text{-}20)$$

$$D_{inlet} = \rho Q V \qquad (5.1\text{-}21)$$

The added waterjet thrust moment is then:

$$M_{thrust} = (T_{gross} Z_{cg}) - (D_{inlet} Z_{thrust\ arm}) \qquad (5.1\text{-}22)$$

$$= \rho Q((Q/A_{jet}) Z_{cg} - V Z_{thrust\ arm}) \qquad (5.1\text{-}22)$$

where:

Z_{cg} = vertical distance of craft center of gravity above baseline

$Z_{thrust\ arm}$ = vertical distance from the foil chord plane to the craft center of gravity

The total moment for the appropriate foil assembly is then:

$$M_{total} = M_{cg} + (M_{thrust})/2240.0 \qquad (5.1\text{-}23)$$

where:

M_{total} = total moment for the appropriate foil assembly, ft-lton

5.2 LIFT CALCULATIONS

The methods used for estimating the lift coefficients are basically those which are shown in References [1] and [4].

In order to calculate the foil lift characteristics, an estimate of the section lift characteristics must be made. The basic section data used is based on a NACA 16 Series section combined with a NACA a=1 camberline. Two section characteristics are required to estimate foil lift. They are the section lift curve slope at infinite depth, and the angle of zero lift. The section lift curve slope and angle of zero lift are developed independently for the center and outboard foil sections.

5.2.1 Section Lift Curve Slope at Infinite Depth

The section lift curve slope at infinite depth is the change in section lift coefficient with changes in angle of attack at infinite depth. Data from References [6] and [7] were used to define this quantity (per degree) as:

$$C_{l_{\alpha_\infty}} = 2\pi/(180/\pi)\ \ (1.0 - 1.563\ (t/c)^{1.35}) \qquad (5.2.1\text{-}1)$$

where:

$C_{l_{\alpha_\infty}}$ = section lift curve slope at infinite depth, /deg

t/c = section thickness ratio

The lift curve slope for the total forward or aft foil assembly is obtained by averaging the center and outboard segment values as:

$$\bar{C}_{l_{\alpha_\infty}} = (C_{l_{\alpha_{\infty_{center}}}} S_{center} + C_{l_{\alpha_{\infty_{OB}}}} S_{OB})/(S_{center} + S_{OB}) \qquad (5.2.1\text{-}2)$$

where:

$C_{l_{\alpha_{\infty_{center}}}}$ = section lift curve slope for center foil segment

$C_{l_{\alpha_{\infty_{OB}}}}$ = section lift curve slope for outboard foil segment

S_{center} = foil center segment projected area, ft2

S_{OB} = foil outboard segment projected area, ft^2

5.2.2 Section Angle of Zero Lift

The following expressions are used to estimate the angle of zero lift:

1) Camberline ideal angle of attack is that angle of attack for which the flow does not turn abruptly around the leading and trailing edge of the section but attaches smoothly and leaves smoothly. This angle is also called the design angle of attack. Data from Reference [6] was used to define the ideal angle of attack:

$$\alpha_i = \alpha_{i_c} \left(C_{l_d} / C_{l_{i_c}} \right) \qquad (5.2.2\text{-}1)$$

where:

α_i = camberline ideal angle of attack, deg

α_{i_c} = theoretical camberline value for ideal angle of attack (equals 0.0 for NACA a=1 camberline)

$C_{l_{i_c}}$ = theoretical camberline design lift coefficient (equals 1.0 for NACA a=1 camberline)

C_{l_d} = section design lift coefficient (this is an input from the current model)

2) Angle of zero lift at infinite depth is that angle of attack for which the section lift is zero when the section is operated at an infinite depth of submergence. Data from References [6] and [7] were used to curve fit an expression for the angle (deg) of zero lift. The following expression was programmed:

$$\alpha_{0_\infty} = \alpha_i - (1.67\, C_{l_d})\,(5.5 - C_{l_d}) \qquad (5.2.2\text{-}2)$$

where:

α_{0_∞} = angle of zero lift at infinite depth, deg

3) The angle of zero lift at finite depth and Froude number is calculated next. A correction to the angle of zero lift for depth effects was developed by utilizing

both model test data and theoretical calculations. Test data included model tests of PCH, PGH-2, and PHM while the theoretical calculations considered finite depth potential flow solutions. The correction for depth is:

$$\Delta \alpha_{0_{h/c}} = 3.54 \left(\left(H_{sub} / (0.75C) \right) + 1 \right)^{-2} \qquad (5.2.2\text{-}3)$$

where:

$\Delta \alpha_{0_{h/c}}$ = correction (for depth) to angle of zero lift, deg

H_{sub} = submergence of foil, ft

C = average foil chord, ft

The Froude number correction was based on data shown in Reference [4]. The following expression is used:

$$\Delta \alpha_{0_{F_c}} = \exp\left(1.658 - 0.8645F_c - 0.6555\ (H_{sub}/C)\right) \qquad (5.2.2\text{-}4)$$

$$F_c = 1.6889\ V_k / (gc)^{1/2} \qquad (5.2.2\text{-}5)$$

where:

$\Delta \alpha_{0_{F_c}}$ = correction (for Froude number) to angle of zero lift, deg

F_c = chord Froude number

g = acceleration due to gravity (32.17), ft/sec^2

The section angle of zero lift is then given by:

$$\alpha_0 = \alpha_{0_\infty} + \Delta \alpha_{0_{h/c}} + \Delta \alpha_{0_{F_c}} \qquad (5.2.2\text{-}6)$$

where:

α_0 = section angle of zero lift, deg

5.2.3 Foil Pitch Lift Curve Slope at Infinite Depth

The foil pitch lift curve slope is the change in foil lift due to changes in pitch angle. The forms used to estimate this component per degree were slight modifications to those given in References [1] and [4]. These are as follows (per degree):

$$C_{L_{\alpha_\infty}} = (\bar{C}_{l_{\alpha_\infty}} \cos \Lambda_{1/4})/ \left[(1 + ((180/\pi^2)(\bar{C}_{l_{\alpha_\infty}} \cos \Lambda_{1/4}/AR))^2) + ((180/\pi^2)(C_{l_{\alpha_\infty}} \cos \Lambda_{1/4}/AR) \right] \qquad (5.2.3\text{-}1)$$

$$\Lambda_{1/4} = \Lambda_{OB}\, Y_{OB}/(Y_{center} + Y_{OB}) \qquad (5.2.3\text{-}2)$$

where:

$\Lambda_{1/4}$ = weighted average of the 25% chord sweep, deg

Λ_{OB} = outboard sweep, deg

Y_{center} = foil center semispan, ft

Y_{OB} = foil outboard semispan, ft

AR = aspect ratio

$\bar{C}_{l_{\alpha_\infty}}$ = average section lift curve slope, / deg

This form is due to Diederich from NACA T.N. 2335.

5.2.4 Correction For Finite Depth

The correction for the image system (finite depth) on lift curve slope was obtained from Reference [1]. The following terms are programmed:

$$K_{\alpha} = 0.7 + 0.025\,AR \qquad \text{for } AR \leq 12 \tag{5.2.4-1}$$

$$= 1.0 \qquad \text{for } AR > 12 \tag{5.2.4-2}$$

$$RATIO_{\alpha} = 1 - (1/(2\ ((H_{sub}/\,\overline{C}\ K_{\alpha}) + 1)^2\ )) \tag{5.2.4-3}$$

$$C_{L_{\alpha_{F_{\infty}}}} = RATIO_{\alpha}\ C_{L_{\alpha_{\infty}}} - 0.00436\,|\overline{\lambda} - 0.2| \tag{5.2.4-4}$$

$$\overline{C} = S_{total}/(2(Y_{center} + Y_{ob})) \tag{5.2.4-5}$$

$$\overline{\lambda} = (Y_{center} + \lambda_{OB}\ Y_{OB})/(Y_{center} + Y_{OB}) \tag{5.2.4-6}$$

where:

$C_{L_{\alpha_{F_{\infty}}}}$ = infinite Froude number finite depth foil lift curve slope, /deg

H_{sub} = foil submergence, ft

$\overline{C}$ = average foil chord, ft

S_{total} = total foil projected area, ft^2

$\overline{\lambda}$ = weighted average of taper ratio

λ_{OB} = outboard taper ratio (tip chord/root chord)

5.2.5 Correction For Finite Froude Number

The correction for finite Froude number on the lift curve slope (per degree) was obtained from Reference [4]. The following terms were programmed.

$$F_c = 1.6889\, V_k / \ (g\, \bar{C})^{1/2} \qquad (5.2.5\text{-}1)$$

$$C_{L_\alpha} = C_{L_{\alpha_{F_\infty}}} (1 - \exp(-0.298 - 0.433\, F_c - 0.544\, (H_{sub}/\bar{C})(5.2.5\text{-}2)$$

where:

F_c = chord Froude number

V_k = speed, kt

5.2.6 Distribution of Lift Curve Slope

In order to estimate incidence and flap lift slopes, a distribution of foil lift curve slopes between the center and outboard foil segments is required. On inverted T foils, no distribution is required because there is only one foil segment; however on PI and 3 STRUT configurations, a distribution is required. For PI and 3 STRUT configurations it was assumed that the spanwise lift distribution follows the same loading curve as shown in Reference [1] for flap deflection lift. Using this assumed loading distribution, the following forms were used to estimate the center and outboard pitch lift curve slopes.

The center segment pitch lift curve slope is as follows:

$$C_{L_{\alpha_{center}}} = \Delta K_b\, C_{L_\alpha}\, S_{total}/S_{center} \qquad (5.2.6\text{-}1)$$

$$\Delta K_b = K_{b_\eta} \qquad (5.2.6\text{-}2)$$

$$K_{b_\eta} = K_\delta \eta + (1 - K_\delta)\eta^4 \qquad (5.2.6\text{-}3)$$

$$K_{\delta} = 1.35 - 0.13\bar{\lambda} \qquad (5.2.6\text{-}4)$$

$$\eta = Y_{center}/(Y_{center} + Y_{OB}) \qquad (5.2.6\text{-}5)$$

where:

$C_{L_{\alpha_{center}}}$ = center segment pitch lift curve slope, /deg

η = span location of outboard strut

$\bar{\lambda}$ = weighted average of taper ratio

Outboard segment pitch lift curve slope is given by:

$$C_{L_{\alpha_{OB}}} = (1 - \Delta K_b)\, C_{L_\alpha}\, S_{total}/S_{OB} \qquad (5.2.6\text{-}6)$$

5.2.7 Foil Incidence Lift Curve Slope

The foil center and outboard segment incidence lift curve slopes were developed directly from foil pitch lift curve slope but were based on a function of the exposed area of each segment. In order to estimate the incidence lift, it was assumed that the foil area used for pitch lift curve slope was reduced by a value equal to one half the foil area covered by the pods. The one half factor used for the foil area covered by the pods was an estimate of the lift spill over onto the pods by the foil segment.

Using the same loading curve from Reference [1] that was used to estimate the pitch lift distribution, a ratio of loading factor based on exposed semispan plus a factor of pod-foil area to semispan was used to ratio the foil segment pitch lift to obtain the incidence lift. The following expressions were used to estimate incidence lift (per degree):

$$C_{L_{i_*}} = C_{L_{\alpha_*}} (\Delta K_{b_{exposed}} / \Delta K_{b_{total}})_* \qquad (5.2.7\text{-}1)$$

$$K_{b_{()}} = (K_{b_{\eta_{outside}}} - K_{b_{\eta_{inside}}})_{()} \qquad (5.2.7\text{-}2)$$

$$K_{b_{\eta_y}} = K_{\delta}\, \eta_y + (1 - K\ )\eta_y^{4} \qquad (5.2.7\text{-}3)$$

$$K = 1.35 - 0.13\, \overline{\lambda} \qquad (5.2.7\text{-}4)$$

where:

$*$ = either center of outboard foil segment

$()$ = either exposed or total

$K_{b_{exposed}}$ = difference in K_{b_η} term based on exposed semispan plus equivalent pod semispan. The equivalent pod-foil semispan was estimated as $(K_{L_{factor}})$ times (Σ ½ pod widths)

$K_{L_{factor}}$ = pod lift carry over factor (assumed equal to 0.5)

Σ ½ pod widths = sum of one-half pod widths on concurrent semispan

$\Delta K_{b_{total}}$ = difference in K_b term based on total concurrent semispan

η_i = ratio of span location to total semispan (i = outside or inside)

Figure 5.2-1 shows how the various ΔK_b terms are related to the foil geometry and the span loading factor K_{b_η}.

