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THESIS

**A COMPUTATIONAL AND EXPERIMENTAL
INVESTIGATION OF INCOMPRESSIBLE OSCILLATORY
AIRFOIL FLOW AND FLUTTER PROBLEMS**

by

Peter J. Riester

June, 1993

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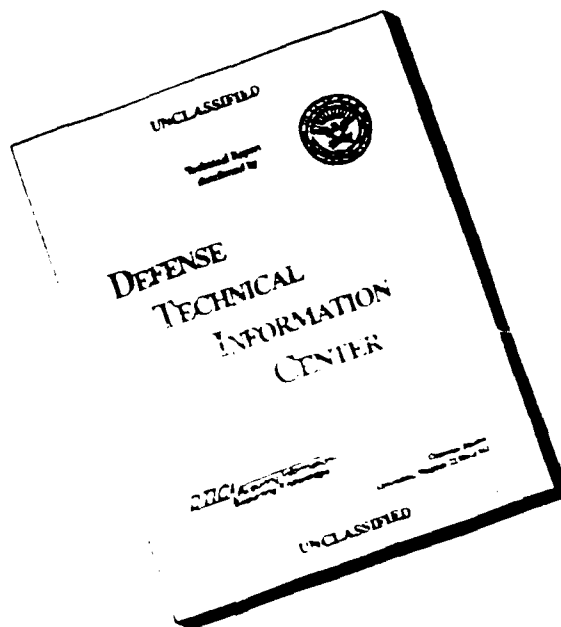
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A COMPUTATIONAL AND EXPERIMENTAL INVESTIGATION OF
INCOMPRESSIBLE OSCILLATORY AIRFOIL FLOW AND FLUTTER PROBLEMS

by

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Lieutenant Commander, United States Navy
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Submitted in partial fulfillment
of the requirements for the degree of

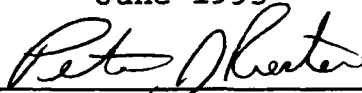
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from the

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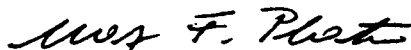
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Author:



Peter J. Riester

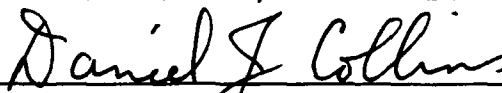
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ABSTRACT

In this thesis several incompressible oscillatory flow and flutter problems were investigated. First, a previously developed unsteady panel code was modified so that systematic comparisons with Theodorsen's classical theory could be accomplished. It was found that the panel code is in excellent agreement with the Theodorsen results. Second, the panel code was applied to the analysis of bending-torsion flutter. Again, general agreement with Theodorsen's flutter predictions was obtained. In the experimental part of the thesis two flow visualization experiments were performed. First, the vortical flow patterns generated by an airfoil executing harmonic plunge oscillations were visualized. In the second experiment, the interference effects between a stationary airfoil and a small vane executing plunge oscillations were explored.

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TABLE OF SYMBOLS

a	elastic axis position taken from the midchord
b	half chord
C_α	spring constant for pitch
C_h	spring constant for plunge
C_D	drag coefficient
C_L	lift coefficient
$C_{L\alpha}$	lift coefficient as a result of pitch
C_{Lh}	lift coefficient as a result of plunge
$C_{M\alpha}$	moment coefficient as a result of pitch
C_{Mh}	moment coefficient as a result of plunge
h	plunge amplitude
i	denotes complex number
I_α	mass moment of inertia
I_L	denotes imaginary part of lift
I_M	denotes imaginary part of moment
Im	Imaginary part
K_p	reduced frequency used in panel code
K_t	reduced frequency used in Theodorsen analysis
κ	mass ratio ($1/\mu$)
L	lift force per unit span
L_α, L_β, L_h	aerodynamic coefficients used for Theodorsen analysis
M	moment
M_h, M_α	aerodynamic coefficients used for Theodorsen analysis
q	dynamic pressure

Re real part
 R_L real part of lift
 R_M real part of moment
 S_α static moment about the elastic axis
 t nondimensional time
 U freestream velocity
 AOA angle of attack
 α pitch amplitude
 ρ density
 ϕ phase angle between force and motion
 $\phi_{L\alpha}$ phase angle between lift force and pitch motion
 ϕ_{Lh} phase angle between lift force and plunge motion
 $\phi_{M\alpha}$ phase angle between moment and pitch motion
 ϕ_{Mh} phase angle between moment and plunge motion
 ω frequency of harmonic oscillation (rad/sec)
 ω_α natural frequency of system for pitch
 ω_h natural frequency of system for plunge

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Finally, I would like to thank my beautiful and gifted wife, Nancy, for her endless support both throughout my tour here and finally in the typing of this thesis.

I. INTRODUCTION

A. GENERAL

In this thesis, several numerical methods were used to analyze the flow about an airfoil performing unsteady motion in an inviscid incompressible fluid. First, the unsteady motion of a single airfoil was analyzed after modifying the U2DIIF code [ref.2]. The primary purpose was to verify the code against the proven theory of Theodorsen for analyzing the phenomenon of flutter. To accomplish this the U2DIIF code was modified to calculate aerodynamic values over a range of reduced frequencies and then apply these values to the flutter analysis.

Next, the propulsive effects of a plunging airfoil were verified through experimental methods using a low speed plexiglas wind tunnel.

Finally, an exploratory test was conducted in the department's smoke tunnel to study the interaction between a plunging airfoil and a stationary large airfoil.

B. SCOPE

Chapter II contains the modification of the single airfoil U2DIIF code into the code UPOT.f and extensive verification of this code against results produced by Theodorsen. Chapter III describes the UPOT code and explains the modifications which

were added to solve the flutter determinant. In chapter IV the flow visualization experiment is described which was performed to study the vortical wake patterns produced by a plunging airfoil. In chapter V a second experiment is described which was performed to explore a plunging airfoil's potential for control of flow separation.

II. SINGLE AIRFOIL ANALYSIS

A. U2DIFF PANEL CODE

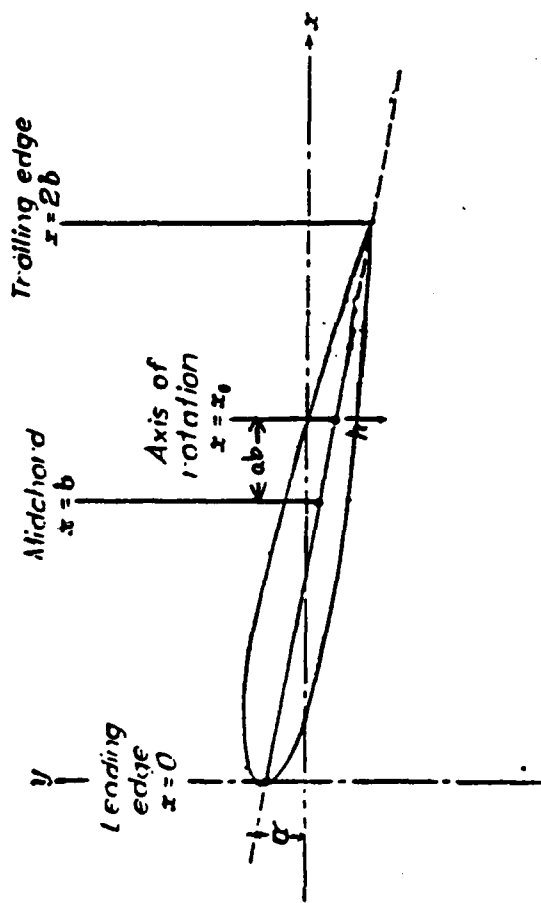
1. Geometry

Figure 2.1 shows a representation of the system that is analyzed using the panel code. Shown are the values for h (plunge) and α (AOA).

2. U2DIFF

The U2DIFF code was developed by TENG [ref.2] for the study of unsteady inviscid and incompressible flow over a single airfoil. The code is based on the extension of the panel method, developed by Hess & Smith [ref.4] for steady potential flow problems, to include the unsteady motion of the airfoil that is continuously shedding vortices into the trailing wake. This vortex shedding process is nonlinear in that the wake vortices influence the flow over the airfoil which in turn alters the vortex shedding as the airfoil proceeds in time.

The non-linearity of the unsteady flow makes this problem different from the steady flow problem which requires only simple Gaussian elimination. Teng developed a code that used an iterative type of solution. Typical program output includes the airfoil pressure distribution, force and moment coefficients, and the trailing vortex wake pattern. No



h = bending deflection of rotation point (elastic axis), positive downward

α = angular deflection about rotation point (elastic axis), positive for leading edge up (radians)

ab = distance between rotation point (elastic axis), and midchord, positive if aft of midchord

Figure 2.1 Airfoil Geometry

attempt is made here to reproduce the work of Teng or to explore the operation of the U2DIIF code, but the reader is encouraged to review reference 2.

B. PHASE PROGRAM

The phase program was put through some verification by Neace [ref.9] and modified slightly in order to present results for harmonic motion. The code PHV3.f (phaseshift) was written by Neace to convert the time dependent output of lift and moment histories to harmonic output using an iterative curve fit algorithm:

$$F(t) = \text{Amp} * \text{Sin}(\omega t + \phi) \quad (2.1)$$

where Amp = amplitude of motion, ω = frequency, and ϕ = phase angle between motion and the aerodynamic forces. One primary output of this program was the values of phaseshift (ϕ) between the AOA and coefficients of lift (C_L) and moment (C_M) for the pitching airfoil and the phaseshift between the plunge value ($h/2b$) and the C_L and C_M for the plunging airfoil. The other output was the amplitude of C_L and C_M for the pitching or plunging case.

C. MODIFICATION OF U2DIIF AND PHASE PROGRAM

In an attempt to make the above mentioned codes more "user friendly", the two codes were combined into a single code named UPOT.f. The modification involved a new input file

called UPOT.in which gives the user several options of operation. The input file can call for the analysis of steady flow only, straight and modified ramp motion, pitch oscillation, plunge oscillation, and the capability of performing the oscillation analysis over a series of reduced frequencies. A sample input file is shown in Figure (2.2).

1. Output

Outputs from the code have been limited to reduce the amount of computer space taken up by the code operation. A sample calculation was run using the input from Figure (2.2) and the on-screen output is shown in Figure (2.3). Of course, the user can modify the output portions of the code to minimize output. The following list describes the input/output files and the data they contain.

- a. UPOT.IN: The input file figure (2.2).
- b. CL.d: This file contains the various AOA values along with its corresponding C_l for each time step.
- c. CM.D: This file contains the various AOA values along with its corresponding C_m for each time step.
- d. PHASE.d: This file contains the values of non dimensional time (t), AOA, C_l , C_m , for each time step.
- e. FOR015.DAT: This file contains the values of non dimensional AOA, curve fit for C_l , curve fit for C_m , (used in the phase portion of program).
- f. CPSS.d: This file contains the steady state pressure coefficient for the mid point locations of all the air foil panels.
- g. CPU005.d: This file contains the unsteady pressure coefficient for the mid point location of all airfoil

panels. (in this case the values are for an AOA equal to 5 degrees).

- h. PHZSWP.d: This file contains the phase information of the reduced frequency sweep portion for the program. The file contains the phase angle of C_l , and C_m , and the amplitude of C_l , C_m .
- i. FLUTTER.IN: This file contains information that can be used to solve the flutter determinant. It contains K_p , C_l Re, C_l Im, C_m Re, C_m Im for the pitch or plunge case.

```

4
.....
      AIRFOIL TYPE : NACA 0012 AIRFOIL
      NLOWER = 50 , NUPPER = 50
.....
IFLAG  NLOWER  NUPPER
0       50      50
AIRFOIL TYPE
7
IRAMP  IOSCIL  ALPI      ALPMAX      PIVOT
0       1       -3.0      3.0         0.37
FREQ    RFQSTP  RFQFNL
.68     0.01    .7
IGUST   UGUST   VGUST
0        0.      0.
ITRANS  DELHX   DELHY DELI  PHASE
0        .00    .0      .0      0.00
CYCLE   NTCYCLE TOL
2        60     0.005
naot & naot X aoa values multiplied by 10 (integer)
2        05 10  20 25 39 50

Comments...

IRAMP  0: n/a          RFREQ is based on full chord
       1: Straight ramp
       2: Modified ramp

IOSCIL 0: n/a          RFREQ is based on full chord
       1: Sinusoidal pitch, motion starts at min Aoa

ITRANS 0: n/a
       1: Translational harmonic oscillation

ALPI/ALPMAX Minimum/MAX AOA in degrees for IRAMP/ITRANS/IOSCIL
            MAX does not apply for ITRANS
PIVOT  Location of Elastic Axis as a fraction of full chord
FREQ   Initial reduced frequency for program
RFQSTP Reduced freq step size for a sweep of freq.'s (enter 0.0 if only one calcu
       lation is desired.)
RFQFNL Final freq for the sweep
DELHX  Translational amount in the chordwise direction (dist/full chord)
DELHY  Max Translational amount in the vertical direction (h/fullchord(b))
DELI   Min Translational amount in the vertical direction (h/b)
CYCLE  : # of cycles for oscillatory motions
       -In case of ramp, cycle=1.5 denotes airfoil is held
         at max aoa for the duration of .5 cycle
       -For steady state solution set it to 0

NTCYCLE: # of time steps for each cycle
        CYCLE*NTCYCLE is limited to 200 currently.
TOL     Tolerance for convergence of the unsteady solution. (recommend using not
       less than .001)
NAOT: # of input aoa for cp output
       - angles should be in increasing order,
       - for oscillatory motions angles should increase
         first, then decrease. Decreasing angles are for
         the return cycle..

```

Figure 2.2 UPOT.IN

```

4
.....
AIRFOIL TYPE : NACA 0012 AIRFOIL
NLOWER = 50 , NUPPER = 50
.....

```

```

=====
IFLAG (C:NACA, 1:INPUT) = 0
NO. PANELS UPPER SURFACE = 50
NO. PANELS LOWER SURFACE = 50
=====

```

```

7
OSCILLATORY MOTION, IOSCIL =
INITIAL ANGLE OF ATTACK = -3.0000
FINAL ANGLE OF ATTACK = 3.0000
REDUCED FREQ. FOR OSCIL = 0.6800
REDUCED FREQ. STEP = 0.0100
FINAL REDUCED FREQ. = 0.7000
PIVOT POINT = 0.3700
=====
TOTAL # OF CYCLES = 2.0000
# of TIME STEPS PER CYCLE = 60
TOLERANCE FOR CONVERGENCE = 0.0050
=====

```

```

FREQ SWEEP
FREQ = 0.680000

```

```

STEADY FLOW SOLUTION AT ALPHA = -3.000000

```

1	0.999507	-1.116717	-0.086820	0.280753	-0.848084
2	0.997535	-1.108171	-0.086820	0.213074	-0.887088
3	0.993600	-1.100064	-0.086820	0.168200	-0.912031
4	0.987718	-1.092523	-0.086820	0.134381	-0.930386
5	0.979910	-1.085444	-0.086820	0.106525	-0.945238
6	0.970208	-1.078820	-0.086820	0.082353	-0.957939
7	0.958651	-1.072610	-0.086820	0.060678	-0.969186
8	0.945283	-1.066794	-0.086820	0.040815	-0.979380
9	0.930159	-1.061323	-0.086820	0.022307	-0.988783
10	0.913336	-1.056157	-0.086820	0.004851	-0.997572
11	0.894883	-1.051250	-0.086820	-0.011780	-1.005873
12	0.874870	-1.046545	-0.086820	-0.027772	-1.013791
13	0.853379	-1.041994	-0.086820	-0.043274	-1.021408
14	0.830493	-1.037547	-0.086820	-0.058416	-1.028793
15	0.806302	-1.033154	-0.086820	-0.073319	-1.036011
16	0.780903	-1.028773	-0.086820	-0.088096	-1.043118
17	0.754395	-1.024362	-0.086820	-0.102850	-1.050167
18	0.726883	-1.019887	-0.086820	-0.117685	-1.057206
19	0.698476	-1.015315	-0.086820	-0.132698	-1.064283
20	0.669285	-1.010628	-0.086820	-0.147973	-1.071435
21	0.639427	-1.005803	-0.086820	-0.163603	-1.078704
22	0.609018	-1.000836	-0.086820	-0.179660	-1.086122
23	0.578179	-0.995714	-0.086820	-0.196223	-1.093720
24	0.547031	-0.990441	-0.086820	-0.213352	-1.101523
25	0.515698	-0.985017	-0.086820	-0.231108	-1.109553
26	0.484302	-0.979449	-0.086820	-0.249545	-1.117830
27	0.452969	-0.973745	-0.086820	-0.268710	-1.126370
28	0.421821	-0.967910	-0.086820	-0.288653	-1.135188
29	0.390982	-0.961956	-0.086820	-0.309418	-1.144298
30	0.360573	-0.955883	-0.086820	-0.331061	-1.153716
31	0.330715	-0.949692	-0.086820	-0.353649	-1.163464
32	0.301524	-0.943373	-0.086820	-0.377267	-1.173570
33	0.273117	-0.936907	-0.086820	-0.402032	-1.184074
34	0.245605	-0.930250	-0.086820	-0.428106	-1.195034
35	0.219097	-0.923337	-0.086820	-0.455707	-1.206527
36	0.193698	-0.916066	-0.086820	-0.485152	-1.218668
37	0.169507	-0.908273	-0.086820	-0.516866	-1.231611
38	0.146621	-0.899722	-0.086820	-0.551434	-1.245566

Figure 2.3a UPOT output

stdin							Page 2
39	0.125130	-0.890054	-0.086820	-0.589671	-1.260822		
40	0.105117	-0.878738	-0.086820	-0.632708	-1.277774		
41	0.086664	-0.864972	-0.086820	-0.682121	-1.296966		
42	0.069841	-0.847530	-0.086820	-0.740144	-1.319145		
43	0.054717	-0.824472	-0.086820	-0.810000	-1.345363		
44	0.041349	-0.792611	-0.086820	-0.896386	-1.377093		
45	0.029792	-0.746398	-0.086820	-1.006151	-1.416387		
46	0.020090	-0.675433	-0.086820	-1.148872	-1.465903		
47	0.012282	-0.558323	-0.086820	-1.334727	-1.527981		
48	0.006399	-0.346398	-0.086820	-1.554189	-1.598183		
49	0.002465	0.075008	-0.086820	-1.656311	-1.629819		
50	0.000493	0.854855	-0.086820	-0.999986	-1.414209		
51	0.000493	1.561213	-0.086820	0.449705	-0.741819		
52	0.002465	1.669507	-0.086820	0.997431	-0.050689		
53	0.006399	1.558290	-0.086820	0.875814	0.352401		
54	0.012282	1.445845	-0.086820	0.674864	0.570207		
55	0.020090	1.357269	-0.086820	0.513069	0.697804		
56	0.029792	1.287651	-0.086820	0.392567	0.779380		
57	0.041349	1.231267	-0.086820	0.302348	0.835256		
58	0.054717	1.184229	-0.086820	0.233416	0.875548		
59	0.069841	1.144055	-0.086820	0.179673	0.905719		
60	0.086664	1.109153	-0.086820	0.137083	0.928933		
61	0.105117	1.078474	-0.086820	0.102934	0.947136		
62	0.125130	1.051316	-0.086820	0.075364	0.961580		
63	0.146621	1.027193	-0.086820	0.053053	0.973112		
64	0.169507	1.005756	-0.086820	0.035030	0.982329		
65	0.193698	0.986749	-0.086820	0.020565	0.989664		
66	0.219097	0.969966	-0.086820	0.009091	0.995444		
67	0.245605	0.955241	-0.086820	0.000149	0.999926		
68	0.273117	0.942428	-0.086820	-0.006640	1.003314		
69	0.301524	0.931390	-0.086820	-0.011593	1.005780		
70	0.330715	0.921993	-0.086820	-0.014984	1.007464		
71	0.360573	0.914106	-0.086820	-0.017049	1.008488		
72	0.390982	0.907597	-0.086820	-0.017994	1.008957		
73	0.421821	0.902331	-0.086820	-0.018001	1.008960		
74	0.452969	0.898173	-0.086820	-0.017221	1.008574		
75	0.484302	0.894989	-0.086820	-0.015784	1.007861		
76	0.515698	0.892645	-0.086820	-0.013805	1.006879		
77	0.547031	0.891016	-0.086820	-0.011369	1.005668		
78	0.578179	0.889982	-0.086820	-0.008545	1.004263		
79	0.609018	0.889434	-0.086820	-0.005387	1.002690		
80	0.639427	0.889276	-0.086820	-0.001926	1.000962		
81	0.669285	0.889426	-0.086820	0.001821	0.999089		
82	0.698476	0.889824	-0.086820	0.005855	0.997068		
83	0.726883	0.890423	-0.086820	0.010190	0.994892		
84	0.754395	0.891196	-0.086820	0.014851	0.992547		
85	0.780903	0.892138	-0.086820	0.019880	0.990010		
86	0.806302	0.893264	-0.086820	0.025328	0.987255		
87	0.830493	0.894605	-0.086820	0.031258	0.984247		
88	0.853379	0.896208	-0.086820	0.037745	0.980946		
89	0.874870	0.898136	-0.086820	0.044881	0.977302		
90	0.894883	0.900467	-0.086820	0.052775	0.973255		
91	0.913336	0.903280	-0.086820	0.061567	0.968728		
92	0.930159	0.906675	-0.086820	0.071417	0.963630		
93	0.945283	0.910746	-0.086820	0.082565	0.957828		
94	0.958651	0.915603	-0.086820	0.095332	0.951141		
95	0.970208	0.921351	-0.086820	0.110175	0.943306		
96	0.979910	0.928123	-0.086820	0.127830	0.933900		
97	0.987718	0.936086	-0.086820	0.149558	0.922194		
98	0.993600	0.945516	-0.086820	0.177698	0.906809		
99	0.997535	0.957020	-0.086820	0.217400	0.884647		
100	0.999507	0.971841	-0.086820	0.280753	0.848084		

*** BEGIN UNSTEADY FLOW SOLUTION ***							

istep	alpha	time	nitr	cl, cd, cm			
1	-3.0000	0.0000	1	-0.3479	0.0002	-0.0403	
2	-2.9836	0.1540	0	-0.3372	-0.0005	-0.0424	
3	-2.9344	0.3080	0	-0.3247	-0.0012	-0.0434	
4	-2.8532	0.4620	0	-0.3101	-0.0019	-0.0441	

