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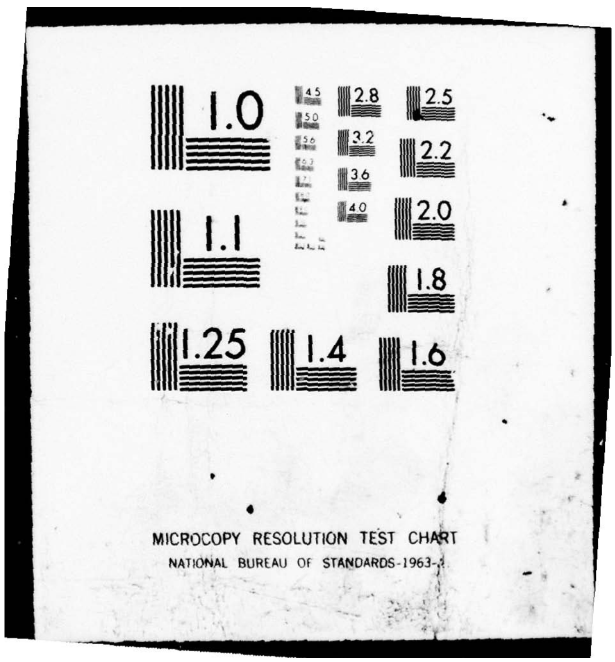
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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

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DOCUMENTATION FOR A SERIES OF COMPUTER PROGRAMS FOR ANALYZING LONGITUDINAL WAVE CUTS AND DESIGNING BOW BULBS

Arthur M. Reed

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DOCUMENTATION FOR SERIES OF COMPUTER PROGRAMS FOR ANALYZING LONGITUDINAL WAVE CUTS AND DESIGNING BOW BULBS

JUNE 1979

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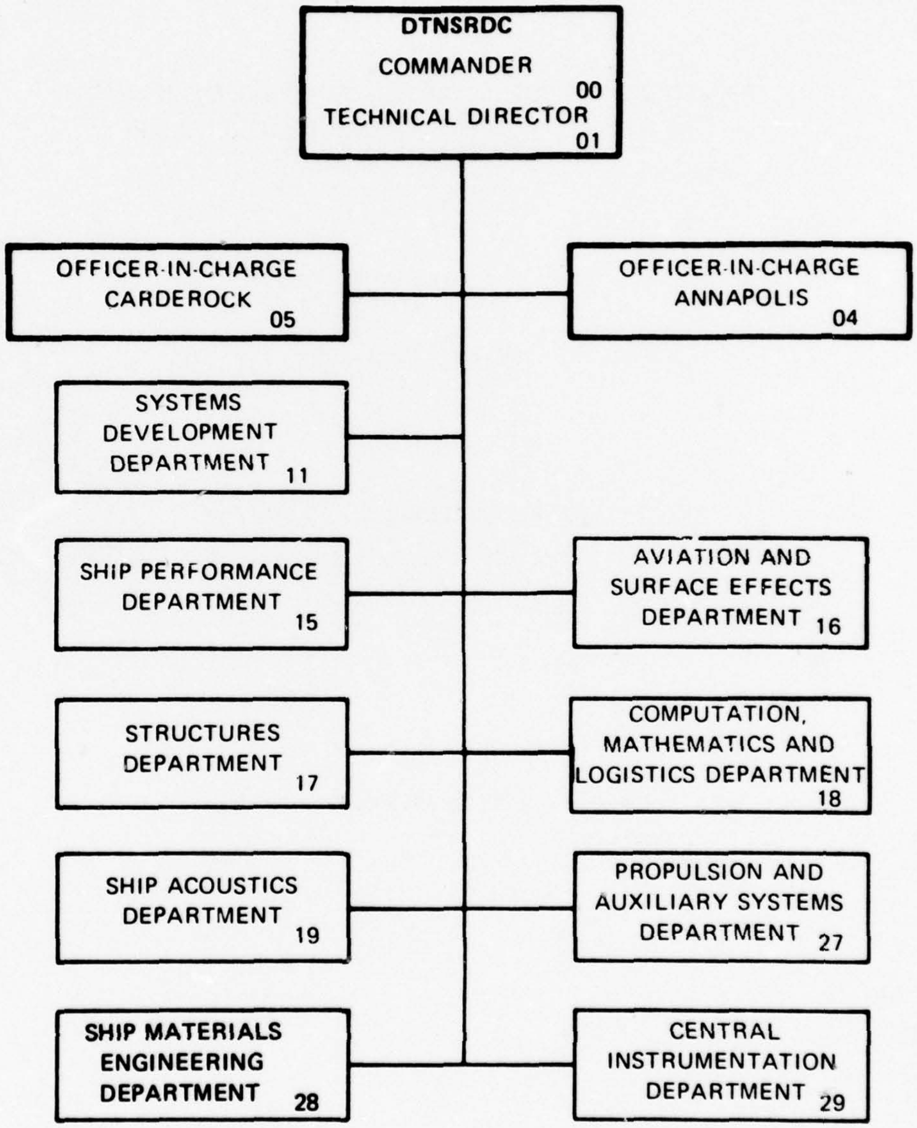

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Several computer programs for the analysis of longitudinal wave cuts which were developed at the University of Michigan under the direction of S.D. Sharma have been converted at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) for use on the CDC 6000 Computer Series. The computer programs that are documented in this report perform the following tasks: convert digital wave cut data for use in a wave analysis program which determines free-wave spectra for a number of transverse wave numbers and calculates the wave resistance; plot the free wave spectra; determine and plot the contours

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of bulb influence factors. The programs have been tested at DTNSRDC on a sample of wave cut data measured at the University of Michigan.

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ABSTRACT

Several computer programs for the analysis of longitudinal wave cuts which were developed at the University of Michigan under the direction of S.D. Sharma have been converted at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) for use on the CDC 6000 Computer Series. The computer programs that are documented in this report perform the following tasks: convert digital wave cut data for use in a wave analysis program which determines free-wave spectra for a number of transverse wave numbers and calculates the wave resistance; plot the free wave spectra; determine and plot the contours of bulb influence factors. The programs have been tested at DTNSRDC on a sample of wave cut data measured at the University of Michigan.

ADMINISTRATIVE INFORMATION

The work reported herein was funded under NAVSEC Project Order 601A2. The work was performed under David W. Taylor Naval Ship Research and Development Center Work Unit 1524-599.

INTRODUCTION

The Naval Ship Engineering Center (NAVSEC) requested that the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) convert several computer programs for use on the CDC 6000 computer series and develop the necessary documentation to use and maintain these programs. These computer programs were developed at The University of Michigan under the direction of S. D. Sharma.

Collectively, these programs are used for the analysis of longitudinal wave cuts. Individually, the programs perform the following tasks: the first program NONDIM converts digital wave cut information for use by the wave analysis program; the Wave Analysis Program (WAVECT) performs wave analysis to determine the free-wave spectra for a number of transverse wave numbers* with an optional truncation correction for height data and also calculates the wave resistance; the Free-Wave Spectra Plotting Program (SPCTRA) is used to plot the free wave spectra derived by the WAVECT program; the Bulb Contour Printer Program (BUBOPT) uses the free-wave spectra provided by the WAVECT program to determine the contours of the bulb influence factor for use by the Bulb Contour Plotter program (BUBPLT); the BUBPLT program plots the contours of the constant bulb influence factor (ETA).

The above programs have been converted and tested on the CDC 6000 Computer Series at the David W. Taylor Naval Ship Research and Development Center. The testing used data reported in Sharma and Naegle (1970).[1]

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*The nondimensional transverse wave number is defined as: $u = \sec\theta \tan\theta$, where the angle θ defines the direction of wave propagation.

[1] References are listed on page 76.

BACKGROUND

For many years there has been continuing interest in the reduction of resistance into components attributable to specific causes such as friction, wind, and wave breaking. In recent years the development of theory and experimental techniques have made it possible to assess more realistically the contribution of wave making phenomena to the total resistance of ships. Specifically, the use of the longitudinal wave cut technique with theory to determine the wave making characteristics of ship hulls from model experiments has been advanced by a number of investigations.[2]

In 1968 S. D. Sharma directed a project at the University of Michigan with the objective of optimizing bulbous bows for ships. The approach was to use experimental methods to determine the profiles of wave patterns for specific hull and bulb configurations and then use theoretical methods to predict the effects of changes in bulb size and location on the wave patterns and, consequently, on the component of resistance due to wave making. Wave profile measurements were obtained for three bulbs fitted to a common hull model. The investigators concluded that the technique was promising as a design tool for optimizing bulb size and location using a minimum of model experiments.

Since the methods developed by Sharma appear to have promise in optimizing hull designs, the programs have been adapted for use by the U.S. Navy as described herein. These programs have also been used in modified form by other investigators.[3]

COMPUTER PROGRAM DESCRIPTIONS (USER'S GUIDE)

This section of the report provides a user's guide for the five computer programs which collectively will be used for the analysis of longitudinal wave cuts. The program operating instructions are for the CDC 6000 computer series. The descriptions provided summarize the purpose, input requirements/format and output for each of the computer programs.

NONDIMENSIONAL WAVE CUT PROGRAM (NONDIM)

The program NONDIM converts digital wave cut information from analog units (i.e., millivolts/inch) to feet, and then nondimensionalizes the wave cut information for use in the Wave Analysis Program (WAVECT).

The input variables for program NONDIM are defined as follows:

LABEL - A vector containing the 80 character title

MMU - A control character indicating whether height data or slope data is to be read in:

$MMU \leq 0$; Height data

$MMU > 0$; Slope data

MAX - The number of points in the wave profile, ZETA - MAX must be less than or equal to 1000

MEAN - The number of points in the wave profile which should be averaged and subtracted from all of the points of the wave profile in order to obtain a zero line

DT - The time interval between successive input points in the profile in seconds

YFT - The transverse distance from the center line of the model to the center wire of the wave probe in feet

VFPS - The model speed in feet per second

ZSCA - Scale factor for use in converting the input data into either inches or slope - ZSCA is the number of input units per inch of wave height, or per radian of slope as indicated by MMU.

XSHUT - Distance from the origin on the model to the trip in feet, with positive measured forward - See Figure 1

XLAG - Distance from center wire of the wave probe to the center of the photo cell in feet with positive upstream - See Figure 1

JMARK - The number of time intervals (fractions allowed) from the trip to where the input begins, with positive measured forward - See Figure 2

ZETA - A vector containing the MAX input points for the longitudinal wave profile.

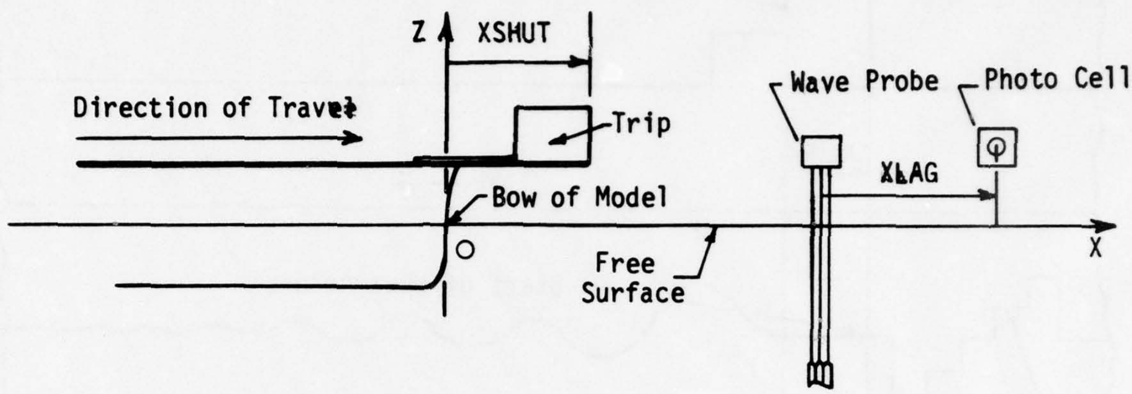


Figure 1 - Longitudinal Section of Testing Tank for Longitudinal Wave Analysis

Note: XLAG and XSHUT are measured positive in the direction of the arrows drawn on the figure.

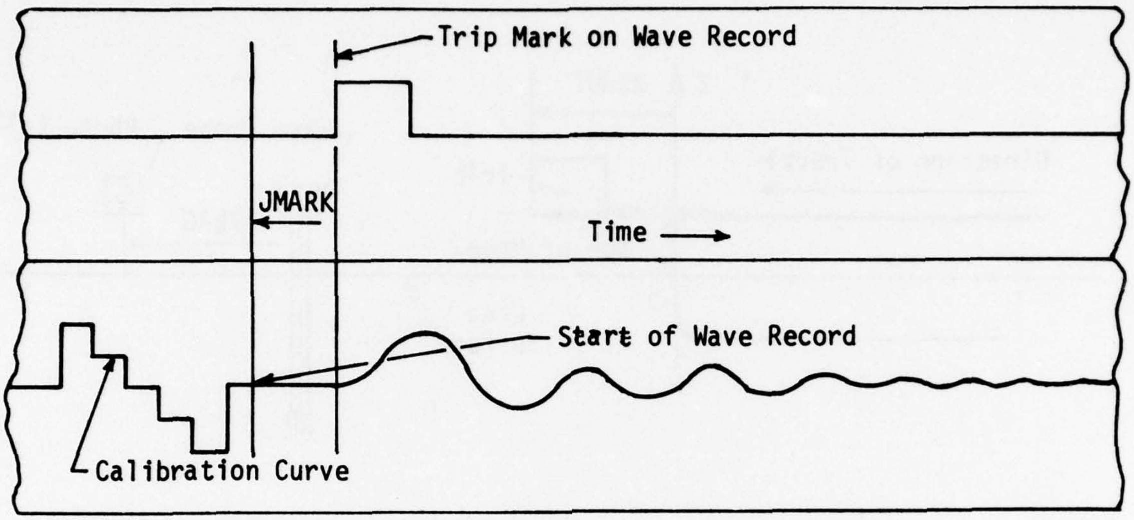


Figure 2 - Sample Wave Record from Longitudinal Wave Cut

Note: JMARK is measured positive in the direction of the arrow drawn on the figure.

The input cards for the NONDIM program are read from logical device Number 5 and should be prepared in the following manner:

CARD	VARIABLES	FORMAT
1	LABEL	8A10
2	MMU, MAX, MEAN	3I5
3	DT, YFT, VFPS	3F10.3
4	ZSCA, XSHUT, XLAG, JMARK	4F10.3
5	IFMT	8A10
6	ZETA (As many cards as necessary)	IFMT

Below is a list of input values used to complete one successful run of the NONDIM program. Because of the size of ZETA, the specific input values for ZETA are omitted from the list but are provided in Table 1.

LABEL = Model 1094 (CV) RUN NO. 4 AUG. 6, 1978 V = 5.360 FT/SEC

MMU = 0

MAX = 451

MEAN = 50

DT = 0.03

YFT = 4.125

VFPS = 5.360

ZSCA = -3.972

XSHUT = 3.0833

XLAG = 1.1667

JMARK = 118.25

IFMT = (15F5.2, 5X)

Table 1 provides a listing of the above sample input in the format required by the progran NONDIM.