An average foil incidence lift curve slope was estimated by using the following expression:

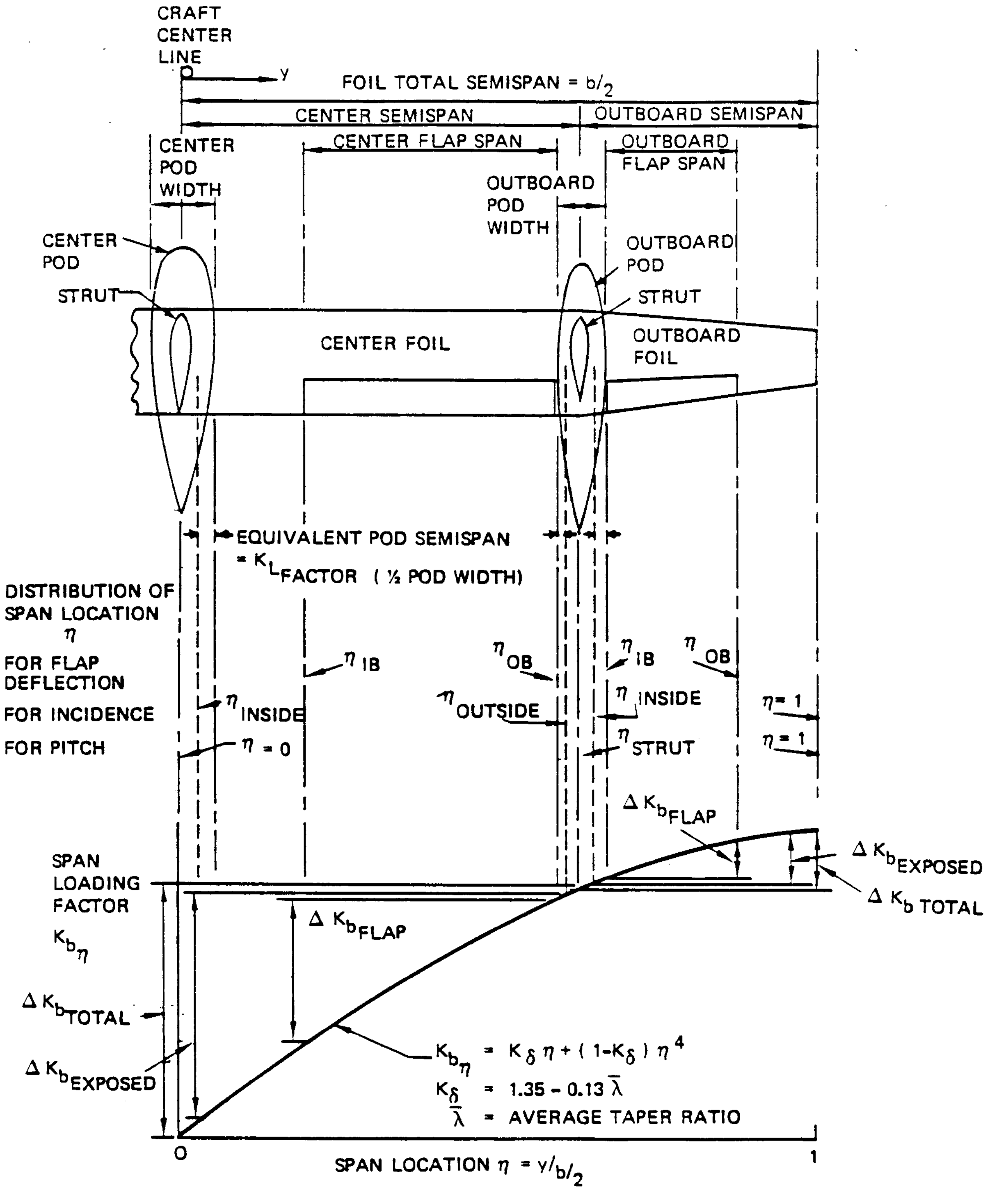


FIGURE 5.2-1 SPAN LOADING FACTOR K_{b_η}

$$C_{L_i} = (C_{L_{i_{OB}}} S_{OB} + C_{L_{i_{center}}} S_{center})/$$

$$(S_{OB} + S_{center}) \qquad (5.2.7\text{-}5)$$

5.2.8 Foil Flap Lift Curve Slope

The foil center and outboard segment flap lift curve slopes were developed in a manner analogous to that of the incidence lift curve slopes. The loading curves were developed using the same expressions as shown above except that the spanwise ratios of η were based on flap span location. It was assumed that the flap started from the pod side and extended either inboard or outboard depending upon which foil segment was being evaluated. The correction for flap chord ratio was a modification of the results shown in Reference [1]. The functions used to estimate the flap lift curve slopes (per degree) were:

$$C_{L_{\delta *}} = C_{L_{\alpha *}} (\Delta K_{b_{flap}} / \Delta K_{b_{total}})_* \text{RATIO}_\delta \qquad (5.2.8\text{-}1)$$

$$\text{RATIO}_\delta = (1 + (1-E)(62.5/(AR + 5)^3))$$

$$(E (2.665 + E(-3.3383 + E(2.4528 - 0.7798E))) \qquad (5.2.8\text{-}2)$$

where:

$*$ = either center or outboard foil segment

$\Delta K_{b_{flap}}$ = difference in K_b term based on flap span

E = flap chord ratio

AR = foil aspect ratio

An average foil flap lift curve slope was estimated by using the following expression:

$$C_{L_\delta} = (C_{L_{\delta_{center}}} S_{center} + C_{L_{\delta_{OB}}} S_{OB}) / (S_{center} + S_{OB}) \qquad (5.2.8\text{-}3)$$

5.2.9 Foil Maximum Lift

Several types of foil lift limiting conditions can occur on a hydrofoil. These include: (1) foil stall due to flow boundary layer separation, (2) leading edge cavitation, (3) mid chord and/or junction cavitation, and (4) flap stall or cavitation.

A method described in the Control Analysis Module User Manual has been developed for estimating $C_{L_{MAX}}$ due to leading edge cavitation. Methods for calculating the limitations due to other causes are not considered by the program at this time.

5.2.10 Total Foil Lift Coefficient

The foil lift coefficient is developed as a function of pitch, incidence, angle of zero lift and flap deflection. The general form used was:

$$C_{L_*} = C_{L_{\alpha_*}} \theta + C_{L_{i_*}} (i_* - \alpha_{o_*}) + C_{L_{\delta_*}} \delta_* \qquad (5.2.10\text{-}1)$$

where:

θ = ship pitch angle, deg

i = foil incidence angle, deg

α_o = foil angle of zero lift, deg

δ = flap deflection, deg

C_{L_α} = lift curve slope due to pitch, /deg

C_{L_i} = lift curve slope due to incidence, /deg

C_{L_δ} = lift curve slope due to flap detection, /deg

* = either center or outboard foil segment

A total foil lift coefficient was estimated by using the following expression:

$$C_L = (C_{L_{center}} S_{center} + C_{L_{OB}} S_{OB})/ (S_{center} + S_{OB}) \qquad (5.2.10\text{-}2)$$

5.2.11 Total Foil Dynamic Lift

The total foil dynamic lift (lbf) for each foil assembly is developed by the following form:

$$L_{DL_{foil}} = C_L \, Sq \qquad (5.2\text{-}11\text{-}1)$$

where:

C_L = total foil lift coefficient

S = foil projected area, ft^2

q = dynamic pressure, lbf/ft^2

5.2.12 Total Foil Assembly Lift

The total foil assembly lift is composed of the foil dynamic lift plus dynamic lift of the pods plus the buoyancy of the foil, struts, and pods. The form used to calculate total lift (lton) is:

$$L_{tot} = L_{B_{foil}} + L_{DL_{foil}} + L_{B_{pod}} + L_{B_{strut}} \qquad (5.2.12\text{-}1)$$

where:

B = buoyancy lift, lton

DL = dynamic lift, lton

It was assumed that the pod and strut dynamic lifts were zero. The foil and pod buoyancies are obtained from the input data. These quantities are calculated in the Foil/Strut Geometry Module. The strut buoyancy is computed by multiplying the per unit length strut buoyancy term by the strut submergence.

5.3 DRAG CALCULATIONS

The methods used for estimating drag are basically those which are shown in References [1] to [4]. These methods are based on typical data given in References [5] to [7] and from a limited set of model experimental data for specific hydrofoil configurations. The foil assembly drags are developed independently for foil, strut, and pod.

The foil drag is broken down into a minimum drag component and drag components due to lift. The strut drag includes profile, spray, and wave drag components, while the pod drag includes profile and wave drag components. A description of the various drag components are listed below and are given in the order calculated in subroutine FODRAG. Figures 5.3-1 to 5.3-3 show typical foil drag buildups using the following foil drag components.

5.3.1 Skin Friction Drag Coefficient

The skin friction drag coefficient is based on a curve fit of the Schoenherr line drag coefficient curve as shown in Reference [5]. The following terms are programmed:

if:

$$R_1 > 10^3 \qquad (5.3.1\text{-}1)$$

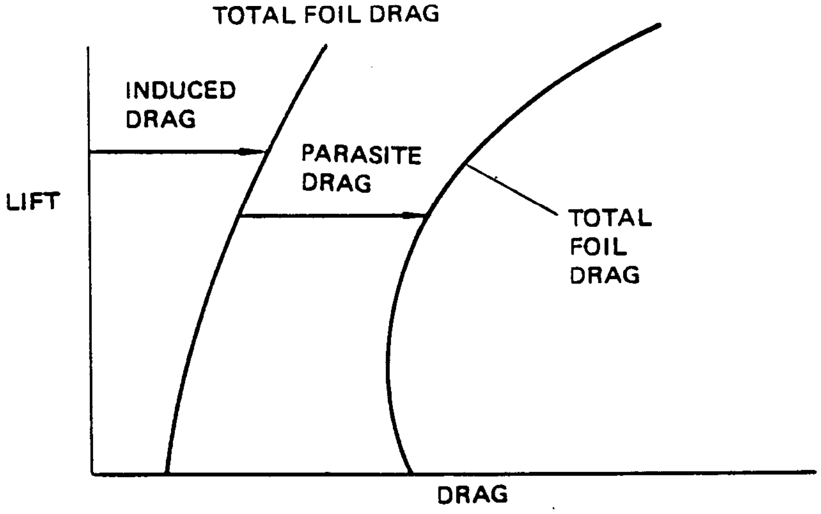


FIGURE 5.3-1 TOTAL FOIL DRAG BUILDUP

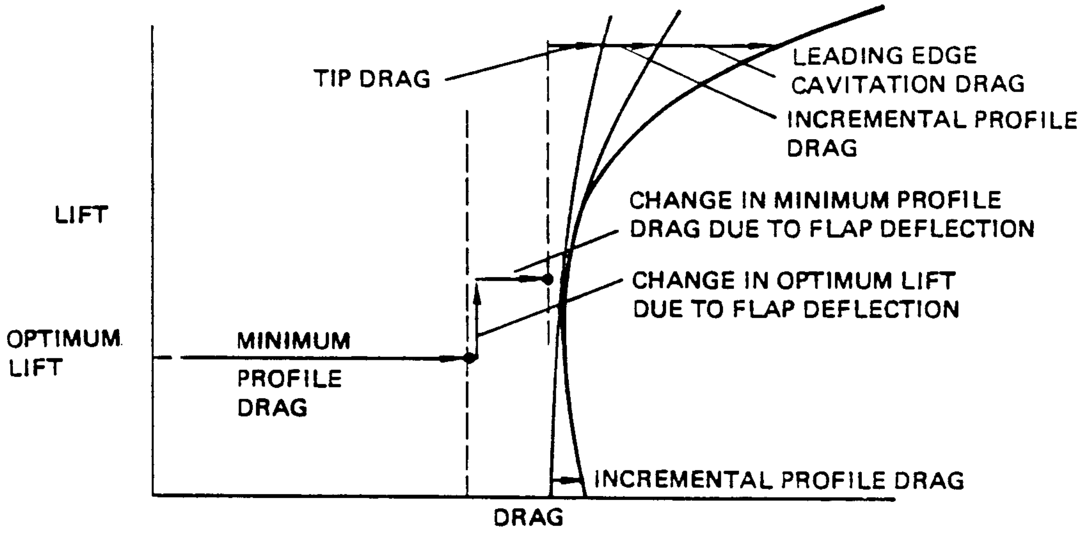


FIGURE 5.3-2 FOIL PARASITE DRAG BUILDUP

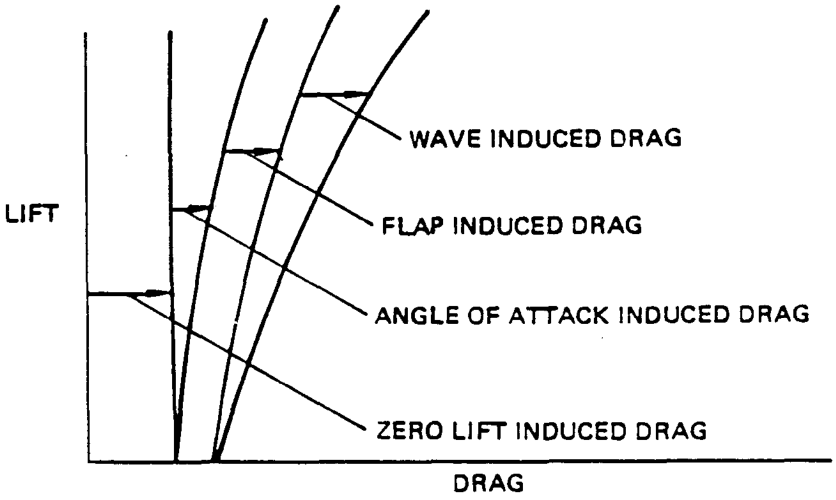


FIGURE 5.3-3 FOIL INDUCED DRAG BUILDUP

then

$$C_f = (15.0154+1.5212(\mathrm{Ln}_e(R_1 x 10^{-6})))^{2} + \Delta C_f \qquad (5.3.1\text{-}2)$$

or if:

$$R_1 < 10^3 \qquad (5.3.1\text{-}3)$$

then

$$C_f = (R_1 + 1)^{-1/2} \qquad (5.3.1\text{-}4)$$

and

$$R_1 = 1.6889\ V_k\ l / \nu \qquad (5.3.1\text{-}5)$$

where:

R_1 = Reynolds number

V_k = speed, kt

l = characteristics length, ft

ν = kinematic viscosity, 1.46×10^{-5} ft^2/sec

C_f = turbulent skin friction coefficient

ΔC_f = roughness allowance (0.0004)

5.3.2 Section Profile Drag and Optimum Lift Coefficient

The basic section data used in ASSET/HYDROFOIL is based on a NACA 16 series section combined with a NACA a=1 camberline. The following terms are required for the foil profile drag and are shown on Figure 5.3-2.

A. The minimum profile drag function was obtained from a modification of data shown in Reference [1]. Equation (5.3.2-1) is used if the Reynold's number 5×10^4; otherwise, equation (5.3.2-2) is used.

$$C_{d_{p_{min}}} = 0.00826\,(1 + 1.7\ t/c)\,(R_c \times 10^{-6})^{-0.1472}\,(F_{C_d}) \qquad (5.3.2\text{-}1)$$

$$C_{d_{p_{min}}} = 25\,(1 + 1.7\ t/c)\,(R_c)^{-0.7}\,(F_{C_d}) \qquad (5.3.2\text{-}2)$$

where:

R_c = Reynolds number based on foil chord

t/c = foil thickness ratio

(F_{C_d}) = section drag allowance (equals 1.03, 3% drag increase assumed)

B. The section angle of zero lift, α_o, is the angle of attack that the foil section must be set at to obtain zero lift. Equations for calculating α_o are given in Section 5.2.2.

C. The section optimum lift coefficient is that section lift coefficient for which a minimum profile drag is obtained. Generally, for cambered sections the minimum profile drag occurs at the camberline ideal angle of attack. The following expressions are required to determine the foil optimum lift coefficient.

1. The section lift curve slope at infinite depth is the change in section lift coefficient with changes in angle of attack at infinite depth. Data from Reference [7] was used to define the section infinite depth lift curve slope (per degree).

$$C_{1_{\alpha_\infty}} = (2\pi/(180/\pi))\,(1.0 - 1.563(t/c)^{1.35}) \qquad (5.3.2\text{-}3)$$

2. Section lift curve slope at finite depth and Froude number. Corrections for depth and Froude number effects on the section lift curve slope were developed in a manner similar to that discussed for the total foil in Section 5.2.5. References [1] and [4] were used to develop the following expression.

$$C_{1_\alpha} = \left[C_{1_{\alpha_\infty}} \left(1 - ½\,((H_{sub}/C) + 1)^{-2}\right)\right] \left[(1 - \exp(-0.298 - 0.433F_c - 0.544\,(H_{sub}/C)\right] \qquad (5.3.2\text{-}4)$$

The first bracketed quantity on the right-hand side of equation (5.3.2-4) is the image term. The second bracketed quantity is the Froude number term.

3. Foil optimum lift coefficient is estimated based on the following expression:

$$C_{L_{OPT_*}} = 0.8\,C_{1_{\alpha_*}} (\alpha_{i_*} - \alpha_{o_*}) \qquad (5.3.2\text{-}5)$$

where:

0.8 = a value obtained from Reference [6] for the effectiveness of a NACA a=1 camberline in developing lift

$*$ = either center or outboard foil segment

α_i = camberline ideal angle of attack as defined in Section 5.2.2.

5.3.3 Foil Parasite Drag

The foil parasite drag is that portion of the total foil drag associated with skin friction and form drag. Actual foil areas between strut centerlines are used for drag calculations. The inclusion of the foil area covered by the struts and pods is assumed to provide an estimate of the interference drag. The following components are computed for parasite drag. Figure 5.3-2 shows a typical foil drag buildup using the following components.

FOIL TIP DRAG

The added foil parasite drag due to the foil tips is obtained from Reference [5] and is defined as:

$$\Delta D_{tips} = \left(\left(0.15(t/c)^2\right)_{tip} + 0.03\, C_L{}^3\right) q\, c^2{}_{tip} \qquad (5.3.3\text{-}1)$$

where:

$(t/c)_{tip}$ = section thickness ratio at foil tip

C_L = foil lift coefficient

c_{tip} = tip chord of foil, ft

q = dynamic pressure, lbf/ft^2

FOIL MINIMUM PROFILE DRAG

The foil minimum profile drag is that value of minimum profile drag for the foil when it is operating at its optimum lift coefficient, as defined in Section 5.3.2, and at a zero flap deflection. It is defined as:

$$D_{P_{min}} = C_{d_{P_{min}}} (S/\cos\gamma)\, q\, (F_{P_m}) \qquad (5.3.3\text{-}2)$$

where:

$C_{d_{p_{min}}}$ = section minimum profile drag as defined in Section 5.3.2

S = projected foil area, ft^2

γ = anhedral angle, deg

q = dynamic pressure, lbf/ft^2

$(F_{P_{min}})$ = three dimensional allowance for profile drag (equals 1.04, 4% drag increase assumed)

FOIL INCREMENTAL PROFILE DRAG

The foil incremental profile drag is the increase in profile drag above the minimum value caused by operating the foil at other than the optimum lift coefficient. The form used for the calculation of incremental profile drag is that shown in Reference [2] and is calculated as follows:

$$\Delta D_{P_{min}} = \Delta C_{D_{P_{min}}} (S/\cos\gamma)\, q \tag{5.3.3-3}$$

$$\Delta C_{D_{P_{min}}} = K\left[(C_L/\cos\gamma) - C_{L_{opt}} - (\Delta C_{L_{min(flap)}}/\cos\gamma)\right]^2 \tag{5.3.3-4}$$

$$K = 0.476 \qquad (\text{for } Re < 5 \times 10^4) \tag{5.3.3-5}$$

$$K = 0.12\,(Rc \times 10^{-6})^{-0.46} \qquad (\text{for } Rc > 5 \times 10^4) \tag{5.3.3-6}$$

$$\Delta C_{L_{min(flap)}} = K_{flap}\,(\Delta C_{L_{(flap)}}) \tag{5.3.3-7}$$

where:

$C_{D_{P_{min}}}$ = incremental profile drag coefficient

$C_{L_{opt}}$ = foil optimum lift coefficient as given in Section 5.3.3

γ = anhedral angle, deg

S = projected foil area, ft^2

q = dynamic pressure, psf

$C_{L_{min(flap)}}$ = change in $C_{L_{opt}}$ due to flap deflection

K_{flap} = a factor relating the change in the section optimum lift coefficient to the change in lift coefficient due to flap deflection. Reference [2] gives a value of 0.5 for this factor

$\Delta C_{L(flap)}$ = change in lift coefficient due to flap deflection

R_c = Reynolds number based on foil chord

FOIL FLAP DRAG INCREMENT

The foil flap drag increment is the increase in the foil minimum profile drag due to flap deflection. The form used for the calculation of flap drag increment is that shown in Reference [2] and is calculated as follows:

$$\Delta D_{P_{min}} = 0.00012 \, |\delta|^{1.6} \, (qS/\cos \gamma) \qquad (5.3.3\text{-}8)$$

where:

$|\delta|$ = absolute value of flap deflection, deg

S = projected foil area, ft^2

γ = anhedral angle, deg

q = dynamic pressure, lbf/ft^2

FOIL SEPARATION DRAG

Several types of separation drag can occur on a foil. These include: 1) a foil stall drag due to flow separation (this is in addition to the section incremental profile drag); 2) a leading edge cavitation drag increment; 3) a mid chord and/or junction cavitation drag increment; and 4) a flap stall/cavitation drag increment. Currently there are no general methods available to calculate any of the above separation drag components.

A review of model test data for PCH, PGH-2, and PHM has provided the following preliminary form for the leading edge cavitation drag increment:

$$\Delta D_{lecav} = \Delta C_{D_{lecav}} \, S \, q \qquad (5.3.3\text{-}9)$$

$$\Delta C_{D_{lecav}} = \xi^{12}(0.5549 + \xi^{2}(0.5598\,\xi^{2} - 1.071))\; C_{L_{max}} \qquad (5.3.3\text{-}10)$$

$$\xi = C_L / C_{L_{max}} \qquad (5.3.3\text{-}11)$$

where:

$C_{L_{max}}$ = maximum lift coefficient with leading edge cavitation (see Control Analysis Module User Manual for the method used to calculate this term)

S = projected foil area, ft^2

q = dynamic pressure, lbf/ft^2

5.3.4 Foil Induced Drag

The foil induced drag is that portion of the total foil drag associated with the deflection of the fluid in which the foil is producing lift. This drag component is a consequence of a finite span lifting surface. The operation of a foil near a free surface introduces addition terms to the induced drag calculation. The following components are computed for induced drag and are stored in arrays as indicated for each component. Figure 5.3-1 shows a typical foil drag build-up using the following components.