Figure 2.3b UPOT output

stdin				Page 3		
5	-2.7406	0.6160	0	-0.2935	-0.0027	-0.0444
6	-2.5981	0.7700	0	-0.2751	-0.0033	-0.0444
7	-2.4271	0.9240	0	-0.2549	-0.0039	-0.0441
8	-2.2294	1.0780	0	-0.2332	-0.0044	-0.0434
9	-2.0074	1.2320	0	-0.2101	-0.0047	-0.0424
10	-1.7634	1.3860	0	-0.1858	-0.0048	-0.0410
11	-1.5000	1.5400	0	-0.1605	-0.0048	-0.0393
12	-1.2202	1.6940	0	-0.1345	-0.0046	-0.0373
13	-0.9271	1.8480	0	-0.1080	-0.0043	-0.0350
14	-0.6237	2.0020	0	-0.0812	-0.0038	-0.0323
15	-0.3136	2.1560	0	-0.0545	-0.0031	-0.0295
16	0.0000	2.3100	0	-0.0280	-0.0023	-0.0264
17	0.3136	2.4640	0	-0.0021	-0.0014	-0.0231
18	0.6237	2.6180	0	0.0230	-0.0004	-0.0197
19	0.9271	2.7720	0	0.0471	0.0006	-0.0161
20	1.2202	2.9260	0	0.0699	0.0016	-0.0124
21	1.5000	3.0800	0	0.0911	0.0025	-0.0087
22	1.7634	3.2340	0	0.1107	0.0034	-0.0050
23	2.0074	3.3880	0	0.1284	0.0042	-0.0013
24	2.2294	3.5420	0	0.1440	0.0048	0.0024
25	2.4271	3.6960	0	0.1573	0.0053	0.0059
26	2.5981	3.8500	0	0.1683	0.0056	0.0093
27	2.7406	4.0040	0	0.1769	0.0057	0.0126
28	2.8532	4.1580	0	0.1829	0.0056	0.0156
29	2.9344	4.3120	0	0.1863	0.0054	0.0184
30	2.9836	4.4660	0	0.1872	0.0050	0.0210
31	3.0000	4.6200	0	0.1855	0.0045	0.0232
32	2.9836	4.7740	0	0.1812	0.0038	0.0252
33	2.9344	4.9280	0	0.1745	0.0031	0.0268
34	2.8532	5.0820	0	0.1653	0.0024	0.0280
35	2.7406	5.2360	0	0.1538	0.0016	0.0289
36	2.5981	5.3900	0	0.1402	0.0008	0.0295
37	2.4270	5.5440	0	0.1246	0.0002	0.0296
38	2.2294	5.6980	0	0.1071	-0.0004	0.0294
39	2.0074	5.8520	0	0.0880	-0.0009	0.0288
40	1.7634	6.0060	0	0.0676	-0.0012	0.0278
41	1.5000	6.1600	0	0.0459	-0.0014	0.0265
42	1.2202	6.3140	0	0.0234	-0.0014	0.0249
43	0.9270	6.4680	0	0.0001	-0.0013	0.0229
44	0.6237	6.6220	0	-0.0235	-0.0010	0.0206
45	0.3136	6.7760	0	-0.0472	-0.0006	0.0181
46	0.0000	6.9300	1	-0.0709	0.0000	0.0153
47	-0.3136	7.0840	0	-0.0941	0.0006	0.0123
48	-0.6237	7.2380	0	-0.1166	0.0014	0.0092
49	-0.9271	7.3920	0	-0.1382	0.0021	0.0059
50	-1.2202	7.5460	0	-0.1586	0.0028	0.0025
51	-1.5000	7.7000	1	-0.1776	0.0035	-0.0010
52	-1.7634	7.8540	0	-0.1950	0.0041	-0.0045
53	-2.0074	8.0080	0	-0.2105	0.0047	-0.0080
54	-2.2294	8.1620	0	-0.2241	0.0051	-0.0114
55	-2.4271	8.3160	0	-0.2356	0.0053	-0.0147
56	-2.5981	8.4700	0	-0.2448	0.0054	-0.0179
57	-2.7406	8.6240	1	-0.2516	0.0053	-0.0210
58	-2.8532	8.7780	0	-0.2559	0.0051	-0.0239
59	-2.9344	8.9320	0	-0.2578	0.0047	-0.0265
60	-2.9836	9.0860	0	-0.2571	0.0042	-0.0289
61	-3.0000	9.2400	0	-0.2539	0.0035	-0.0309
62	-2.9836	9.3940	0	-0.2482	0.0028	-0.0327
63	-2.9344	9.5480	0	-0.2400	0.0020	-0.0342
64	-2.8532	9.7020	0	-0.2295	0.0011	-0.0353
65	-2.7406	9.8560	0	-0.2168	0.0003	-0.0360
66	-2.5981	10.0100	0	-0.2019	-0.0005	-0.0364
67	-2.4271	10.1640	0	-0.1851	-0.0012	-0.0365
68	-2.2294	10.3180	0	-0.1664	-0.0017	-0.0361
69	-2.0074	10.4720	0	-0.1463	-0.0022	-0.0354
70	-1.7634	10.6260	0	-0.1247	-0.0025	-0.0343
71	-1.5000	10.7800	0	-0.1020	-0.0026	-0.0329
72	-1.2202	10.9340	0	-0.0784	-0.0026	-0.0311
73	-0.9271	11.0880	0	-0.0542	-0.0024	-0.0290
74	-0.6237	11.2420	0	-0.0296	-0.0020	-0.0267
75	-0.3136	11.3960	0	-0.0050	-0.0015	-0.0240
76	0.0000	11.5500	0	0.0195	-0.0008	-0.0211
77	0.3136	11.7040	0	0.0436	-0.0001	-0.0181

Figure 2.3c UPOT output

stdin							Page 4
78	0.6237	11.8580	0	0.0670	0.0007	-0.0148	
79	0.9270	12.0120	0	0.0894	0.0016	-0.0114	
80	1.2202	12.1660	1	0.1106	0.0024	-0.0079	
81	1.5000	12.3200	0	0.1304	0.0033	-0.0044	
82	1.7633	12.4740	0	0.1486	0.0040	-0.0008	
83	2.0074	12.6280	0	0.1649	0.0046	0.0028	
84	2.2294	12.7820	0	0.1792	0.0051	0.0063	
85	2.4270	12.9360	1	0.1913	0.0055	0.0097	
86	2.5981	13.0900	0	0.2012	0.0057	0.0130	
87	2.7406	13.2440	0	0.2087	0.0057	0.0161	
88	2.8532	13.3980	0	0.2137	0.0056	0.0191	
89	2.9344	13.5520	0	0.2161	0.0053	0.0218	
90	2.9836	13.7060	0	0.2160	0.0048	0.0242	
91	3.0000	13.8600	0	0.2134	0.0042	0.0263	
92	2.9936	14.0140	1	0.2083	0.0036	0.0282	
93	2.9344	14.1680	0	0.2007	0.0028	0.0297	
94	2.8532	14.3220	0	0.1907	0.0020	0.0309	
95	2.7406	14.4760	0	0.1785	0.0012	0.0317	
96	2.5981	14.6300	0	0.1641	0.0005	0.0321	
97	2.4271	14.7840	0	0.1478	-0.0002	0.0322	
98	2.2294	14.9380	0	0.1297	-0.0008	0.0319	
99	2.0074	15.0920	0	0.1100	-0.0013	0.0312	
100	1.7634	15.2460	0	0.0889	-0.0016	0.0302	
101	1.5000	15.4000	0	0.0666	-0.0017	0.0288	
102	1.2202	15.5540	0	0.0435	-0.0017	0.0271	
103	0.9271	15.7080	0	0.0197	-0.0016	0.0251	
104	0.6238	15.8620	0	-0.0044	-0.0013	0.0228	
105	0.3136	16.0160	0	-0.0287	-0.0008	0.0202	
106	0.0000	16.1700	0	-0.0528	-0.0002	0.0173	
107	-0.3136	16.3239	1	-0.0765	0.0005	0.0143	
108	-0.6237	16.4779	0	-0.0994	0.0012	0.0111	
109	-0.9270	16.6319	0	-0.1215	0.0020	0.0078	
110	-1.2202	16.7859	0	-0.1423	0.0028	0.0043	
111	-1.5000	16.9399	0	-0.1617	0.0035	0.0008	
112	-1.7633	17.0939	1	-0.1795	0.0042	-0.0027	
113	-2.0074	17.2479	0	-0.1955	0.0047	-0.0063	
114	-2.2294	17.4019	0	-0.2095	0.0052	-0.0097	
115	-2.4270	17.5559	0	-0.2212	0.0054	-0.0131	
116	-2.5981	17.7099	0	-0.2308	0.0056	-0.0164	
117	-2.7406	17.8639	0	-0.2379	0.0055	-0.0195	
118	-2.8532	18.0179	1	-0.2426	0.0053	-0.0224	
119	-2.9344	18.1719	0	-0.2447	0.0049	-0.0250	
120	-2.9836	18.3259	0	-0.2444	0.0044	-0.0274	

PHASE SHIFT ANALYSIS						
FREQ = 0.6800000						
AMPLITUDE;	clamp,	cmamp :	0.2304234	3.4331881E-02		
PHASE;	clp,	cmp :	184.9092	-37.54200		
AVERAGE DRAG,	TOTAL DRAG :	1.5421067E-03	9.4068512E-02			
ETAS, WBAR	:	-0.2168084	-7.1127615E-03			

FREQ SWEEP
FREQ = 0.690000

STEADY FLOW SOLUTION AT ALPHA = -3.000000

1	0.999507	-1.116717	-0.086820	0.280753	-0.848084
2	0.997535	-1.108171	-0.086820	0.213074	-0.887088
3	0.993600	-1.100064	-0.086820	0.168200	-0.912031
4	0.987718	-1.092523	-0.086820	0.134381	-0.930386
5	0.979910	-1.085444	-0.086820	0.106525	-0.945238
6	0.970208	-1.078820	-0.086820	0.082353	-0.957939
7	0.958651	-1.072610	-0.086820	0.060678	-0.969186
8	0.945283	-1.066794	-0.086820	0.040815	-0.979380
9	0.930159	-1.061323	-0.086820	0.022307	-0.988783
10	0.913336	-1.056157	-0.086820	0.004851	-0.997572
11	0.894883	-1.051250	-0.086820	-0.011780	-1.005873
12	0.874870	-1.046545	-0.086820	-0.027772	-1.013791

Figure 2.3d UPOT output

13	0.853379	-1.041994	-0.086820	-0.043274	-1.021408
14	0.830493	-1.037547	-0.086820	-0.058416	-1.028793
15	0.806302	-1.033154	-0.086820	-0.073319	-1.036011
16	0.780903	-1.028773	-0.086820	-0.088096	-1.043118
17	0.754395	-1.024362	-0.086820	-0.102850	-1.050167
18	0.726883	-1.019887	-0.086820	-0.117685	-1.057206
19	0.698476	-1.015315	-0.086820	-0.132698	-1.064283
20	0.669285	-1.010628	-0.086820	-0.147973	-1.071435
21	0.639427	-1.005803	-0.086820	-0.163603	-1.078704
22	0.609018	-1.000836	-0.086820	-0.179660	-1.086122
23	0.578179	-0.995714	-0.086820	-0.196223	-1.093720
24	0.547031	-0.990441	-0.086820	-0.213352	-1.101523
25	0.515698	-0.985017	-0.086820	-0.231108	-1.109553
26	0.484302	-0.979449	-0.086820	-0.249545	-1.117830
27	0.452969	-0.973745	-0.086820	-0.268710	-1.126370
28	0.421821	-0.967910	-0.086820	-0.288653	-1.135188
29	0.390982	-0.961956	-0.086820	-0.309418	-1.144298
30	0.360573	-0.955883	-0.086820	-0.331061	-1.153716
31	0.330715	-0.949692	-0.086820	-0.353649	-1.163464
32	0.301524	-0.943373	-0.086820	-0.377267	-1.173570
33	0.273117	-0.936907	-0.086820	-0.402032	-1.184074
34	0.245605	-0.930250	-0.086820	-0.428106	-1.195034
35	0.219097	-0.923337	-0.086820	-0.455707	-1.206527
36	0.193698	-0.916066	-0.086820	-0.485152	-1.218668
37	0.169507	-0.908273	-0.086820	-0.516866	-1.231611
38	0.146621	-0.899722	-0.086820	-0.551434	-1.245566
39	0.125130	-0.890054	-0.086820	-0.589671	-1.260822
40	0.105117	-0.878738	-0.086820	-0.632708	-1.277774
41	0.086664	-0.864972	-0.086820	-0.682121	-1.296966
42	0.069841	-0.847530	-0.086820	-0.740144	-1.319145
43	0.054717	-0.824472	-0.086820	-0.810000	-1.345363
44	0.041349	-0.792611	-0.086820	-0.896386	-1.377093
45	0.029792	-0.746398	-0.086820	-1.006151	-1.416387
46	0.020090	-0.675433	-0.086820	-1.148872	-1.465903
47	0.012282	-0.558323	-0.086820	-1.334727	-1.527981
48	0.006399	-0.346398	-0.086820	-1.554189	-1.598183
49	0.002465	0.075008	-0.086820	-1.656311	-1.629819
50	0.000493	0.854855	-0.086820	-0.999986	-1.414209
51	0.000493	1.561213	-0.086820	0.449705	-0.741819
52	0.002465	1.669507	-0.086820	0.997431	-0.050689
53	0.006399	1.558290	-0.086820	0.875814	0.352401
54	0.012282	1.445845	-0.086820	0.674864	0.570207
55	0.020090	1.357269	-0.086820	0.513069	0.697804
56	0.029792	1.287651	-0.086820	0.392567	0.779380
57	0.041349	1.231267	-0.086820	0.302348	0.835256
58	0.054717	1.184229	-0.086820	0.233416	0.875548
59	0.069841	1.144055	-0.086820	0.179673	0.905719
60	0.086664	1.109153	-0.086820	0.137083	0.928933
61	0.105117	1.078474	-0.086820	0.102934	0.947136
62	0.125130	1.051316	-0.086820	0.075364	0.961580
63	0.146621	1.027193	-0.086820	0.053053	0.973112
64	0.169507	1.005756	-0.086820	0.035030	0.982329
65	0.193698	0.986749	-0.086820	0.020565	0.989664
66	0.219097	0.969966	-0.086820	0.009091	0.995444
67	0.245605	0.955241	-0.086820	0.000149	0.999926
68	0.273117	0.942428	-0.086820	-0.006640	1.003314
69	0.301524	0.931390	-0.086820	-0.011593	1.005780
70	0.330715	0.921993	-0.086820	-0.014984	1.007464
71	0.360573	0.914106	-0.086820	-0.017049	1.008488
72	0.390982	0.907597	-0.086820	-0.017994	1.008957
73	0.421821	0.902331	-0.086820	-0.018001	1.008960
74	0.452969	0.898173	-0.086820	-0.017221	1.008574
75	0.484302	0.894989	-0.086820	-0.015784	1.007861
76	0.515698	0.892645	-0.086820	-0.013805	1.006879
77	0.547031	0.891016	-0.086820	-0.011369	1.005668
78	0.578179	0.889982	-0.086820	-0.008545	1.004263
79	0.609018	0.889434	-0.086820	-0.005387	1.002690
80	0.639427	0.889276	-0.086820	-0.001926	1.000962
81	0.669285	0.889426	-0.086820	0.001821	0.999089
82	0.698476	0.889824	-0.086820	0.005855	0.997068
83	0.726883	0.890423	-0.086820	0.010190	0.994892
84	0.754395	0.891196	-0.086820	0.014851	0.992547
85	0.780903	0.892138	-0.086820	0.019880	0.990010

Figure 2.3e UPOT output

stdin						Page 6
86	0.806302	0.893264	-0.086820	0.025328	0.987255	
87	0.830493	0.894605	-0.086820	0.031258	0.984247	
88	0.853379	0.896208	-0.086820	0.037745	0.980946	
89	0.874870	0.898136	-0.086820	0.044881	0.977302	
90	0.894883	0.900467	-0.086820	0.052775	0.973255	
91	0.913336	0.903280	-0.086820	0.061567	0.968728	
92	0.930159	0.906675	-0.086820	0.071417	0.963630	
93	0.945283	0.910746	-0.086820	0.082565	0.957828	
94	0.958651	0.915603	-0.086820	0.095332	0.951141	
95	0.970208	0.921351	-0.086820	0.110175	0.943306	
96	0.979910	0.928123	-0.086820	0.127830	0.933930	
97	0.987718	0.936086	-0.086820	0.149558	0.922194	
98	0.993600	0.945516	-0.086820	0.177698	0.906809	
99	0.997535	0.957020	-0.086820	0.217400	0.884647	
100	0.999507	0.971841	-0.086820	0.280753	0.848084	

*** BEGIN UNSTEADY FLOW SOLUTION ***						

step	alpha	time	nitr	cl, cd, cm		
1	-3.0000	0.0000	1	-0.3479	0.0002	-0.0403
2	-2.9836	0.1518	0	-0.3370	-0.0005	-0.0425
3	-2.9344	0.3035	0	-0.3243	-0.0012	-0.0435
4	-2.8532	0.4553	0	-0.3096	-0.0020	-0.0442
5	-2.7406	0.6071	0	-0.2929	-0.0027	-0.0445
6	-2.5981	0.7588	0	-0.2744	-0.0034	-0.0446
7	-2.4271	0.9106	0	-0.2542	-0.0039	-0.0442
8	-2.2294	1.0624	0	-0.2323	-0.0044	-0.0436
9	-2.0074	1.2141	0	-0.2091	-0.0047	-0.0426
10	-1.7634	1.3659	0	-0.1848	-0.0049	-0.0412
11	-1.5000	1.5177	0	-0.1595	-0.0049	-0.0395
12	-1.2202	1.6694	0	-0.1334	-0.0047	-0.0375
13	-0.9271	1.8212	0	-0.1069	-0.0043	-0.0352
14	-0.6237	1.9730	0	-0.0802	-0.0038	-0.0326
15	-0.3136	2.1247	0	-0.0535	-0.0031	-0.0297
16	0.0000	2.2765	1	-0.0271	-0.0023	-0.0267
17	0.3136	2.4283	0	-0.0012	-0.0014	-0.0234
18	0.6237	2.5801	0	0.0238	-0.0004	-0.0199
19	0.9271	2.7318	0	0.0478	0.0006	-0.0164
20	1.2202	2.8836	0	0.0704	0.0016	-0.0127
21	1.5000	3.0354	1	0.0916	0.0026	-0.0090
22	1.7634	3.1871	0	0.1110	0.0034	-0.0052
23	2.0074	3.3389	0	0.1285	0.0042	-0.0015
24	2.2294	3.4907	0	0.1439	0.0048	0.0022
25	2.4271	3.6424	0	0.1571	0.0053	0.0057
26	2.5981	3.7942	1	0.1679	0.0056	0.0092
27	2.7406	3.9460	0	0.1763	0.0057	0.0124
28	2.8532	4.0977	0	0.1822	0.0056	0.0155
29	2.9344	4.2495	0	0.1855	0.0054	0.0183
30	2.9836	4.4013	0	0.1862	0.0050	0.0209
31	3.0000	4.5530	0	0.1843	0.0045	0.0231
32	2.9836	4.7048	0	0.1799	0.0038	0.0251
33	2.9344	4.8566	0	0.1729	0.0031	0.0267
34	2.8532	5.0083	0	0.1636	0.0023	0.0280
35	2.7406	5.1601	1	0.1520	0.0016	0.0289
36	2.5981	5.3119	0	0.1383	0.0008	0.0295
37	2.4271	5.4636	0	0.1226	0.0001	0.0296
38	2.2294	5.6154	0	0.1050	-0.0005	0.0294
39	2.0074	5.7672	0	0.0859	-0.0009	0.0288
40	1.7634	5.9189	0	0.0654	-0.0013	0.0279
41	1.5000	6.0707	0	0.0437	-0.0014	0.0266
42	1.2202	6.2225	0	0.0211	-0.0014	0.0250
43	0.9271	6.3742	0	-0.0021	-0.0013	0.0230
44	0.6237	6.5260	0	-0.0257	-0.0010	0.0207
45	0.3136	6.6778	0	-0.0494	-0.0006	0.0182
46	0.0000	6.8295	1	-0.0729	0.0000	0.0154
47	-0.3136	6.9813	0	-0.0960	0.0007	0.0125
48	-0.6237	7.1331	0	-0.1185	0.0014	0.0093
49	-0.9270	7.2849	0	-0.1399	0.0021	0.0060
50	-1.2202	7.4366	0	-0.1602	0.0029	0.0026
51	-1.5000	7.5884	1	-0.1791	0.0036	-0.0009