Table 1 - Sample Listing of Input for Program NONDIM

```
            MODEL 1094 (CV) RUN NO.4  AUG. 6,1968  V=5.360 FT./SEC
   0  451    50
     0.03       4.125      5.360
    -3.972     3.0833     1.1667     118.25
(15F5.2,5X)
8.03 8.05 8.05 8.06 8.09 8.10 8.05 8.06 8.03 8.05 8.09 8.09 8.09 8.09 8.10      1
8.10 8.02 8.10 8.02 8.05 8.02 8.00 8.03 8.03 8.06 8.05 8.09 8.05 8.03 8.04      2
8.10 8.08 8.10 8.10 8.10 8.07 6.10 8.10 8.06 8.04 8.02 8.05 8.03 8.08 8.06      3
8.05 8.10 8.08 8.06 8.06 8.07 8.09 8.00 8.02 8.03 8.08 8.04 8.00 8.00 8.00      4
8.07 8.05 8.05 8.06 8.02 8.00 8.03 8.06 8.05 8.02 8.04 8.06 8.09 8.06 8.03      5
8.05 8.07 8.07 8.03 8.04 8.10 8.10 8.07 8.07 8.05 8.04 8.05 8.06 8.06 8.07      6
8.09 8.10 8.10 8.10 8.06 8.10 6.07 8.12 8.07 8.09 8.10 8.08 8.03 8.05 8.05      7
8.05 8.04 8.07 8.05 8.06 8.08 8.07 6.09 8.05 8.05 8.00 8.02 8.00 8.03 8.00      8
7.98 7.96 7.99 7.96 7.94 7.93 7.93 7.92 7.94 7.96 7.95 7.96 7.93 7.93 7.95      9
7.90 7.93 7.92 7.92 7.95 7.90 7.94 7.90 7.94 8.00 8.02 8.04 8.04 8.06 8.14     10
8.17 8.19 8.23 8.30 8.36 8.38 8.50 8.53 8.57 8.70 8.73 8.80 8.82 8.87 8.96     11
9.03 9.02 8.98 9.00 9.03 8.98 8.92 8.86 8.79 8.67 8.58 8.45 8.23 8.15 8.00     12
7.95 7.82 7.75 7.72 7.70 7.77 7.86 7.90 8.07 8.22 8.52 8.70 8.85 9.06 9.14     13
9.23 9.20 9.17 9.03 8.82 8.56 8.18 7.80 7.33 7.00 6.70 6.42 6.26 6.28 6.44     14
6.90 7.33 8.00 8.52 8.98 9.46 9.69 9.75 9.74 9.52 9.06 8.63 8.06 7.53 6.80     15
6.67 6.72 7.04 7.50 7.92 8.40 8.68 8.76 8.80 8.63 8.34 8.07 7.90 7.70 7.83     16
8.02 8.23 8.42 8.55 8.62 8.59 8.53 8.26 8.23 8.02 7.85 7.69 7.70 7.72 7.82     17
7.94 8.00 7.96 7.88 7.74 7.55 7.50 7.53 7.62 7.80 7.96 8.28 8.45 8.63 8.68     18
8.73 8.72 8.76 8.75 8.76 8.72 8.73 8.60 8.43 8.22 8.04 7.73 7.38 7.09 6.66     19
6.62 6.48 6.55 6.83 7.37 7.96 8.53 8.98 9.40 9.52 9.55 9.40 9.23 8.98 8.62     20
8.38 8.16 7.96 7.87 7.84 7.92 8.01 8.14 8.16 8.14 8.20 8.10 8.00 7.82 7.56     21
7.37 7.32 7.38 7.56 7.87 8.03 8.26 8.28 8.23 8.15 8.18 8.14 8.23 8.35 8.43     22
8.56 8.60 8.62 8.53 8.47 8.30 8.23 8.17 8.20 8.28 8.26 8.25 8.12 8.02 7.95     23
7.85 7.74 7.80 7.76 7.82 7.88 7.96 8.02 8.10 8.13 8.14 8.14 8.16 8.22 8.28     24
8.24 8.33 8.35 8.37 8.42 8.32 8.37 8.35 8.32 8.34 8.22 8.23 8.18 8.15 8.12     25
8.00 7.96 7.90 7.83 7.85 7.76 7.80 7.80 7.82 7.90 7.92 7.90 7.93 7.93 8.06     26
8.10 8.15 8.18 8.25 8.37 8.39 8.45 8.46 8.46 8.50 8.43 8.44 8.37 8.36 8.35     27
8.30 8.22 8.16 8.15 8.12 8.00 7.98 7.94 7.92 7.86 7.84 7.90 7.91 7.90 7.88     28
7.86 7.86 7.90 7.90 7.95 7.98 8.03 8.14 8.20 8.20 8.25 8.30 8.30 8.40 8.32     29
8.36 8.38 8.32 8.37 8.36 8.30 8.23 8.22 8.14 8.07 7.98 7.94 7.90 7.88 7.85     30
7.78                                                                           31
```

The output from the NONDIM program consists of two types; formatted printer output and unformatted file output. The formatted output consists of the longitudinal step size (DX) which is the distance between input points in the wave profiles (DX should be negative); the distance of the first input point forward from the origin on the model (XONE); the distance from the centerline of the model to the center of the wave wire (Y); and the number of points in the wave profile (MAX). This is followed by the points of the wave profile (ZETA), which have been adjusted to zero by averaging a number of points from the wave profile (this number is determined by the input variable MEAN). Both dimensional and nondimensional forms are printed. Table 2 provides a sample listing of the dimensional output; Table 3 provides a sample listing of the nondimensional output. The non-dimensionalized data is also written unformatted on a file for use by the Wave Analysis Program (WAVECT) and the Free-Wave Spectra Plotting Program (SPCTRA). The length information is nondimensionalized by the fundamental wave-number $\left[g/U^2\right]$.

The NONDIM program uses device numbers 4, 5, and 6 for its input and output. Device number 5 should be assigned to the card reader for the input, device number 6 should be assigned to the line printer for the formatted output, and device number 4 should be assigend to a permanent file (disk or magnetic tape) which needs to be requested and catalogued.

Sample control cards used to run program NONDIM on the CDC 6000 Series Computers are as follows:

```
CHRENON,CM60000,T100,P3.

CHARGE,CHRE,XXXXXXXXXX.

REQUEST,TAPE4,*PF.

FTN(T)

LGO.

CATALOG,TAPE4,PERMFILE4,ID=CHRE.

7/8/9 END OF RECORD CARD
```

Table 2 - Sample of Dimensionalized Output for Program NONDIM

MODEL 1094 (CV) RUN NO.4 AUG. 6,1968 V=5.360 FT./SEC

ALL QUANTITIES GIVEN IN FEET
HEIGHT DATA (FEET*100)

THE LONGITUDINAL STEP SIZE IS -.16080 (DX)
INPUT BEGINS 20.77049 FROM THE ORIGIN (XONE)
WAVE CUT TAKEN 4.12500 FROM CENTE-LINE OF MODEL (Y)
451 POINTS WERE GIVEN (MAX)

ZETA

.0697	.0277	.0277	.0067	-.0562	-.0772	.0277	.0067	.0497	.0277
-.0562	-.0562	-.0562	-.0352	-.0772	-.0772	.0906	-.0772	.0906	.0277
.0906	.1326	.0697	.0697	.0067	.0277	-.0562	.0277	.0497	.0487
-.0772	-.0352	-.0772	-.0772	-.0772	-.0143	-.0772	-.0772	.0067	.0487
.0906	.0277	.0697	-.0352	.0067	.0277	-.0772	-.0352	.0067	.0067
-.0143	-.0562	.1326	.0906	.0697	-.0352	.0487	.1326	.1326	.1326
-.0143	.0277	.0277	.0067	.0906	.1326	.0697	.0067	.0277	.0906
.0487	.0067	-.0562	.0067	.0697	.0277	-.0143	-.0143	.0497	.0487
-.0772	-.0772	-.0143	-.0143	.0277	.0487	.0277	.0067	.0067	-.0143
-.0562	-.0772	-.0772	-.0772	.0067	-.0772	-.0143	-.1192	-.0143	-.0562
-.0772	-.0352	.0697	.0277	.0277	.0277	.0487	-.0143	.0277	.0067
-.0352	-.0143	-.0562	.0277	.0277	.1326	.0906	.1326	.0497	.1326
.1746	.2165	.1536	.2165	.2585	.2795	.2795	.3004	.2585	.2165
.2375	.2165	.2795	.2795	.2375	.3424	.2795	.3004	.3004	.2375
.3424	.2585	.3424	.2585	.1326	.0906	.0487	.0487	.0067	-.1611
-.2241	-.2660	-.3499	-.4968	-.6227	-.5647	-.9164	-.9794	-1.0433	-1.3360
-1.3990	-1.5458	-1.5878	-1.6927	-1.8815	-2.0284	-2.0074	-1.9235	-1.[illegible]454	-2.0284
-1.9235	-1.7976	-1.5717	-1.5248	-1.2731	-1.0943	-.8115	-.3499	-.1821	.1326
.2375	.5102	.5571	.7200	.7620	.6151	.4263	.3424	-.0143	-.3290
-.9584	-1.3360	-1.5507	-2.0913	-2.2591	-2.4480	-2.3850	-2.3221	-2.0284	-1.5878
-1.0423	-.2450	.5522	1.5383	2.2306	2.8600	3.4475	3.7831	3.[illegible]412	3.4055
2.4404	1.5383	.1326	-.9584	-1.9235	-2.9305	-3.4131	-3.5389	-3.[illegible]180	-3.0564
-2.0913	-1.1892	.0067	1.1187	2.6502	2.9230	2.8181	2.1467	1.1816	.3004
-.7066	-1.2941	-1.4619	-1.5458	-1.1892	-.5807	-.0143	.3424	.[illegible]620	.4593
.0906	-.3499	-.7486	-1.0213	-1.1682	-1.1052	-.9794	-.4129	-.3499	.0906
.4473	.7830	.7620	.7200	.5102	.2585	.1326	.2165	.3844	.6781
1.0767	1.1916	1.1187	.9298	.5522	.2165	-.4549	-.8115	-1.1892	-1.2941
-1.3990	-1.3780	-1.4619	-1.4409	-1.4619	-1.3780	-1.3990	-1.1262	-.7696	-.3290
.0487	.6991	1.4334	2.0418	2.9439	3.0279	3.3216	3.1747	2.5873	1.4543
.2165	-.9794	-1.9235	-2.8046	-3.0564	-3.1193	-2.8046	-2.4480	-1.9235	-1.1562
-.6647	-.2031	.2165	.4053	.4682	.3004	.1116	-.1611	-.2631	-.1611
-.2870	-.0772	.1326	.5102	1.0557	1.4543	1.5592	1.4334	1.0557	.4053
.0697	-.4129	-.4549	-.3499	-.1821	-.2450	-.1611	-.3499	-.6617	-.7696
-1.0423	-1.1262	-1.1682	-.9794	-.8535	-.4968	-.3499	-.2241	-.2870	-.4549
-.4129	-.3919	-.1192	.0906	.2375	.4473	.6781	.5522	.[illegible]361	.5102
.3844	.2165	.0906	-.0772	-.1401	-.1611	-.1611	-.2031	-.[illegible]590	-.4549
-.3709	-.5598	-.5017	-.6437	-.7486	-.5388	-.6437	-.6017	-.5388	-.5807
-.3290	-.3499	-.2450	-.1821	-.1192	.1326	.2165	.3424	.4893	.4473
.6361	.5522	.5522	.5102	.3424	.3004	.3424	.2795	.2795	.0067
-.0772	-.1821	-.2450	-.3919	-.6437	-.6856	-.8115	-.8325	-.8325	-.9164
-.7696	-.7905	-.6437	-.6227	-.6017	-.4968	-.3290	-.2031	-.1821	-.1192
.1326	.1746	.2585	.3004	.4263	.4683	.3424	.3214	.3[illegible]24	.3844
.4263	.4263	.3424	.3424	.2375	.1746	.0697	-.1611	-.2870	-.2870
-.3919	-.4968	-.4968	-.7066	-.5388	-.6227	-.6647	-.5388	-.6437	-.6227
-.4968	-.3499	-.3290	-.1611	-.0143	.1746	.2585	.3424	.3844	.4473

Table 3 - Sample of Nondimensionalized Output for Program NONDIM

MODEL 1094 (CV) RUN NO.4 AUG. 6,1968 V=5.360 FT./SEC

ALL QUANTITIES ARE DIMENSIONLESS
HEIGHT DATA

THE LONGITUDINAL STEP SIZE IS -.14008 (DX)
INPUT BEGINS 23.26660 FROM THE ORIGIN (XONE)
WAVE CUT TAKEN 4.41955 FROM CENTERLINE OF MODEL (Y)
451 POINTS WERE GIVEN (MAX)

ZETA

.0008	.0007	.0003	.0001	-.0006	-.0009	.0003	.0001	.0009	.0003
-.0006	-.0006	-.0006	-.0006	-.0009	-.0009	.0010	-.0009	.0010	.0003
.0010	.0015	.0008	.0008	.0001	.0003	-.0006	.0003	.0008	.0005
-.0009	-.0004	-.0009	-.0009	-.0009	-.0002	-.0009	-.0009	.0001	.0005
.0010	.0003	.0008	-.0004	.0001	.0003	-.0009	-.0004	.0001	.0001
-.0002	-.0005	.0015	.0010	.0008	-.0004	.0005	.0015	.0015	.0015
-.0002	.0003	.0003	.0001	.0010	.0015	.0008	.0001	.0003	.0010
.0015	.0001	-.0006	.0001	.0008	.0003	-.0002	-.0002	.0008	.0005
-.0009	-.0009	-.0002	-.0002	.0003	.0005	.0003	.0001	.0001	-.0002
-.0006	-.0009	-.0009	-.0009	.0001	-.0009	-.0002	-.0013	-.0002	-.0006
-.0009	-.0004	.0008	.0003	.0003	.0003	.0005	-.0002	.0003	.0001
-.0014	-.0002	-.0006	.0003	.0003	.0015	.0010	.0015	.0009	.0015
.0020	.0024	.0017	.0024	.0029	.0031	.0031	.0034	.0029	.0024
.0027	.0024	.0031	.0031	.0027	.0038	.0031	.0034	.0034	.0027
.0038	.0029	.0038	.0029	.0015	.0010	.0005	.0005	.0001	-.0018
-.0025	-.0030	-.0039	-.0056	-.0070	-.0074	-.0103	-.0110	-.0119	-.0150
-.0157	-.0173	-.0178	-.0190	-.0211	-.0227	-.0225	-.0215	-.0220	-.0227
-.0215	-.0201	-.0187	-.0171	-.0143	-.0121	-.0091	-.0039	-.0020	.0015
.0027	.0057	.0074	.0081	.0065	.0069	.0048	.0038	-.0002	-.0037
-.0107	-.0150	-.0185	-.0214	-.0253	-.0274	-.0267	-.0260	-.0227	-.0178
-.0117	-.0027	.0062	.0172	.0250	.0320	.0386	.0424	.0419	.0381
.0273	.0172	.0015	-.0137	-.0215	-.0328	-.0382	-.0396	-.0394	-.0342
-.0234	-.0133	.0001	.0125	.0247	.0327	.0315	.0240	.0132	.0034
-.0079	-.0145	-.0164	-.0173	-.0133	-.0065	-.0002	.0038	.0065	.0055
.0010	-.0039	-.0084	-.0114	-.0131	-.0124	-.0110	-.0046	-.0039	.0010
.0050	.0049	.0065	.0081	.0057	.0029	.0015	.0024	.0043	.0075
.0121	.0132	.0125	.0104	.0062	.0024	-.0051	-.0091	-.0133	-.0145
-.0157	-.0154	-.0164	-.0161	-.0164	-.0154	-.0157	-.0126	-.0086	-.0037
.0005	.0078	.0161	.0229	.0330	.0339	.0372	.0356	.0290	.0163
.0024	-.0110	-.0215	-.0314	-.0342	-.0349	-.0314	-.0274	-.0215	-.0131
-.0074	-.0023	.0024	.0045	.0052	.0034	.0012	-.0018	-.0023	-.0018
-.0032	-.0009	.0015	.0057	.0118	.0163	.0175	.0161	.0118	.0045
.0008	-.0046	-.0051	-.0039	-.0020	-.0027	-.0018	-.0039	-.0067	-.0086
-.0117	-.0126	-.0131	-.0110	-.0096	-.0055	-.0039	-.0025	-.0032	-.0051
-.0046	-.0044	-.0013	.0010	.0027	.0050	.0076	.0062	.0071	.0057
.0043	.0024	.0010	-.0009	-.0016	-.0019	-.0018	-.0023	-.0037	-.0051
-.0042	-.0063	-.0067	-.0072	-.0084	-.0060	-.0072	-.0067	-.0060	-.0065
-.0037	-.0039	-.0027	-.0020	-.0013	.0015	.0024	.0038	.0055	.0050
.0071	.0062	.0062	.0057	.0039	.0034	.0038	.0031	.0031	.0001
-.0009	-.0020	-.0027	-.0044	-.0072	-.0077	-.0091	-.0093	-.0093	-.0103
-.0086	-.0089	-.0072	-.0070	-.0067	-.0056	-.0037	-.0023	-.0020	-.0013
.0015	.0020	.0029	.0034	.0048	.0052	.0038	.0036	.0038	.0043
.0048	.0048	.0038	.0038	.0027	.0020	.0008	-.0018	-.0032	-.0032
-.0044	-.0056	-.0056	-.0079	-.0060	-.0070	-.0074	-.0060	-.0072	-.0070
-.0056	-.0039	-.0037	-.0018	-.0002	.0020	.0029	.0038	.0043	.0050

Source Deck

7/8/9 END OF RECORD CARD

Data Cards

6/7/8/9 END OF FILE CARD

Note: PERMFILE4 is the name of the permanent file (disk) on which the unformatted output is to be stored.