FOIL INDUCED DRAG COEFFICIENT DUE TO ANGLE OF ATTACK AT INFINITE DEPTH

The infinite depth induced drag coefficient is obtained from Reference [1] and is defined as:

$$\Delta(dC_{D_I}/dC^2_{L_\alpha})_\infty = ((\pi AR)\cos(\Lambda_{1/4}-5^o))^{-1} + \Delta(dC_{D_I}/dC^2_{L_\alpha})_\infty \qquad (5.3.4\text{-}1)$$

and

$$\Delta(dC_{D_I}/dC^2_{L_\alpha})_\infty = 0.0005(\overline{\lambda} - \lambda_o)/(\lambda(1-\lambda_o)) \quad \text{if } \overline{\lambda} > \lambda_o \qquad (5.3.4\text{-}2)$$

$$\Delta(dC_{D_I}/dC^2_{L_\alpha})_\infty = 0.02(\lambda_o - \overline{\lambda})^2/\lambda_o \quad \text{if } \overline{\lambda} \le \lambda_o \qquad (5.3.4\text{-}3)$$

$$\lambda_o = 0.4 - 0.3(0.08\,H_{sub}/C + 1)^{-5} \qquad (5.3.4\text{-}4)$$

$$= \text{tip chord/root chord} \quad \text{(for T foils)} \qquad (5.3.4\text{-}5)$$

$$= \text{(center span + (tip chord/root chord) (outboard span))/total span} \quad \text{(for PI foils)} \qquad (5.3.4\text{-}6)$$

where:

$\Delta(dC_{D_I}/dC^2_{L_\alpha})_\infty$ = increase in angle of attack induced drag due to non-optimum foil taper ratio

$\bar{\lambda}$ = weighted taper ratio

λ_o = optimum taper ratio

H_{sub} = submergence of foil, ft

C = average foil chord, ft

CORRECTION OF INDUCED DRAG COEFFICIENT FOR DEPTH EFFECT

The correction of the infinite depth induced drag coefficient for the free surface image effect was obtained from Reference [1].

The programmed form is:

$$(dC_{D_i}/dC^2_{L_\alpha}) = R\,(dC_{D_i}/dC^2_{L_\alpha})_\infty \qquad (5.3.4\text{-}7)$$

$$R = 1 + (H_{sub}/((C)(L_\alpha)) + 1)^{-2} \qquad (5.3.4\text{-}8)$$

$$L_\alpha = 0.2 + 0.14\ AR \qquad (5.3.4\text{-}9)$$

where:

R = induced depth correction term

AR = foil aspect ratio

H_{sub} = foil submergence, ft

C = average foil chord, ft

The induced drag due to angle of attack lift is given by:

$$D_{ind} = (dC_{D_i}/dC^2_{L_\alpha})\ S\ q\ C^2_L \qquad (5.3.4\text{-}10)$$

where:

S = projected foil area, ft^2

q = dynamic pressure, lbf/ft^2

C_L = foil lift coefficient

INDUCED DRAG COMPONENT DUE TO FLAP LIFT

When flaps are deflected to produce lift changes, a redistribution of span loading occurs which in turn changes the total induced drag. Using the results shown in Reference [1], the following expressions have been programmed to estimate the effect of flap lift on induced drags. Figure 5.2-1 shows how the ΔK_b term is related to the foil geometry and span loading factor K_{b_η}.

$$K_\delta = 1.35 - 0.13\bar{\lambda} \qquad (5.3.4\text{-}11)$$

$$K_{b_{\eta_*}} = K_\delta \eta_* + (1 + K_\delta)\eta_*^4 \qquad (5.3.4\text{-}12)$$

$$\Delta K_b = \Sigma (K_{b_{\eta_{tip}}} - K_{b_{\eta_{root}}}) \qquad (5.3.4\text{-}13)$$

$$\Phi_{\eta_*} = 0.4545\,(1 + 1.2\,\eta_*)(\eta_*)^{1/4} \qquad (5.3.4\text{-}14)$$

$$\Delta\Phi = \Sigma (\Phi_{\eta_{tip}} - \Phi_{\eta_{root}}) \qquad (5.3.4\text{-}13)$$

where:

$\bar{\lambda}$ = weighted taper ratio

$*$ = tip or root

η_* = flap span location ratio of semispan for tip end and for root end of flap, respectively

The ΔK_b and $\Delta\Phi$ terms are summed for all flap segments on the foil.

The induced drag coefficient due to flap lift is:

$$\Delta C_{D_{i_\delta}} = (dC_{D_i}/dC^2_{L_\alpha}) \left[((1/\Delta\Phi)-1)(\Delta C_{L_{flap}})^2 + ((\Delta K_b/\Delta\Phi)-1)(C_L - \Delta C_{L_{flap}})(\Delta C_{L_{flap}}) \right. \qquad (5.3.4\text{-}16)$$

where:

$\Delta C_{L_{flap}}$ = change in lift coefficient due to flap deflection

Figure 5.3-4 from Reference [1] is included to clarify the above expressions for the flap induced drag coefficient.

The change in induced drag due to flap lift is computed by:

$$\Delta D_{ind_{flap}} = \Delta C_{D_{i_\delta}} \; S \; q \qquad (5.3.4\text{-}17)$$

WAVE INDUCED DRAG

The increase in induced drag due to free surface wave making was obtained from References [1] and [4] and is defined as:

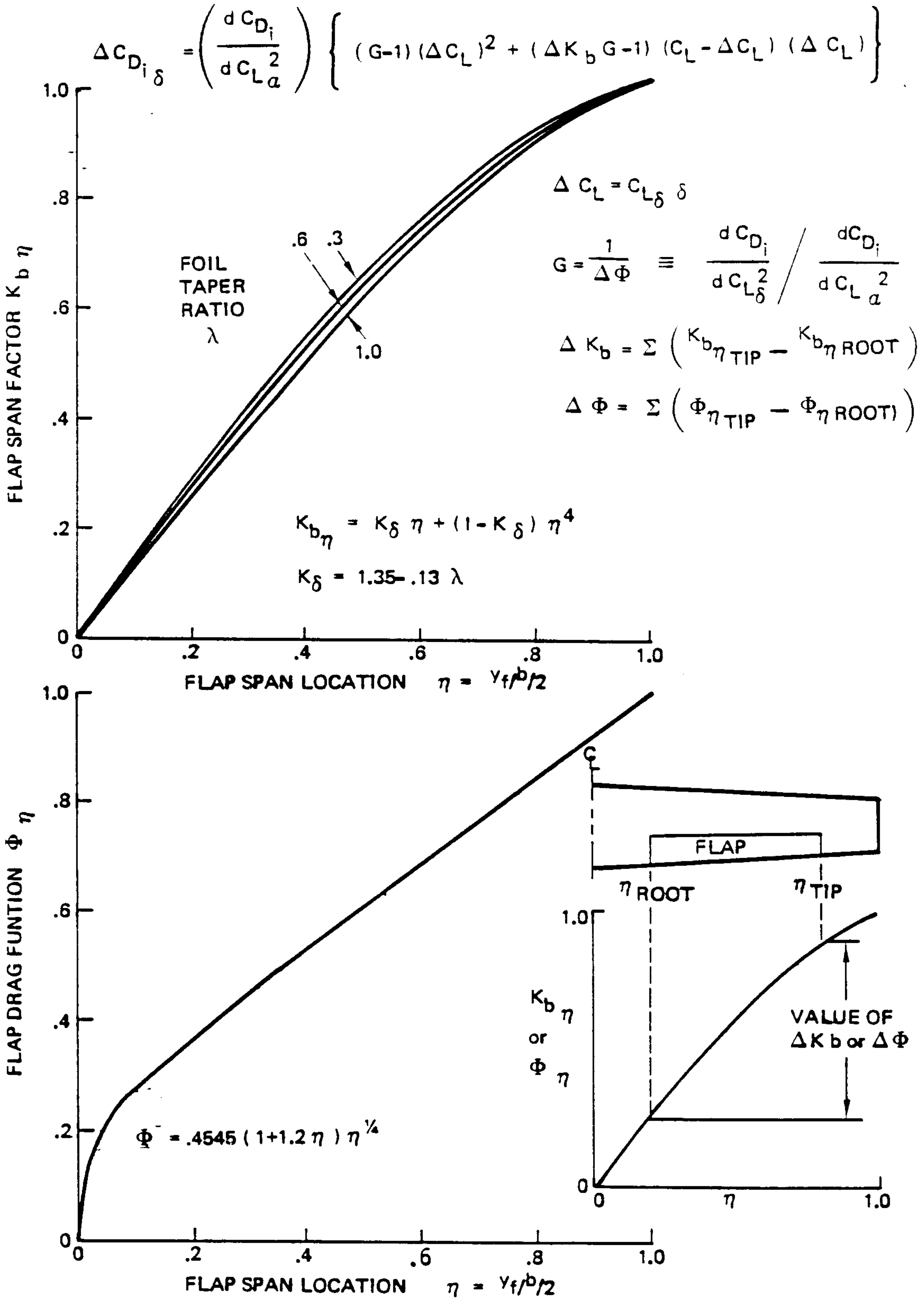
$$F_c = 1.6889\, V_K/(g\, c)^{1/2} \qquad (5.3.4\text{-}18)$$

$$F_h = 1.6889\, V_K/(gH_{sub})^{1/2} \qquad (5.3.4\text{-}19)$$

where:

V_K = speed, kt

F_c = chord Froude number



$$\Delta C_{D_{i\delta}} = \left(\frac{d C_{D_i}}{d C_{L_\alpha}^{2}}\right)\left\{(G-1)(\Delta C_L)^2 + (\Delta K_b G-1)(C_L - \Delta C_L)(\Delta C_L)\right\}$$

$\Delta C_L = C_{L_\delta}\,\delta$

$G = \frac{1}{\Delta\Phi} \equiv \frac{d C_{D_i}}{d C_{L_\delta}^{2}} \Big/ \frac{d C_{D_i}}{d C_{L_\alpha}^{2}}$

$\Delta K_b = \Sigma\left(K_{b_{\eta\,TIP}} - K_{b_{\eta\,ROOT}}\right)$

$\Delta\Phi = \Sigma\left(\Phi_{\eta\,TIP} - \Phi_{\eta\,ROOT}\right)$

$K_{b_\eta} = K_\delta\,\eta + (1-K_\delta)\,\eta^4$

$K_\delta = 1.35 - .13\,\lambda$

$\Phi = .4545\,(1+1.2\,\eta)\,\eta^{1/4}$

FIGURE 5.3-4 INDUCED DRAG DUE TO FLAP DEFLECTION

F_n = submergence Froude number

then:

$$K_W = (1 + 2.6/F_c^3)(0.17 + 0.013\ AR)(H_{sub}/C)^{(0.012\ AR - 1.42)} \qquad (5.3.4\text{-}20)$$

$$P = (F_h^2 \exp(2/F_h^2))^{-1} \qquad (5.3.4\text{-}21)$$

$$\Delta D_{wave} = K_W P C_L^2 S q \qquad \text{for } H_{sub} \geq 0.5t \qquad (5.3.4\text{-}22)$$

$$\Delta D_{wave} = 0 \qquad \text{for } H_{sub} < 0.5t \qquad (5.3.4\text{-}23)$$

If H_{sub} is less than one half the foil thickness, the wave drag is set to zero.

INDUCED DRAG AT ZERO LIFT

At zero lift and zero flap deflection a typical foil has a span load distribution which produces an induced drag. No simple expression has been developed for this component, but based on theoretical analysis of several current hydrofoil configurations, the following form has been used as a preliminary estimate for this drag component.

$$D_{zero} = 0.0002\ S q \qquad (5.3.4\text{-}24)$$

5.3.5 Strut Drag Components

Three components of strut drag are computed. They are profile, spray, and wave drag.