Figure 2.3f UPOT output

stdin							Page 7
52	-1.7634	7.7402	0	-0.1963	0.0042	-0.0044	
53	-2.0074	7.8919	0	-0.2117	0.0047	-0.0079	
54	-2.2294	8.0437	0	-0.2251	0.0051	-0.0113	
55	-2.4270	8.1955	0	-0.2364	0.0053	-0.0147	
56	-2.5981	8.3472	1	-0.2454	0.0054	-0.0179	
57	-2.7406	8.4990	0	-0.2520	0.0053	-0.0210	
58	-2.8532	8.6508	0	-0.2562	0.0051	-0.0238	
59	-2.9344	8.8025	0	-0.2578	0.0047	-0.0265	
60	-2.9836	8.9543	0	-0.2570	0.0042	-0.0289	
61	-3.0000	9.1061	0	-0.2536	0.0035	-0.0310	
62	-2.9836	9.2578	0	-0.2477	0.0028	-0.0328	
63	-2.9344	9.4096	0	-0.2394	0.0019	-0.0342	
64	-2.8532	9.5614	0	-0.2288	0.0011	-0.0354	
65	-2.7406	9.7131	0	-0.2159	0.0003	-0.0361	
66	-2.5981	9.8649	0	-0.2009	-0.0005	-0.0365	
67	-2.4270	10.0167	0	-0.1839	-0.0012	-0.0366	
68	-2.2294	10.1684	0	-0.1652	-0.0018	-0.0362	
69	-2.0074	10.3202	0	-0.1450	-0.0022	-0.0355	
70	-1.7634	10.4720	0	-0.1233	-0.0025	-0.0345	
71	-1.5000	10.6237	0	-0.1006	-0.0027	-0.0330	
72	-1.2202	10.7755	0	-0.0770	-0.0026	-0.0313	
73	-0.9271	10.9273	0	-0.0528	-0.0024	-0.0292	
74	-0.6237	11.0790	0	-0.0282	-0.0020	-0.0269	
75	-0.3136	11.2308	0	-0.0036	-0.0015	-0.0242	
76	0.0000	11.3826	0	0.0209	-0.0008	-0.0213	
77	0.3136	11.5343	0	0.0448	-0.0001	-0.0183	
78	0.6237	11.6861	0	0.0681	0.0007	-0.0150	
79	0.9270	11.8379	0	0.0904	0.0016	-0.0116	
80	1.2202	11.9897	0	0.1115	0.0025	-0.0081	
81	1.5000	12.1414	1	0.1311	0.0033	-0.0045	
82	1.7634	12.2932	0	0.1493	0.0040	-0.0010	
83	2.0074	12.4450	0	0.1654	0.0047	0.0026	
84	2.2294	12.5967	0	0.1796	0.0052	0.0061	
85	2.4270	12.7485	0	0.1915	0.0055	0.0095	
86	2.5981	12.9003	1	0.2012	0.0057	0.0129	
87	2.7406	13.0520	0	0.2085	0.0058	0.0160	
88	2.8532	13.2038	0	0.2133	0.0056	0.0189	
89	2.9344	13.3556	0	0.2156	0.0053	0.0217	
90	2.9836	13.5073	0	0.2153	0.0048	0.0241	
91	3.0000	13.6591	0	0.2125	0.0042	0.0263	
92	2.9836	13.8109	0	0.2072	0.0036	0.0282	
93	2.9344	13.9626	0	0.1995	0.0028	0.0297	
94	2.8532	14.1144	0	0.1894	0.0020	0.0309	
95	2.7406	14.2662	0	0.1770	0.0012	0.0317	
96	2.5981	14.4179	1	0.1625	0.0005	0.0322	
97	2.4271	14.5697	0	0.1461	-0.0002	0.0323	
98	2.2294	14.7215	0	0.1279	-0.0008	0.0320	
99	2.0074	14.8732	0	0.1081	-0.0013	0.0313	
100	1.7634	15.0250	0	0.0870	-0.0016	0.0303	
101	1.5000	15.1768	0	0.0647	-0.0018	0.0289	
102	1.2202	15.3285	0	0.0415	-0.0018	0.0272	
103	0.9271	15.4803	0	0.0178	-0.0016	0.0252	
104	0.6237	15.6321	0	-0.0063	-0.0013	0.0229	
105	0.3136	15.7838	0	-0.0305	-0.0008	0.0203	
106	0.0000	15.9356	1	-0.0546	-0.0002	0.0175	
107	-0.3136	16.0874	0	-0.0782	0.0005	0.0145	
108	-0.6237	16.2391	0	-0.1011	0.0012	0.0113	
109	-0.9270	16.3909	0	-0.1230	0.0020	0.0079	
110	-1.2202	16.5427	0	-0.1437	0.0028	0.0044	
111	-1.5000	16.6945	1	-0.1630	0.0035	0.0009	
112	-1.7634	16.8462	0	-0.1807	0.0042	-0.0026	
113	-2.0074	16.9980	0	-0.1965	0.0048	-0.0061	
114	-2.2294	17.1498	0	-0.2103	0.0052	-0.0096	
115	-2.4270	17.3015	0	-0.2219	0.0055	-0.0130	
116	-2.5981	17.4533	1	-0.2312	0.0056	-0.0163	
117	-2.7406	17.6051	0	-0.2382	0.0055	-0.0194	
118	-2.8532	17.7568	0	-0.2427	0.0053	-0.0223	
119	-2.9344	17.9086	0	-0.2446	0.0049	-0.0250	
120	-2.9836	18.0604	0	-0.2441	0.0044	-0.0274	

PHASE SHIFT ANALYSIS
FREQ = 0.6900000

Figure 2.3g UPOT output

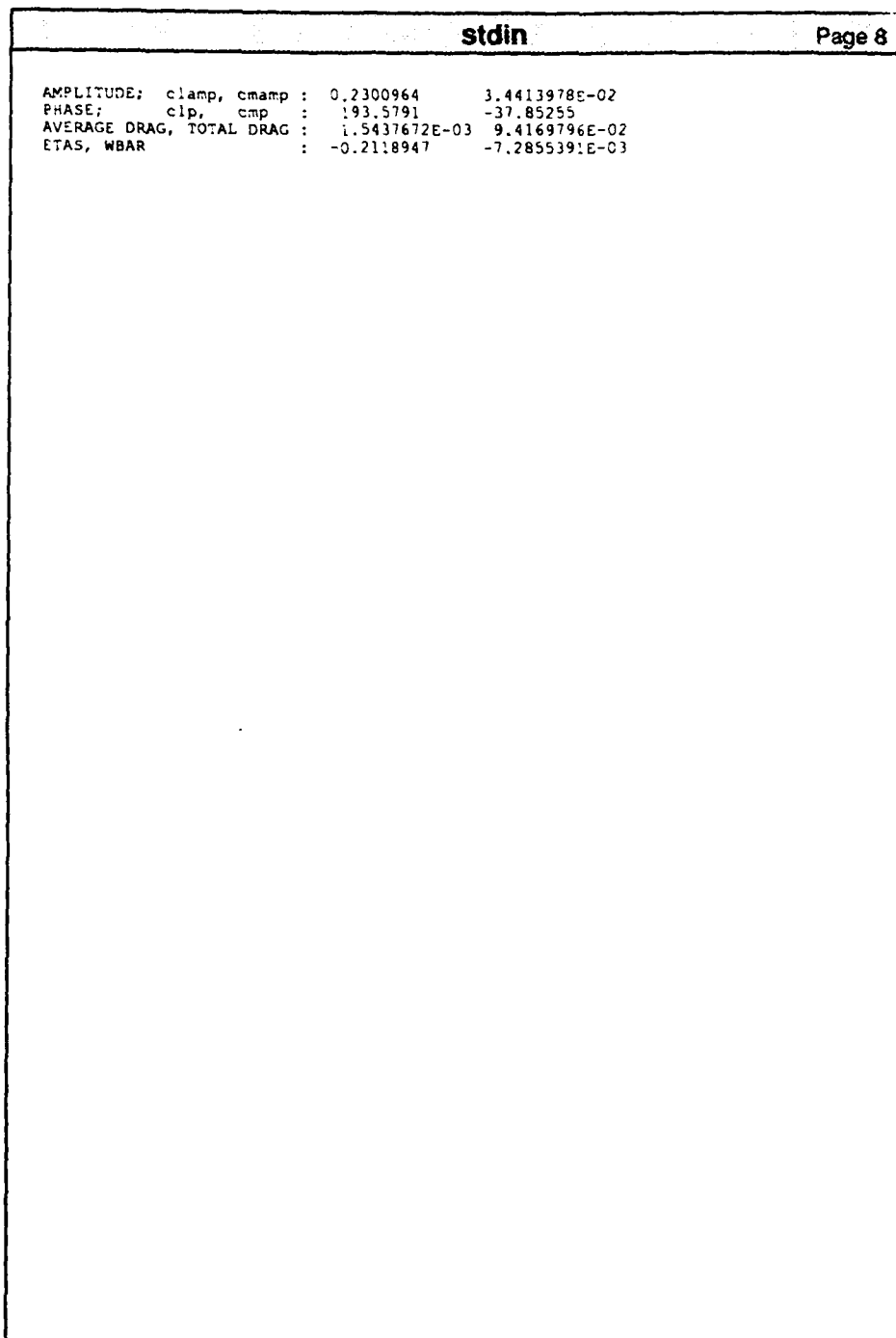


Figure 2.3h UPOT output

2. Difference Between UPOT and U2DIIF/Phase

The input file format was changed along with the following:

- The program can now analyze a pitch, plunge or ramp motion that starts from any minimum value of Alpha or plunge ($h/2b$). Previously, the program only accepted the initial position of zero. This program does not need to go through the origin.
- The phase portion of the program was changed to curve fit C_L and C_M to a cosine function:

$$F(t) = \text{Amp} * \cos(\omega t + \phi) \quad (2.2)$$

where, Amp = amplitude of motion, ω = frequency of motion, ϕ = phase angle between motion and the aerodynamic forces. This was done since the alpha and plunge values were allowed to start from a new zero position.

- The phase portion uses the middle 180 degrees of the final 360 degree cycle specified in the UPOT.in file. This change was done to capture an all positive area of the cosine curve for phasing analysis. The program integrates this portion of the cosine curve, and for proper code operation the area under the curve must be kept to one sign. If the areas of integration were chosen to include both sides of the axis, then the code would produce errors near 90 and 270 degrees.

3. UPOT Verification

The code UPOT did not incorporate any drastic changes to the prior codes, but the original code had never been extensively compared to prior theories over a wide range of reduced frequencies. When conducting these comparisons, it is easy to become confused. This section will go through the comparisons slowly to help alleviate that problem.

a. $K_{panel} (K_p)$ vs. $K_{Theodorsen} (K_t)$.

The equation for reduced frequency is:

$$K_p = \frac{\omega 2b}{U} \quad K_t = \frac{\omega b}{U} \quad (2.3)$$

where: ω = frequency of oscillation (rad/sec)

b = half chord (units to match U)

U = free stream velocity (units to match b).

The difference between K_p and K_t lies in the fact that K_p calls for the full chord and K_t calls for the half chord, hence, it is important to remember that K_p is twice K_t .

b. *Aerodynamic Forces*

The aerodynamic forces problem of simple harmonic motion about an equilibrium position was solved theoretically by Theodorsen in NACA TR-496 [ref.10] and outlined by Fung in [ref.5]. The complex equations were simplified using the simple harmonic motion equation and resulted in the following:

$$L = \pi \rho b^3 \omega^2 (L_h \frac{h}{b} + [L_\alpha - (\frac{1}{2} + a) L_h] \alpha + [L_\beta - (c - e) L_z] \beta) e^{i(\omega t + \phi_L)} \quad (2.4)$$

$$\begin{aligned} M = & \pi \rho b^4 \omega^2 ([M_h - (\frac{1}{2} + a) L_h] \frac{h}{b} + \\ & [M_\alpha - (\frac{1}{2} + a) (L_\alpha + M_h) + (\frac{1}{2} + a)^2 L_h] \alpha \\ & + [M_\beta - (\frac{1}{2} + a) L_\beta - (c - e) M_z + (c - e) (\frac{1}{2} + a) L_z] \beta) e^{i(\omega t + \phi_M)} \end{aligned} \quad (2.5)$$

L , M are the lift and moment per unit span of the airfoil about the elastic axis, b , h/b , a and α (radians), are

shown in Figure (2.1)., L_h , L_α , L_β , and M_α are defined by Scanlan [ref.6,pp.412-424] for various values of K_t and e . This analysis will not cover airfoil aileron combinations. Therefore β becomes zero and equations 2.4 and 2.5 reduce to:

$$L = \pi \rho b^3 \omega^2 (L_h \frac{h}{b} + [L_\alpha - (\frac{1}{2} + a) L_h] \alpha) e^{i(\omega t + \phi_L)} \quad (2.6)$$

$$M = \pi \rho b^4 \omega^2 ([M_h - (\frac{1}{2} + a) L_h] \frac{h}{b} + [M_\alpha - (\frac{1}{2} + a) (L_\alpha + M_h) + (\frac{1}{2} + a)^2 L_h] \alpha) e^{i(\omega t + \phi_L)} \quad (2.7)$$

The UPOT panel code used the following equations in defining lift and moment:

$$C_L = \frac{L}{2qb} = \sqrt{R_L^2 + I_L^2} e^{i(\omega t + \phi_L)} \quad \phi_L = \tan^{-1} \frac{I_L}{R_L} \quad (2.8)$$

$$C_M = \frac{M}{4qb^2} = \sqrt{R_m^2 + I_m^2} e^{i(\omega t + \phi_m)} \quad \phi_m = \tan^{-1} \frac{I_m}{R_m} \quad (2.9)$$

where R_L and I_L are the real and imaginary parts of C_L , and R_m and I_m are the real and imaginary parts of C_m . For the same conditions the lift (L) and moment (M) should be the same for both the panel code and Theodorsen. This fact allows for comparison of the magnitude, real, imaginary and phase of lift and moment.

For lift: L_t (eqn 2.6) equals L_p (eqn 2.8)

$$\pi \rho b^3 \omega^2 [L_h h/b + (L_a - (1/2 + a) L_h) \alpha] e^{i(\omega t + \phi_L)} = 2qb \sqrt{R_L^2 + I_L^2} e^{i(\omega t + \phi_L)} \quad (2.10)$$

After canceling $e^{i(\omega t + \phi_L)}$:

$$\pi \rho b^3 \omega^2 [L_h (h/b) + (L_a - (1/2 + a) L_h) \alpha] = 2qb \sqrt{R_L^2 + I_L^2} \quad (2.11)$$

$$C_L = \sqrt{R_L^2 + I_L^2}$$

For pitch case, $h/b = 0$, 2.11 reduces to:

$$\pi \rho b^3 \omega^2 [(L_a - (1/2 + a) L_h) \alpha] = 2qb C_{L\alpha} \quad (2.12)$$

Substitute $K_t = b\omega/U$ for ω and $q = \frac{1}{2}\rho U^2$ into equation 2.12 which gives:

$$2\pi qb K_t^2 (L_a - (1/2 + a) L_h) \alpha = 2qb C_{L\alpha} \quad (2.13)$$

After cancelling and substituting K_p for K_t :

$$\frac{\pi K_p^2}{4} [L_a - (1/2 + a) L_h] \alpha = C_{L\alpha} \quad (2.14)$$

This relationship can be further broken down into the real and imaginary parts:

$$\text{Imag: } \frac{\pi K_p^2}{4} [iL_a - (1/2 + a) iL_h] \alpha = C_{L\alpha} \sin(\phi_L) \quad (2.15)$$

Plunge Case: $\alpha=0$ using equation 2.11 gives:

$$\text{Real: } \frac{\pi K_p^2}{4} [L_a - (\frac{1}{2} + a) L_h] \alpha = C_{L_a} \cos(\phi_L) \quad (2.16)$$

$$\pi \rho b^3 \omega^2 L_h \frac{h}{b} = 2 q b C_{L_h} \quad (2.17)$$

The panel code uses $h/2b$ for analysis because it uses full chord vice half chord. Therefore equation 2.17 becomes:

$$2 \pi \rho b^3 \omega^2 L_h \left(\frac{h}{2b} \right) = 2 q b C_{L_h} \quad (2.18)$$

Substituting as before for ω :

$$2 \pi q b K_t^2 L_h 2 \left(\frac{h}{2b} \right) = 2 q b C_{L_h} \quad (2.19)$$

Cancel and substitute K_p :

$$\left(\frac{\pi K_p^2}{2} \right) \left(\frac{h}{2b} \right) L_h = C_{L_h} \quad (2.20)$$

This can also be broken up into imaginary and real parts as before.

MOMENT:

Equating equations 2.7 and 2.9 results in:

$$\begin{aligned} \pi \rho b^4 \omega^2 \left([M_h - (\frac{1}{2} + a) L_h] \frac{h}{b} + [M_a - (\frac{1}{2} + a) (L_a + M_h) + (\frac{1}{2} + a)^2 L_h] \alpha \right) \\ = 4 q b^2 \sqrt{R_m^2 + I_m^2} \end{aligned} \quad (2.21)$$

For pitch: $h/b = 0$

$$M_p = 4qb^2 \sqrt{R_m^2 + I_m^2} e^{i(\omega t + \phi_m)} \quad (2.22)$$

$$C_{M\alpha} = \sqrt{R_m^2 + I_m^2} \quad (2.23)$$

resulting in:

$$\pi \rho b^4 \omega^2 ([M_\alpha - (\frac{1}{2} + a) (L_\alpha + M_h) + (\frac{1}{2} + a)^2 L_h] \alpha) = 4qb^2 C_{M\alpha} \quad (2.24)$$

After substituting and cancelling:

$$\frac{\alpha \pi K_p^2}{8} [M_\alpha - (\frac{1}{2} + a) (L_\alpha + M_h) + (\frac{1}{2} + a)^2 L_h] = C_{M\alpha} \quad (2.25)$$

$$\text{REAL} \quad M_h = \frac{1}{2}$$

$$\frac{\alpha \pi K_p^2}{8} [M_\alpha - (\frac{1}{2} + a) (L_\alpha + \frac{1}{2}) + (\frac{1}{2} + a)^2 L_h] = C_{M\alpha} \cos(\phi_{M\alpha}) \quad (2.26)$$

$$\text{IMAG:} \quad M_h = 0$$

$$\frac{\alpha \pi K_p^2}{8} [iM_\alpha - (\frac{1}{2} + a) (iL_\alpha) + (\frac{1}{2} + a)^2 iL_h] = C_{M\alpha} \sin(\phi_{M\alpha}) \quad (2.27)$$

For plunge, $\alpha = 0$, equation 21 reduces to :

$$\text{REAL:} \quad M_h = \frac{1}{2}$$

$$\frac{\pi}{4} K_p^2 \left(\frac{h}{2b} \right) [M_h - (\frac{1}{2} + a) L_h] = C_{Mh} \cos(\phi_{Mh}) \quad (2.28)$$

IMAG: $M_h = 0$

$$\frac{\pi}{4} K_p^2 \left(\frac{h}{2b} \right) (\frac{1}{2} + a) L_h = C_{Mh} \sin(\phi_{Mh}) \quad (2.29)$$

Comparisons are shown for various cases of pitch and plunge. The tables include pitch values of 1 (Tables 2.2-2.3) and 6.7 degrees (Tables 2.4-2.5), plunge ($h/2b$) values of .01 (Table 2.8) and .0833 (Table 2.6-2.7). The graphs include 1 degree pitch (Figures 2.7-12, 2.13-20), 6.7 degree pitch (Figures 2.21-28, 2.29-36), .01 $h/2b$ plunge (Figures 2.53-56), and .0833 $h/2b$ plunge (Figures 2.37-44, 2.45-52).

4. Results

The tables and graphs show that the panel code predicts the Theodorsen results accurately. An initial question that was first addressed for the comparisons was how many cycles to use for good consistent phase results. Initial runs were made at several different cycle values and the results are shown in Table 2.1. It can be seen that the panel code predicts Theodorsen's results, using a cycle number of three. Increasing the cycle number just takes more computer time and only results in marginal increases in accuracy.

The most glaring difference appears in the I_M C_{Mh} comparisons of Figures 2.47-48. The panel code drops off sharply at the higher end of the reduced frequency spectrum. The reason for this is believed to be due to the magnitude of $h/2b$ chosen for the comparison. The code was rerun for a

Comparison of Phase Calculations Using Various Cycles.					
(Pitch, 6.7 deg., NACA 0007, .37c, 50 panels top and bottom)					
Kp	# Cycles	Cl Phase Angle	Cm Phase Angle	Cl Amplitude	Cm amplitude
1.00	1	182.0537	-54.409	0.4884	0.08937
1.00	2	208.1592	-46.424	0.5109224	0.083932
1.00	3	206.001	-44.313	0.51527	0.083169
% Diff. 2/3		1.05%	4.76%	0.84%	0.92%
1.00	4	204.9365	-43.33887	0.51668	0.082951
1.00	5	204.3955	-42.86817	0.5172907	0.082865
1.00	6	204.0596	-42.58497	0.517598	0.082822
1.00	7	203.8291	-42.3916	0.517776	0.082792
1.00	8	203.6031	-42.25684	0.51789	0.082784
% Diff. 7/8		0.11%	0.32%	0.02%	0.01%
3.60	2	264.44052	-59.79002	1.0931	0.212011
3.60	3	261.9737	-58.29977	1.09954	0.21936
% Diff. 2/3		0.94%	2.56%	0.59%	3.35%
3.60	4	260.17877	-57.4404	1.10271	0.21903
3.60	5	259.2686	-56.79395	1.104505	0.218845
3.60	6	258.5186	-56.3252	1.105599	0.218739
3.60	7	257.9483	-56.0098	1.106306	0.218673
3.60	8	257.6163	-55.380567	1.106764	0.218632
% Diff. 7/8		0.13%	1.14%	0.04%	0.02%

TABLE 2.1 PHASE CALCULATION VS CYCLE NUMBER

series of $h/2b$ values and the percent difference for the panel code to Theodorsen was plotted in Figure 2.4. This chart shows that the $h/2b$ value chosen has a tremendous impact on the code results. An $h/2b$ value of .01 gave an acceptable error of 10% at $K_p = 8$. Runs were completed with a value of .01 $h/2b$ and the favorable results are shown in Figures 2.53-56.