WAVE ANALYSIS PROGRAM (WAVECT)

The program WAVECT determines the free-wave spectra, wave resistance, and side force on a body from a wave profile measured along a line parallel to the path of the model (longitudinal wave cut). The method used is that developed by Sharma.[2] WAVECT uses the nondimensionalized data from the program NONDIM and does the actual wave analysis with an optional truncation correction which can be applied to height data.

The input variables for the WAVECT program are defined as follows:

MU - Control character indicating whether height or slope data is to be read and whether or not the truncation correction is to be made in the case of height data:

MU < 0; height data without truncation correction

MU = 0; height data with truncation correction

MU > 0; slope data

N - The number of elementary waves to be analyzed during the wave analysis.

DU - The size of the increment for the transverse wave number which is used to determine the N elementary waves which are to be analyzed

M - The number of points which are to be read from the wave profile

MP - The number of the points on the wave profile at which the analysis for determining the asymptotic behavior of the wave profile should begin - This is used in making the truncation correction and is not read unless MU = 0.

C3 - A nondimensional distance indicating where, in relation to the origin on the model, is the origin for use in determining the beginning of the asymptotic behavior of the wave - This variable is not read unless MU = 0.

LABEL - A vector which contains the 80 character title

DX - Distance between the input points in the wave profile

XONE - The distance of the first input point forward of the origin on the model

Y - The distance from the centerline of the model to the center of the wave wire

MAX - The number of points in the wave profile

MMU - A control character indicating whether height or slope data is to be read in:

MMU $\leq$ 0; Height data

MMU > 0; Slope data

ZETA - A vector containing the MAX input points for the longitudinal wave profile.

The input variables LABEL, DX, XONE, Y, MAX, MMU, and ZETA are the unformatted output of Program NONDIM and are read by Program WAVECT from device number 4. The input variables MU, N, DU, M, MP, and C3 are user inputs read by WAVECT from device number 5 and should be prepared as follows:

CARD	VARIABLES	FORMAT
1	MU	I5
2	N, DU	I5, F10.3
3(if MU ≠ 0)	M	I5
3(if MU = 0)	M, MP, C3	2I5, F10.3

Listed below are sample input values used to complete a successful run of the WAVECT program.

MU = 0

N = 100

DU = 0.1

M = 451

MP = 416

C3 = 0.0

Table 4 provides a listing of the above sample input in the format required by program WAVECT.

The output of the Wave Analysis Program consists of a number of error statements, one of two forms of printed output on device number 6, and the free-wave spectra written on device number 3 which is a disk file, for use by the Bulb Contour Printer program. The first form of the printed output is that generated for either slope data or height data without the truncation correction, the second output form is generated when the calculations on height data are made with the truncation correction.

The error statements are printed to indicate that there is an error in the input, or that the user input is inconsistent with the input which is read from the Nondimensionalization Program (NONDIM) output. Error statements are output by program WAVECT if any of the following conditions exist:

1) If either N or DU is less than or equal to zero

2) If MU indicates a different type of data than MMU from the Nondimensionalization program (i.e., if MU = +1 and MMU = 0, the Wave Analysis Program expects slope data while the Nondimensionalization program is giving height data)

3) If M is not between one and MAX

4) If MP is not between one and M (this applies only for height data with truncation correction).

Execution of the program is terminated after any of the above errors have been detected.

Table 4 - Sample Input for Program WAVECT

```
  0
100      0.100
451  416      0.000
```

If no errors have been found, the program then proceeds to calculate the free-wave spectra, transverse force, and wave resistance, and to print the output. The printer output on device number 6 consists of the title, the number of elementary waves to be analyzed, the transverse wave number step size, the longitudinal distance between the points in the wave profile, and the number of points in the wave profile. If the truncation correction is to be made (height data only) the point in the wave profile where the asymptotic behavior of the wave is assumed to begin is printed along with the three constants describing the asymptotic behavior of the wave. This is then followed by the definition of all terms given in the heading of the output columns. These headings and their definitions for the output with slope data and height data without the truncation correction are as follows:

NU - The number of the elementary wave being analyzed

UNU - The transverse wave number - Sec $\theta \cdot$ Tan θ

SNU - The longitudinal wave number - Sec θ

TNU - Tan θ

SNU* - The sine component of the Fourier transform of the wave profile

CNU* - The cosine component of the Fourier transform of the wave profile

F - The sine component of the free-wave spectra calculated

G - The cosine component of the free-wave spectra calculated

E - The square root of the sum of the squares of F and G

T - The nondimensional transverse force**

R - The nondimensional wave resistance.

**The wave pattern on each side of the ship exerts a transverse force on the ship. If the ship is symmetric, it generates a symmetric wave pattern, and therefore antisymmetric transverse forces. If, however, the ship is asymmetric, it generates an asymmetric wave pattern, which exerts an asymmetric transverse force on the ship. The net transverse force on an asymmetric ship due to wave making can be determined by taking the difference between the side forces calculated from the wave pattern measured on each side of the ship. The longitudinal force on an asymmetric ship is the average of the wave resistance computed from the wave pattern on each side of the ship.

The variables T and R, printed with each step, are the integrals of the free-wave spectra through that elementary number.

When the wave analysis is applied to height data with truncation correction, the output on device number 6 is as follows:

NU - The number of the elementary wave being analyzed

UNU - The transverse wave number - Sec $\theta \cdot$ Tan θ

SNU - The longitudinal wave number - Sec θ

TNU - Tan θ

SNU* - The sine component of the Fourier transform applied to the wave profile without the truncation correction

SNU*T - The sine component of the Fourier transform of the wave profile with the truncation correction

CNU* - The cosine component of the Fourier transform of the wave profile without the truncation correction

CNU*T - The cosine component of the Fourier transform of the wave profile with the truncation correction

F - The sine component of the free-wave spectra calculated with the truncation correction

G - The cosine component of the free-wave spectra calculated with the truncation correction

E - The square root of the sum of the squares of F and G

T - The nondimensional transverse force calculated without the truncation correction*

TT - The nondimensional transverse force calculated with the truncation correction*

R - The nondimensional wave resistance calculated without the truncation correction

RT - The nondimensional wave resistance calculated using the truncation correction.

The wave resistance and side force are nondimensionalized by multiplication by $1/\rho g^{-2} V^6$.

A sample output listing showing the output of program WAVECT is provided in Table 5.

---

*See the footnote on page 16.

Table 5 - Sample Output for Program WAVECT

```
MODEL 1094 (CV) RUN NO.  4 AUG. 6, 1968  V = 5.360 FT/ SEC

NUMBER OF SPECTRA                                    100
TRANSVERSE WAVE NUMBER STEP SIZE                  .10000
LONGITUDINAL STEP SIZE                           -.18008
NUMBER OF POINTS IN THE WAVE PROFILE                 451
TRUNCATION CORRECTION BEGINS AT POINT                416
C1                                               -.00567
C2                                               -.04653
C3                                               0.00000

    DEFINITION OF OUTPUT VARRIABLES

NU - THE NUMBER OF THE ELEMENTARY WAVE
UNU - THE TRANSVERSE WAVE NUMBER-SEC(THETA)XTAN(THETA)
SNU - THE LONGITUDINAL WAVE NUMBER-SEC(THETA)
TNU - TAN(THETA)
SNU- - THE SINE COMPONENT OF THE FOURIER TRANSFORM WITHOUT TRUNCATION CORRECTION
SNUXT - THE SINE COMPONENT OF THE FOURIER TRANSFORM WITH TRUNCATION CORRECTION
CNU- - THE COSINE COMPONENT OF THE FOURIER TRANSFORM WITHOUT TRUNCATION CORRECTION
CNUXT - THE COSINE COMPONENT OF THE FOURIER TRANSFORM WITH TRUNCATION CORRECTION
F - THE SINE COMPONENT OF THE FREE-WAVE SPECTRA
G - THE COSINE COMPONENT OF THE FREE-WAVE SPECTRA
F - THE SQUARE ROOT OF THE SUM OF THE SQUARES OF F AND G
T - THE NONDIMENSIONAL TRANSVERSE FORCE WITHOUT TRUNCATION CORRECTION
TT - THE NONDIMENSIONAL TRANSVERSE FORCE WITH TRUNCATION CORRECTION
R - THE NONDIMENSIONAL WAVE RESISTANCE WITH OUT TRUNCATION CORRECTION
RT - THE NONDIMENSIONAL WAVE RESISTANCE WITH TRUNCATION CORRECTION
```

Table 5 - Sample Output for Program WAVECT (Cont'd)

NU	UNU	SNU	TNU	SNU*	SNU*T	CNU*	CNU*T	F	G	E	T	TT	R	RT
0	0.0000	1.0000	0.0000	0.0000	-.0362	0.0000	-.0463	-.1448	-.1850	.2350	0.0000	0.0000	0.0000	0.0000
1	.1000	1.0049	.0995	-.0123	-.0141	-.0120	-.0509	-.1384	-.1539	.2070	.0000	.0000	.0000	.0001
2	.2000	1.0191	.1963	-.0123	.0100	-.0333	-.0492	-.1235	-.1397	.1865	.0000	.0000	.0000	.0002
3	.3000	1.0407	.2883	.0168	.0324	-.0484	-.0346	-.0962	-.1310	.1625	.0000	.0000	.0001	.0002
4	.4000	1.0679	.3746	.0518	.0401	-.0183	-.0061	-.0525	-.1152	.1266	.0000	.0000	.0001	.0003
5	.5000	1.0937	.4551	.0270	.0191	.0316	.0195	.0044	-.0771	.0772	.0001	.0001	.0002	.0003
6	.6000	1.1318	.5301	-.0328	-.0203	.0145	.0116	.0593	-.0089	.0599	.0001	.0001	.0002	.0003
7	.7000	1.1663	.6002	-.0334	-.0357	-.0497	-.0383	.0907	.0811	.1217	.0001	.0001	.0003	.0003
8	.8000	1.2014	.6659	.0182	.0097	-.0833	-.0898	.0828	.1728	.1916	.0001	.0001	.0003	.0004
9	.9000	1.2368	.7277	.0879	.0970	-.0772	-.0816	.0354	.2437	.2462	.0002	.0002	.0004	.0005
10	1.0000	1.2720	.7862	.1575	.1574	-.0062	.0034	-.0321	.2798	.2816	.0003	.0004	.0005	.0007
11	1.1000	1.3070	.8416	.1463	.1381	.1189	.1148	-.0948	.2817	.2973	.0006	.0005	.0009	.0010
12	1.2000	1.3416	.8944	.0395	.0463	.1914	.1857	-.1400	.2591	.2945	.0008	.0008	.0011	.0012
13	1.3000	1.3758	.9449	-.0729	-.0704	.1706	.1788	-.1677	.2192	.2760	.0010	.0010	.0014	.0015
14	1.4000	1.4095	.9933	-.1440	-.1523	.0990	.0984	-.1772	.1676	.2439	.0012	.0012	.0015	.0017
15	1.5000	1.4426	1.0398	-.1614	-.1582	.0027	-.0047	-.1633	.1158	.2002	.0013	.0013	.0017	.0018
16	1.6000	1.4752	1.0846	-.1123	-.1064	-.0707	-.0655	-.1266	.0787	.1491	.0014	.0014	.0018	.0019
17	1.7000	1.5073	1.1278	-.0500	-.0565	-.0739	-.0697	-.0787	.0637	.1013	.0015	.0015	.0018	.0019
18	1.8000	1.5389	1.1697	-.0379	-.0403	-.0486	-.0559	-.0343	.0653	.0738	.0015	.0015	.0019	.0020
19	1.9000	1.5699	1.2102	-.0516	-.0442	-.0570	-.0578	.0004	.0740	.0741	.0015	.0015	.0019	.0020
20	2.0000	1.6005	1.2496	-.0441	-.0447	-.0908	-.0834	.0277	.0875	.0918	.0016	.0016	.0019	.0020
21	2.1000	1.6306	1.2879	-.0131	-.0201	-.1266	-.1284	.0504	.1093	.1204	.0016	.0016	.0019	.0020
22	2.2000	1.6602	1.3252	.0486	.0513	-.1609	-.1676	.0664	.1405	.1554	.0017	.0017	.0020	.0021
23	2.3000	1.6893	1.3615	.1541	.1604	-.1551	-.1517	.0708	.1737	.1876	.0018	.0018	.0021	.0022
24	2.4000	1.7180	1.3970	.2525	.2487	-.0594	-.0535	.0620	.1981	.2075	.002[illegible]	.0020	.0022	.0023
25	2.5000	1.7463	1.4316	.2569	.2532	.0957	.0916	.0433	.2068	.2112	.0022	.0022	.0024	.0025
26	2.6000	1.7742	1.4655	.1603	.1646	.2169	.2115	.0214	.2013	.2024	.0024	.0024	.0025	.0026

Table 5 - Sample Output for Program WAVECT (Cont'd)