The current version considers only steady state straight ahead motions; therefore, the only strut profile drag component considered at this time is the minimum profile drag component. Only the exposed and submerged portion of the strut is used to calculate profile drag. No interference drag allowances are made to the strut drag; however, the pod profile drag does include a wetted area equal to the strut section area.

If the strut submergence becomes zero or less, all strut drag components are set to zero. If the strut submergence becomes greater than the strut length, the strut spray drag is set to zero and the wave drag term is replaced by a strut hull interference drag term. The strut drag components are as follows:

STRUT PROFILE DRAG (ZERO SIDE SLIP ANGLE)

The strut minimum profile drag function was obtained from a modification of data shown in Reference [1] and is calculated as follows:

$$C_{d_{P_{min}}} = 0.00826(1 + 1.7\ t/c)\,(R_c 10^{-6})^{-0.1472}(F_{C_d}) \quad \text{for } R_c > 5 \times 10^4 \qquad (5.3.5\text{-}1)$$

$$= 25(1 + 1.7\ t/c)\,(R_c)^{-0.7}(F_{C_D}) \quad \text{for } R_c < 5 \times 10^4 \qquad (5.3.5\text{-}2)$$

$$D_{P_{min}} = C_{d_{P_{min}}}\ S\ q \qquad (5.3.5\text{-}3)$$

where:

R_c = Reynolds number based on average wetted strut chord

t/c = average wetted strut thickness ratio

(F_{C_d}) = section drag allowance (equals 1.04, 4% drag increase assumed)

S = strut actual area from pod top to waterline, ft^2

q = dynamic pressure, lbf/ft^2

STRUT SPRAY DRAG

The general form used to estimate strut spray drag was obtained from Reference [3] and is calculated as follows:

$$D_{spray} = C_s^2 \ (\xi/C_s)^2 \ (0.006 + 0.0375 \, (t/C_s)(C_s/\xi)q \qquad (5.3.5\text{-}4)$$

where:

C_s = strut waterline chord, ft

ξ = chordwise distance from leading edge of strut to maximum thickness location at strut waterline, ft

t = strut maximum thickness at waterline, ft

q = dynamic pressure, lbf/ft^2

Currently a value of

$$\xi/C_s = 0.5 \qquad (5.3.5\text{-}5)$$

is used.

STRUT WAVE DRAG

The general form used to estimate strut wave drag was obtained by curve fitting strut wave drag data shown in Reference [5], and was calculated as follows:

$$D_{wave} = C_{D_t} \ q \ (t/C_s)^2 \, C_s^2 \qquad (5.3.5\text{-}6)$$

$$C_{D_t} = 0.6116 \ (F_{C_s}^3 \ \exp \ (0.15/F_{C_s}^3)^{-1}$$

$$F_{C_s} = 1.6889\ V_K / (gC_s)^{1/2} \qquad (5.3.5\text{-}7)$$

where:

F_{C_s} = strut waterline chord Froude number

V_K = speed, kt

STRUT-HULL INTERFERENCE DRAG

When the submergence of the strut is greater than the strut length, the strut spray drag is set to zero and the strut wave drag component is replaced by a strut-hull interference drag term. An estimate of the strut-hull interference drag was obtained by using data provided in Reference [7] and is calculated as follows:

$$D_{int} = 0.3\ t^2\ q \qquad (5.3.5\text{-}7)$$

where:

t = strut thickness at the strut-hull intersection, ft

5.3.6 Pod Drag Components

Currently, two types of pod configurations are considered. Control and propeller drive pods are assumed to have a circular frontal shape while waterjet inlet pods are assumed to have a rectangular frontal shape. All pods consist of three sections: a nose section of varying frontal area, a mid body section of constant frontal area, and a tail section of varying frontal area. Any pod, however, has the same frontal shape from leading edge to trailing edge. The following expressions are programmed for calculating pod drags.

POD PROFILE DRAG

The total pod length is obtained by summing the pod section lengths and this value is used to estimate the skin friction coefficient, C_f. This term is obtained by the expression given in Section 5.3.1. The value obtained for C_f is used to estimate pod profile drag for both types of pods. The definition of wetted area is dependent upon the pod shape. No reduction in pod wetted area has been made for either strut or foil intersections. The following forms are used for pod profile drag calculations:

CONTROL AND PROPELLER PODS

For this type of pod the following shapes were assumed: frontal shape is circular, nose section shape is ellipsoidal, center section shape is cylindrical, tail section shape is ogive.

The wetted areas for each section was obtained as follows. The surface area of the nose ellipsoidal section was obtained from the following expression by numerically integrating the surface area equation and then curve fitting the K' factor over a practical range of ratios of nose length to pod diameter.

$$e = (((L_n)^2 - (D/2)^2)^{1/2})/L_n \qquad (5.3.6\text{-}1)$$

$$S_n = \tfrac{1}{2}(2\pi(D/2)^2 + 2\pi(D/2)L_n(\sin^{-1}e)/e) \qquad (5.3.6\text{-}2)$$

$$S_n = K' D^2 \qquad (5.3.6\text{-}3)$$

where:

S_n = surface area of nose section, ft^2

L_n = nose section length, ft

D = pod diameter, ft

The curve fit of K' for a range of L_n/D from 1 to 7 gives:

$$K' \quad = \quad 0.2513 + 2.434\ L_n/D \qquad (5.3.6\text{-}4)$$

The surface area of the center cylindrical section was obtained by the following expression:

$$S_c \quad = \quad \pi\ L_c\ D \qquad (5.3.6\text{-}5)$$

where:

S_c = surface area of center section, ft^2

L_c = center section length, ft

The surface area of the tail ogive section was obtained from the following expressions by numerically integrating the surface area equation and then curve fitting the K' factor over a practical range of ratios of tail length to pod diameter:

$$S_t \quad = \quad \int_0^{L_t} (2\ \pi\ y\ (\ 1 + (y')^2)^{1/2}\ dx \qquad (5.3.6\text{-}6)$$

$$= \quad K'\ D^2 \qquad (5.3.6\text{-}7)$$

where:

S_t = surface area of tail section, ft^2

Now,

$$y' \quad = \quad (X/L_t)(L_t/D)(1-((X/L_t)(L_t/D)/(\xi\ /D))^2)^{-1/2}\ D \qquad (5.3.6\text{-}8)$$

$$y \quad = \quad (D/2) - \xi\ + \xi\,(1-(X/\xi\ )^2)^{1/2} \qquad (5.3.6\text{-}9)$$

$$\xi \quad = \quad ((L_t/D)^2 + (1/4))\ D \qquad (5.3.6\text{-}10)$$

where:

x,y = ogive coordinates with reference at centerline of pod and at trailing edge of the center pod section (leading edge of ogive tail section)

L_t = tail length, ft

D = pod diameter, ft

The curve fit of K' for a range of L_t/D from 1 to 7 gives:

$$K' = 0.2316 + 2.257\ (L_t/D) \qquad (5.3.6\text{-}11)$$

The total pod area is then:

$$S_{wet} = S_n + S_c + (0.2316D + 2.257\ L_t)D \qquad (5.3.6\text{-}12)$$

which is used for computing profile drag.

The drag of the pod is computed by using the following expression which was obtained from Reference [5].

$$D_{P_{min}} = C_{D_{wet}}\ S_{wet}\ q \qquad (5.3.6\text{-}13)$$

$$C_{D_{wet}} = C_f(1 + 1.5(D/L)^{1.5} + 7(D/L)^3) \qquad (5.3.6\text{-}14)$$

where:

L = pod total length, ft

C_f = skin friction coefficient

q = dynamic pressure, lbf/ft^2

WATERJET INLET POD

For this type of pod the following shapes are assumed: frontal area is rectangular, nose section shape is a rectangular box with a surface area factor to account for contour shape, center section shape is a rectangular box, tail section shape is a wedge shape boat tail with a surface area factor to account for contour shape.

The wetted areas for each section are obtained as follows:

The surface area of the rectangular box section of the nose was computed by the following expression.

$$S_n = 2(W + H) L_n (0.8) = 1.6(W + H) L_n \qquad (5.3.6\text{-}15)$$

where:

S_n = surface area of nose section, ft^2

W = pod width, ft

H = pod height, ft

L_n = nose length, ft

0.8 = assumed surface area factor

The surface area of the center rectangular box is obtained by the following expression:

$$S_c = 2(W + H) L_c \qquad (5.3.6\text{-}16)$$

where:

S_c = surface area of center section, ft^2

L_c = center section length, ft

The surface area of the wedge boat tail is obtained as follows:

$$S_t = 1.1(2((W/2)L_t + ((H + (H-W))/2)L_t) \quad (5.3.6\text{-}17)$$

$$= 2(H\ L_t)\ (1.1) = 2.2\ H\ L_t \quad (5.3.6\text{-}18)$$

where:

S_t = surface area of tail section, ft^2

L_t = tail length, ft

1.1 = assumed surface area factor

The total pod area is then:

$$S_{wet} = S_n + S_c + S_t \quad (5.3.6\text{-}19)$$

which is used to compute profile drag.

The drag of the pod is computed using the expressions given below.

A skin friction drag is computed using the following:

$$D_{F_{min}} = C_f\ S_{wet}\ q \quad (5.3.6\text{-}20)$$

where:

C_f = skin friction coefficient

q = dynamic pressure, lbf/ft^2

A flow separation drag due to the boat tail was computed using data from Reference [5] and is as follows:

$$D_{sep} = C_f\, 7\, (D/L)^3\, S_{ref}\, q \tag{5.3.6-21}$$

For the boat tail the following factors were assumed:

$$D = ((4/\pi)\, WH)^{1/2} \tag{5.3.6-22}$$

$$L = L_t + \tfrac{1}{2} L_c \tag{5.3.6-23}$$

$$S_{ref} = S_t \tag{5.3.6-24}$$

and the separation drag becomes:

$$D_{sep} = 10 C_f ((WH)^{1/2} / (L_t + \tfrac{1}{2} L_c))^3 S_t q \tag{5.3.6-25}$$

The total pod profile drag is then:

$$D_{P_{min}} = D_{F_{min}} + D_{sep} \tag{5.3.6-26}$$

No allowance has been made for waterjet inlet lip spillage drag. It is assumed that a proper inlet lip design would be available for which there would be no spillage drag developed at design conditions.