Comparison of the Effect of $h/2b$ Values on Code Accuracy at High K_p

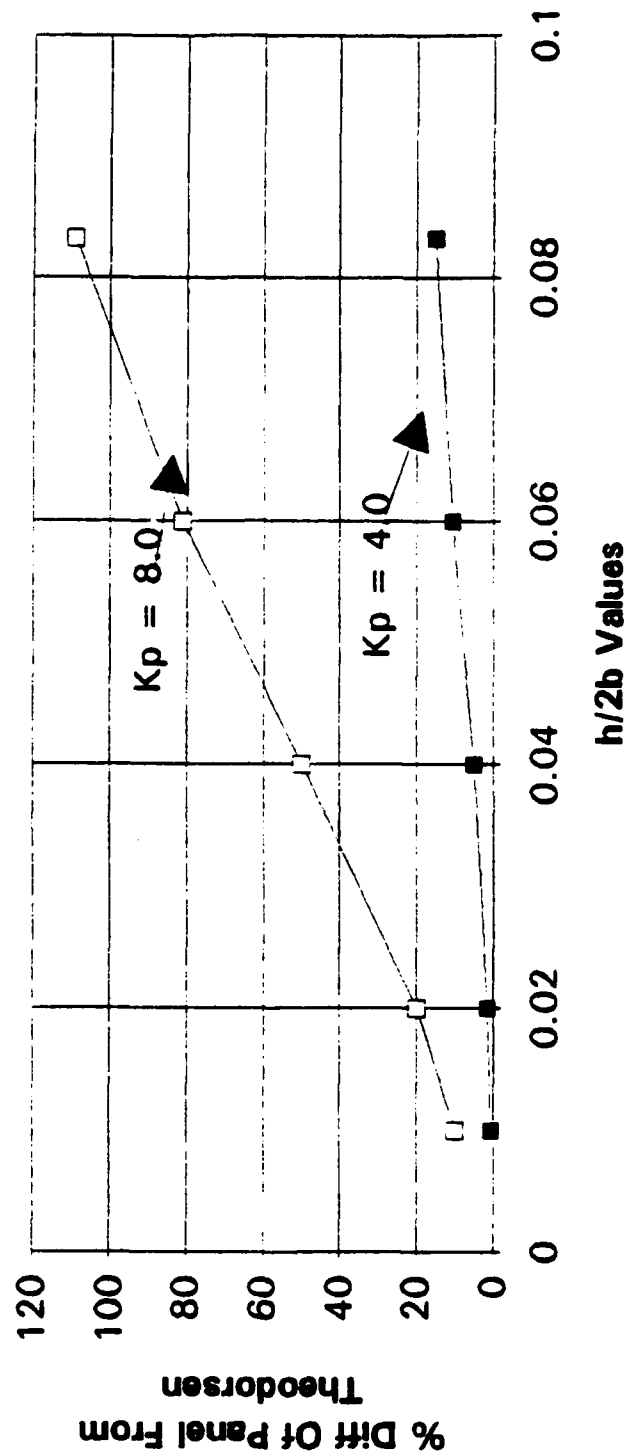


Figure 2.4 Effect of $h/2b$ values on $\text{Im } C_m$

Comparison of Panel Cl Values with Theodorsen Results (pitch, 1.0 deg., .37c, NACA 0007, 50 panels top and bottom, 3cyc66calc.)													
%DIFF taken wrt Theodorsen values.													
1/Rt	Kpanel	Real pan.	Real theo.	% DIFF.	Imag Pan.	Imag Theo.	% DIFF.	Mag Pan.	Mag Theo.	% DIFF.	Phase Pn.	Phase Th.	% DIFF.
18.87	0.11988	-0.10312	-0.098452	4.74%	0.01082	0.00788418	37.24%	0.1038881	0.0987874	4.98%	174.01008	175.42145	0.80%
12.5	0.16	-0.09854	-0.095343	4.40%	0.01094	0.00749857	48.52%	0.10013838	0.0963448	4.71%	173.72806	175.52214	1.02%
10	0.2	-0.08634	-0.082634	4.11%	0.0104	0.00647761	60.55%	0.09689972	0.0927608	4.46%	173.83872	176.9957	1.23%
8.33	0.24	-0.08354	-0.080022	3.81%	0.00944	0.00510846	84.88%	0.09401513	0.0901689	4.27%	174.23728	178.75341	1.42%
6.25	0.32	-0.08089	-0.085787	3.59%	0.00906	0.00182887	308.38%	0.08810923	0.085802	3.85%	175.71373	178.91367	1.79%
5	0.4	-0.08522	-0.082367	3.46%	0.00328	-0.0024119	236.99%	0.0862831	0.0824026	3.50%	177.78586	181.6773	2.14%
4.17	0.48	-0.08232	-0.079546	3.49%	-0.00048	-0.0067203	92.88%	0.0823214	0.0798296	3.12%	180.33408	184.82905	2.43%
3.75	0.53	-0.08084	-0.077683	4.09%	-0.00278	-0.006731	70.96%	0.08088778	0.0782506	3.37%	181.98956	187.02716	2.70%
3.33	0.6	-0.07842	-0.076126	3.01%	-0.01176	-0.013414	12.33%	0.07829687	0.0772882	2.59%	188.52962	189.99348	0.77%
2.94	0.68	-0.07684	-0.074217	1.92%	-0.01632	-0.0178149	8.90%	0.07738067	0.0763489	1.35%	192.17543	193.57073	0.72%
2.6	0.8	-0.07272	-0.071761	1.34%	-0.02328	-0.0248749	5.66%	0.07635546	0.0758948	0.62%	197.75153	198.9752	0.61%
2	1	-0.06849	-0.068284	0.28%	-0.03466	-0.036806	3.20%	0.07673387	0.077102	0.48%	208.85223	207.67124	0.39%
1.87	1.2	-0.0646	-0.062233	0.87%	-0.04584	-0.0487313	2.34%	0.07808585	0.0802443	1.43%	215.24128	215.61898	0.17%
1.25	1.6	-0.06704	-0.064408	3.98%	-0.06658	-0.068368	2.14%	0.08767245	0.0903233	2.93%	228.41288	228.8726	0.24%
0.83	2.4	-0.041893	-0.046737	10.36%	-0.108072	-0.1100887	3.83%	0.11404518	0.1195806	4.83%	248.44832	246.99287	0.59%
0.5	4	-0.002503	-0.008851	71.72%	-0.179738	-0.188358	4.82%	0.17975543	0.1890431	4.91%	269.2022	267.31851	0.71%
0.25	8	0.1604088	0.1826884	3.96%	-0.365727	-0.3805373	5.73%	0.38134264	0.4138552	5.44%	293.55768	293.14781	0.14%
Values for Kp equal to 2.4, and 8 above were calculated using 200 panels top and bottom and 4 cycles of 100 calculations.													
The below values were calculated using 75 panels and 3cyc66calc.													
0.83	2.4	-0.0416	-0.046737	10.99%	-0.10618	-0.1100887	4.44%	0.11310788	0.1195806	5.41%	248.42059	246.99287	0.58%
0.5	4	-0.00489	-0.008851	43.73%	-0.17716	-0.188358	6.19%	0.17722998	0.1890431	6.25%	268.38883	267.31851	0.40%
0.25	8	0.1382	0.1826884	16.28%	-0.35464	-0.3805373	6.81%	0.37899468	0.4138552	8.21%	291.00838	293.14781	0.73%

TABLE 2.2 1 DEGREE PITCH C_L

Real Part of C_l for Panel and Theodorsen (pitch, 1.0 deg, .37c,
NACA0007, 75 panels top and bottom, 3cycles of 85 calc. per cycle)

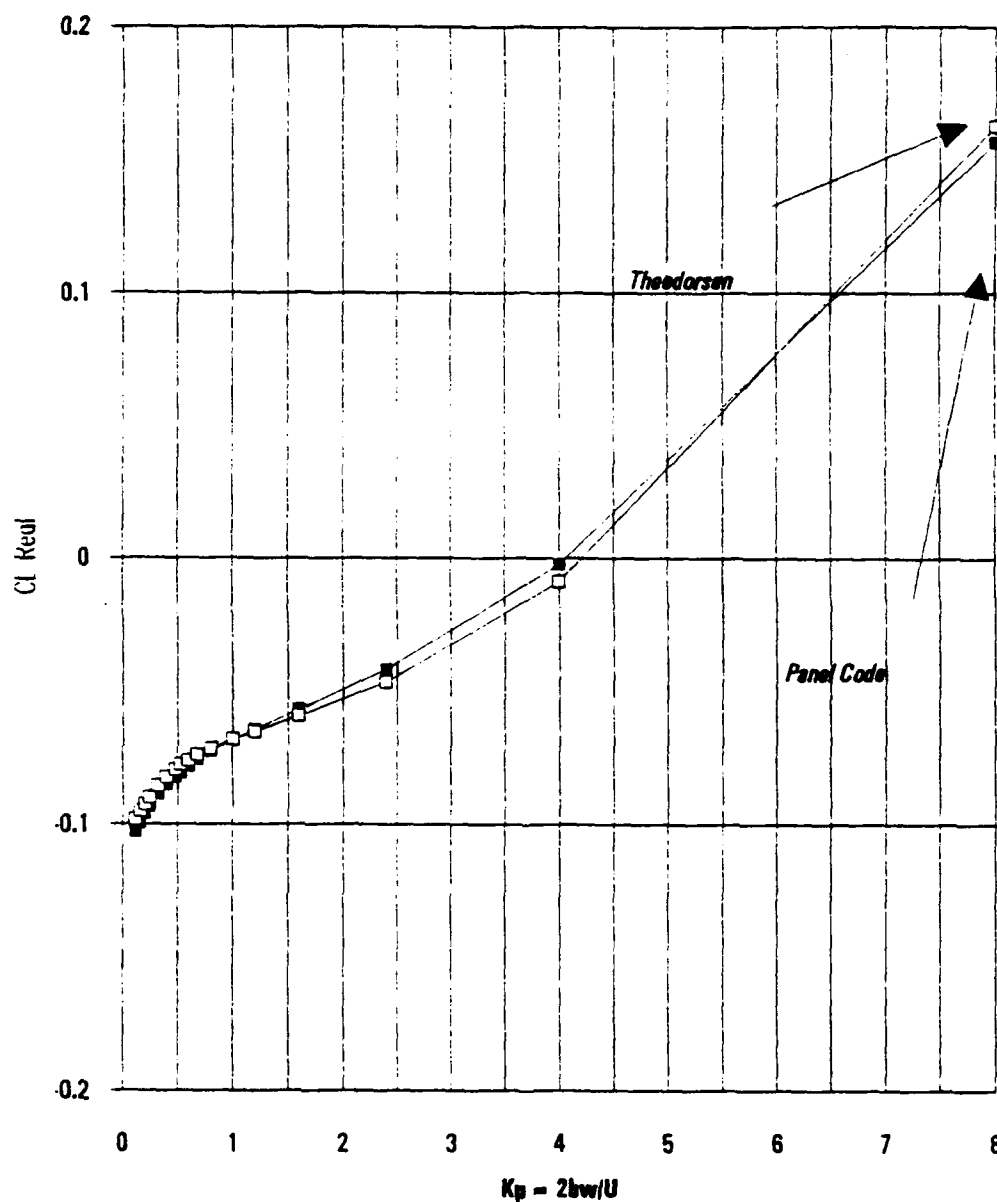


Figure 2.5 1 Degree pitch C_l Re

Real Part of C_l for Panel and Theodorsen (pitch, 1.0 deg. .37c,
NACA0007, 75 panels top and bottom, 3cycles of 85 calc. per cycle)

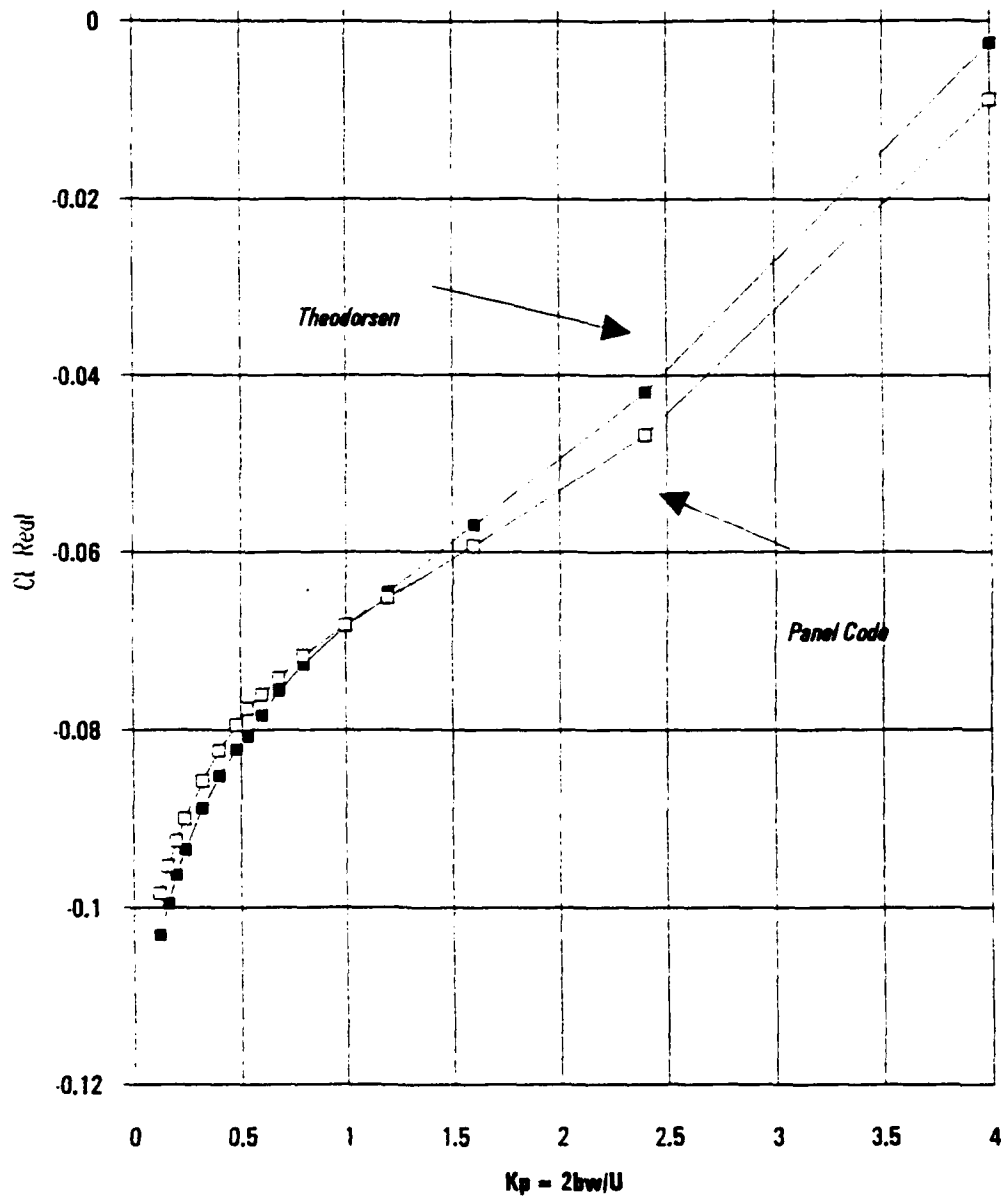


Figure 2.6 1 degree pitch C_L Re

Imag. Part of C_l for Panel and Theodorsen (pitch, 1.0 deg, .37c,
NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)

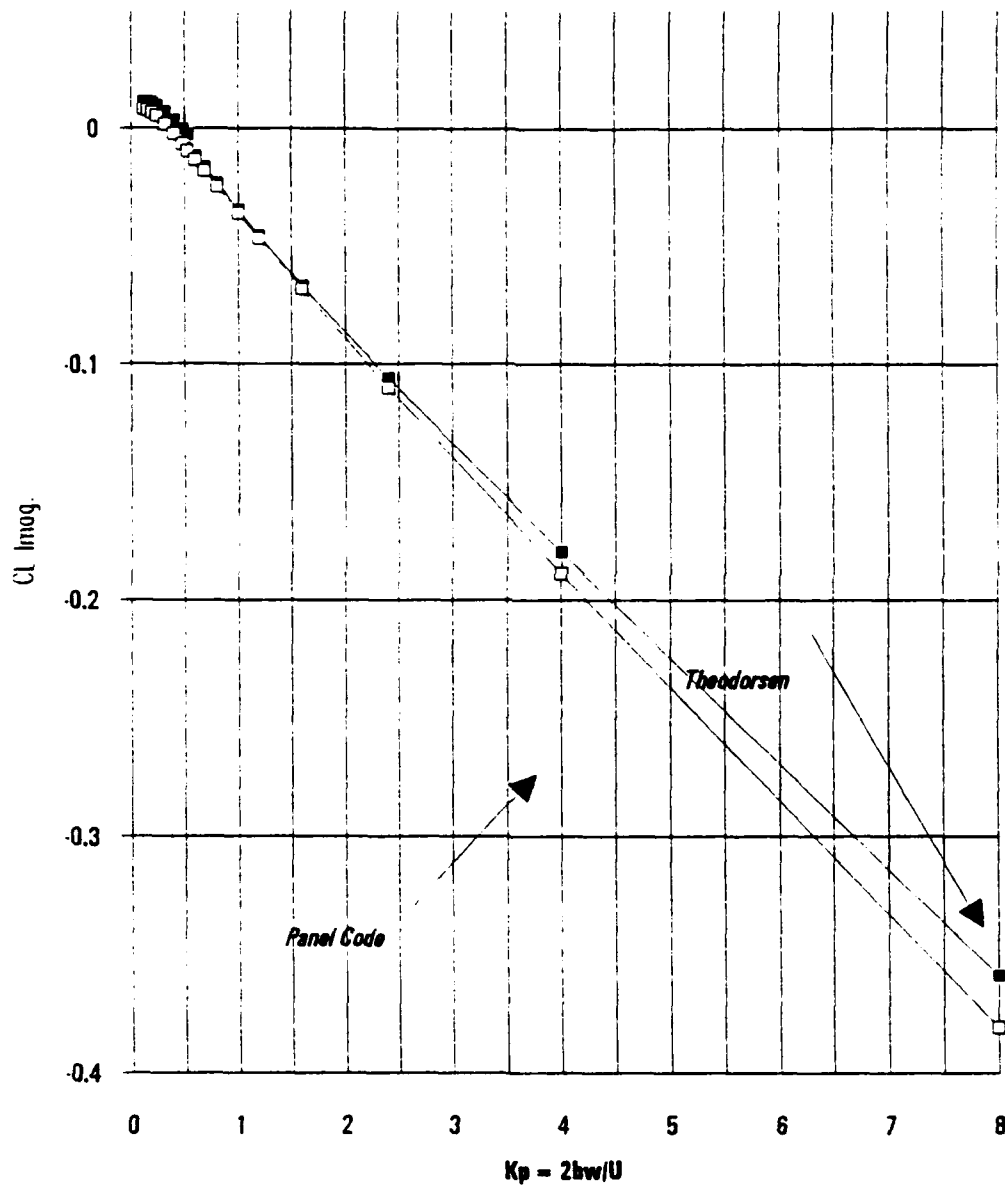


Figure 2.7 1 Degree pitch $C_L \text{ Im}$

Imag. Part of C_l for Panel and Theodorsen (pitch, 1.0 deg, .37c,
NACA0007, 75 panels top and bottom, 3cycles of 85 calc. per cycle)

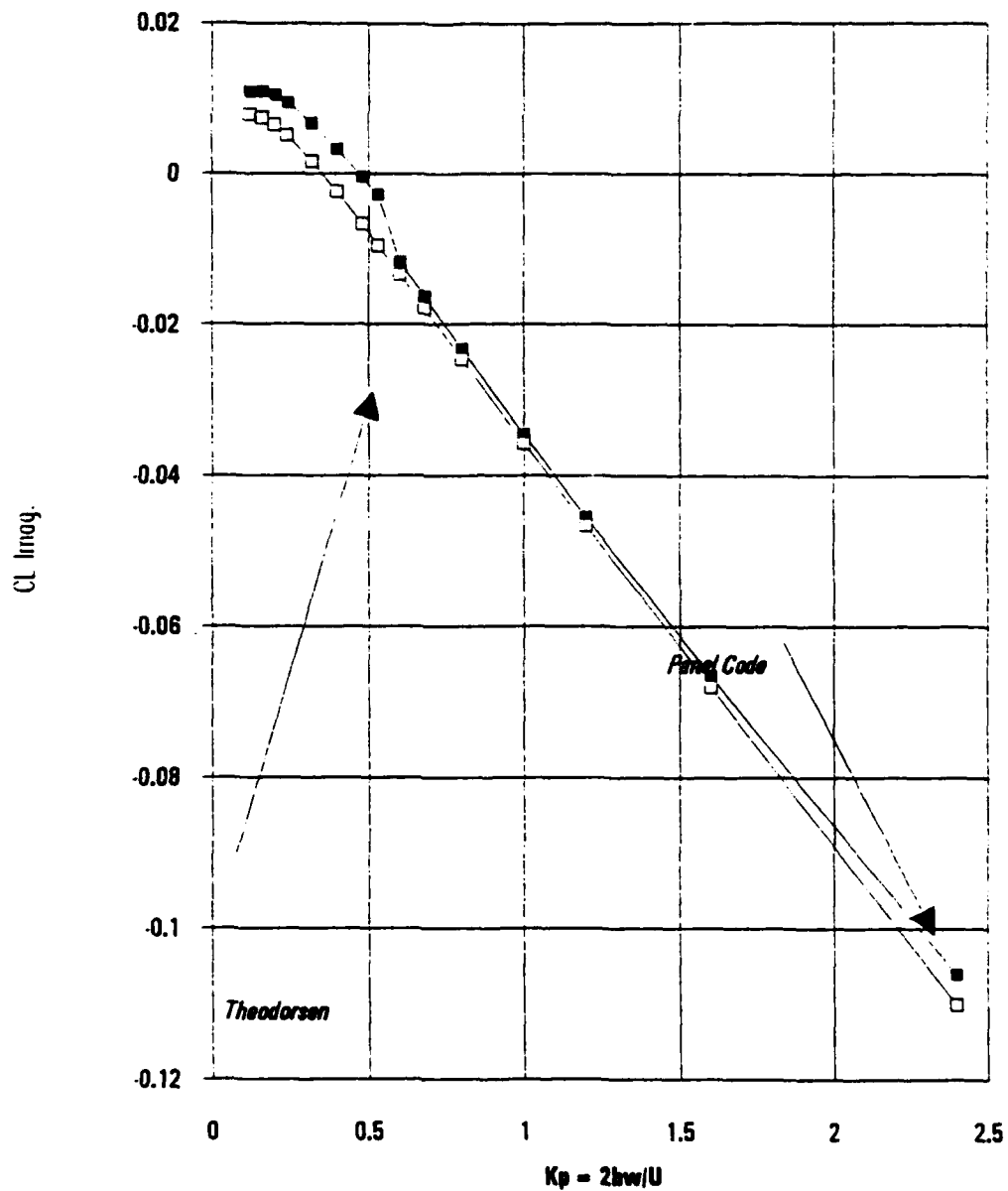


Figure 2.8 1 Degree pitch $C_l \text{ Im}$

Mag. of C_l for Panel and Theodorsen (pitch, 1.0 deg, .37c,
NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)