27	2.7000	1.8914	1.4988	.0215	.0268	.2525	.2598	.0020	.1881	.1881	.0026	.0026	.0027	.0027
28	2.8000	1.8247	1.5311	-.1050	-.1043	.2173	.2227	-.0120	.1725	.1729	.0028	.0028	.0028	.0029
29	2.9000	1.8555	1.5629	-.1841	-.1895	.1364	.1323	-.0205	.1557	.1571	.0029	.0029	.0028	.0030
30	3.0000	1.8819	1.5942	-.2130	-.2092	.0269	.0213	-.0243	.1361	.1383	.0030	.0030	.0029	.0030
31	3.1000	1.9079	1.6248	-.1729	-.1671	-.0729	-.0696	-.0242	.1127	.1153	.0031	.0031	.0030	.0031
32	3.2000	1.9334	1.6549	-.0906	-.0934	-.1170	-.1109	-.0200	.0873	.0896	.0032	.0032	.0030	.0031
33	3.3000	1.9590	1.6845	-.0236	-.0298	-.1011	-.1032	-.0117	.0633	.0644	.0032	.0032	.0030	.0031
34	3.4000	1.9841	1.7136	-.0031	-.0018	-.0698	-.0753	.0010	.0438	.0438	.0032	.0032	.0031	.0032
35	3.5000	2.0089	1.7423	-.0107	-.0041	-.0603	-.0599	.0172	.0293	.0340	.0032	.0032	.0031	.0032
36	3.6000	2.0334	1.7705	-.0128	-.0121	-.0780	-.0715	.0354	.0184	.0399	.0033	.0032	.0031	.0032
37	3.7000	2.0576	1.7982	.0045	-.0018	-.1034	-.1016	.0537	.0092	.0544	.0033	.0033	.0031	.0032
38	3.8000	2.0815	1.8256	.0437	.0378	-.1232	-.1290	.0701	.0007	.0701	.0033	.0033	.0031	.0032
39	3.9000	2.1052	1.8525	.0965	.1015	-.1261	-.1300	.0837	-.0063	.0839	.0033	.0033	.0031	.0032
40	4.0000	2.1286	1.8791	.1648	.1697	-.0921	-.0881	.0943	-.0102	.0949	.0034	.0034	.0031	.0032
41	4.1000	2.1518	1.9054	.2159	.2131	-.0074	-.0016	.1027	-.0101	.1032	.0034	.0034	.0032	.0033
42	4.2000	2.1748	1.9312	.2107	.2044	.1112	.1099	.1095	-.0065	.1097	.0035	.0035	.0032	.0033
43	4.3000	2.1975	1.9568	.1333	.1329	.2167	.2104	.1150	-.0008	.1150	.0036	.0036	.0033	.0034
44	4.4000	2.2200	1.9820	.0074	.0134	.2640	.2619	.1183	.0051	.1184	.0037	.0037	.0033	.0034
45	4.5000	2.2423	2.0069	-.1216	-.1180	.2374	.2426	.1187	.0101	.1191	.0038	.0038	.0034	.0035
46	4.6000	2.2643	2.0315	-.2145	-.2183	.1517	.1567	.1153	.0137	.1162	.0039	.0039	.0034	.0035
47	4.7000	2.2862	2.0559	-.2564	-.2563	.0357	.0336	.1082	.0162	.1094	.0040	.0040	.0034	.0035
48	4.8000	2.3073	2.0799	-.2246	-.2244	-.0789	-.0851	.0979	.0178	.0995	.0041	.0041	.0035	.0036
49	4.9000	2.3293	2.1037	-.1473	-.1413	-.1610	-.1629	.0856	.0184	.0876	.0042	.0041	.0035	.0035
50	5.0000	2.3505	2.1272	-.0461	-.0423	-.1878	-.1828	.0726	.0175	.0747	.0042	.0042	.0035	.0036
51	5.1000	2.3716	2.1505	.0408	.0375	-.1584	-.1531	.0597	.0148	.0615	.0042	.0042	.0036	.0037
52	5.2000	2.3925	2.1735	.0845	.0784	-.0982	-.0995	.0475	.0100	.0485	.0043	.0042	.0036	.0037
53	5.3000	2.4132	2.1963	.0832	.0821	-.0439	-.0499	.0359	.0037	.0361	.0043	.0043	.0036	.0037
54	5.4000	2.4337	2.2188	.0631	.0653	-.0184	-.0217	.0251	-.0034	.0254	.0043	.0043	.0036	.0037
55	5.5000	2.4541	2.2411	.0429	.0479	-.0195	-.0160	.0151	-.0103	.0183	.0043	.0043	.0036	.0037
56	5.6000	2.4743	2.2632	.0446	.0433	-.0290	-.0230	.0059	-.0164	.0174	.0043	.0043	.0036	.0037

The input and output of the WAVECT program is done using devices number 3, 4, 5, and 6. Device 5 should be assigned to the card reader for the user input, device 6 should be assigned to the line printer for the printed output, device 4 should be assigned to permanent file containing the unformatted nondimensional output of program NONDIM to be used as input, and device 3 should be assigned to a permanent file which is requested and catalogued for the free-wave spectra output of WAVECT. The file containing the free-wave spectra output is used by the Bulb Contour Printer Program (BUBOPT) and the Bulb Contour Plotter Program (BUBPLT).

Sample control cards used to run program WAVECT on the CDC 6000 Series Computers are shown below:

```
CHREFWS,CM46000,T100,P3.
CHARGE,CHRE,XXXXXXXXXX.
REQUEST,TAPE3,*PF
ATTACH,TAPE4,PERMFILE4,ID=CHRE.
FTN(T)
LGO.
CATALOG,TAPE3,PERMFILE3,ID=CHRE.
7/8/9 END OF RECORD CARD
Source Deck
7/8/9 END OF RECORD CARD
Data Cards
6/7/8/9 END OF FILE CARD
```

Note: PERMFILE4 is the name of the permanent file which contains the unformatted nondimensional output of program NONDIM, PERMFILE3 is the name of the permanent file on which the free-wave spectra output of program WAVECT is to reside.

FREE WAVE SPECTRA PLOTTING PROGRAM (SPCTRA)

The SPCTRA program plots the sine component of the free-wave spectra (F), the cosine component of the free-wave spectra (G), and the amplitude (E).

The input variables for the SPCTRA program are defined as follows:

N - The number of free-wave spectra.

DU - The transverse wave number step size.

LABEL - An 80 character title for the output.

F - The sine component of the free-wave spectra.

G - The cosine component of the free-wave spectra.

The user inputs (N, DU, and LABEL) are read from device number 5 and should be prepared as follows:

CARD	VARIABLES	FORMAT
1	N, DU	I5, F10.5
2	LABEL	8A10

The variables F and G are outputs of the Wave Analysis Program (WAVECT) and are read by SPCTRA from device number 4.

The values of user input shown below were used to complete a successful run on the CDC 6000 Series Computer.

N = 100
DU = 0.1
LABEL = MODEL 1094 (CV) RUN NO. 4 AUG. 6, 1968 V = 5.360 FT/SEC

Table 6 provides a listing of the above sample input in the format required by the program SPCTRA.

Table 6 - Sample Input for Program SPCTRA

```
 100 .1
MODEL 1094 (CV)  RUN NO. 4  AUG.6,1968  V=5.360  FT/SEC
```

The output for the SPCTRA program consists of plots of the sine component of the free-wave spectra (F) versus speed (S) and versus heading (U), the cosine component of the free-wave spectra (G) versus S and versus U, and for the amplitude ($E = \sqrt{F^2 + G^2}$) versus S and versus U. F, G, and E are plotted along the vertical axis while U and S vary along the horizontal axis. The plot file is automatically written on a magnetic tape which has to be requested in the control cards. The tape is then mounted on the CalComp Plotter which does the actual plotting. Figure 3 is a sample of the plotted output of program SPCTRA using the CalComp plotter.

The input and output of the SPCTRA program is done via devices numbers 4, 5, 6, and 7. Device number 5 should be assigned to a card reader for user inputs. The printed output is printed on logical device number 6. Device number 4 should be assigned to the permanent file written by the Wave Analysis Program (WAVECT) to be used as input and device number 7 should be assigned to a 7-track magnetic tape on which the commands are written which drive the CalComp plotter.

Sample control cards used to run SPCTRA on the CDC 6000 Series Computers are:

```
CHREFWS,CM50000,MT1,T100,P3.
CHARGE,CHRE,XXXXXXXXXX.
FTN(T)
ATTACH,TAPE4PERMFILE4,ID=CHRE.
VSN,TAPE7=RAE01=SLOT32.
REQUEST,TAPE7,HI,RING.                (SLOT32,RAE01)
ATTACH,CALC936.
LDSET,(LIB=CALC936)
LGO.
RETURN,TAPE7.
7/8/9 END OF RECORD CARD
Source Deck
```

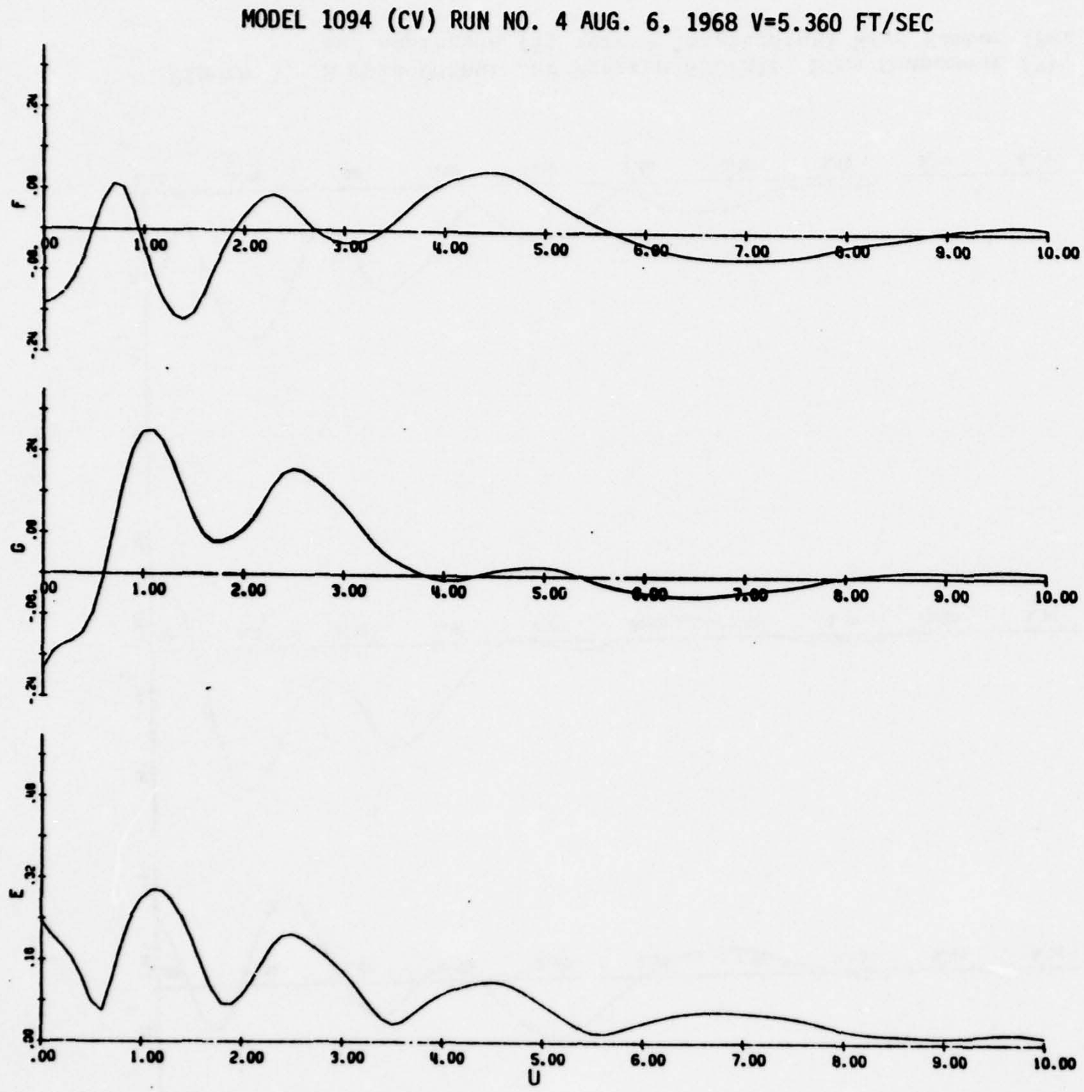


Figure 3 - Sample Output for Program SPCTRA: Sine Component (F), Cosine (G), and Amplitude (E) versus Transverse Wave Number (Sec θ TAN θ)

MODEL 1094 (CV) RUN NO. 4 AUG. 6, 1968 V=5.360 FT/SEC

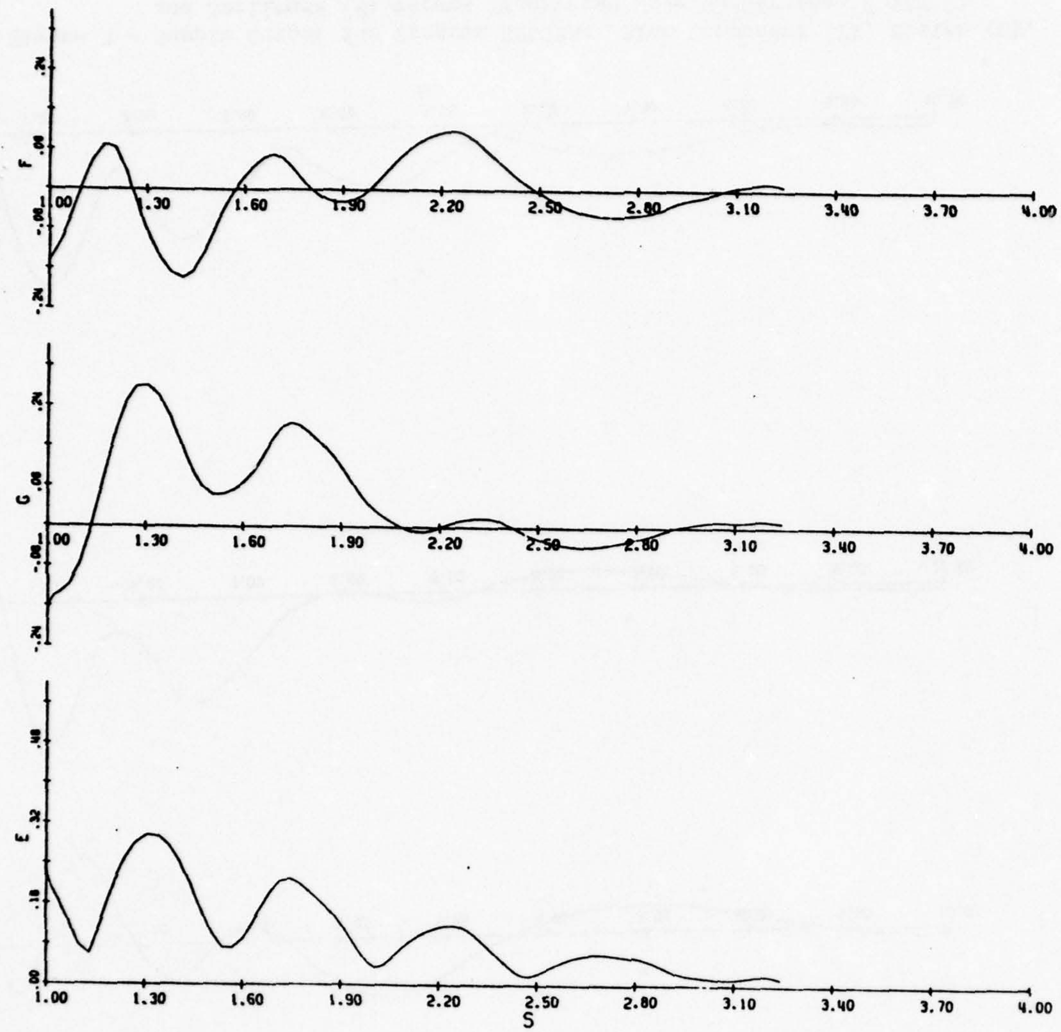


Figure 3 - Sample Output for Program SPCTRA: Sine Component (F), Cosine (G), and Amplitude (E) versus Longitudinal Wave Number (Sec θ) (Cont'd)

7/8/9 END OF RECORD CARD

Data Cards

6/7/8/9 END OF FILE CARD

Note: PERMFILE4 is the name of the permanent file on which the free-wave spectra output of program WAVECT resides, RAE01 is the name of the 7-track magnetic tape being used which must be provided by the user.

BULB CONTOUR PRINTER PROGRAM (BUBOPT)

The program BUBOPT determines the coarse contours of the bulb influence factor. This program is primarily intended for determining the range of variables to use as input to the BUBPLT (Plotter) program.