POD WAVE DRAG

If the pod submergence is greater than half its height, a wave drag is calculated, otherwise, wave drag is zero. Data from Reference [5] has been curve fit to provide a wave drag calculation term. The expression used to estimate pod wave drag is as follows:

$$\Delta C_{D_{wave}} = (D/l)^2(0.0875(H_{sub}/l)^{-1.3}(F_l)^{3.5} \exp(0.0884/(F_l)^{3.5}))^{-1} \qquad (5.3.6\text{-}27)$$

$$F_l = 1.6889V_k/(g\ l)^{1/2} \qquad (5.3.2\text{-}28)$$

$$D = (4/\pi)^{1/2}\ (S)^{1/2} \qquad (5.3.6\text{-}29)$$

where:

l = total length of pod, ft

H_{sub} = submergence of pod, ft

F_l = Froude number

D = equivalent pod diameter, ft

S = frontal area, ft^2

The wave drag is computed by:

$$D_{wave} = \Delta C_{D_{wave}}\ S\ q \qquad (5.3.6\text{-}30)$$

5.3.7 Ship Air Drag

The air drag is based on a ship frontal area and a drag coefficient. An empirical expression for ship frontal area has been developed as a function of length between perpendiculars. The form used was:

$$S_{front} = 0.157\ (L_{PP})^{1.807} \qquad (5.3.7\text{-}1)$$

where:

S_{front} = ship frontal area, ft^2

L_{pp} = length between perpendiculars, ft

Using an assumed drag coefficient of 0.5 the air drag is:

$$D_{air} = 0.5\,(\rho_{air}/2)(1.6889)^2 V_k^2 S_{front} \qquad (5.3.7\text{-}2)$$

where:

ρ_{air} = air density, $slug/ft^3$

V_k = ship speed, kt

To provide a lever arm for moment calculations about the ship center of gravity, an empirical expression for the location of center of air drag above the baseline has been estimated as a function of length between perpendiculars. The form used is:

$$Z_{air} = 0.119(L_{pp})^{1.042} \qquad (5.3.7\text{-}4)$$

where:

Z_{air} = distance of center of air drag above baseline, ft

5.3.8 Total Foil Drag

The total foil drag is developed in terms of a parasite drag plus an induced drag. The following components show a typical drag build-up:

a) Parasite (See Figure 5.3-2)

$$D_{P_{total}} = \Delta D_{tips} + D_{P_{min}} + \Delta D_{P_{min}} + \Delta D_{P_{min(flap)}} + D_{lecav} \quad (5.3.8\text{-}1)$$

b) Induced (See Figure 5.3-3)

$$D_{ind_{total}} = D_{ind} + \Delta D_{ind_{(flap)}} + \Delta D_{wave} + D_{zero} \quad (5.3.8\text{-}2)$$

c) Total (See Figure 5.3-1)

$$D = D_{P_{total}} + D_{ind_{total}} \quad (5.3.8\text{-}3)$$

5.3.9 Total Strut Drag

The total strut drag is developed by the following expression.

$$D = D_{P_{min}} + D_{spray} + D_{wave} \quad (5.3.9\text{-}1)$$

5.3.10 Total Pod Drag

The total pod drag is developed by the following expression.

$$D = D_{P_{min}} + D_{wave} \quad (5.3.10\text{-}1)$$

5.3.11 Total Foil Assembly Drag

The total foil assembly drag is composed of the foil plus strut plus pod drags and is given by:

$$D_{assembly} = D_{foil} + D_{strut} + D_{pod} \quad (5.3.11\text{-}1)$$

5.3.12 Total Foilborne Drag

The total foilborne drag is composed of the forward and aft foil assembly drags plus the air drag. It is calculated using the form:

$$D_{FB} = D_{forward} + D_{aft} + D_{air} \qquad (5.3.12\text{-}1)$$

6.0 THEORY: TAKEOFF HYDRODYNAMICS

This section contains a discussion of the procedures used to estimate takeoff drag and, if requested, to calculate the maximum required waterjet inlet area.

6.1 INTRODUCTION

The takeoff hydrodynamic calculation provides an estimate of the drag and speed at takeoff for use in estimating the takeoff thrust required from the foilborne propulsion system. The takeoff calculation is based on a steady state static equilibrium condition determined by the method described in Section 5.1.2. The additional calculations required for the takeoff thrust include:

1) Development of the minimum takeoff drag curve as a function of speed.

2) Determination of the minimum drag at a fixed speed for a variation of two independent operating parameters.

3) Estimate the hull forces and moment as a function of the operating parameters and then pass this data into the foilborne static equilibrium calculation in order to estimate the takeoff drag at the input operating condition.

4) Estimate the required maximum waterjet inlet area based on the takeoff drag curve and an assumed maximum cavitation-limited inlet flow velocity.

6.2 TAKEOFF DRAG CALCULATION

The calculation of the takeoff drag involves a comparison of the takeoff drag and foilborne drag as functions of speed. The takeoff drag is the total hull and foil/strut drag that results when the foil lift equals that portion of the total ship weight not carried by the hull. The foilborne drag is that drag that would result if the foils could support the total ship weight by unlimited control deflections. These two drags are compared over a range of speeds to determine the maximum drag during takeoff and the speed at which takeoff occurs. Figure 6.2-1 shows a typical takeoff drag curve. The objective of the takeoff drag calculation is to provide the current model an estimate of the maximum drag which can occur during takeoff. This value can then be used to estimate the maximum power required for takeoff.

The takeoff drag is the minimum drag possible under steady state equilibrium conditions at each speed. The takeoff drag curve is developed at each fixed speed utilizing a simple searching technique on the ship pitch angle and hull lift to determine the minimum drag. The following discussion pertains to the method used to estimate the takeoff drag. Figure 6.2-1 is included to show the various terms.

The calculation of the takeoff drag and corresponding speed requires an initial speed, a speed increment, and bounds on the values of hull lift and pitch angles used to find the minimum drag. The following values are used:

1) Speed variation.

$$\text{Initial speed} = 13 \text{ kt} \tag{6.2-1}$$

$$\text{Speed increment} = 3 \text{ kt} \tag{6.2-2}$$

2) Limit values of search parameters.

a) First independent parameter: hull lift.

$$\Delta_{TO_{min}} = 0 \tag{6.2-3}$$

$$\Delta_{TO_{max}} = 0.9 \tag{6.2-4}$$

where:

Δ = full load weight, lton

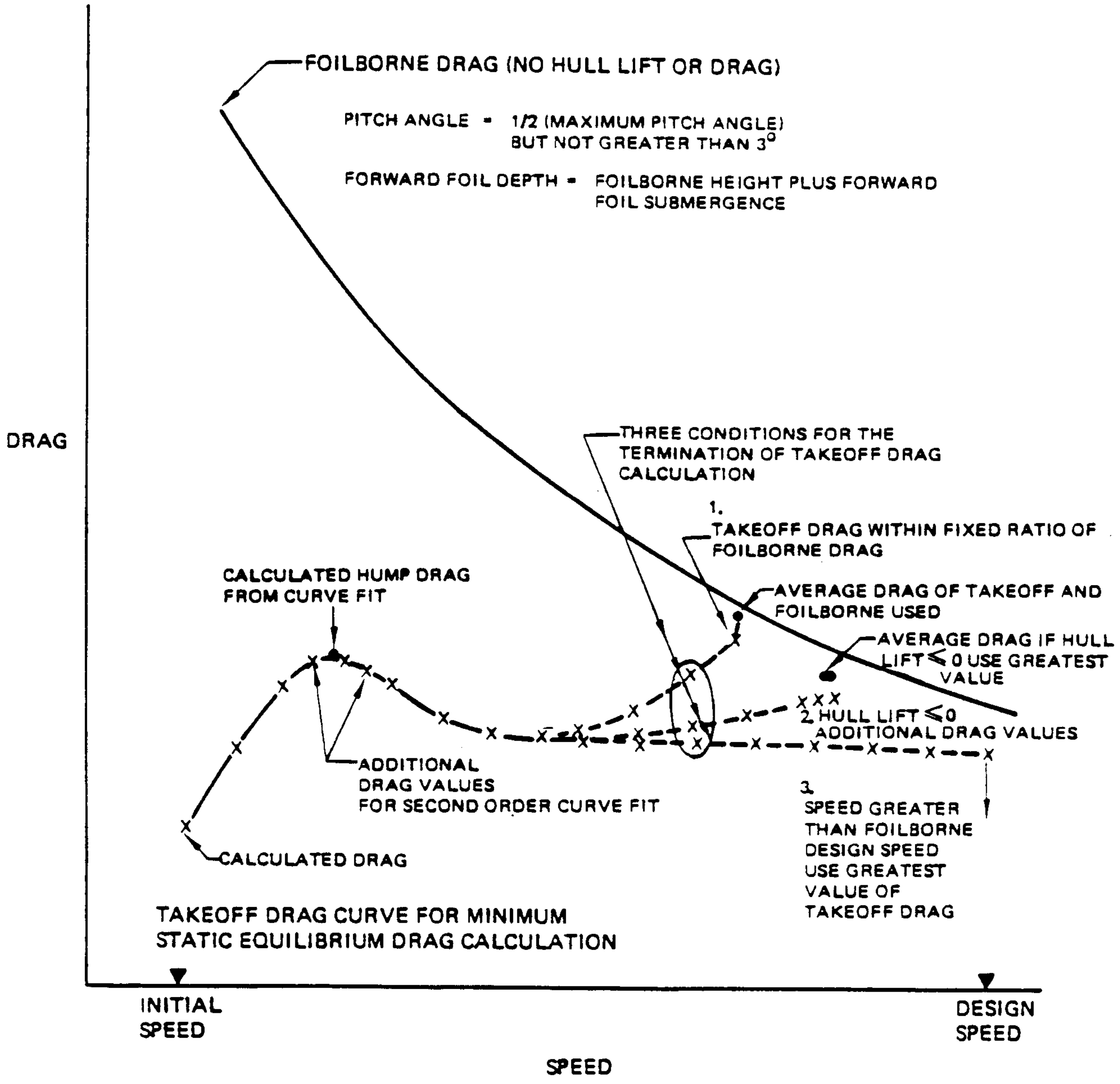


FIGURE 6.2-1 TAKEOFF DRAG CALCULATIONS

$\Delta_{TO_{min}}$ = minimum hull lift, lton

$\Delta_{TO_{max}}$ = maximum hull lift, lton

b) Second independent parameter: pitch angle.

$$\theta_{TO_{min}} = -1 \text{ deg} \qquad (6.2\text{-}5)$$

$$\theta_{TO_{max}} = \tan^{-1}((H_{sub_{fwd}} + H_{FB} - 1)/(L_{PP} - X_{fwd})) \qquad (6.2\text{-}6)$$

where:

$\theta_{TO_{min}}$ = minimum pitch angle, deg

$\theta_{TO_{max}}$ = maximum pitch angle, which equals maximum rotation of the baseline at the aft perpendicular which moves the forward foil a vertical distance equal to the forward foil submergence plus the foilborne height less one (1) foot, deg

L_{PP} = longitudinal distance between perpendiculars, ft

X_{fwd} = distance from forward perpendicular to forward foil, ft

3) Initial values of search parameters.

The search technique utilizes these maximum and minimum values to normalize the hull lift and pitch angle values so that the range of search is fixed between zero to one.

a) First independent parameter: hull lift.

$$X(1)_i = 0.9 \qquad \text{for } V_k \leq 8.5 \qquad (6.2\text{-}7)$$

$$X(1)_i = 1.25 - 0.041\, V_k \quad \text{for } 8.5 < V_k < 28 \qquad (6.2\text{-}8)$$

$$X(1)_i = 0.1 \quad \text{for } V_k > 28 \qquad (6.2\text{-}9)$$

$$X(1) = (\Delta_c - \Delta_{TO_{min}})/(\Delta_{TO_{max}} - \Delta_{TO_{min}}) \qquad (6.2\text{-}10)$$

where:

$X(1)$ = hull lift parameter

V_k = speed, kt

c = current calculation value of hull lift

i = denotes initial value

b) Second independent parameter: pitch angle

$$X(2)_i = (2.0 - \theta_{TO_{min}})/(\theta_{TO_{max}} - \theta_{TO_{min}}) \qquad (6.2\text{-}11)$$

for $X(2)_i < 1.0$

$$X(2)_i = 0.9 \quad \text{for } X(2)_i \geq 1.0 \qquad (6.2\text{-}12)$$

$$X(2) = (\theta_c - \theta_{TO_{min}})/(\theta_{TO_{max}} - \theta_{TO_{min}}) \qquad (6.2\text{-}13)$$

where:

$X(2)$ = pitch angle parameter

θ_c = current calculation value of pitch angle

i = denotes initial value

The termination of the takeoff drag calculation is set by one of three tests. These tests are discussed below and are shown on Figure 6.2-1.

1) Takeoff Drag Within Fixed Ratio of Foilborne Drag.

At each takeoff speed an estimate of an equivalent foilborne (no hull lift or drag) drag is made and the calculated takeoff drag is compared with it. If the takeoff drag is equal to or greater than 0.96 times the foilborne drag, the calculation of takeoff drag is terminated. An average drag is then passed to the current model as the takeoff drag and the corresponding speed is passed as the takeoff speed. The following conditions are used:

a) Conditions for estimating foilborne drag.

Speed = current takeoff calculation speed

Weight = full load weight

Pitch angle = 0 for incidence controlled craft

= ½ $\theta_{TO_{max}}$ for flap controlled craft but not greater than three (3), deg

Forward Foil Depth = foilborne height plus forward foil submergence

b) Estimation of foilborne drag.