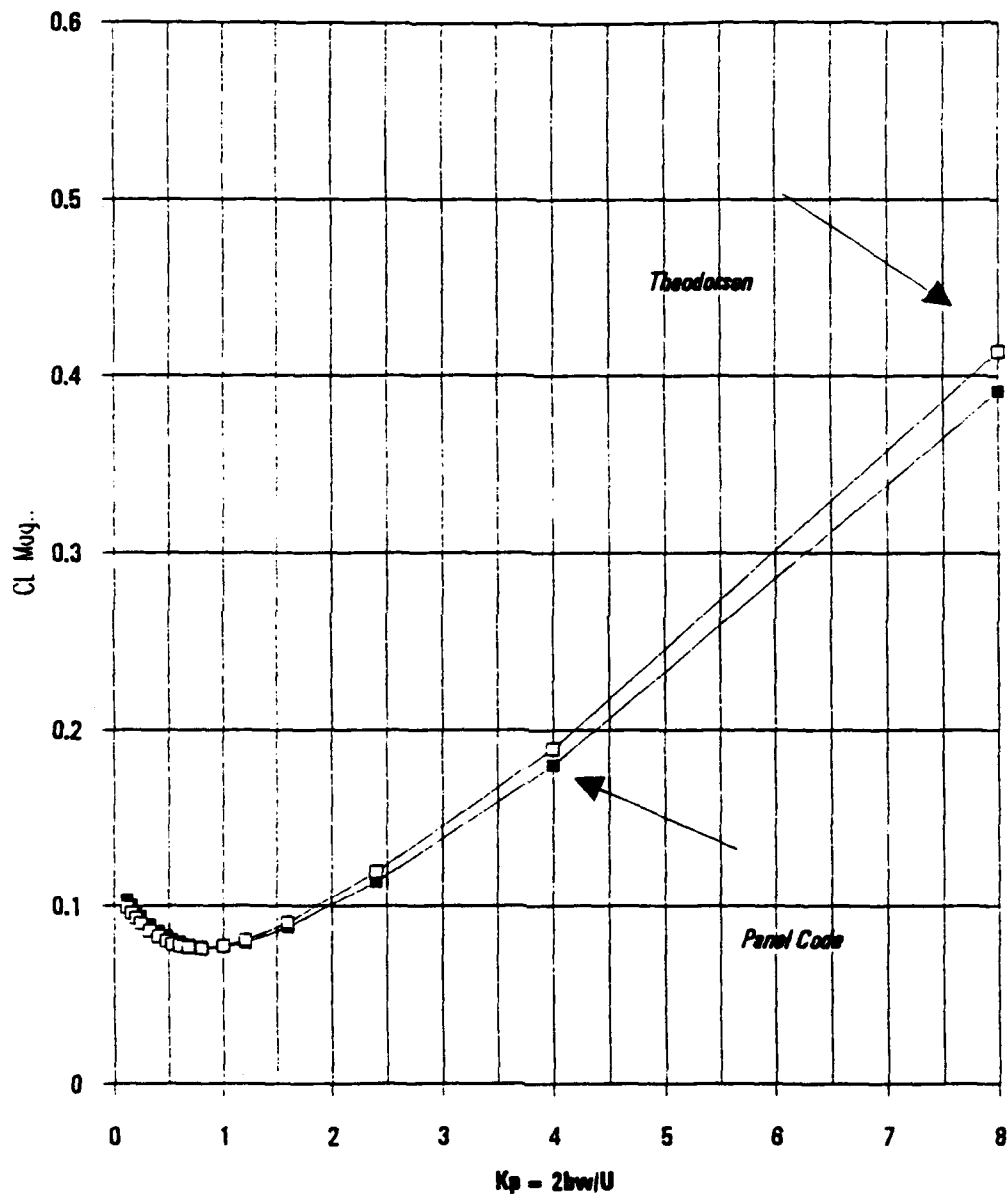


Figure 2.9 1 Degree pitch C_l Magnitude

**Mag. of C_l for Panel and Theodorsen (pitch, 1.0 deg, .37c,
NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)**

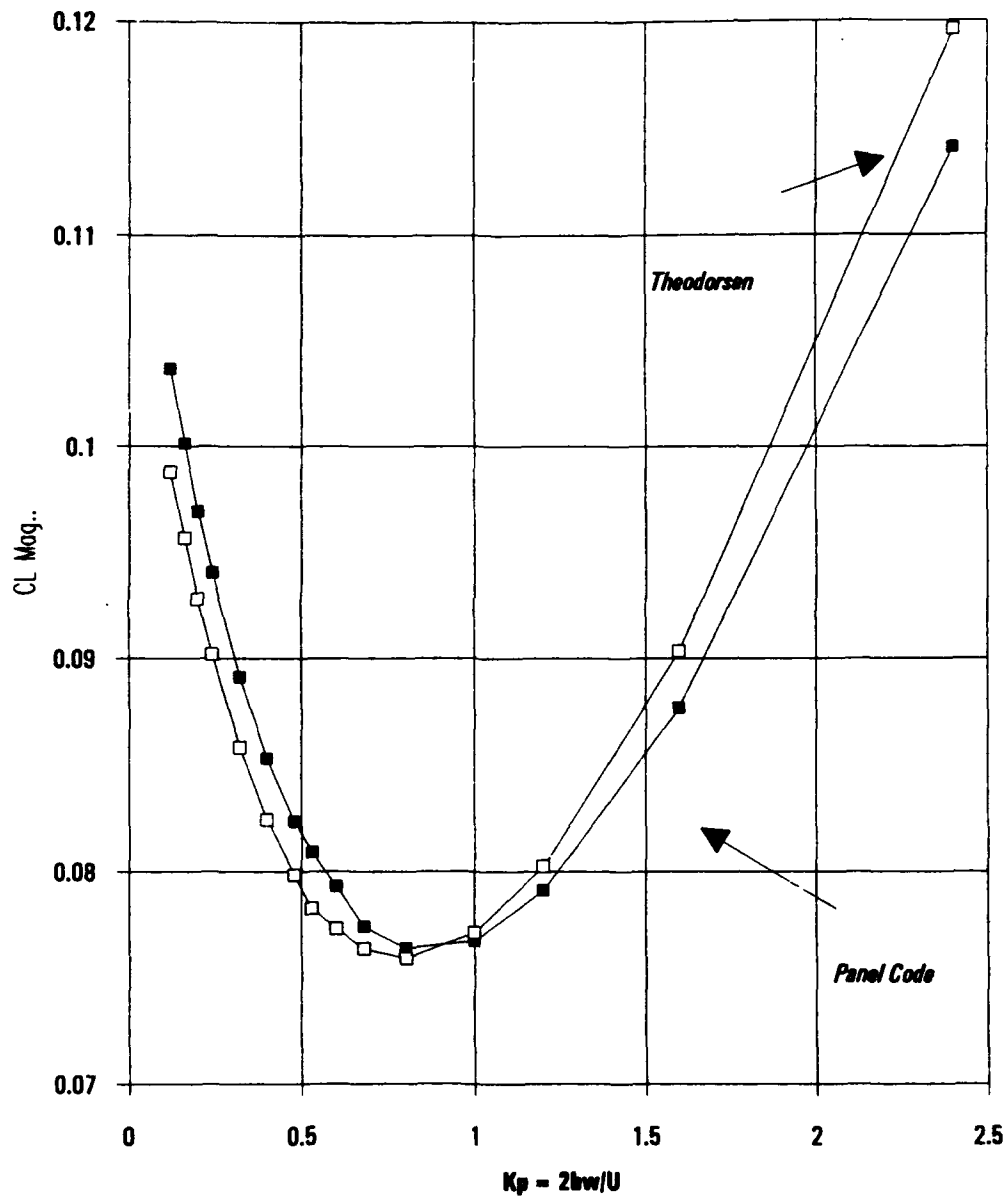


Figure 2.10 1 Degree pitch C_L Magnitude

Phase of C_l for Panel and Theodorsen (pitch, 1.0 deg, .37c,
NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)

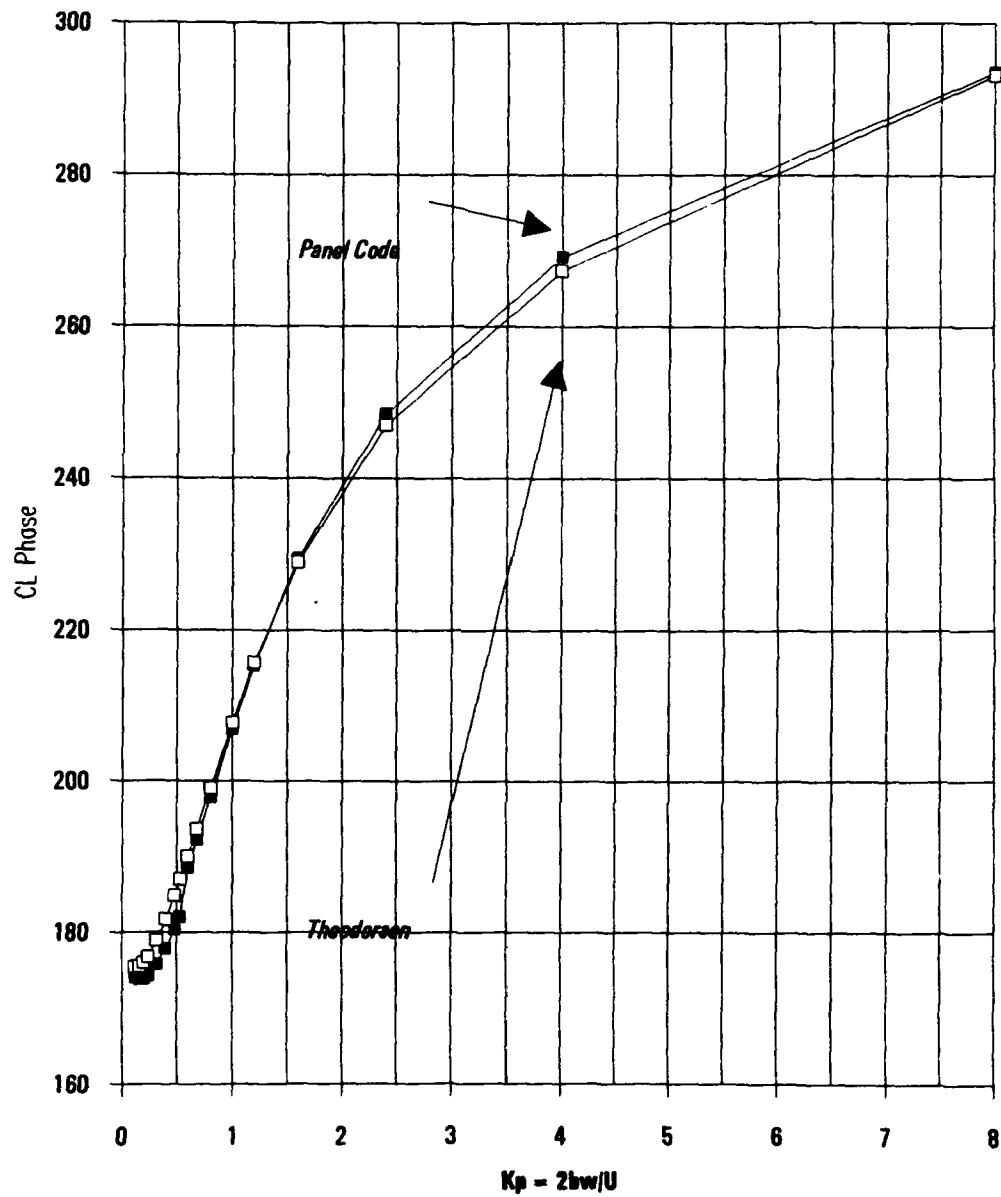


Figure 2.11 1 Degree pitch C_l Phase

**Phase of C_l for Panel and Theodorsen (pitch, 1.0 deg, .37c,
NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)**

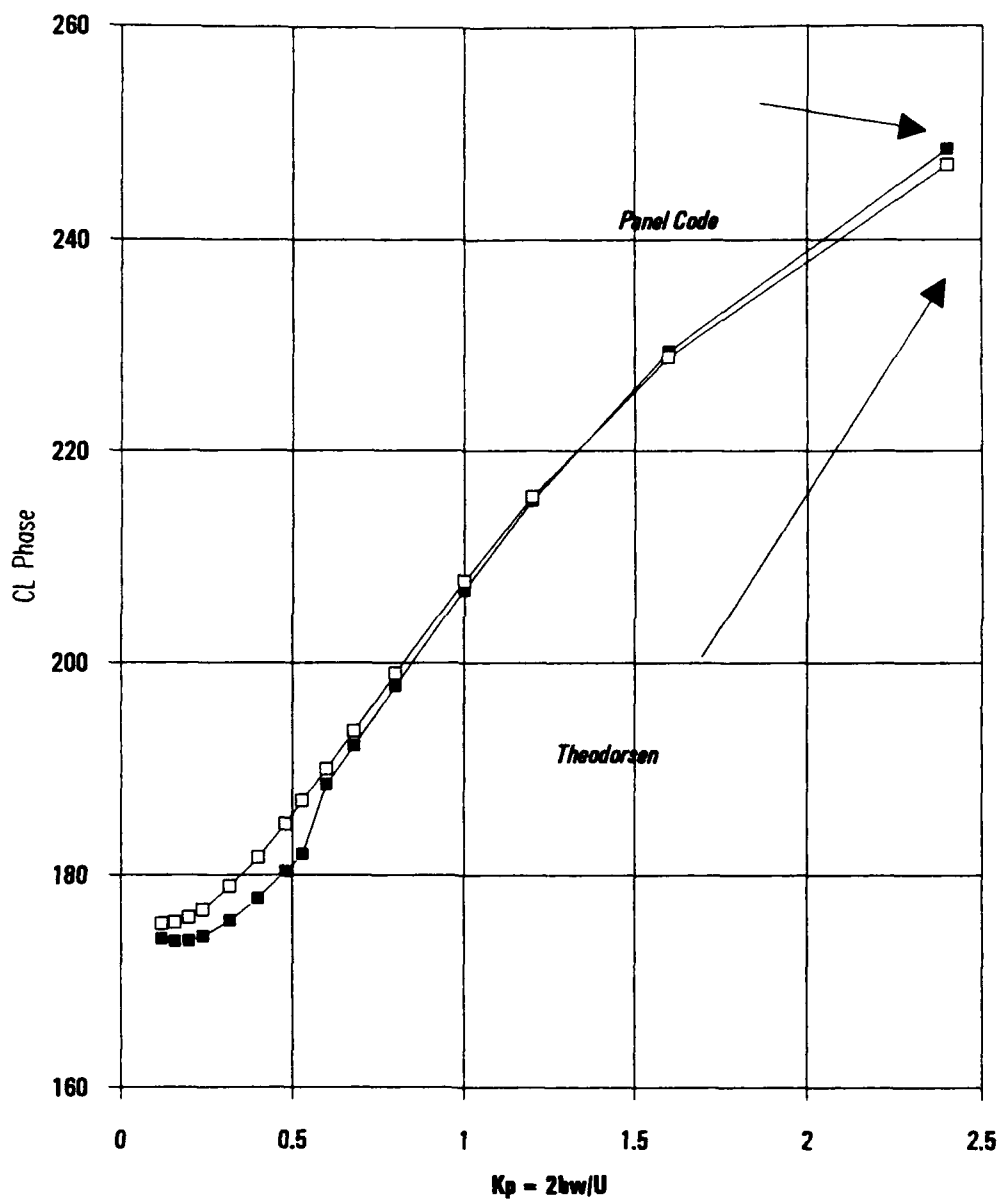


Figure 2.12 1 degree pitch C_l Phase

Comparison of Panel Moment Aerodynamic Values (CM) with Theodoren Results (pitch, 1.0 deg., .37c, NACA 0007, 76 panels top and bottom)													
1/Kt	Kpanel	Rp	Rt	% DIFF	Imag Pen.	Imag t	% DIFF	Mag Pen.	Mag Th.	% DIFF	Phase Ph.	Phase Th.	% DIFF
16.67	0.11998	0.01188	0.0118391	0.36%	-0.00282	-0.002591	1.14%	0.0121655	0.0121192	0.38%	347.56314	347.65745	0.03%
12.5	0.16	0.01147	0.0114656	0.14%	-0.0031	-0.003069	0.36%	0.0118616	0.0118638	0.10%	344.87699	344.9458	0.02%
10	0.2	0.01111	0.0111736	0.57%	-0.0036	-0.003619	0.64%	0.0116483	0.0117148	0.57%	342.51393	342.5197	0.00%
8.33	0.24	0.01081	0.0108118	0.93%	-0.00365	-0.003602	1.34%	0.0114751	0.0115896	0.98%	340.39656	340.32136	0.02%
6.26	0.32	0.0103	0.0104731	1.95%	-0.00447	-0.004919	7.23%	0.0112261	0.0115294	2.60%	336.54009	336.29363	0.37%
5	0.4	0.00993	0.0101633	2.30%	-0.00602	-0.006194	3.34%	0.0111268	0.0114134	2.51%	333.18163	332.93184	0.07%
4.17	0.48	0.00955	0.0098323	2.84%	-0.00654	-0.006773	4.04%	0.0111272	0.0114853	3.14%	330.14016	329.53193	0.09%
3.76	0.53	0.0095	0.0096299	3.33%	-0.00685	-0.006864	3.64%	0.0111567	0.0115576	3.47%	328.37668	328.23904	0.04%
3.33	0.6	0.00936	0.0097636	4.24%	-0.00629	-0.006615	4.91%	0.0112688	0.0117935	4.45%	325.0702	325.88165	0.08%
2.94	0.66	0.00922	0.0097216	5.16%	-0.0068	-0.007172	5.18%	0.0114564	0.0120809	5.17%	323.59022	323.59433	0.00%
2.5	0.8	0.00912	0.009729	6.26%	-0.00762	-0.008005	4.81%	0.0118944	0.0125991	5.87%	320.12036	320.55117	0.13%
2	1	0.00911	0.0099403	8.35%	-0.00864	-0.009412	6.08%	0.012084	0.0130802	7.27%	315.88177	316.58403	0.22%
1.67	1.2	0.00924	0.0103033	10.32%	-0.01017	-0.010942	6.20%	0.0137407	0.0149668	8.13%	312.26886	313.5408	0.41%
1.25	1.6	0.0092	0.0116031	14.51%	-0.01289	-0.013768	6.38%	0.0162653	0.0180056	9.67%	307.58148	310.12196	0.82%
0.83	2.4	0.013738	0.0156299	12.10%	-0.018818	-0.019796	4.94%	0.0232987	0.0252225	7.63%	306.13184	308.29271	0.70%
0.5	4	0.0260217	0.0290264	13.79%	-0.03081	-0.032172	4.23%	0.0369606	0.04333	8.40%	309.06103	312.05982	0.96%
0.25	8	0.0610346	0.0623334	12.24%	-0.062024	-0.063899	3.09%	0.1020471	0.1123447	9.17%	322.56932	325.27302	0.83%
Values for Kp equal to 2.4, and 8 above were calculated using 200 panels top and bottom and 4 cycles of 100 calculations.													
The below values were calculated using 76 panels and 3 cyc 66 calc.													
0.83	2.4	0.0126	0.0156299	20.02%	-0.01858	-0.019796	6.14%	0.0223934	0.0252225	11.22%	303.93134	308.29271	1.41%
0.5	4	0.0223	0.0290264	23.17%	-0.03048	-0.032172	5.32%	0.0377505	0.04333	12.88%	306.20814	312.05982	1.87%
0.25	8	0.0716	0.0923334	22.45%	-0.06212	-0.063899	2.94%	0.0947916	0.1123447	15.82%	319.05517	325.27302	1.91%

TABLE 2.3 1 DEGREE PITCH C_M COMPARISON

**Cm Real vs Kp for Panel and Theodorsen (pitch, 1.0 deg, .37c,
NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)**

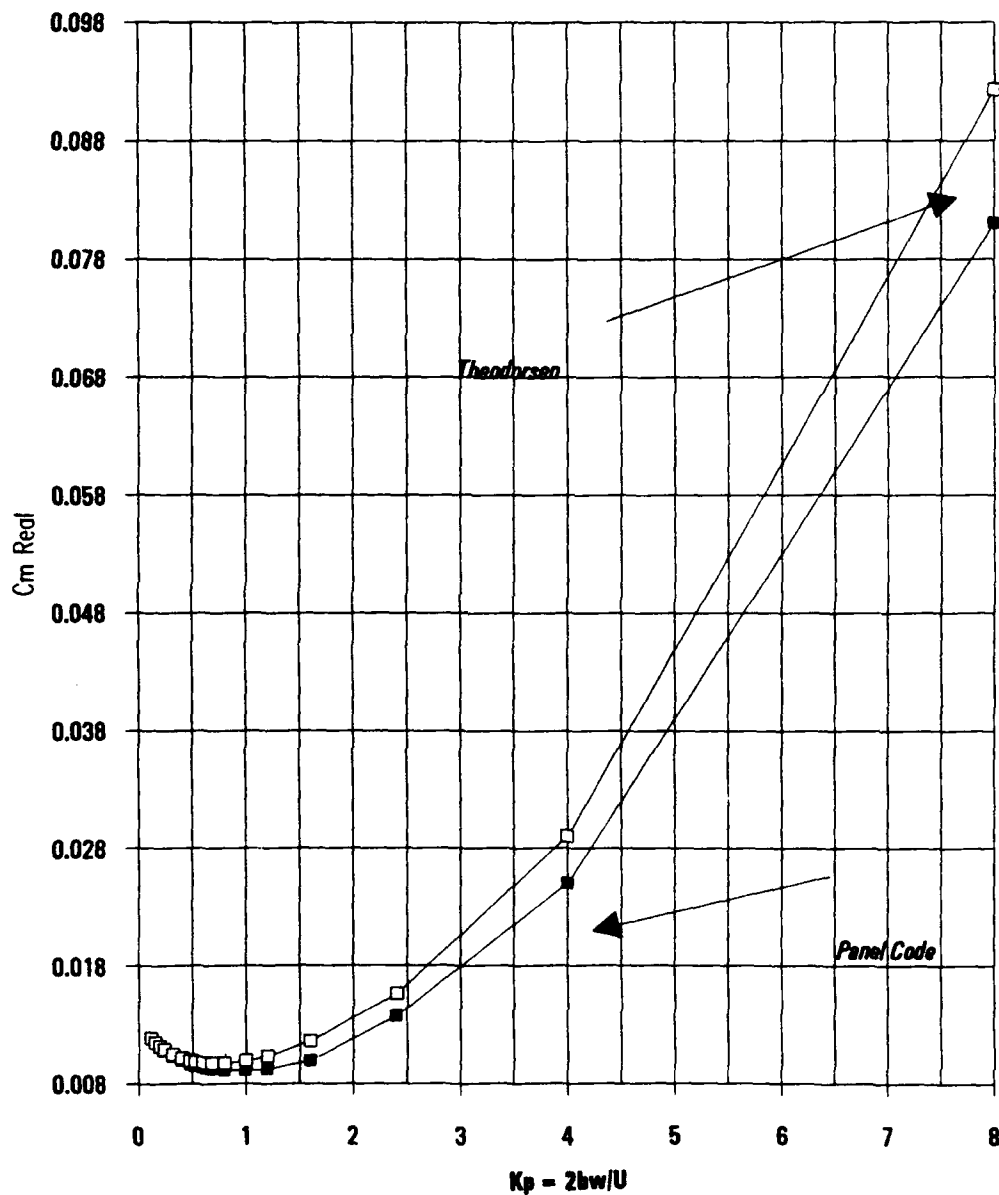


Figure 2.13 1 Degree pitch C_M Re

**Cm Real vs Kp for Panel and Theodorsen (pitch, 1.0 deg, .37c,
NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)**