The input variables used in the BUBOPT program are defined as follows:

LABEL - An 80 character title for the output

DU - The transverse wave number step size

L - The nondimensional length

LAMBDA - A control character indicating the type of data to be read:

LAMBDA = 0; hull-bulb spectra is given and the bulb spectra must be separated from this

LAMBDA ≠ 0; bulb spectra given

N - The number of free-wave spectra

NCONT - A control character controlling the calculation of contour points:

NCONT = 0; calculate and print the points for plotting contours of NU = constant

NCONT ≠ 0; do not calculate points for the contours

QMIN - Starting location of bulb as a fraction of ship length*

QMAX - Ending location of bulb as a fraction of ship length*

DQ - The step size for Q

---

*Positive locations mean the new bulb is forward of the location of the current bulb, and negative locations are aft.

ETAMIN - The minimum eta for which contours are wanted (must be zero or larger) - Eta is defined as

$$\eta = \frac{R_{w_{OPT}}}{R_{w_{BH}}}$$

ETAMAX - The maximum eta for which contours are wanted

DETA - The distance between contours

FH - Sine component of the free-wave spectra without bulb output by program WAVECT

GH - Cosine component of the free-wave spectra without bulb output by program WAVECT

FBO - Sine component of the free-wave spectra with bulb output by program WAVECT

GBO - Cosine component of the free-wave spectra with bulb output by program WAVECT.

The user input variables LABEL, DU, . . ., DETA for the BUBOPT program are read from device 5 and should be prepared as follows:

CARD	VARIABLES	FORMAT
1	LABEL	8A10
2	DU, L, LAMBDA, N, NCONT	2F10.5, 3I5
3	QMIN, QMAX, DQ, ETAMIN, ETAMAX, DETA	6F10.5

Values of user input data that were used to perform a sample run of BUBOPT on the CDC 6000 Series Computer are provided below:

LABEL - FROM MODELS 1094CV AND 1094-B2 AT V = 5.360 FT/SEC (AUG. 1968)

DU - 0.1

L - 14.01

LAMBDA - 0

N - 100

NCONT - 0

QMIN - -.08

QMAX - 0.08

DQ - 0.01

ETAMIN - 0.6

ETAMAX - 2.0

DETA - 0.1

Table 7 provides a listing of the above sample input in the format required by program BUBOPT.

The input variables FH and GH are read from device number 3 and should be the free-wave spectra output of program WAVECT without a bulb. Input variables FBO and GBO are read from device number 4 and should be the free-wave spectra output of program WAVECT with a bulb.

The output of the BUBOPT (Printer) program consists of the following:

Q - The longitudinal location of the bulb

P(MIN) - P location of ETA(MIN) for a given Q

A, B, C - For a given Q; ETA is quadratic in P

ETA - $AP^2 + BP + C$

P(1) - The bulb volume for eta = 1

For eta = constant, a given Q gives P1 and P2 for plotting contours. It obtains P1 and P2 from the solution to $AP^2 + BP + (C - ETA) = 0$, for eta = constant. P1 and P2 = $\frac{-B \pm \sqrt{B^2 - 4A\,(C - ETA)}}{2A}$

P - Bulb volume - current bulb is (P=1) - As fraction of bulb volume

Table 8 is a sample of the output and output format that is generated by program BUBOPT.

The input and output of program BUBOPT is done via devices 3, 4, 5, and 6. Device number 5 should be assigned to the card reader for the user

Table 7 - Sample Input for Program BUBOPT

```
FROM MODELS 1094CV AND 1094-B2 AT V=5.36 FT/SEC (AUG. 1968)
  0.10000  14.01000     0  100     0
  -.08000   0.08000   0.01000   0.60000   2.00000   0.10000
```

Table 8 - Sample Output for Program BUBOPT

Q	P(MIN)	ETA(MIN)	A	B	C	P(1)
-.0800	-.6609	.8966	.2367	.2129	1.0000	-1.3218
-.0700	-.3240	.9748	.2367	.1543	1.0000	-.6519
-.0600	.0355	.9997	.2367	-.0168	1.0000	.0710
-.0500	.3950	.9631	.2367	-.1870	1.0000	.7900
-.0400	.7242	.8758	.2367	-.3429	1.0000	1.4484
-.0300	.9975	.7645	.2367	-.4723	1.0000	1.9950
-.0200	1.1947	.6621	.2367	-.5656	1.0000	2.3894
-.0100	1.3029	.5982	.2367	-.6169	1.0000	2.6057
.0000	1.3174	.5891	.2367	-.6238	1.0000	2.6349
.0100	1.2422	.6347	.2367	-.5882	1.0000	2.4845
.0200	1.0897	.7194	.2367	-.5155	1.0000	2.1774
.0300	.8743	.8190	.2367	-.4139	1.0000	1.7486
.0400	.6293	.9089	.2367	-.2937	1.0000	1.2407
.0500	.3495	.9711	.2367	-.1655	1.0000	.6990
.0600	.0835	.9983	.2367	-.0396	1.0000	.1671
.0700	-.1599	.9940	.2367	.0752	1.0000	-.3178
.0800	-.3636	.9687	.2367	.1722	1.0000	-.7272

ETA = .6000

Q	P1	P2
-.0100	1.2148	1.3910
.0000	1.1030	1.5319

ETA = .7000

Q	P1	P2
-.0200	.7947	1.5946
-.0100	.6470	1.9588
.0000	.6331	2.0018
.0100	.7170	1.7675

ETA = .8000

Q	P1	P2
-.0300	.6100	1.3849
-.0200	.4315	1.9578
-.0100	.3795	2.2262
.0000	.3736	2.2613
.0100	.4056	2.0779
.0200	.5052	1.6722

ETA = .9000

Q	P1	P2
-.0800	-.7809	-.5409
-.0400	.4048	1.0436
-.0300	.2408	1.7541
-.0200	.1923	2.1971
-.0100	.1737	2.4320
.0000	.1715	2.4634
.0100	.1836	2.3009
.0200	.2153	1.9621
.0300	.2895	1.4591

ETA = 1.0000

Q	P1	P2

Table 8 - Sample Output for Program BUBOPT (Cont'd)

-.0800	-1.3218	-.0000
-.0700	-.6519	-.0000
-.0600	.0000	.0710
-.0500	.0000	.7900
-.0400	.0000	1.4484
-.0300	.0000	1.9950
-.0200	.0000	2.3894
-.0100	.0000	2.6057
.0000	.0000	2.6349
.0100	.0000	2.4845
.0200	.0000	2.1774
.0300	.0000	1.7486
.0400	.0000	1.2407
.0500	.0000	.6990
.0600	.0000	.1671
.0700	-.3178	-.0000
.0800	-.7272	-.0000

ETA = 1.1000

Q	P1	P2
-.0800	-1.5879	.2660
-.0700	-1.0530	.4011
-.0600	-.6154	.6864
-.0500	-.3655	1.1556
-.0400	-.2499	1.6973
-.0300	-.1931	2.1880
-.0200	-.1654	2.5547
-.0100	-.1531	2.7599
.0000	-.1516	2.7865
.0100	-.1598	2.6443
.0200	-.1792	2.3567
.0300	-.2151	1.9637
.0400	-.2781	1.5188
.0500	-.3835	1.0875
.0600	-.5718	.7388
.0700	-.8280	.5102
.0800	-1.1094	.3811

ETA = 1.2000

Q	P1	P2
-.0800	-1.7930	.4712
-.0700	-1.3312	.6493
-.0600	-.8843	.9553
-.0500	-.6054	1.3955
-.0400	-.4450	1.8944
-.0300	-.3589	2.3539
-.0200	-.3127	2.7020
-.0100	-.2916	2.8973
.0000	-.2890	2.9239
.0100	-.3031	2.7876
.0200	-.3351	2.5136
.0300	-.3943	2.1429
.0400	-.4896	1.7292
.0500	-.6339	1.3329
.0600	-.8394	1.0065
.0700	-1.0917	.7739

inputs, device 6 should be assigned to the line printer for the printed output, device 3 should be assigned to the permanent file containing the free-wave spectra output of Program WAVECT without a bulb, and device 4 should be assigned to the permanent file containing the free-wave spectra output of program WAVECT with a bulb.

Sample control cards to run the program BUBOPT on the CDC 6000 Series Computers are shown below:

```
CHREOPT,CM60000,T120,P3.

CHARGE,CHRE,XXXXXXXXXX.

ATTACH,TAPE3,PERMFILE3,ID=CHRE.

ATTACH,TAPE4,PERMFILE4,ID=CHRE.

FTN.

LGO.

7/8/9 END OF RECORD CARD

Program Cards

7/8/9 END OF RECORD CARD

Data Cards

6/7/8/9 END OF FILE CARD
```

Note: PERMFILE3 and PERMFILE4 are, respectively, the names of the permanent files containing the free-wave spectra output of program WAVECT with and without a bulb.

BULB CONTOUR PLOTTER PROGRAM (BUBPLT)

The program BUBPLT determines and plots the contours of the constant bulb influence factor (ETA) in the P-Q space.

The input variables for the BUBPLT program are defined as follows:

LABEL - A title for the output, up to 80 characters

NCHAR - The number of characters in the title

N - The number of free-wave spectra

LAMBDA - A control character indicating the type of data to be read in:

LAMBDA = 0; the hull-bulb spectra is given, and the bulb spectra must be separated from this

LAMBDA ≠ 0; bulb spectra given

DU - The transverse wave number step size

L - The nondimensional length

QMIN - Starting location of bulb as a fraction of ship length

QMAX - Ending location of bulb as a fraction of ship length

DQ1 - The step size for Q

ETAMIN - The minimum eta for which contours are wanted

ETAMAX - The maximum eta for which contours are wanted

DETA1 - The distance between contours

DETA2 - The distance between contours

FH - Sine component of free-wave spectra without bulb output by program WAVECT

GH - Cosine component of free-wave spectra without bulb output by program WAVECT

FBO - Sine component of free-wave spectra with bulb output by program WAVECT

GBO - Cosine component of free-wave spectra with bulb output by program WAVECT

The user input variables LABEL, NCHAR, . . ., DETA2 for the BUBPLT program are read from device 5 and should be prepared as shown below:

CARD	VARIABLES	FORMAT
1	LABEL	8A10
2	NCHAR, N, LAMBDA, DU, L	3I5, 2F10.5
3	QMIN, QMAX, DQ1, ETAMIN, ETAMAX, DETA1, DETA2	7F10.2

Values of user input data used to complete a successful run of the BUBPLT program on the CDC 6000 Series Computer are provided below:

LABEL = FROM MODELS 1094CV AND 1094 - B2 AT V=5.360 FT/SEC (AUG. 1968)

NCHAR = 72

N = 100

LAMBDA = 0

DU = 0.1

L = 14.01

QMIN = -.08

QMAX = .08

DQ1 = .01

ETAMIN = .60

ETAMAX = 2.0

DETA1 = .05

DETA2 = .20

Table 9 provides a listing of this sample input data in the format required by program BUBPLT.

The input variables FH and GH are read from device number 3 and should be the free-wave spectra output of program WAVECT without a bulb. Input variables FBO and GBO are read from device number 4 and should be the free-wave spectra output of program WAVECT with a bulb.

Table 9 - Sample Input for Program BUBPLT

```
FROM MODELS 1094CV AND 1094-B2 AT V=5.36 FT/SEC (AUG. 1968)
  72  100    0    0.10000  14.01000
-0.08       0.08       0.01       0.6        2.0        0.05       0.2
```

The BUBPLT program has printed output consisting of the maximum and minimum of the P and Q values, as well as, eta plus plotter commands output to a magnetic tape which will drive the CalComp plotter. A sample of the CalComp plots for program BUBPLT is shown in Figure 4.

The input and output of program BUPPLT is performed via devices number 3, 4, 5, 6, and 7. Device number 5 should be assigned to the card reader for the user inputs, device 6 to the line printer for the printed output, device 7 to a 7-track magnetic tape for the CalComp plotter commands, and device numbers 3 and 4 should be assigned, respectively, to the permanent file containing the free-wave spectra output of program WAVECT run with and without a bulb.

Sample control cards to complete a successful run of the BUBPLT program on the CDC 6000 Series Computers are listed below:

```
CHREPLOT,CM60000,T120,MT1,P2.
CHARGE,CHRE,XXXXXXXXXX.
FTN(T)
ATTACH,TAPE3,PERMFILE3,ID=CHRE.
ATTACH,TAPE4,PERMFILE4,ID=CHRE.
VSN,TAPE7=SLOT33=RAEO3.
REQUEST,TAPE7,HI,RING.            (SLOT33,RAEO3)
ATTACH,CALC936.
ATTACH,CALCFN.
LDSET,LIB=CALC936.
LDSET,LIB=CALCFN.
LGO.
RETURN,TAPE7.
7/8/9 END OF RECORD CARD
Source Deck
7/8/9 END OF RECORD CARD
```

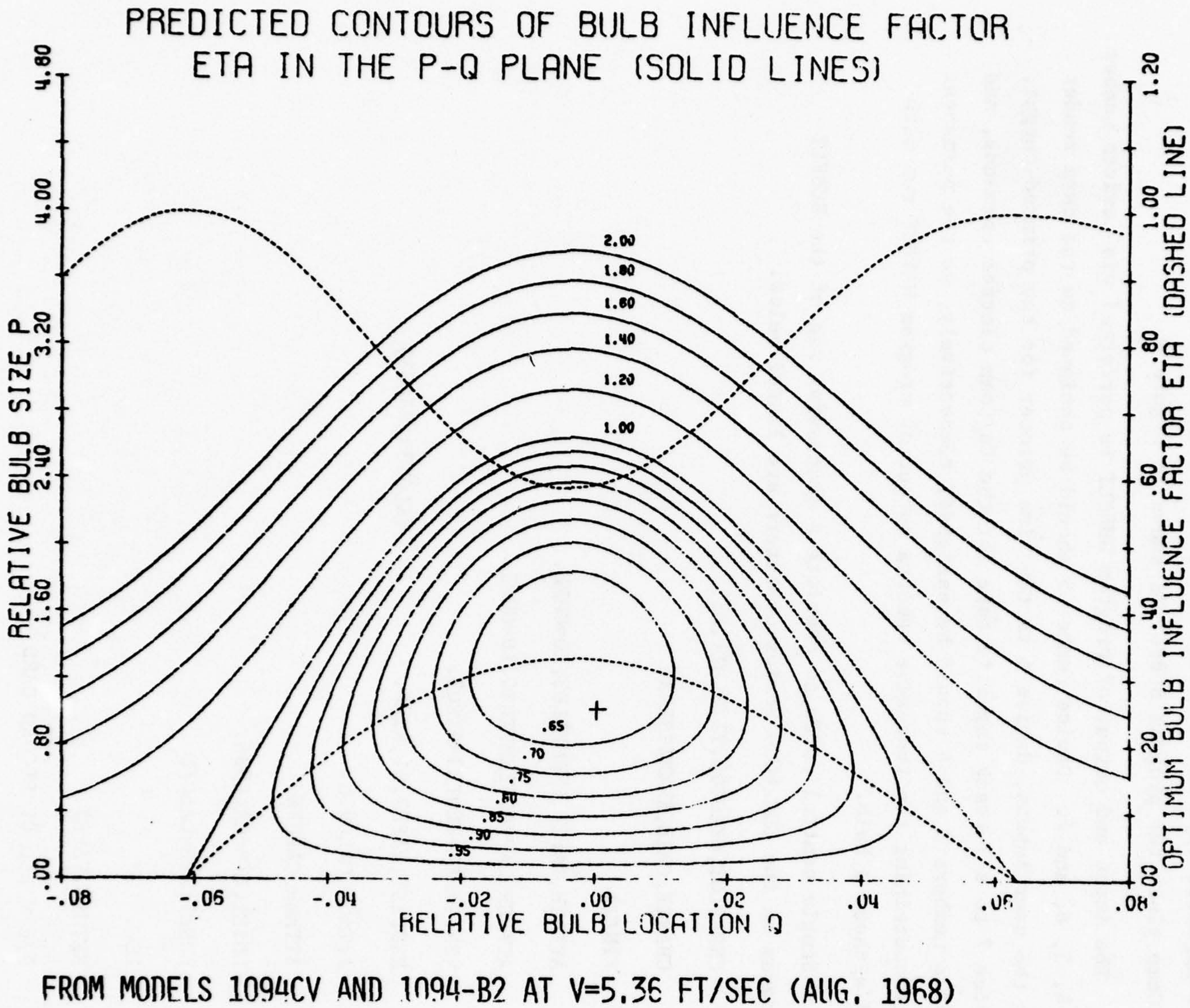


Figure 4 - Sample Output for program BUBPLT via Calcomp Plotter

Data Cards

6/7/8/9 END OF FILE CARD

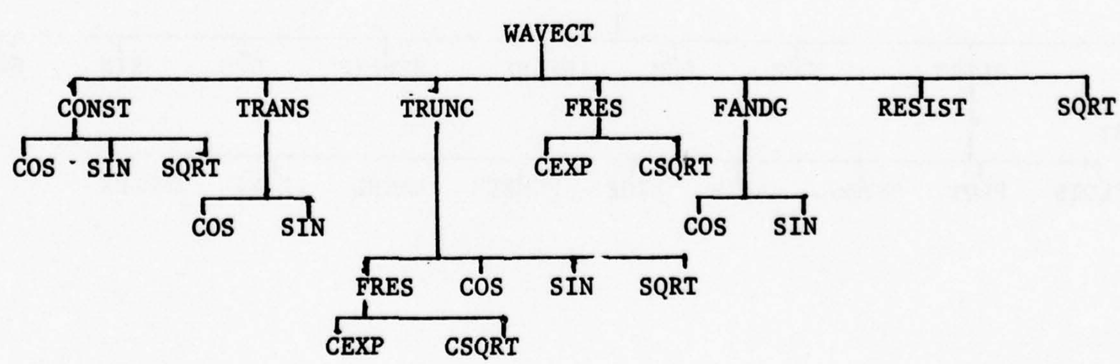
Note: PERMFILE3 AND PERMFILE4 are, respectively, the names of the permanent files containing the free-wave spectra output of program WAVECT with and without a bulb.