The foil system drag is then calculated using the above conditions.

c) Average drag.

When the takeoff drag calculation is terminated, an average drag is calculated. The average drag is calculated by:

$$D = \tfrac{1}{2}(D_{foilborne} + D_{takeoff}) \qquad (6.2\text{-}14)$$

The average drag is passed into the current model as the takeoff drag.

2) Hull Lift Equal to Zero

A test is made on the hull lift for each speed calculated. If the hull lift is zero then an average drag is saved, otherwise only the takeoff drag is saved. The maximum value of these drags is passed as the takeoff drag. The corresponding speed is also passed into the current model.

3) Speed Greater than Foilborne Design Speed

If the takeoff speed is incremented to a value greater than the foilborne speed required, the calculation of takeoff drag is terminated. A search of the calculated takeoff drags is made and the maximum value is passed as well as the corresponding speed. The following comment is printed out in the data summary, "TAKEOFF SPEED IS ABOVE FOILBORNE SPEED - TAKEOFF DRAG IS SET TO MAX. VALUE."

When a peak in the takeoff drag curve is detected by comparing the current takeoff drag with the previous takeoff drag value, a hump drag calculation is performed. This calculation determines three speeds which bracket the peak drag value and then uses a second order curve fit of these three points to estimate the hump drag and its corresponding speed. If the hump drag is less than the foilborne drag, the calculation of takeoff drag is continued by incrementing the speed from the last incremented speed value.

The calculated takeoff drag is passed into the current model for only the takeoff condition. The calculated hump drags are not passed. In order to provide the user information on hump drags and to allow for checking of the maximum power required during takeoff, the following note is printed in the summary if a hump drag has been calculated. "NOTE - THE FOLLOWING HUMP TAKEOFF DRAGS WERE FOUND

AND A CHECK OF THE TAKEOFF POWER SHOULD BE DONE TO ESTABLISH MAXIMUM TAKEOFF POWER." A list of the hump drags are then printed.

6.3 DRAG MINIMIZATION TECHNIQUE

The objective of the drag minimization technique is to estimate the minimum takeoff drag at a fixed speed for a variation of ship pitch angle and hull lift.

The technique utilizes a simple search method which includes the following operations. For reference, see Figure 6.3-1.

1) A fixed speed and initial values of X(1) = hull lift, X(2) = pitch angle are set to start the calculation.

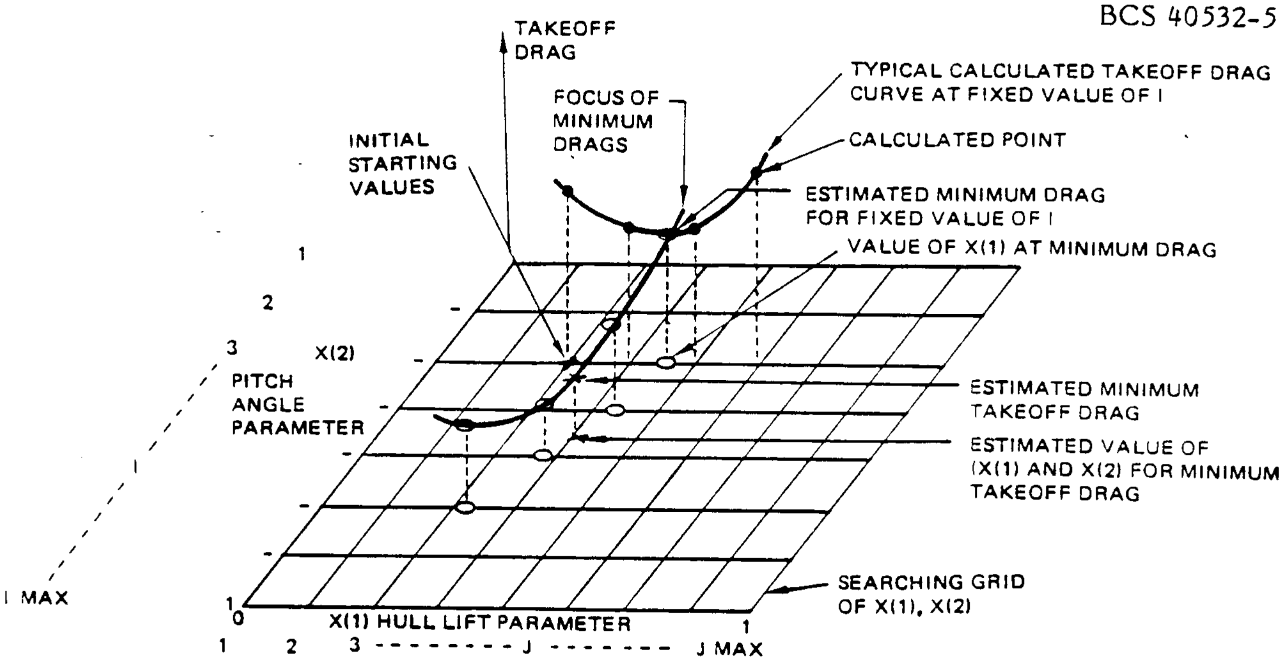
2) A searching grid of X(1), X(2) is developed utilizing uniform spacing for each parameter. Both parameters are normalized to range from zero to one.

3) The initial values of X(1) and X(2) are rounded to the nearest grid values and the search for minimum takeoff drag is initiated.

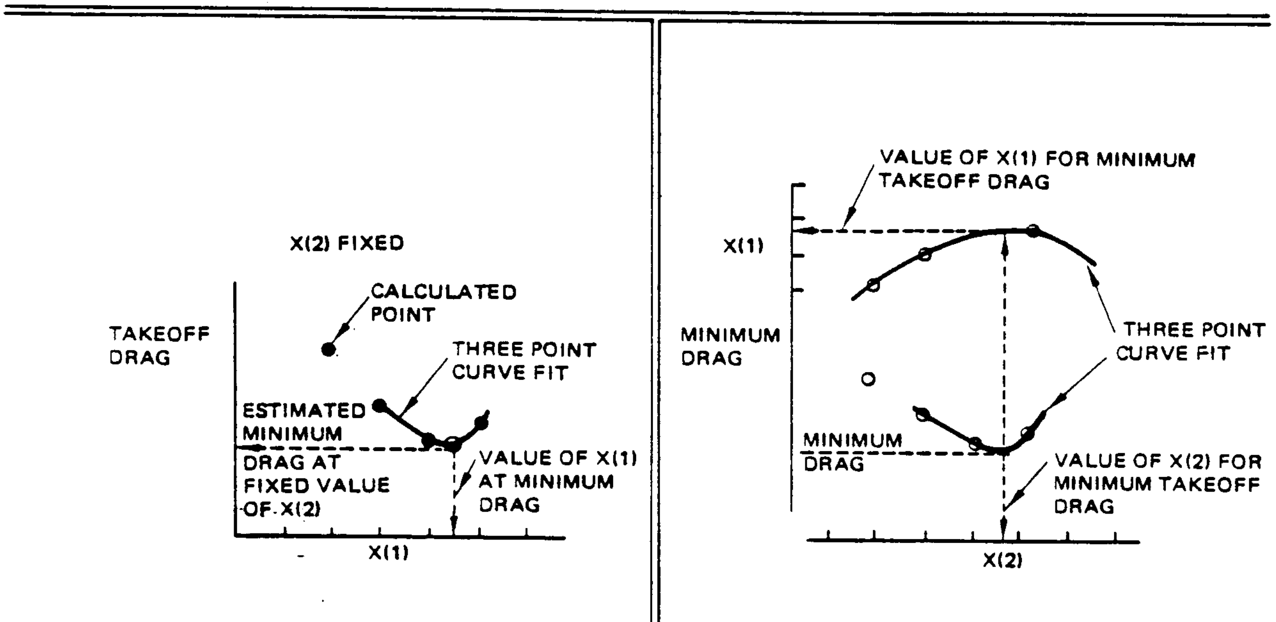
4) The value of X(2) is held fixed while X(1) is varied until a minimum calculated drag is detected or the boundary is reached.

5) If a minimum is detected, a second order curve fit of the calculated drags around the detected minimum drag is done in subroutine SECOFT. This subroutine takes three input points and computes the minimum value of the takeoff drag and the corresponding value for the X(1) parameter. See Figure 6.3-1.

6) X(2) is incremented and steps 4 and 5 are repeated. The starting value of X(1) is the last value used from the previous pass of X(2).



(a) TAKEOFF DRAG SEARCHING GRID



(b) ESTIMATED MINIMUM DRAG FOR FIXED VALUE OF X(2)

(c) ESTIMATION OF X(1) AND X(2) FOR MINIMUM TAKEOFF DRAG

FIGURE 6.3-1 TAKEOFF DRAG MINIMIZATION TECHNIQUE

7) Step 6 is repeated until a minimum calculated drag as a function of X(2) is detected or the X(2) boundary is reached.

8) When a minimum drag has been detected, a second order curve fit as a function of X(2) is then made as was done in step 5 for X(1). The value of X(2) for this minimum drag is then used to calculate the value of X(1) corresponding to the minimum drag. See Figure 6.3-1.

9) Using the values of X(1) and X(2) obtained in 8, a final calculation of takeoff drag is made. This drag is estimated minimum takeoff drag at the fixed input speed.

6.4 HULL CHARACTERISTICS - STATIC TAKEOFF CALCULATION

The calculation of a steady state takeoff drag equilibrium condition is based on a technique which minimizes the takeoff drag at a fixed speed for a variation of ship pitch angle and hull lift. A search for the maximum takeoff drag by incrementing speed is done until either a hump drag or a lift-off drag is obtained. This maximum takeoff drag and corresponding speed are then passed to the current model. This technique requires the ability to estimate hull resistance over a range of both hull trim, displacement, and speed. Typically, the hull trim range is from about -1 to +6 degrees while the hull displacement range is from zero to about 90% of the full load displacement and a speed range of 10 knots to about 40 knots.

The takeoff hull resistance calculation methods are the same as those used by the Hullborne Hydrodynamic Module. They consist of a merging of planing hull, transom-stern, and Froude and Reynolds number scaling methods. The hull characteristics and operating condition are compared to the range of applicability of each method and the appropriate method is selected. For hull characteristics and operating conditions that fall outside the range of these methods, interpolation and extrapolation is used.

The estimation of the hull resistance during the takeoff calculations is done by subroutine HYDHUL. However, before execution of the takeoff calculations, subroutine HULDAT is called to generate hull geometric properties. A detailed description of this subroutine is given in the Hullborne Hydrodynamic Module User Manual. Subroutine HYDHUL next calls subroutine HULPAR which estimates the static trim hull geometric parameters as a function of both pitch angle and hull displacement. Subroutine HULDRG is then called to compute the hull resistance at the input operating condition. The hull resistance computed by subroutine HYDHUL is then passed to the takeoff drag calculation subroutine, TOCAL.

6.5 WATERJET INLET AREA SIZING

A waterjet inlet area can be sized based on takeoff drags and an assumed inlet cavitation limit velocity. The required takeoff margin will be provided.

The following conditions are required to start the inlet area sizings:

1) A takeoff calculation must be done.
2) The foilborne propulsion system must be a waterjet, and
3) The foilborne duct size indicator must specify that the duct is to be sized.

If these conditions are met, the inlet area will be calculated and passed to the current model. The inlet area calculation consists of the following operations:

1) At each speed used for the takeoff calculations, the thrust required is assumed to be equal to the takeoff drag times the design takeoff margin. This required thrust is then used to calculate the required waterjet flow. A discussion of the waterjet calculations is given in Section 5.1.4.