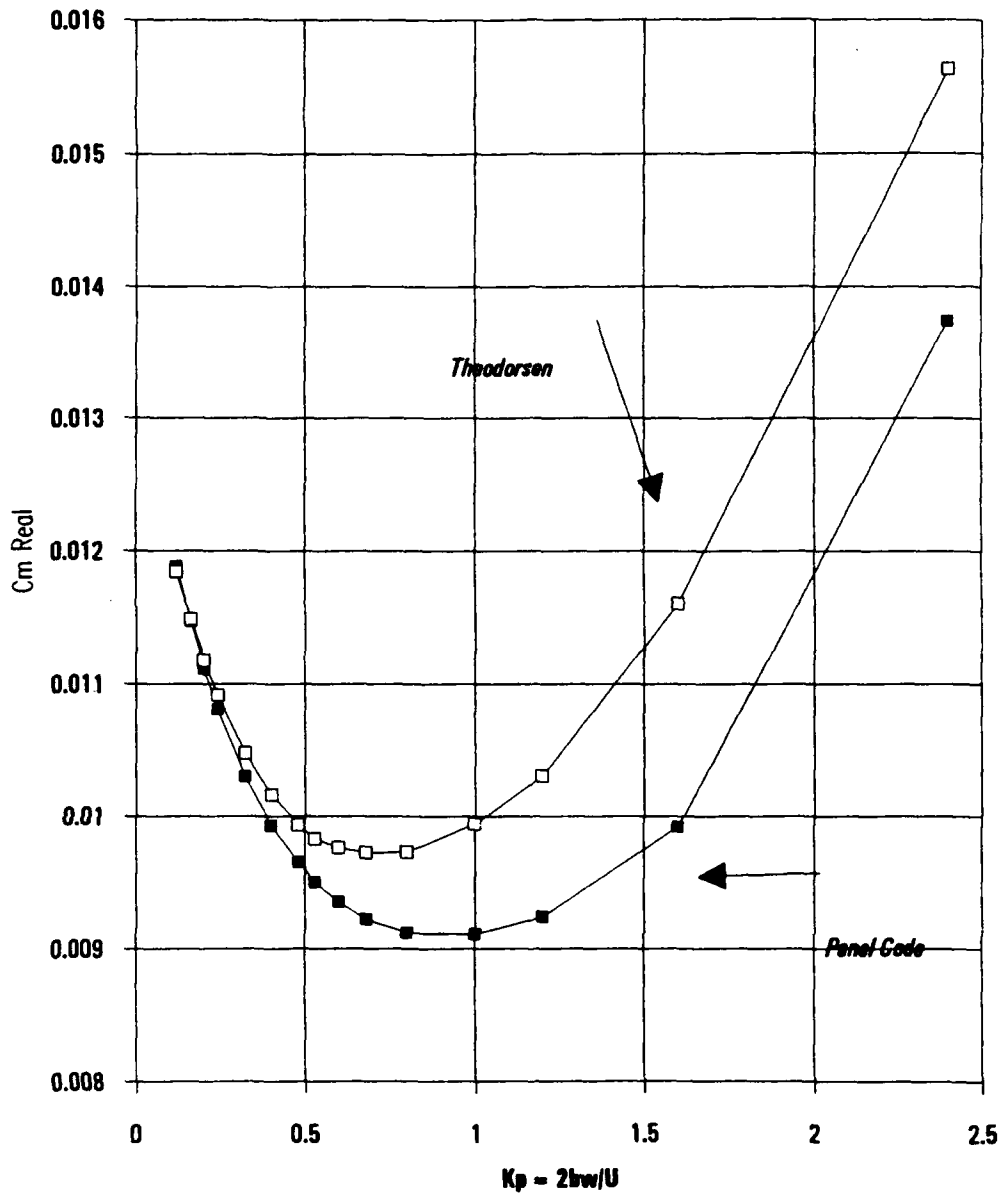


Figure 2.14 1 Degree pitch C_M Re

Cm Imag vs Kp for Panel and Theodorsen (pitch, 1.0 deg, .37c, NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)

$$K_p = 2bw/U$$

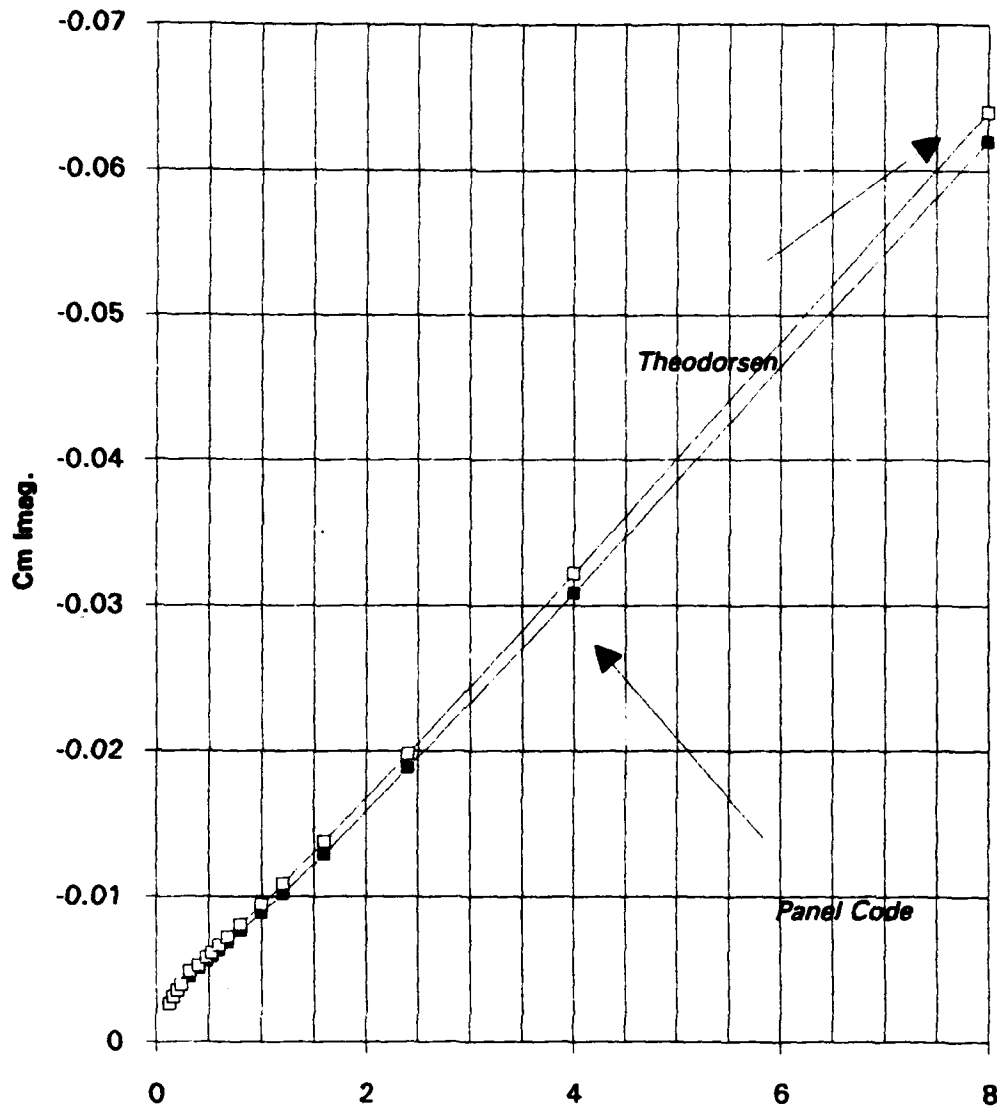


Figure 2.15 1 Degree pitch $C_m \text{ Im}$

Cm Imag vs Kp for Panel and Theodorsen (pitch, 1.0 deg, .37c, NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)

$$Kp = 2bw/U$$

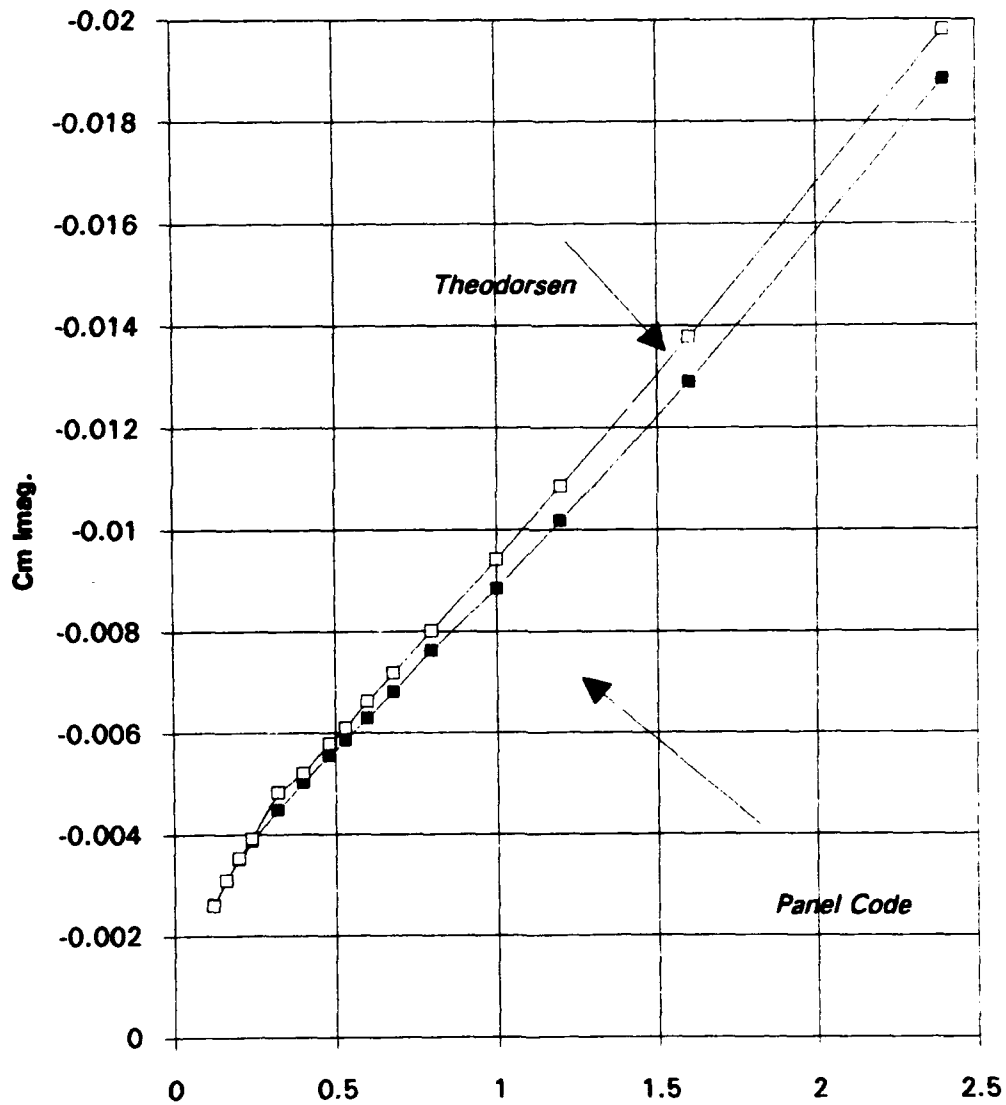


Figure 2.16 1 Degree pitch $C_M \text{ Im}$

Cm Magnitude vs Kp for Panel and Theodorsen
 (pitch, 1.0 deg, .37c, NACA0007, 75 panels top and
 bottom, 3cycles of 65 calc. per cycle)

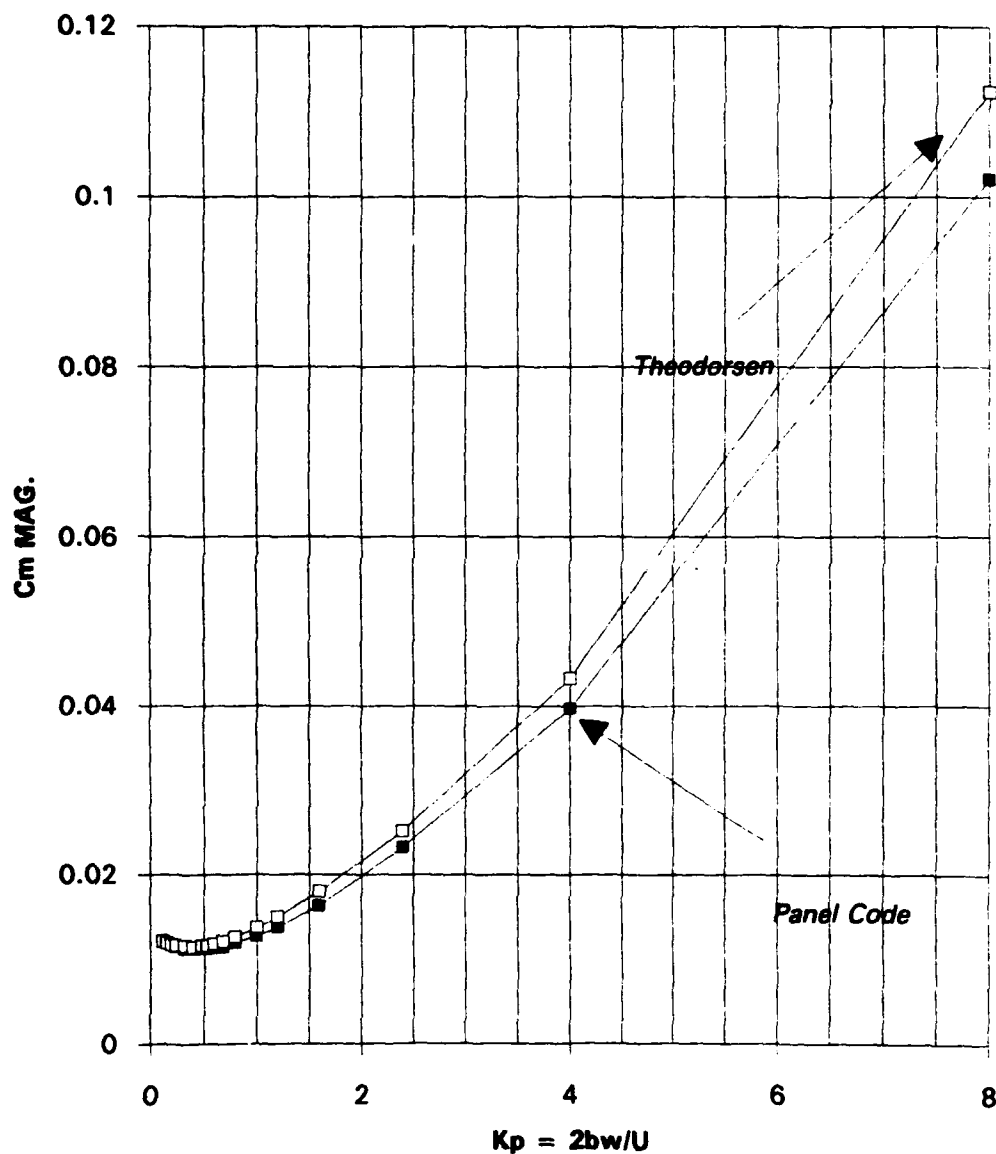


Figure 2.17 1 Degree pitch C_M Magnitude

**Cm Magnitude vs Kp for Panel and Theodorsen (pitch,
1.0 deg, .37c, NACA0007, 75 panels top and
bottom, 3cycles of 65 calc. per cycle)**

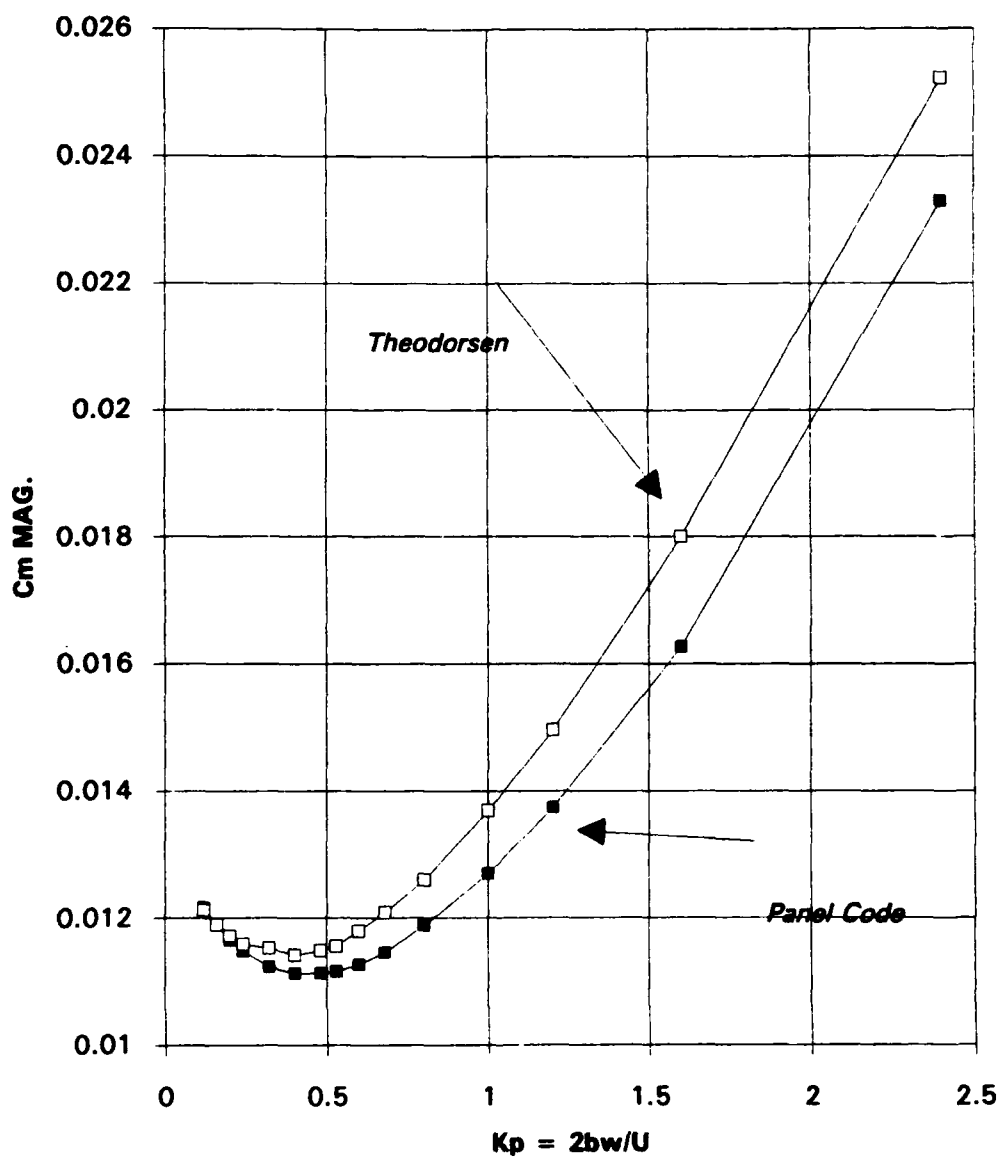


Figure 2.18 1 Degree pitch C_m Magnitude

Cm Phase vs Kp for Panel and Theodorsen (pitch, 1.0 deg, .37c, NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)

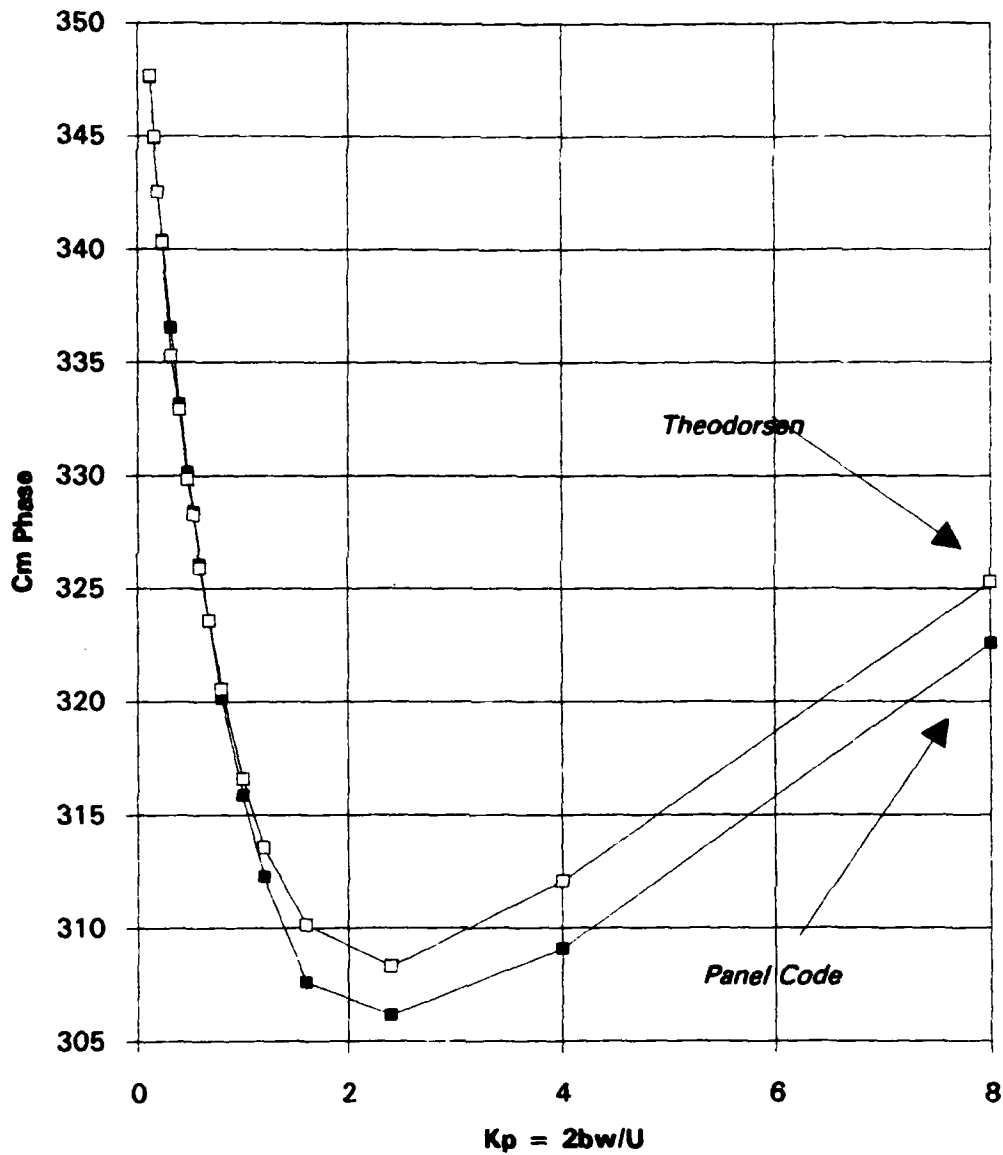


Figure 2.19 1 Degree pitch C_M Phase

Cm Phase vs Kp for Panel and Theodorsen (pitch, 1.0 deg, .37c, NACA0007, 75 panels top and bottom, 3cycles of 65 calc. per cycle)