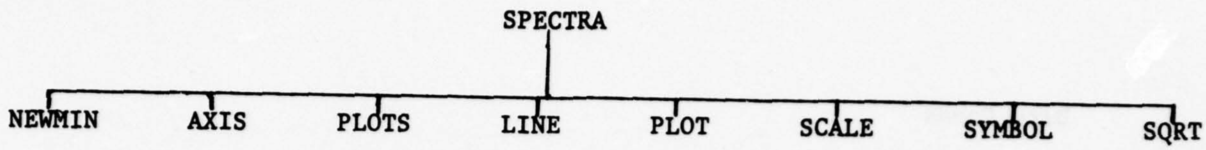
COMPUTER PROGRAM DOCUMENTATION

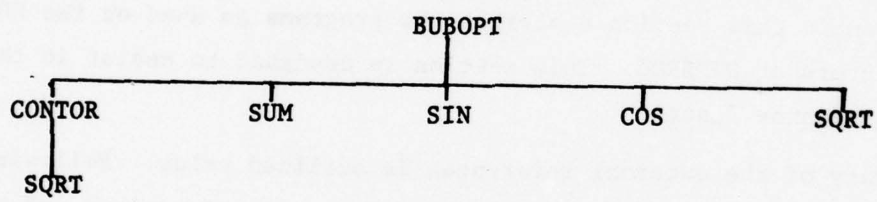
This section of the report contains the calling sequences and external references of the five computer programs and related subroutines which collectively will be used for the analysis of longitudinal wave cuts. The documentation in this section describes the programs as used on the CDC 6000 series computers at DTNSRDC. This section is designed to assist in the program maintenance function.

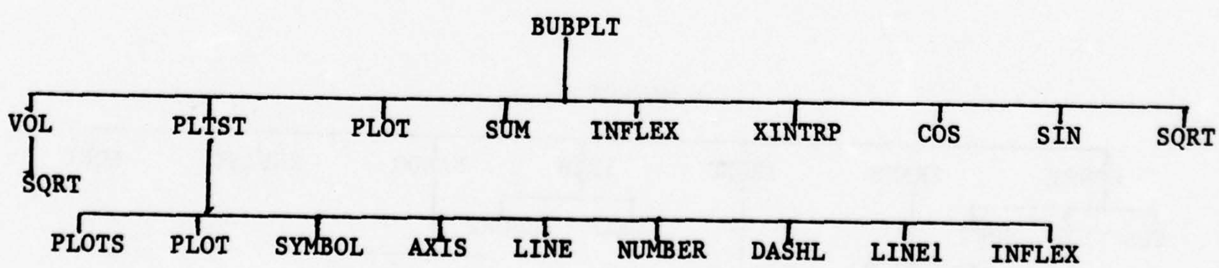
A summary of the external references is outlined below. Following the summary, documentation for programs and non-system functions and subroutines is provided.

NONDIM (no references)




SPECTRA
NEWMIN
AXIS
PLOTS
LINE
PLOT
SCALE
SYMBOL
SQRT


BUBOPT
CONTOR
SUM
SIN
COS
SQRT
SQRT


BUBPLT
VOL
PLTST
PLOT
SUM
INFLEX
XINTRP
COS
SIN
SQRT
SQRT
PLOTS
PLOT
SYMBOL
AXIS
LINE
NUMBER
DASHL
LINE1
INFLEX

NAME:	PROGRAM NONDIM
PURPOSE:	To convert wave cut information from analog units to feet, and then nondimensionalize the information for the wave analysis program
CALLING SEQUENCE:	MAIN PROGRAM
ARGUMENTS:	TAPE5 - Card Reader
	TAPE6 - Line Printer
	TAPE4 - Disk File (Nondimensional Data)
SUBROUTINES CALLED:	None
COMMENTS:	None

NAME:	PROGRAM WAVECT
PURPOSE:	To perform wave analysis using the fourier transform method with an optional truncation method which can be applied to height data
CALLING SEQUENCE:	MAIN PROGRAM
ARGUMENTS:	TAPE5 - Card Reader
	TAPE6 - Line Printer
	TAPE3 - Disk File (Free Wave Spectra Without Bulb)
	TAPE4 - Disk File (Nondimensional Data)
SUBROUTINES CALLED:	CONST, TRANS, TRUNC, FRES, FANDG, RESIST
FUNCTIONS CALLED:	SQRT
COMMENTS:	None

NAME:	SUBROUTINE CONST
PURPOSE:	By using least square analysis, CONST determines the asymptotic behavior of the waves behind the ship: ZETA = (C1*Cos (X) + C2 *Sin (X))/ (C3 - X), as X approaches (-) infinity.
CALLING SEQUENCE:	CALL CONST (ZETA, M, MP, XONE, DX, C1, C2, C3)
ARGUMENTS:	ZETA - The vector of length MAX containing the input points for the longitudinal wave profile
	M - An integer indicating the number of points which are to be analyzed from the wave profile
	MP - An integer which indicates at which point on the wave profile the analysis for determining the asymptotic behavior of the wave profile should begin - MP is not read unless MU = 0.
	XONE - The distance of the first input point forward of the origin on the model
	DX - The distance between the input in the wave profile
	C1 - The real part of the complex amplitude of the asymptotic wave behavior
	C2 - The imaginary part of the complex amplitude of the asymptotic wave behavior
	C3 - A nondimensional distance indicating where the asymptotic behavior of the wave begin in relation to the origin on the model - C3 is read only if MU = 0.
SUBROUTINES CALLED:	None.
FUNCTIONS CALLED:	COS, SIN, SQRT
COMMENTS:	None

NAME: SUBROUTINE TRANS

PURPOSE: To compute the sine and cosine components of the Fourier Transform at transverse wave-number SNU

CALLING SEQUENCE: CALL TRANS (ZETA, MU, M, DX, XM, SNU, TNU, CNUSTR, SNUSTR)

ARGUMENTS:

ZETA - The vector of length MAX containing the input points for the longitudinal wave profile

MU - An integer control character indicating whether slope or height data is to be read and whether or not the truncation correction is to be made in the case of height data

MU < 0, height data without truncation correction

MU $= 0$, height data with truncation correction

MU > 0, slope data

M - An integer indicating the number of points which are to be analyzed in the wave profile

DX - The distance between the input points in the wave profile

XM - The point at which the asymptotic behavior of the wave is assumed to start - point from which the truncation correction is made

SNU - The longitudinal wave number - Sec θ

TNU - Tan θ

CNUSTR - The cosine component of the Fourier Transform of the wave profile without the truncation correction

SNUSTR - The sine component of the Fourier Transform applied to the wave profile without the truncation correction

SUBROUTINES CALLED: None

FUNCTIONS CALLED: COS, SIN

COMMENTS: None

NAME: SUBROUTINE TRUNC

PURPOSE: To determine the truncation correction to the free-wave spectra due to finite length of record

CALLING SEQUENCE: CALL TRUNC (XM, SNU, C1, C2, C3, DCSTR, DSSTR)

ARGUMENTS:

XM - The point at which the asymptotic behavior of the wave is assumed to start - point from which the truncation correction is made

SNU - The longitudinal wave number - Sec θ

C1 - The real part of the complex amplitude of the asymptotic wave behavior

C2 - The imaginary part of the complex amplitude of the asymptotic wave behavior

C3 - A nondimensional distance indicating where the origin for use determining where the asymptotic behavior of the wave begin in relation to the origin on the model

DCSTR - The truncation correction for the cosine component of the Fourier Transform of the wave profile without the truncation correction

DSSTR - The truncation correction of the sine component of the Fourier Transform which applies to the wave profile without the truncation correction

SUBROUTINES CALLED: FRES

FUNCTIONS CALLED: COS, SIN, SQRT

COMMENTS: None

NAME:	SUBROUTINES FRES
PURPOSE:	To calculate the value of the Fresne integral from zero to Z and return the real (CT) and imaginary (ST) parts using the method developed by Boersma (1960)[4]
CALLING SEQUENCE:	CALL FRES (Z, CT, ST)
ARGUMENTS:	Z - The upper limit of the Fresnel integral
	CT - The real part of the Fresnel integral from zero to Z
	ST - The imaginary part of the Fresnel integral from zero to Z
SUBROUTINES CALLED:	None
FUNCTIONS CALLED:	CEXP, CSQRT
COMMENTS:	None

NAME: SUBROUTINE FANDG

PURPOSE: To compute the "true" free-wave spectra, F and G.

CALLING SEQUENCE: CALL FANDG (MU, Y, UNU, VNU, CNUSTR, SNUSTR, F, G)

ARGUMENTS: MU is an integer control character

MU < 0; Height data without truncation correction

MU = 0; Height data with truncation correction

MU > 0; Slope data

Y - The distance from the center line of the model to the center of the wave wire

UNU - The transverse wave number - $\text{Sec}\ \theta \cdot \text{Tan}\ \theta$

VNU - The function of wave number used in evaluating various integrands - VNU = $\sqrt{(1 + 4\ \text{Sec}\ \theta\ \text{Tan}\ \theta)}$

CNUSTR - The cosine component of the Fourier transform of the wave profile without the truncation correction

SNUSTR - The sine component of the Fourier transform applied to the wave profile without the truncation correction

F - The sine component of the free-wave spectra

G - The cosine component of the free-wave spectra

SUBROUTINES CALLED: None

FUNCTIONS CALLED: COS, SIN

COMMENTS: None

NAME:	SUBROUTINE RESIST
PURPOSE:	To compute the incremental increase in wave resistance and side force due to a single step in wave number
CALLING SEQUENCE:	CALL RESIST (DU, VNU, SNU, UNU, CNUSTR, SNUSTR, DR, DT)
ARGUMENTS:	DU - The size of the increment for the transverse wave number which is used to determine the N elementary waves which are to be analyzed
	VNU - The function of wave number used in evaluating various integrands. VNU - $\sqrt{(1 + 4\ \mathrm{Sec}\theta\ \mathrm{Tan}\theta)}$
	SNU - The longitudinal wave number - Secθ
	UNU - The transverse wave number - Sec$\theta \cdot$ Tanθ
	CNUSTR - The cosine component of the Fourier transform of the wave profile without the truncation correction
	SNUSTR - The sine component of the Fourier transform applied to the wave profile without the truncation correction
	DR - The incremental increase in wave resistance due to a single step in wave number
	DT - The incremental increase in side force due to a single step in wave number
SUBROUTINES CALLED:	None
COMMENTS:	None

NAME:	PROGRAM SPCTRA
PURPOSE:	To plot the sine and cosine component of the free-wave spectra
CALLING SEQUENCE:	MAIN PROGRAM
ARGUMENTS:	TAPE4 - Disk File (Free-Wave Spectra)
	TAPE5 - Card Reader
	TAPE6 - Line Printer
	TAPE7 - 7-Track Magnetic Tape
SUBROUTINES CALLED:	NEWMIN, AXIS, PLOTS, LINE, PLOT, SCALE, SYMBOL
FUNCTIONS CALLED:	SQRT
COMMENTS:	None

NAME:	SUBROUTINE NEWMIN
PURPOSE:	To determine the scaling to be used when plotting the free-wave spectra
CALLING SEQUENCE:	CALL NEWMIN (AMIN, AX, DV, AORG)
ARGUMENTS:	AMIN - The vertical range in which the spectra is to be plotted
	AX - The maximum value of the spectra arrays F, G, and E
	DV - The number of data units per inch of axis
	AORG - A shifting factor for the spectra arrays
SUBROUTINES CALLED:	None
COMMENTS:	None

NAME:	PROGRAM BUBOPT (PRINTER)
PURPOSE:	To determine coarse contours of the bulb influence factor
CALLING SEQUENCE:	MAIN PROGRAM
ARGUMENTS:	TAPE3 - Disk File (Free-Wave Spectra Without Bulb)
	TAPE4 - Disk File (Free-Wave Spectra With Bulb)
	TAPE5 - Card Reader
	TAPE6 - Line Printer
SUBROUTINES CALLED:	CONTOR
FUNCTIONS CALLED:	SUM, SIN, COS, SQRT
COMMENTS:	None

NAME:	SUBROUTINE CONTOR
PURPOSE:	To determine the contours of constant ETA in the P-Q space and print them
CALLING SEQUENCE:	CALL CONTOR (QMIN, QMAX, DQ, ETAMIN, ETAMAX, DETA, A, B, C, I)
ARGUMENTS:	QMIN - The starting value of Q
	QMAX - The ending value of Q
	DQ - The transverse size for Q
	ETAMIN - The minimum ETA for which contours are wanted
	ETAMAX - The maximum ETA for which contours are wanted
	DETA - The ETA distance between contours
	A,B,C - For a given Q, ETA is quadratic in P
	I - A counter used to dimension the argument B in the subroutine CONTOR
SUBROUTINES CALLED:	None
FUNCTIONS CALLED:	SQRT
COMMENTS:	None

NAME: FUNCTION SUM

PURPOSE: To determine the interference wave resistance of a hull bulb combination - This is used to evaluate the B term in the quadratic expression (in bulb volume) for wave resistance at a given longitudinal position.