2) The minimum inlet area (ft^2) which can pass the required flow corresponding to the above conditions is calculated by the following expression:

$$A_{inlet} = Q_{to}/(V_{lim} N_{duct}) \qquad (6.5\text{-}1)$$

where:

Q_{to} = required waterjet flow from 2 above, ft^3/sec

N_{duct} = number of water inlet ducts on foilborne propulsion system

V_{lim} = estimated inlet cavitation limit velocity, ft/sec

An empirical expression for V_{lim} has been obtained from PHM data. This expression is evaluated in the function ELVLIM. This function is also used in the Foilborne Propulsion Module.

$$V_{lim} = 0.6\ V_k + ((2066 + \rho gH)/2066)^{1/2}\ 29.06 \qquad (6.5\text{-}2)$$

where:

V_k = craft speed, kt

ρ = density of water, $slugs/ft^3$

H = submergence of inlet pod (assumed equal to the distance from the pod to the baseline), ft

3) The maximum inlet area required is passed to the current model.

7.0 THEORY: CALCULATION LIMITATIONS

This section contains a list of the major limitations which exist in the Foilborne Hydrodynamic Module.

7.1 FOIL ASSEMBLY LIMITATIONS

The major limitations which currently exist for the calculation of lift and drag are as follows:

1) The lift is assumed to be linear with regard to both angle of attack and flap deflection.

2) No limits are applied to lift due to stall, cavitation, or ventilation.

3) No limits are applied to flap deflections or incidence angles that are calculated by the static balance calculation.

4) There is no correction for structural deflections.

5) There is no correction for flow interactions between foil assemblies.

6) The foil lift is assumed at 50% chord - no corrections are made for foil pitching moments.

7) No checks are made for control authority or the effectiveness of the foil assembly geometry.

7.2 TAKEOFF DRAG LIMITATIONS

The major limitations which currently exist in the calculation of takeoff drag are as follows:

1) The limitations which exist for the foil assembly as given above also apply to the takeoff calculation.

2) The takeoff drags are based on steady state calculations and do not include a dynamic takeoff simulation.

8.0 EXAMPLES

Several examples are given in the following sections which demonstrate the output of the Foilborne Hydrodynamic Module when the input is modified by the user. Three examples will be given. The basic MODEL 900 configuration will be perturbed into the following configurations: (1) inlet duct size will be calculated for an increased design weight, (2) a foilborne propeller propulsion system will be used, and (3) several operating conditions will be changed. All of the above examples will use the same geometry. Changes to the geometry can be made by modifying the appropriate geometric parameter to the desired value.

8.1 EXAMPLE 1 - INLET DUCT SIZE CALCULATED FOR MODEL 900

In this example the waterjet inlet duct will be calculated for the MODEL 900 based on takeoff requirements.

COMMANDS	DESCRIPTION
C,E >USE, MODEL 900	Use MODEL 900.
C,E >SET, FB DUCT SIZE IND, CALC	Set FB DUCT SIZE IND to CALC. This will cause the module to calculate a required waterjet inlet duct area.
C,E >SET, ONLINE, FB HYDRO MODULE, 1, 5	Request that the first and fifth printed report be included in the data printout.
C,E >SET, FULL LOAD WT, 245	Set full load weight to 245 lton.
C,E >RUN, FB HYDRO MODULE	Initiate execution of the module.

The summary output shown on Figure 8.1-1 is provided by the Foilborne Hydrodynamic Module for the above configuration.

```
   ASSET/HYDROFOIL VERSION 2.0 - FB HYDRO MODULE -  3/31/86 09.26.28.

PRINTED REPORT NO. 1 - SUMMARY

 FB PROP TYPE-WATERJET
 FB DUCT SIZE-CALC
 NUMBER OF DUCTS              2.
 AREA/DUCT, FT2           2.303

CONDITION       SPEED,KT    WT,LTON     DRAG,LBF  DRAG+FACTOR,LBF
FB DESIGN          45.0      245.0      39881.        39881.
FB RANGE           44.0      226.9      37395.        37395.
TO DESIGN          25.0      245.0      49304.        61630.
```

FIGURE 8.1-1 EXAMPLE 1 - SUMMARY

The takeoff summary data shown on Figure 8.1-2 is provided by the Foilborne Hydrodynamic Module for the above configuration. An additional column is provided for this case which lists the required waterjet inlet area at each calculated speed.

8.2 EXAMPLE 2 - FOILBORNE PROPELLER PROPULSION SYSTEM REPLACING WATERJET ON MODEL 900

In this example the waterjet inlet system pods will be replaced by propeller pods with a gearbox diameter of 2.5 feet. The reference ship for this example is the same ship as used for the previous example.

COMMANDS	DESCRIPTION
`C,E>SET, FB PROP TYPE IND, PROPELLER`	Set foilborne propulsion to propeller type.
`C,E>SET, FB LWR GBX DIA, 2.5`	Set lower gearbox diameter to 2.5 feet in order to size power pod.
`C,E>RUN, FB HYDRO MODULE`	Initiate execution of the module.

The summary output shown on Figure 8.2-1 is provided by the Foilborne Hydrodynamic Module for the above configuration.

```
PRINTED REPORT NO. 5 - TAKEOFF DATA

SPEED FOILBORNE TAKEOFF    FOIL      HULL  HULL LIFT PITCH DRAFT WJ DUCT
  KT   DRAG,LBF DRAG,LBF DRAG,LBF DRAG,LBF    LTON    DEG   AP,FT   FT2
 13.0  264789.   18680.    5223.   13457.    220.5   -0.15  6.22  1.626
 16.0  185207.   30268.    8076.   22192.    204.3   -0.08  6.01  1.978
 19.0  130013.   39646.   14051.   25595.    166.3    0.27  5.62  2.184
 22.0   69352.   43541.   22442.   21099.    115.6    1.36  5.63  2.228
 25.0   50264.   49304.   35002.   13343.     44.5    3.39  6.55  2.303
```

FIGURE 8.1-2 EXAMPLE 1 - TAKEOFF DATA

```
   ASSET/HYDROFOIL VERSION 2.0 - FB HYDRO MODULE -  3/31/86 09.27.51.

PRINTED REPORT NO. 1 - SUMMARY

 FB PROP TYPE-PROPELLER

CONDITION       SPEED,KT    WT,LTON      DRAG,LBF  DRAG+FACTOR,LBF
FB DESIGN         45.0       245.0        44810.        44810.
FB RANGE          44.0       226.9        42138.        42138.
TO DESIGN         25.0       245.0        51362.        64203.
```

FIGURE 8.2-1 EXAMPLE 2 - SUMMARY

8.3 EXAMPLE 3 - MODIFICATION OF OPERATING CONDITIONS FOR MODEL 900

In this example the operating conditions for Model 900 will be changed. These include changes in operating speed, weight, center of gravity location and foil submergence.

COMMANDS	DESCRIPTION
C,E >USE, MODEL 900	Use MODEL 900.
C,E >SET, FB SPEED REQ, 50	Set required foilborne design speed to 50 kt.
C,E >SET, FB RANGE SPEED REQ, 45	Set required foilborne range speed to 45 kt.
C,E> SET, FULL LOAD WT, 200	Set full load weight to 200 1 ton.
C,E >SET, FWD FOIL SUBMERGE, 7	* Set forward foil submergence to 7 ft.
C,E> SET, AFT FOIL SUBMERGE, 8.5	* Set aft foil submergence to 8.5 ft.
C,E >SET, FB HEIGHT, 5	* Set foilborne height to 5 ft.
C,E> SET, FULL LOAD CG ARRAY	Signals that input data will be provided for the full load center of gravity foils down array.
I >0.541868, 0.580552, Q	Input values of the longitudinal and vertical CG location. A 64 foot LCG and an 8 foot VCG is used.

*Note: In order to properly change foilborne submergence, these three terms must be changed concurrently to preserve the strut length.

C,E > SET, FOIL LOADING FRAC, 0.3608	Adjusts forward foil loading fraction for given foil system in order to maintain same value of foil/strut longitudinal location.
C,E > SET,ONLINE, FB HYDRO MODULE, 1, 2	Request that the first and second printed reports be included in the data printout.
C,E > SET, TO SPEED, -1	Input takeoff speed less than zero to suppress takeoff calculations.
C,E > RUN, FB HYDRO MODULE	Initiate execution of the module.

The outputs shown on Figures 8.3-1 and 8.3-2 are provided by the Foilborne Hydrodynamic Module for the above configuration.

```
HYDRO MODULE  **WARNING** TO SPEED SET AT LESS THAN ZERO
                          - NO TAKEOFF CALCULATIONS WILL BE MADE

   ASSET/HYDROFOIL VERSION 2.0 - FB HYDRO MODULE -  3/31/86 09.29.50.

PRINTED REPORT NO. 1 - SUMMARY

 FB PROP TYPE-WATERJET
 FB DUCT SIZE-CALC
 NUMBER OF DUCTS               2.
 AREA/DUCT, FT2             2.170

CONDITION         SPEED,KT    WT,LTON       DRAG,LBF  DRAG+FACTOR,LBF
FB DESIGN           50.0       200.0         43979.          43979.
FB RANGE            45.0       181.9         37338.          37338.
```

FIGURE 8.3-1 EXAMPLE 3 - SUMMARY

```
PRINTED REPORT NO. 2 - FOILBORNE FOIL/STRUT DATA

                    DESIGN SPEED CONDITION I RANGE SPEED CONDITION
                    SPEED  =   50.0 KNOTS  I SPEED  =   45.0 KNOTS
                    WEIGHT =  200.0 LTON   I WEIGHT =  181.9 LTON
                    PITCH  =   0.00 DEG    I PITCH  =   0.37 DEG
                    LCG    =  64.00 FT     I LCG    =  64.00 FT
                    VCG    =   7.99 FT     I VCG    =   7.99 FT

                       FORWARD     AFT     I    FORWARD     AFT
                       FOIL        FOIL    I    FOIL        FOIL

FOIL SUBMERGENCE, FT    7.00        8.50   I     7.00        9.07
FOIL INCIDENCE, DEG     1.09        0.38   I     1.09        0.38
FLAP DEFLECTION, DEG    0.34        0.32   I     0.22       -0.11
FOIL X LOCATION, FT     7.71       95.77   I     7.71       95.77
FOIL DRAGS, LBF                            I
 PROFILE               6024.      12736.   I    5001.      10514.
 INDUCED               2258.       2528.   I    2237.       2419.
 TOTAL                 8282.      15263.   I    7239.      12933.
STRUT DRAGS, LBF                           I
 PROFILE               1473.       3974.   I    1211.       3623.
 SPRAY                  904.       4793.   I     732.       3976.
 WAVE                    10.        109.   I      11.        127.
 TOTAL                 2387.       8875.   I    1955.       7726.
POD DRAGS, LBF                             I
 PROFILE               1253.       4232.   I    1028.       3470.
 WAVE                     0.          2.   I       1.          2.
 TOTAL                 1254.       4234.   I    1029.       3472.

TOTAL DRAGS, LBF      11922.      28372.   I   10222.      24131.

FOIL LIFT, LTON                            I
 DYNAMIC              74.28       118.48   I    66.93      107.64
 BUOYANCY              1.08         2.67   I     1.08        2.67
 TOTAL                75.35       121.15   I    68.01      110.31
STRUT LIFT, LTON                           I
 BUOYANCY              0.39         0.84   I     0.39        0.89
POD LIFT, LTON                             I
 BUOYANCY              0.73         1.89   I     0.73        1.89

TOTAL LIFT, LTON      76.42       123.58   I    69.08      112.80
F/S LIFT/DRAG RATIO   14.36         9.76   I    15.14       10.47
DYN LOADING, LBF/FT2 1180.4        877.4   I   1063.7       797.1

AIR DRAG, LBF         3684.                I    2984.

SHIP DRAG, LBF       43979.                I   37338.
SHIP WEIGHT/DRAG      10.19                I    10.91
```

FIGURE 8.3-2 EXAMPLE 3 - FOILBORNE FOIL/STRUT DATA

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