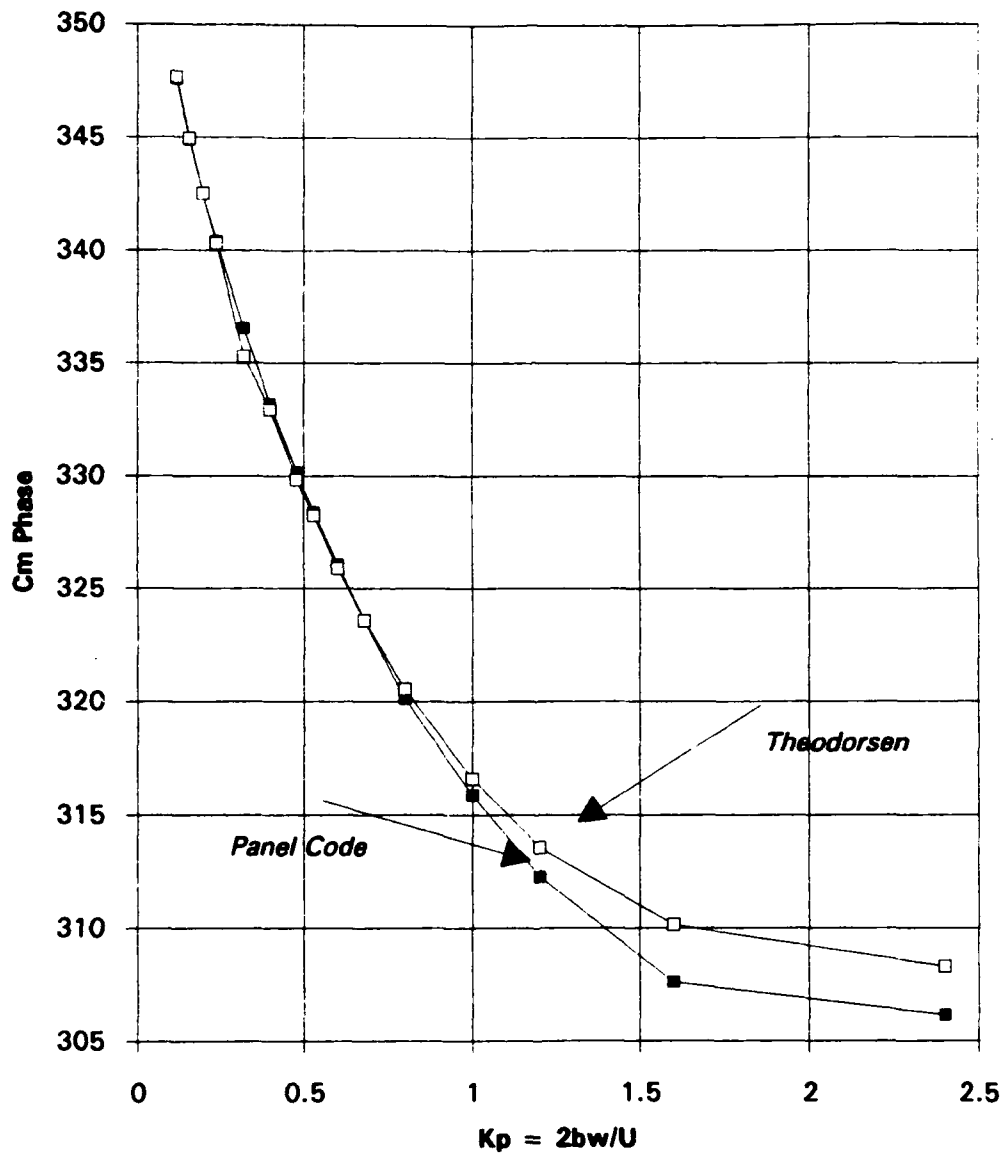


Figure 2.20 1 Degree pitch C_M Phase

Comparison of Panel CL Values with Theoderson Results													
(pitch, 6.7 deg., 37c, NACA 0007, 75 panels top and bottom, 3cyc/65calc.)													
Kpanel (equal to 2 x Theoderson Kl)													
%DIFF taken wrt Theoderson values.													
Kpanel	1/kl	Real pan.	Real theo.	% DIFF.	Imag Pan.	Imag Theo.	% DIFF.	(Mag Pan.	(Mag Theo.	% DIFF.	Phase Pa.	Phase Th.	% DIFF.
0.11888	18.87	-0.86804	-0.85883	4.46%	0.07158	0.052824	35.51%	0.892748	0.8617417	4.89%	174.08818	175.42145	0.77%
0.18	12.5	-0.86442	-0.838786	4.01%	0.07227	0.050028	44.48%	0.888337	0.8407518	4.31%	173.78224	175.52214	0.89%
0.2	10	-0.84218	-0.81888	3.58%	0.07024	0.0434	61.84%	0.84588	0.8214872	3.94%	173.75778	175.9857	1.27%
0.24	8.33	-0.82342	-0.803148	3.36%	0.06214	0.0342133	81.83%	0.828608	0.804118	3.71%	174.30778	178.75341	1.38%
0.32	6.25	-0.58084	-0.57477	2.80%	0.04384	0.0108	294.98%	0.582407	0.5748733	3.05%	175.83227	178.91357	1.72%
0.4	5	-0.58528	-0.55186	2.43%	0.02282	-0.01818	241.83%	0.585744	0.5520888	2.47%	177.87814	181.8773	2.20%
0.48	4.17	-0.54524	-0.53288	2.30%	-0.023584	-0.045026	47.82%	0.54575	0.5348588	2.04%	182.47875	184.82805	1.27%
0.53	3.75	-0.53384	-0.52034	2.58%	-0.04174	-0.08414	34.82%	0.535488	0.5242782	2.13%	184.47078	187.02715	1.37%
0.6	3.33	-0.5204	-0.51004	2.03%	-0.08788	-0.08874	24.48%	0.524808	0.5178878	1.35%	187.42843	188.98348	1.55%
0.88	2.94	-0.50848	-0.497258	1.85%	-0.0872	-0.12003	18.02%	0.515703	0.5115378	0.81%	180.88413	183.57073	1.46%
0.8	2.5	-0.48888	-0.4808	1.70%	-0.13888	-0.18532	17.15%	0.507778	0.5084283	0.13%	185.84781	186.8752	1.87%
1	2	-0.46848	-0.4575	1.96%	-0.2087	-0.2388	13.01%	0.511037	0.5165833	1.07%	204.10342	207.87124	1.72%
1.2	1.87	-0.4482	-0.43708	2.55%	-0.27804	-0.3131	11.20%	0.527437	0.5378385	1.90%	211.81332	215.81888	1.78%
1.6	1.25	-0.41788	-0.39804	4.98%	-0.41218	-0.45584	9.58%	0.588841	0.805188	3.01%	224.80517	228.8725	1.88%
2.4	0.83	-0.38118	-0.31314	15.33%	-0.87442	-0.73748	8.55%	0.785035	0.8011881	4.51%	241.83042	248.98287	2.89%
4	0.5	-0.04413	-0.0583	25.58%	-1.25887	-1.2852	0.86%	1.257844	1.2885888	0.71%	287.88828	287.31851	0.25%
8	0.25	0.888234	1.080012	8.80%	-2.8321	-2.5488	11.08%	3.002211	2.77283	8.27%	288.38008	283.14781	1.26%
Values above for Kp of 4 and 8 were calculated using 200 panels and 4 cycles of 100 calculations per cycle.													
Below calculations were done with 75 panels and 3cyc of 85 calcs													
4	0.5	-0.2078	-0.0583	250.42%	-1.1974	-1.2852	5.38%	1.215287	1.2885888	4.05%	280.15478	287.31851	2.89%
8	0.25	0.58584	1.080012	48.11%	-2.8048	-2.5488	18.01%	2.881888	2.77283	3.18%	281.40143	283.14781	4.01%

TABLE 2.4 6.7 DEGREE PITCH C_L COMPARISON

**Cl Real vs Kp Panel Code (Pitch, 6.7 deg, .37c, NACA 0007, 50 panels
top and bottom)**

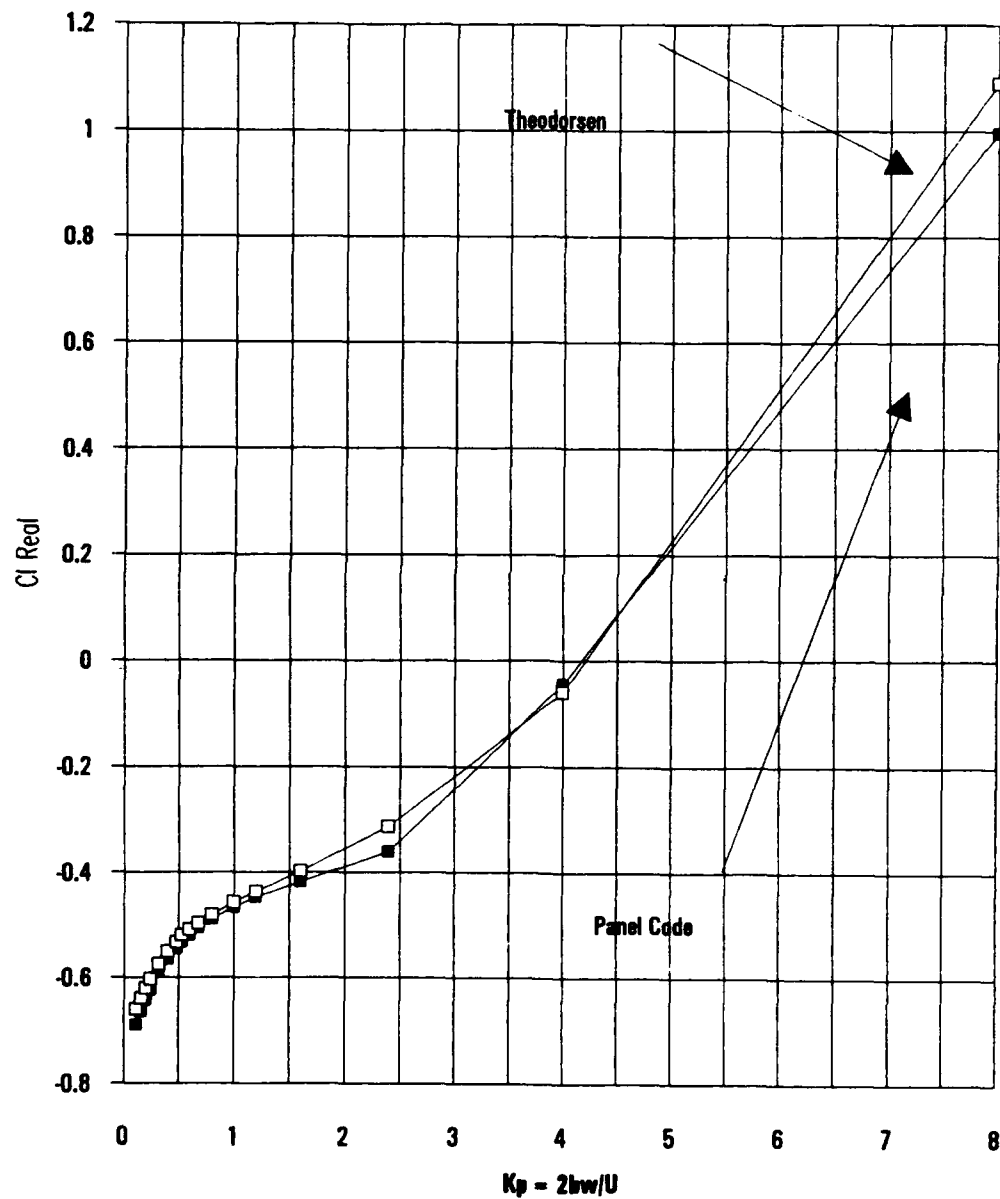


Figure 2.21 6.7 degrees pitch C_l Re

**Cl Real vs Kp Panel Code (Pitch, 6.7 deg. .37, NACA 0007, 75 panels
top and bottom)**

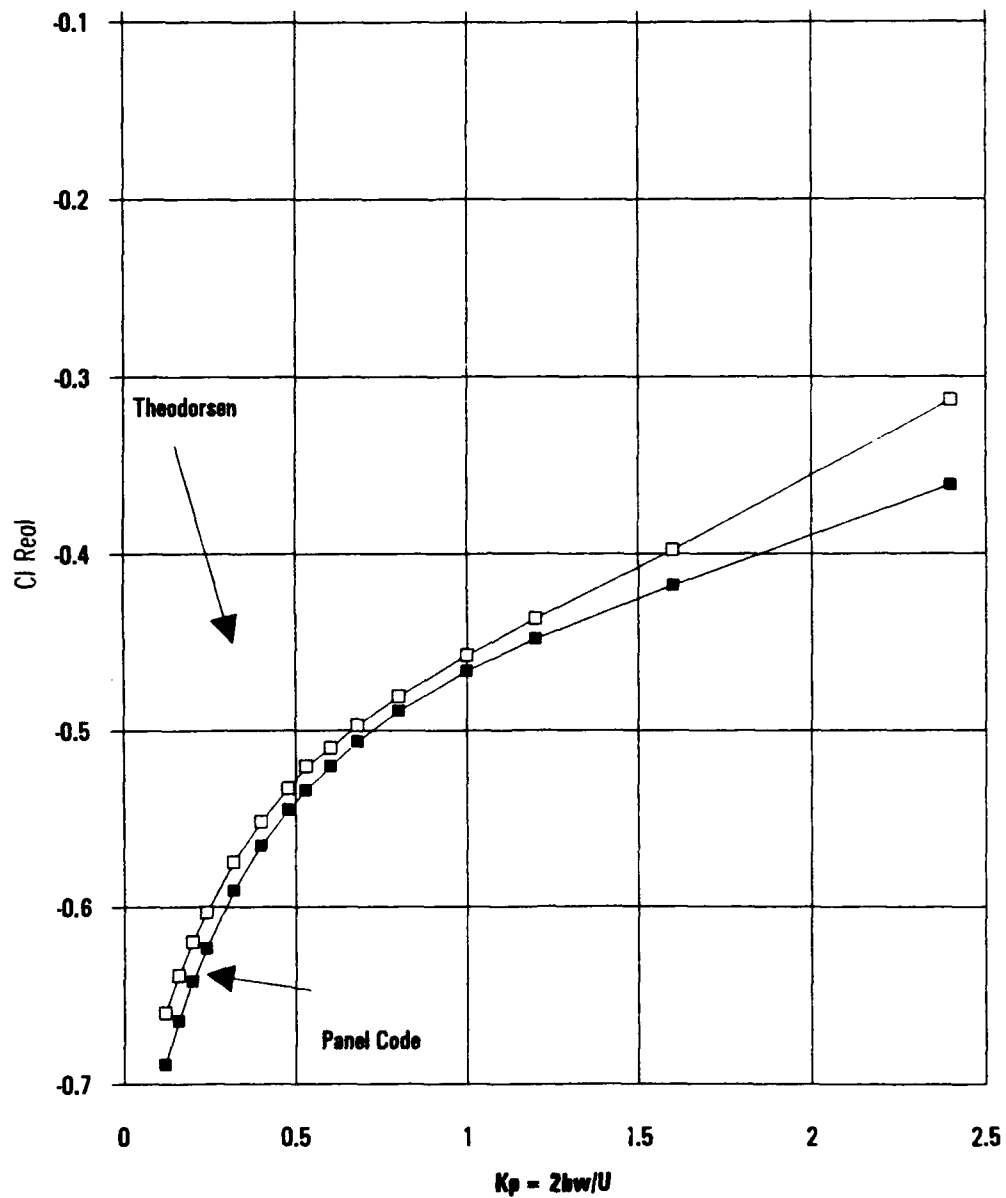


Figure 2.22 6.7 degrees pitch C_L Re

CI Imag. vs Kp Panel Code (pitch, 6.7 deg, .37c, NACA 0007, 75 panel
top and bottom)