CALLING SEQUENCE: S = SUM (NN, DU, FA, FB, GA, GB, W)

ARGUMENTS:

NN - The number of free-wave spectra

DU - The transverse wave number step size

FA - The sine component of the free-wave spectra for the hull

FB - The sine component of the free-wave spectra for the bulb

GA - The cosine component of the free-wave spectra for the hull

GB - The cosine component of the free-wave spectra for the bulb

W - Denominator of the Integrand

$$W = \sqrt{(1 + 4U^2)} / (1 + \sqrt{1 + 4U^2})$$

SUBROUTINES CALLED: None

COMMENTS: None

NAME:	PROGRAM BUBPLT
PURPOSE:	To determine and plot the contours of the constant bulb influence factor (ETA)
CALLING SEQUENCE:	MAIN PROGRAM
ARGUMENTS:	TAPE3 - Disk File (Free-Wave Spectra Without Bulb)
	TAPE4 - Disk File (Free-Wave Spectra With Bulb)
	TAPE5 - Card Reader
	TAPE6 - Line Printer
	TAPE7 - 7-Track Magnetic Tape
SUBROUTINES CALLED:	VOL, PLTST, PLOT
FUNCTIONS CALLED:	SUM, INFLEX, XINTRP, COS, SIN, SQRT
COMMENTS:	None

NAME: SUBROUTINE VOL

PURPOSE: To solve the quadratic equation, $ETA = AP^2 + BP + C$, for the bulb volumes which yield a given value of ETA

CALLING SEQUENCE: CALL VOL (ETA, A, B, C, PA, PB, T)

ARGUMENTS:

- ETA - The given value of bulb influence factor for which contours are designed
- A - Coefficient on quadratic term in bulb volume
- B - Coefficient on linear term in bulb volume
- C - Coefficient on constant term
- PA - The lower bulb volume for the contour
- PB - The upper bulb volume for the contour
- T - Used as a switch on the number of values of P

SUBROUTINES CALLED: None

FUNCTIONS CALLED: SQRT

COMMENTS: None

NAME: SUBROUTINE PLTST

PURPOSE: To perform the actual calcomp plotting of the contours of the constant bulb influence factor

CALLING SEQUENCE: CALL PLTST (N, A, AX, B, BX, BMIN, K, L, ETA, LABEL, NCHAR, IENTRY)

- N - The number of points on a given contour to be plotted
- A - The Q values to plot on a contour
- AX - The scaling constant for the Q plot
- B - The P values corresponding to Q
- BX - The scaling constant for the P plot
- BMIN - The minimum value of P
- K - A switch used to denote open or closed contours
- L - A switch used to denote solid or dashed lines
- ETA - The value of the bulb influence factor being plotted
- LABEL - A title for the output
- NCHAR - The number of characters in the title
- IENTRY - A switch used to denote scale set-up, plot contours or dashed lines

SUBROUTINES CALLED: PLOTS, PLOT, SYMBOL, AXIS, LINE, NUMBER, DASHL, LINE1

FUNCTIONS CALLED: INFLEX

COMMENTS: None

NAME:	FUNCTION SUM
PURPOSE:	To determine the interference wave resistance of a hull bulb combination - This is used to evaluate the B term in the quadratic expression (in bulb volume) for wave resistance at a given longitudinal position.
CALLING SEQUENCE:	S = SUM (NN, DU, FA, FB, GA, GB, W)
ARGUMENTS:	NN - The number of free-wave spectra
	DU - The transverse wave number step size
	FA - The sine component of the free-wave spectra for the hull
	FB - The sine component of the free-wave spectra for the bulb
	GA - The cosine component of the free-wave spectra for the hull
	GB - The cosine component of the free-wave spectra for the bulb
	W - Denominator of the Integrand: $W = \sqrt{1 + 4U^2} \; / \; 1 + \sqrt{1 + 4U^2}$
SUBROUTINES CALLED:	None
COMMENTS:	None

NAME:	FUNCTION INFLEX
PURPOSE:	To determine the inflection point in a given set of data - the vector A
CALLING SEQUENCE:	I = INFLEX (A, N)
ARGUMENTS:	A - A vector of values which has a maximum or minimum
	N - The number of elements in the vector A
SUBROUTINES CALLED:	None
COMMENTS:	None

NAME:	FUNCTION XINTRP
PURPOSE:	To interpolate a set of data Y for a value of Z = X using quadratic interpolation
CALLING SEQUENCE:	XX = XINTRP (X, Y, N, Z)
ARGUMENTS:	X - The vector of X values in which to interpolate
	Y - The vector of Y values in which to interpolate
	N - The number of elements in vectors X and Y
	Z - The value of X at which a value of Y is desired
SUBROUTINES CALLED:	None
COMMENTS:	A value of 100.0 is returned to denote interpolation fails

APPENDIX A - NONDIMENSIONAL SCHEME

In order that the results of the Wave Analysis would be independent of the size of the model or ship from which the data was obtained, it was decided that nondimensional quantities would be used in the actual wave analysis. For use in the dimensional analysis, a set of basic units of density ($\underline{\rho}$), gravity ($\underline{g}$), and velocity (V) were chosen, for use in representing all data in a nondimensional form.

We can now form nondimensional quantities as follows; let $\underline{Q}$ be any dimensional quantity such that:

$$[\underline{Q}] = [M^a L^b T^c]$$

Then, letting Q be the corresponding nondimensional quantity, we have:

$$Q = \frac{\underline{Q}}{\underline{\rho}^{\alpha}\underline{g}^{\beta}\underline{V}^{\gamma}}$$

With the following relationships between $\underline{V}$, $\underline{g}$, $\underline{\rho}$ and M, L, T:

	General	(English)	(Metric)
$[\underline{V}]$	L/T	(ft/sec)	(m/s)
$[\underline{g}]$	L/T^2	(ft/sec^2)	(m/s^2)
$[\underline{\rho}]$	M/L^3	$(slug/ft^3 = Lb\ sec^2/ft^4)$	(Kg/m^3)

we can obtain the following equation relating a, b, c and α, β, γ

$$M^a L^b T^c = (ML^{-3})^{\alpha}(LT^{-2})^{\beta}(LT^{-1})^{\gamma}$$

which yields the following relationships:

$$a = \alpha$$
$$b = -3\alpha + \beta + \gamma$$
$$c = -2\beta - \gamma$$

$$\alpha = a$$
$$\beta = -3a - b - c$$
$$\gamma = 6a + 2b + c$$

APPENDIX B - MATHEMATICAL DEVELOPMENT*

According to theoretical hydrodynamics the potential for a source distribution over some region (D) in the lower half plane ($z < 0$) can be described by the following integral

$$\phi(x,y,z) = \int_D \sigma(x',y',z')G(x,y,z,x',y',z')dD \; . \tag{1}$$

where $\sigma(x',y',z')$ is the local source strength for a point (x',y',z'); and the Green's function $G(x,y,z,x',y',z')$ is the potential of a source of unit strength located at a point with coordinates (x', y', z'). Havelock (1932)[5] gives the following expression for the Green's function:

$$G(x,y,z,x',y',z') = \frac{r_1 - r_2}{r_1 r_2}$$

$$+ \lim_{\mu \to 0} \frac{1}{\pi} \int_{-\pi}^{\pi} d\theta \int_0^{\infty} dk \, \frac{\sec^2 \theta \exp\{k(z + z' + i\bar{\omega})\}}{k - \sec^2 \theta + i\mu \sec \theta} \; , \tag{2}$$

$$\begin{aligned} \text{where } r_1 &= [(x - x')^2 + (y - y')^2 + (z - z')^2] \; , \\ r_2 &= [(x - x')^2 + (y - y')^2 + (z + z')^2] \; , \text{ and} \\ \bar{\omega} &= (x - x') \cos \theta + (y - y') \sin \theta \; . \end{aligned} \tag{3}$$

Defining the steady state free surface deformation as:

$$z = \zeta(x,y) \; ,$$

we can, by the assumption of small amplitude, define this free surface deformation in terms of the potential function as:

$$z = \zeta(x,y) = \phi_x(x,y,0) \tag{4}$$

If we define the Kochin functions $H(k,\theta)$ and $J(u,s)$ as follows:

$$H(k,\theta) = 4\pi \int_D \sigma(x',y',z')\exp[kz' + ik(x \cos \theta + y' \sin \theta)]dD \text{ and} \tag{5}$$

---

*For a more detailed analysis see Sharma (1966)[6].

$$J(u,s) = 4\pi \int_D \sigma(x',y',z')\exp[z'\sqrt{u^2 + s^2} + i(sx' + uy')]dD \ . \qquad (6)$$

Then we can obtain the following relationships between H and J:

$$H(k,\theta) = J(k \sin \theta,\ k \cos \theta) \text{ and}$$

$$J(u,s) = H\left(\sqrt{u^2 + s^2},\ \tan^{-1} \frac{u}{s}\right) . \qquad (7)$$

Using the Kochin functions, we can now obtain the free surface deformation as:

$$\zeta(x,y) = \text{Re} \lim_{\mu \to 0} \frac{i}{4\pi^2} \int_{-\pi}^{\pi} d\theta \int_0^{\infty} dk \frac{\overline{H}(k,\theta) k \sec \theta}{k - \sec^2 \theta + i\mu \sec \theta} \ .$$

$$\exp[ik(x \cos \theta + y \sin \theta)] \ , \qquad (8)$$

where $\overline{H}(k,\theta)$ is the complex conjugate of $H(k,\theta)$

Defining the wave resistance R_w by the following equation,

$$R_w = +4\pi \int_D \sigma(x,y,z)\phi_x(x,y,z)dD \ , \qquad (9)$$

and substituting for $\phi_x(x,y,z)$, we obtain

$$R_w = \frac{1}{2\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} H(\sec^2 \theta,\theta) \cdot \overline{H}(\sec^2 \theta,\theta)\sec^3 \theta \ d\theta \ . \qquad (10)$$

From the above equation for the wave resistance it can be observed that the Kochin function has degenerated from a function of two variables (k,θ) to what is essentially a function of one variable (θ). From this it can be seen that k must be defined as follows:

$$k = \sec^2 \theta \ . \qquad (11)$$

Outside the region near the source distribution, the surface deformation is caused predominantly by those waves for which $k = \sec^2 \theta$. These are the so-called free-waves.

It can be shown that, for any y, as $x \to \infty$ the surface deformation becomes:

$$\zeta(x,y) = \text{Re} \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{\overline{J}(u,s)\exp[i(uy + sx)]}{\sqrt{1 + 4u^2}}$$

$$(1 + \sqrt{1 + 4u^2})du \ , \tag{12}$$

and that, for any x, as $Y \to \infty$

$$\zeta(x,y) = I_m \frac{1}{\pi} \int_{0}^{-1} \frac{\overline{J}(-is\sqrt{1 - s} ,s)}{\sqrt{1 - s^2}}$$

$$\exp[isx - s\sqrt{1 - s^2}y]s^2 \, ds$$

$$+ \text{Re} \frac{1}{\pi} \int_{1}^{\infty} \frac{\overline{J}(s\sqrt{s^2 - 1},s)}{\sqrt{s^2 - 1}} \exp[i(sx + s\sqrt{s^2 - 1},y)]s^2 ds \ , \tag{13}$$

where s is related to u by the following relationship:

$$s = \left(\frac{1 + \sqrt{1 + 4u}}{2} \right)^{1/2} \geq 1 \ . \tag{14}$$

From this it can be seen that the various forms of the Kochin function are related as follows:

$$H(\sec^2 \theta,\theta) = J(u,s) = J(s\sqrt{s^2 - 1}, \ |s|) \ . \tag{15}$$

From this, it can be seen that the variables u, s, and θ are related as follows:

$$u = \text{Sec}\ \theta\ \text{Tan}\ \theta \ ,$$

$$s = \text{Sec}\ \theta \ , \text{ and}$$

$$u = s\sqrt{s^2 - 1} \ . \tag{16}$$

(16)

Using these variables we can define a "free-wave spectra" in terms of the two real functions, F and G, of the variable u,

$$G(u) + iF(u) = \frac{2(1 + \sqrt{1 + 4u^2})}{\sqrt{1 + 4u^2}} J(u,s) , \tag{17}$$

and the wave elevation as $x \to \infty$ can be found by the Fourier integral,

$$\zeta(x,y) = \frac{1}{4\pi} \int_{-\infty}^{\infty} [F(u) \sin (sx + uy) + G(u) \cos (sx + uy)]du . \tag{18}$$

Taking a longitudinal wave cut (y held constant), the following Fourier transform can be applied to the wave profile:

$$C(s,y) + iS(s,y) = \int_{-\infty}^{\infty} \zeta(x,y)e^{isx} dx . \tag{19}$$

If the value of y has been chosen such that it is great enough that the waves are free waves, we can apply the Fourier inversion theorem to equation (19), and for $1 \leq s \leq \infty$ obtain the following relationships:

$$\begin{aligned} Re[\bar{J}(s\sqrt{s^2 - 1},s)\exp\{is\sqrt{s^2 - 1}\ y\}] &= \frac{\sqrt{s^2 - 1}}{s^2} C(s,y) \text{ and} \\ I_m[\bar{J}(s\sqrt{s^2 - 1},s)\exp\{-is\sqrt{s^2 - 1}\ y\}] &= \frac{\sqrt{s^2 - 1}}{s^2} S(s,y) . \end{aligned} \tag{20}$$

From these equations we can easily solve for the free-wave spectra, in terms of the Fourier transform of equation (19):

$$\begin{aligned} F(u) &= \frac{4\sqrt{s^2 - 1}}{(2s^2 - 1} [C(s,y) \sin (uy) + S(s,y) \cos (uy)] \text{ and} \\ G(u) &= \frac{4\sqrt{s^2 - 1}}{(2s^2 - 1} [C(s,y) \cos (uy) + S(s,y) \sin (uy)] . \end{aligned} \tag{21}$$

These equations (21) are true for height data; however, there can be significant errors from using these equations with only a finite length of wave cut. To avoid these errors, it is possible to instead measure the transverse wave slope h_y which would yield the following equations for the free-wave spectra.

$$F(u) = \frac{4}{s(2s^2 - 1)} [C_y(s,y) \cos (uy) - S_y(s,y) \sin (uy)]$$
$$G(u) = \frac{4}{s(2s^2 - 1)} [C_y(s,y) \sin (uy) + S_y(s,y) \cos (uy)] \qquad (22)$$

A method which might possibly be used to correct for the use of a finite length of longitudinal cut, with height data, would be to assume that at a large distance from the origin, the waves decay asymptotically, and that they may be fit by an equation such as follows, for $x \to -\infty$:

$$\zeta(x,y) \simeq \frac{(C_1 \cos x + C_2 \sin x)}{\sqrt{C_3 - x}} , \qquad (23)$$

where the unknown constants C_1, C_2, and C_3 might be determined by a least-squares fit.

In order to determine the error due to truncation let's define a modified Fourier transform,

$$\tilde{C}*(s,y) + i\tilde{S}*(s,y) = \int_{-\infty}^{\infty} \sqrt{s^2 - 1}\ \zeta(s,y)e^{isx}\, dx . \qquad (24)$$

Then, if we define the point x_M as the point at which the wave profile has been truncated, the error becomes:

$$\Delta C*(x,y) + i\Delta S*(s,y) = \int_{\infty}^{x_M} \sqrt{s^2 - 1}\ \zeta(x,y)e^{isx}\, dx , \qquad (25)$$

where the values of $\zeta(x,y)$ are defined by using equation (23). Using equations (25) and (23) we can obtain the values of $\Delta C*$ and $\Delta S*$ by using the following equations:

$$\Delta C^* = \sqrt{\frac{\pi}{2}}\,[d_1 C_F(z^+) + d_2 S_F(z^+) + d_3 C_F(z^-) + d_4 S_F(z^-)] \text{ and}$$

$$\Delta S^* = \sqrt{\frac{\pi}{2}}\,[d_2 C_F(z^+) - d_1 S_F(z^+) + d_4 C_F(z^-) - d_3 S_F(z^-)] \,, \tag{26}$$

where

$$\begin{aligned} d_1 &= \sqrt{\pi - 1}\,[C_1 \cos C_3(s+1) + C_2 \sin C_3(s+1)] \,, \\ d_2 &= \sqrt{\pi - 1}\,[C_1 \sin C_3(s+1) - C_2 \cos C_3(s+1)] \,, \\ d_3 &= \sqrt{\pi + 1}\,[C_1 \cos C_3(s-1) - C_2 \sin C_3(s-1)] \text{, and} \\ d_4 &= \sqrt{\pi + 1}\,[C_1 \sin C_3(s-1) + C_2 \cos C_3(s-1)] \,. \end{aligned} \tag{27}$$

C_F and S_F are the real and imaginary parts of the Fresnel integral,

$$C_F(z) + i\, S_F(z) = \int_z^{\infty} e^{i \frac{\pi}{2} t^2}\, dt \,, \tag{28}$$

and

$$z \pm = \left(\frac{2(C - x_M)\ (s \pm 1)}{\pi} \right)^{1/2} . \tag{29}$$

Using the real and imaginary components of the modified Fourier transform (24) we can now define the wave resistance and transverse forces as

$$R_W = \frac{1}{\pi} \int_0^{\infty} \frac{(C^*)\ \ + (S^*)^2}{s^2(2s^2 - 1)}\, du \text{ and} \tag{30}$$

$$T = \frac{1}{\pi} \int_0^{\infty} \frac{(C^*)^2 + (S^*)^2}{s^3(2s^2 - 1)}\, du \,. \tag{31}$$

APPENDIX C - NUMERICAL ANALYSIS AND THE DEVELOPMENT OF THE ALGORITHM

We will use the following definitions in our evaluation of the equations in Appendix B:

$$
\begin{aligned}
\nu &= 0,1,2,\ldots N \quad \text{the number of an elementary wave with angle } \theta_\nu , \\
U_\nu &= \nu \cdot \Delta u \qquad (\sec\theta_\nu \tan\theta_\nu), \\
V_\nu &= (1 + 4u_\nu)^{1/2} \qquad (1 + 2\tan^2\theta_\nu), \\
S_\nu &= \{(1 + V_\nu)/2\}^{1/2} \qquad (\sec\theta_\nu), \\
T_\nu &= u_\nu/s_\nu \qquad (\tan\theta_\nu), \\
\varepsilon_j &= 1/2 \qquad j = j_{min} \text{ and } j_{max} \\
&= 1 \qquad j = j_{min} + 1,\ldots,j_{max} - 1 ,
\end{aligned}
\tag{32}
$$

Δx the spacing between points in the wave profile, and

M = the number of the most negative x-location in the wave profile.

Taking the truncated Fourier transform integral:

$$
C^*(s) + iS^*(s) = \sqrt{S_\nu^{\,2} - 1}\int_{x_m}^{\infty} \zeta(x,y)e^{isx}dx , \tag{33}
$$

we can separate the real and imaginary parts and integrate by the trapizoidal rule obtaining the equations:

$$
\begin{aligned}
S_\nu^* &= T_\nu|\Delta x|\sum_{j=1}^{m} \zeta_j \sin(X_j S_\nu)\varepsilon_j \quad \text{and} \\
C_\nu^* &= T_\nu|\Delta x|\sum_{j=1}^{m} \zeta_j \cos(X_j S_\nu)\varepsilon_j .
\end{aligned}
\tag{34}
$$

Using these results with equation (21) we can obtain the free-wave spectra:

$$F_\nu = \frac{4}{V_\nu}\{C_\nu^* \sin (U_\nu Y) + S_\nu^* \cos (U_\nu Y)\} \, , \tag{35a}$$

$$G_\nu = \frac{4}{V_\nu}\{C_\nu^* \cos (U_\nu Y) - S_\nu^* \sin (U_\nu Y)\} \, , \text{ and} \tag{35b}$$

$$E_\nu = \{(F_\nu)^2 + (G_\nu)^2\}^{1/2} \, . \tag{35c}$$

Then by integrating equations (30) and (31) by the trapizoidal rule we can obtain the wave resistance and transverse force:

$$R_\nu = \frac{2\Delta U}{\pi} \sum_{j=0}^{\nu} \{(C_j^*)^2 + (S_j^*)^2\} \frac{\varepsilon_j}{V_j(1 + V_j)} \quad \text{and} \tag{36}$$

$$T_\nu = \frac{2\Delta U}{\pi} \sum_{j=0}^{\nu} \{(C_j^*)^2 + (S_j^*)^2\} \frac{\varepsilon_j}{V_j S_j} \, . \tag{37}$$

When being used with a slope cut the equations develop as follows:

$$\tilde{C}^*(s) + i\, \tilde{S}^*(s) = \frac{1}{s} \int_{x_m}^{\infty} \zeta_y(x,y) e^{isx} dx \, . \tag{38}$$

This equation then separates into the sums:

$$\tilde{S}_\nu^* = \frac{|\Delta x|}{S_\nu} \sum_{j=1}^{m} \zeta_{y_j} \sin (X_j S_\nu) \varepsilon_j \quad \text{and}$$

(39)

$$\tilde{C}_\nu^* = \frac{|\Delta x|}{S_\nu} \sum_{j=1}^{m} \zeta_{y_j} \cos (X_j S_\nu) \varepsilon_j \, .$$

The free wave spectra are given by the following equations:

$$F_\nu = \frac{4}{V_\nu}\{\tilde{C}_\nu{*} \cos (U_\nu Y) - \tilde{S}_\nu{*} \sin (U_\nu Y)\} \text{ and}$$

$$G_\nu = \frac{-4}{V_\nu}\{\tilde{C}_\nu{*} \sin (U_\nu Y) + \tilde{S}_\nu{*} \cos (U_\nu Y)\} . \tag{40}$$

The values of E_ν, R_ν, and T_ν are then calculated as in equations (35c), (36), and (37) respectively.

The evaluation of $C_\nu{*}$ and $S_\nu{*}$ can be much simplified if it is noted that the summations of equations (34) and (39) are simply Chebyshev polynomials to which the following recursive formulas apply:

$$U_{M+1} = U_{M+2} = 0$$

and

$$U_n = \zeta_n + 2 \cos (S_\nu \Delta x) U_{n+1} - U_{n+2} , \tag{41}$$

where

$$\zeta_n = \zeta_n/2 \quad \text{for } n = 0,M$$

This equation is iterated from M to zero, and $S_\nu{*}$ and $C_\nu{*}$ are calculated from the following equations:

$$S_\nu{*} = T_\nu |\Delta X| U_1 \sin (S_\nu \Delta X) \text{ and}$$

$$C_\nu{*} = T_\nu |\Delta X| \left(\frac{U_0 - U_2}{2} \right) . \tag{42}$$

The truncation corrections $\Delta C_\nu{*}$ and $\Delta S_\nu{*}$ are calculated and added to $C_\nu{*}$ and $S_\nu{*}$ from equation (34) to obtain $\tilde{C}_\nu{*}$ and $\tilde{S}_\nu{*}$, and then the free-wave spectra, transverse force and wave resistance are calculated using equations (35), (36), and (37). The truncation corrections $\Delta C_\nu{*}$ $\Delta S_\nu{*}$ are calculated using equations (26) and (27), where the values of the constants C_1, C_2, and C_3 are determined as follows: C_3 is chosen as the nondimensional distance from the origin on the model to the origin of the most significant waves on the hull. The constants C_1 and C_2 are calculated by least squares.

The error δ_j is calculated such that

$$\delta_j = \zeta_j - \frac{C_1 \cos x_j + C_2 \sin x_j}{\sqrt{C_3 - x_j}} \tag{43}$$

Then the sum of the squared errors, Q, is calculated,

$$Q = \sum_{j=M}^{M} (\delta_j)^2 . \tag{44}$$

It is desired to find C_1 and C_2 such that Q is a minimum; and Q is a minimum when

$$\frac{\partial Q}{\partial C_1} = -\sum_{j=M'}^{M} \left(\zeta_j - \frac{C_1 \cos X_j + C_2 \sin X_j}{\sqrt{C_3 - X_j}} \right) \frac{\cos X_j}{\sqrt{C_3 - X_j}} = 0 ,$$

and when (45)

$$\frac{\partial Q}{\partial C_2} = -\sum_{j=M}^{M} \left(\zeta_j - \frac{C_1 \cos X_j + C_2 \sin X_j}{\sqrt{C - X_j}} \right) \frac{\sin X_j}{\sqrt{C_3 - X_j}} = 0 .$$

From this we obtain:

$$C_1 \sum_{j=M'}^{M} \frac{\cos^2 X_j}{C_3 - X_j} + C_2 \sum_{j=M'}^{M} \frac{\sin X_j \cos X_j}{C_3 - X_j} = \sum_{j=M'}^{M} \zeta_j \frac{\cos X_j}{\sqrt{C_3 - X_j}} \quad \text{and}$$

(a) (b) (c)

$$C_1 \sum_{j=M'}^{M} \frac{\cos S_j \sin X_j}{C_3 - X_j} + C_2 \sum_{j=M'}^{M} \frac{\sin^2 X_j}{C_3 - X_j} = \sum_{j=M'}^{M} \zeta_j \frac{\sin X_j}{\sqrt{C_3 - X_j}} \tag{46}$$

(d) (e) (f)

Hence we find that C_1 and C_2 can be defined as follows:

$$C_1 = \frac{(e)\,(c) - (b)\,(f)}{(a)\,(e) - (b)\,(b)}$$

$$C_2 = \frac{(a)\,(f) - (b)\,(c)}{(a)\,(e) - (b)\,(b)} \quad . \tag{47}$$

In equations (44), (45), and (46); M' corresponds to the point at which the wave profile is assumed to begin its asymptotic behavior. Both M and M' should be chosen so that $(X_M - X_{M'})$ is either one or else one-half of one fundamental wave length.

The Fresnel integrals of equation (28) are evaluated by using the method developed by J. Boersma (1960).[4]

APPENDIX D - BULB OPTIMIZATION SCHEME

If we are given a main hull spectrum $F_\nu^{(h)}$ and $G_\nu^{(h)}$ and a hull-bulb spectrum $F_\nu^{(hbo)}$ and $G_\nu^{(hbo)}$ FOR $\nu = 0,1, \ldots, N$ for some definite bulb size and location, along with the transverse wave number step size ΔU, and the nondimensional hull "length: $L = \underline{Lg} / \underline{V^2} = 1/F_\eta^{\ 2}$, we can predict the new hull-bulb spectra ($F^{(hb)}$ AND $G^{(hb)}$) for various bulb sizes (P) and Longitudinal positions (Q); and calculate a predicted $R_w^{(hb)}$ and bulb influence factor (η) for these spectra,

$$\eta = \frac{R_w^{(hb)}}{R_w^{(h)}} .$$

If we generate these values of η for a number of positions and sizes, one can even plot contours of efficiency. These contours might look as shown in Figure D-1:

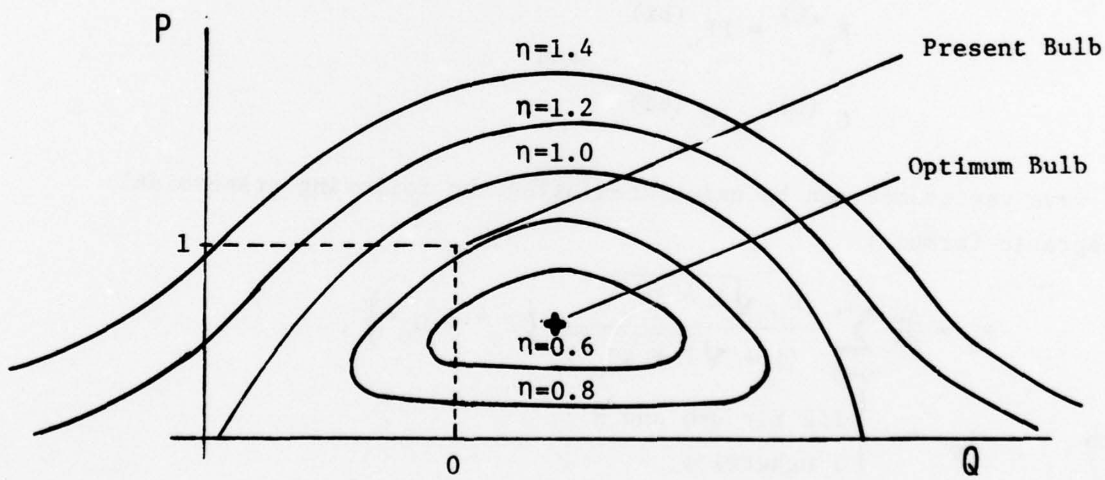


Figure D-1 - Bulb Contours of Efficiency for Various Bulb sizes versus Longitudinal Position

It can also be shown in a linear sense that these efficiencies are a quadratic function of P for a given Q. That is $\eta = aP^2 + bP + C$, $a(Q)$, $b = b(Q)$, $c = c(Q)$. You will see later that "a" is actually a constant depending on the given hull and bulb, and that "c" is always equal to one.

To develop the necessary equations one assumes that:

$$F_\nu^{(bo)} = F_\nu^{(hbo)} - F_\nu^{(h)}$$

and $\qquad \nu = 0, 1, . . ., N$

$$G_\nu^{(bo)} = G_\nu^{(hbo)} - G_\nu^{(h)}$$

If we shift the bulb spectra by a distance X_s we get:

$$F_\nu^{(bi)} = F_\nu^{(bo)}\cos(S_\nu X_s) + G_\nu^{(bo)}\sin(S_\nu X_s)$$

and

$$G_\nu^{(bi)} = G_\nu^{(bo)}\cos(S_\nu X_s) - F_\nu^{(bo)}\sin(S_\nu X_s) \ ,$$

where $S = [(1 + \sqrt{1 + 4U_\nu^2})/2]^{1/2}$ and $U_\gamma = \nu \cdot \Delta U$. The effect of changing the bulb size by a given factor P yields:

$$F_\nu^{(b)} = PF_\nu^{(bi)}$$

and

$$G_\nu^{(b)} = PG_\nu^{(bi)} .$$

The wave resistance can be calculated using the following trapezoidal integratic formula:

$$R_w = \frac{\Delta U}{8\pi} \sum_{\nu=0}^{N} \frac{\varepsilon_\nu \sqrt{1 + 4U_\nu^2}}{(1 + \sqrt{1 + 4U_\nu^2})} \left\{F_\nu^2 + G_\nu^2\right\},$$

with $\qquad \varepsilon_\nu = \begin{cases} 1/2 \text{ for } \nu = o \text{ and } N \\ 1 \text{ otherwise} \end{cases}$.

We would use the principle of linear superposition to obtain the F_ν and G_ν and follows:

$$F_\nu = F_\nu^{(h)} + PF_\nu^{(bi)}$$

and

$$G_\nu = G_\nu^{(h)} + PG_\nu^{(bi)} .$$

By the analysis shown, one can find the constants of the quadratic equation. The important thing to note is that in the equation for "a":

$$a = \frac{1}{R_w^{(h)}} \frac{\Delta U}{8\pi} \sum_{\nu=o}^{N} \frac{\varepsilon_\nu \sqrt{1 + 4U^2}}{(1 + \sqrt{1 + 4U^2}} \left\{ (F_\nu^{(bi)})^2 + (G_\nu^{(bi)})^2 \right\}$$

we are calculating a sum which is simply the wave resistance of the bulb with a phase shift and because a simple phase shift will not change the wave resistance, the coefficient "a" is a constant.

Once the coefficients of the quadratic equation are known, one can find the value of P for an optimum bulb at any Q and the line $\eta = 1$.

P is the relative bulb size. That is, the original bulb has size P = 1 and no bulb has size P = 0. The longitudinal position Q is the decimal shift in length of the bulb relative to the length of the hull.

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