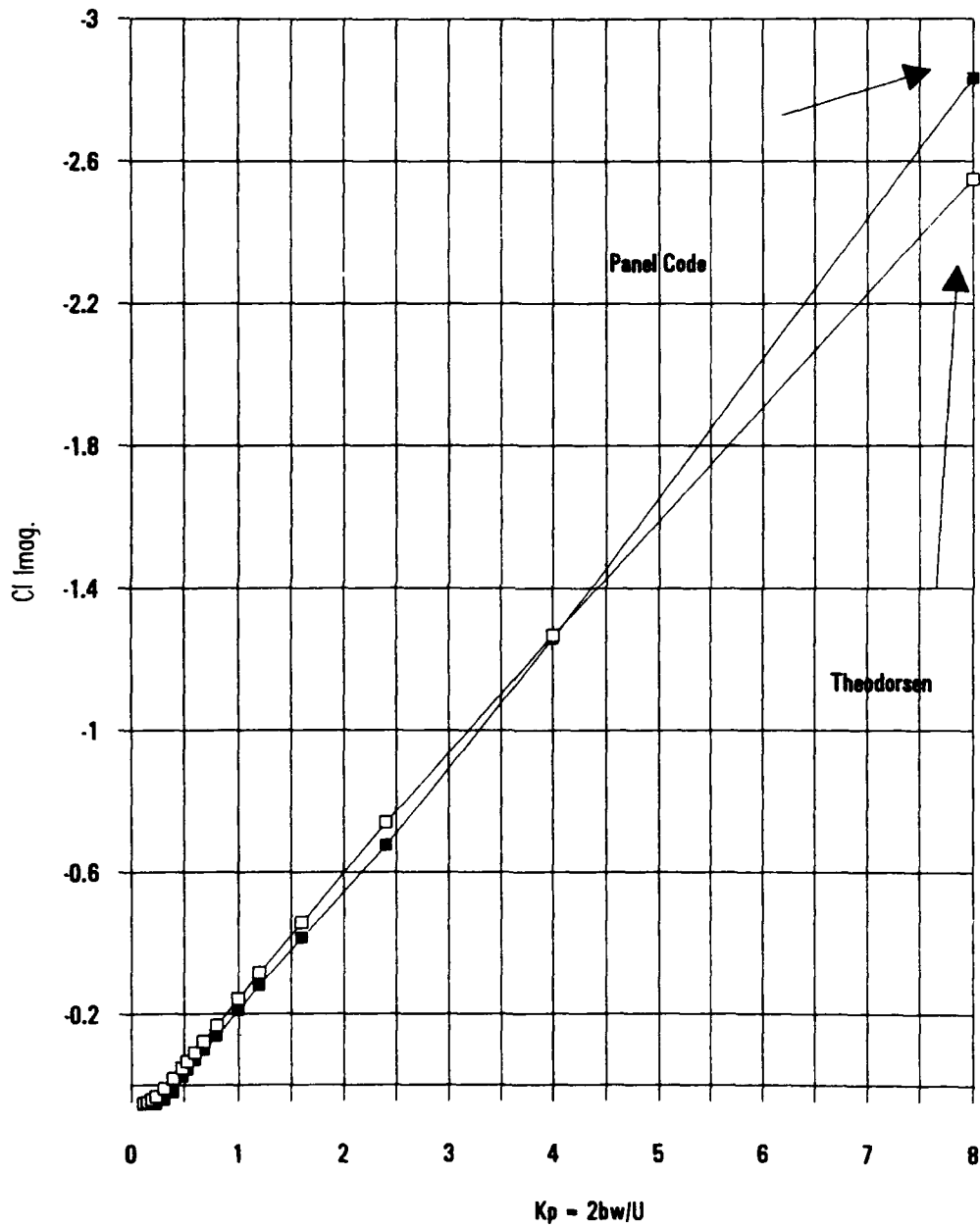


Figure 2.23 6.7 degrees pitch $C_L \text{ Im}$

**Cl Imag. vs Kp Panel Code (pitch, 6.7 deg, .37c, NACA 0007, 75 panel
top and bottom)**

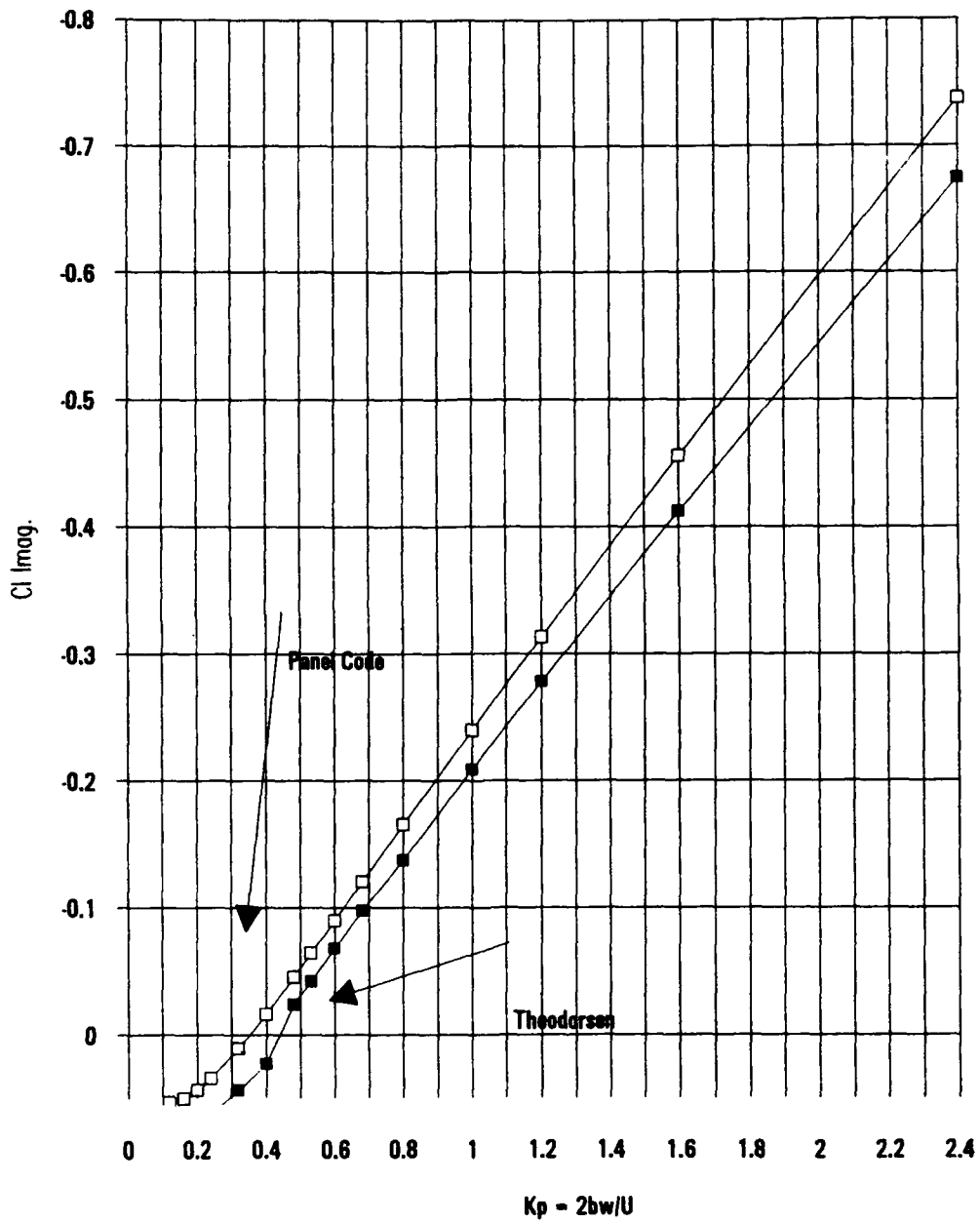


Figure 2.24 6.7 degrees pitch $C_L\ Im$

**Cl Magnitude vs Kp Panel Code (pitch, 6.7 deg, .37c, NACA 0007, 50
panels top and bottom)**

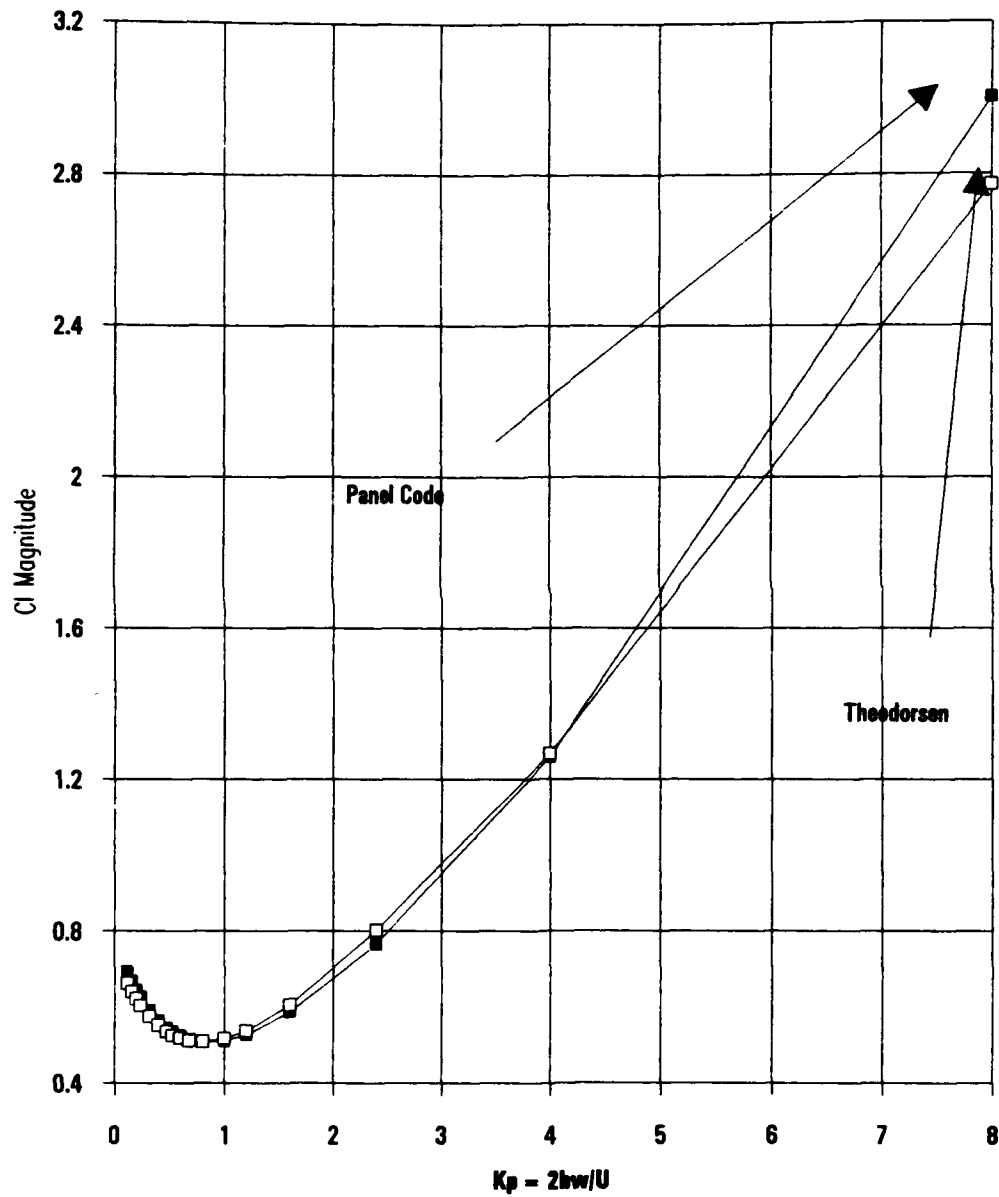


Figure 2.25 6.7 degrees pitch C_l Magnitude

Mag. of CL for Panel and Theodorsen (Pitch, 6.7deg, .37 c, NACA
0007, 75 panels top and bottom, 3cyc85calc.)

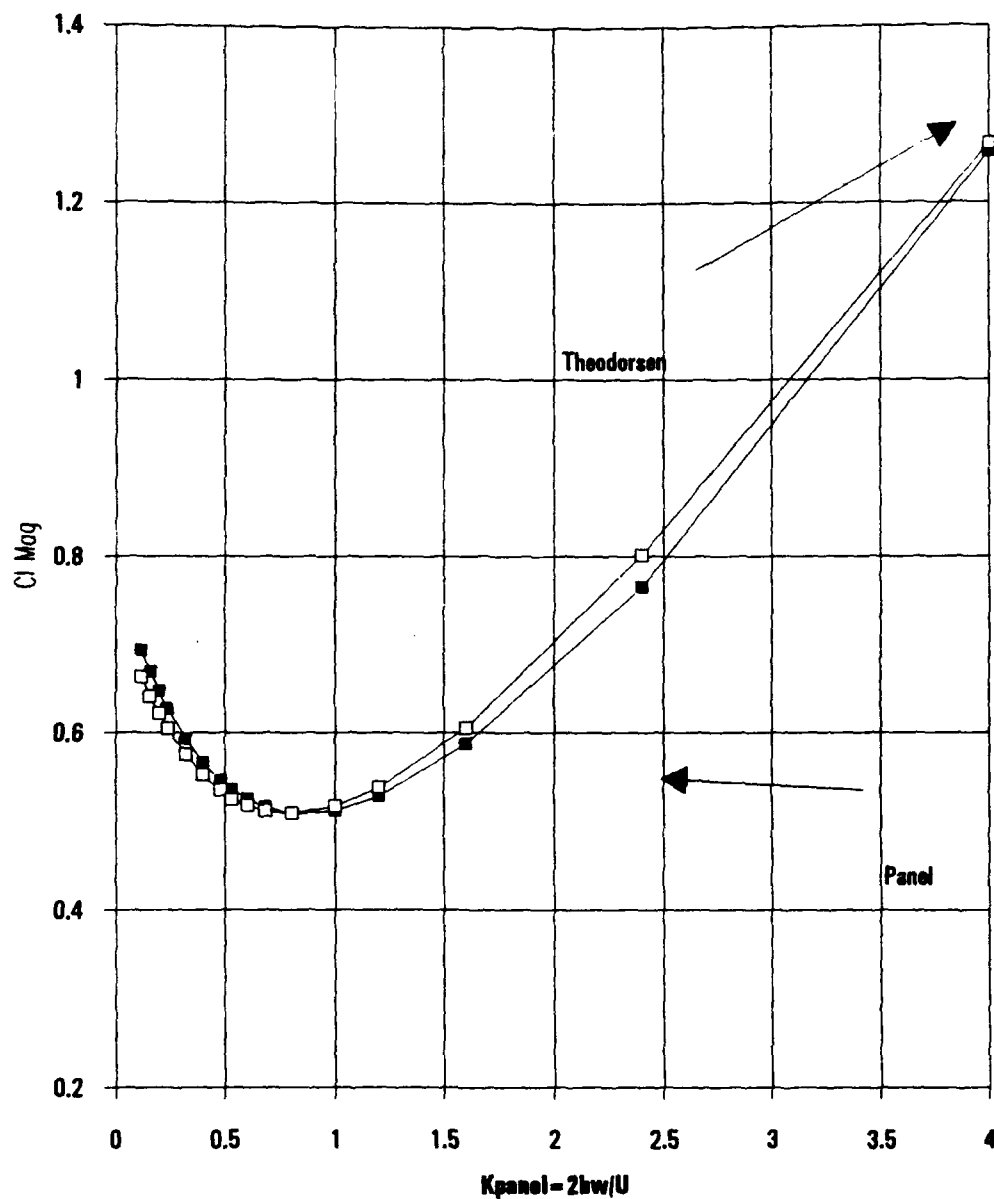


Figure 2.26 6.7 degrees pitch C_L Magnitude

Cl Phase vs Kp (pitch, 6.7 deg, .37c, NACA 0007, 75 panel top and bottom)

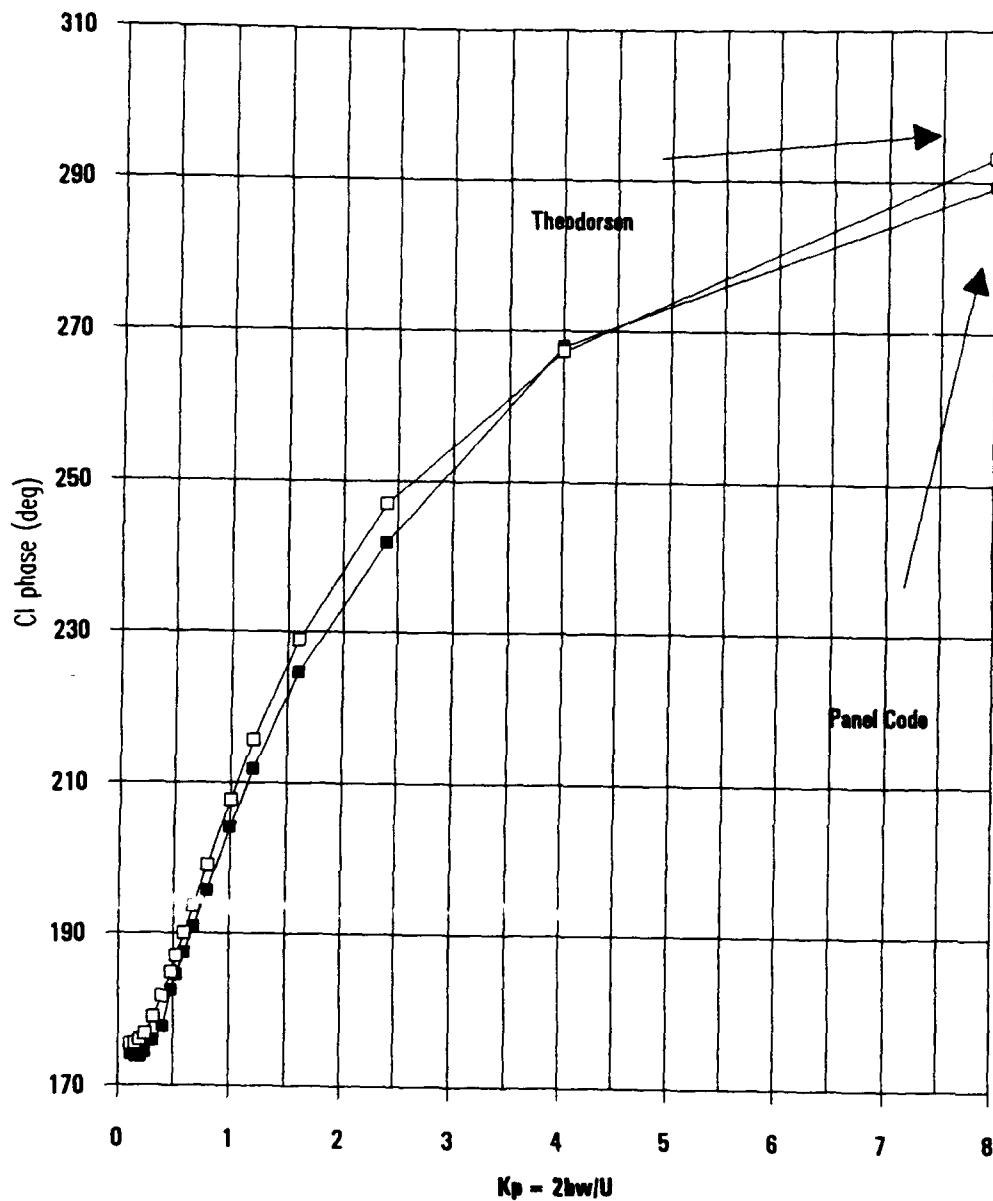


Figure 2.27 6.7 degrees pitch C_l phase

Cl Phase vs Kp (pitch, 6.7 deg, .37c, NACA 0007, 50 panel top and bottom)

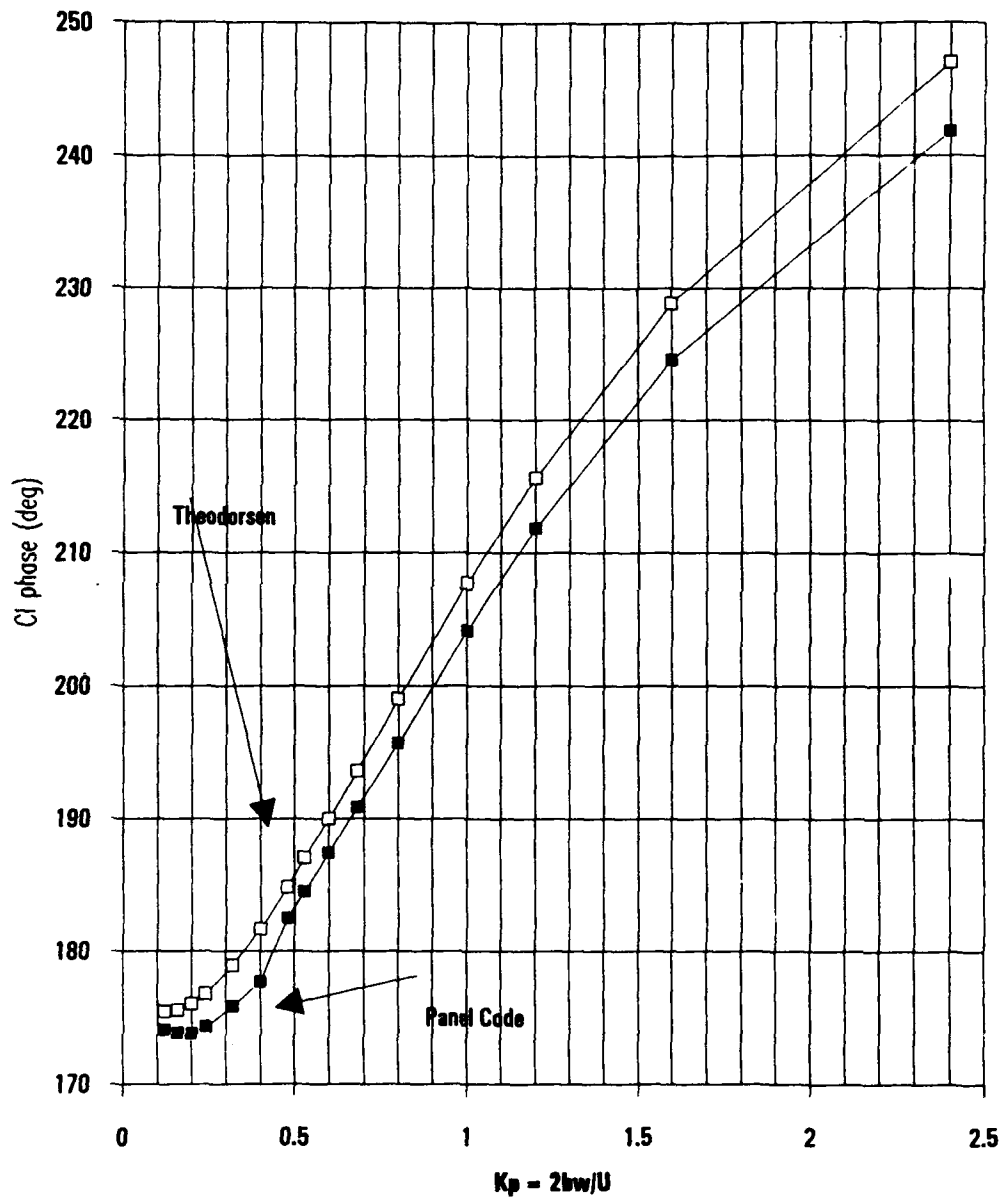


Figure 2.28 6.7 degrees pitch C_L Phase

Comparison of Panel Moment Aerodynamic Values (CM) with Theodorean Results													
(pitch, 6.7 deg., .37c, NACA 0007, 50 panels top and bottom, 30cyc/6calc.)													
1/Kt	Kpanel (equal to 2 x Theodorean Kt)		Mh = .5		%		%		%		%		
	Rp	Rt	Imag Pen.	Imag Th.	% DIFF	Mag Pen.	Mag Th.	% DIFF	Phase Ph.	Phase Th.	% DIFF		
16.67	0.11988	0.079057	0.079322	0.079322	0.33%	-0.018262	-0.017304	5.48%	0.081136	0.081188	0.06%	347	347.6938 0.20%
12.5	0.16	0.078019	0.078953	0.078953	1.21%	-0.021798	-0.020988	5.32%	0.078083	0.078988	0.76%	344	344.9450 0.27%
10	0.2	0.071865	0.074904	0.074904	4.02%	-0.023347	-0.023676	0.87%	0.078553	0.078489	3.74%	341.9999	342.5187 0.15%
8.33	0.24	0.072101	0.073109	0.073109	1.39%	-0.024828	-0.026148	5.05%	0.078268	0.077644	1.79%	341.0004	340.3203 0.20%
6.25	0.32	0.068532	0.07017	0.07017	2.33%	-0.029115	-0.030988	5.16%	0.07446	0.076591	2.78%	336.8621	336.3714 0.16%
5	0.4	0.065941	0.068094	0.068094	3.19%	-0.032575	-0.034788	6.39%	0.073649	0.07647	3.82%	333.7106	332.932 0.23%
4.17	0.48	0.064013	0.066548	0.066548	3.81%	-0.035849	-0.038981	7.32%	0.073397	0.076872	4.86%	330.7498	329.8319 0.26%
3.76	0.53	0.063065	0.06584	0.06584	4.23%	-0.037849	-0.041223	7.95%	0.073592	0.07768	5.28%	328.9608	327.9488 0.31%
3.33	0.6	0.062071	0.065418	0.065418	5.11%	-0.040477	-0.044321	8.67%	0.074103	0.078016	6.22%	326.8914	325.8917 0.31%
2.94	0.68	0.061269	0.065135	0.065135	5.95%	-0.043608	-0.04806	8.24%	0.075195	0.08094	7.10%	324.5541	323.594 0.30%
2.5	0.8	0.060328	0.065184	0.065184	6.99%	-0.048282	-0.053836	10.02%	0.077492	0.084414	8.20%	321.4788	320.5512 0.29%
2	1	0.060704	0.0666	0.0666	8.85%	-0.064202	-0.072839	11.62%	0.08818	0.100209	11.01%	313.8523	313.5415 0.13%
1.87	1.2	0.061898	0.069032	0.069032	10.34%	-0.064202	-0.072839	11.62%	0.08818	0.100209	11.01%	313.8523	313.5415 0.13%
1.25	1.6	0.06836	0.07741	0.07741	13.90%	-0.06115	-0.062249	12.03%	0.105193	0.120838	12.80%	309.5187	310.1219 0.20%
0.83	2.4	0.064477	0.10472	0.10472	19.33%	-0.117642	-0.132833	11.38%	0.14475	0.168981	14.34%	305.7047	308.2927 0.84%
0.5	4	0.163099	0.19447	0.19447	16.13%	-0.21796	-0.215551	1.12%	0.272228	0.290311	6.23%	306.8074	312.0588 1.68%
0.25	8	0.534359	0.618934	0.618934	13.82%	-0.52513	-0.428778	22.47%	0.7492	0.752089	0.46%	315.4981	325.2741 3.01%
Values for Kp equal to 4 and 8 above were calculated using 200 panels top and bottom and 4 cycles of 100 calculations.													
The below values were calculated using 75 panels and 3 cyc of 66 calc.													
0.5	4	0.144459	0.19447	0.19447	25.72%	-0.200537	-0.215551	6.97%	0.247151	0.290311	14.87%	305.7676	312.0588 2.02%
0.25	8	0.448236	0.618934	0.618934	27.54%	-0.495685	-0.428778	15.59%	0.698221	0.752089	11.22%	312.128	325.2741 4.04%

TABLE 2.5 6.7 DEGREES PITCH C_M COMPARISON

**Cm Real vs Kp Panel Code (pitch, 6.7deg, .37c, NACA 0007, 50
panels top and bottom)**

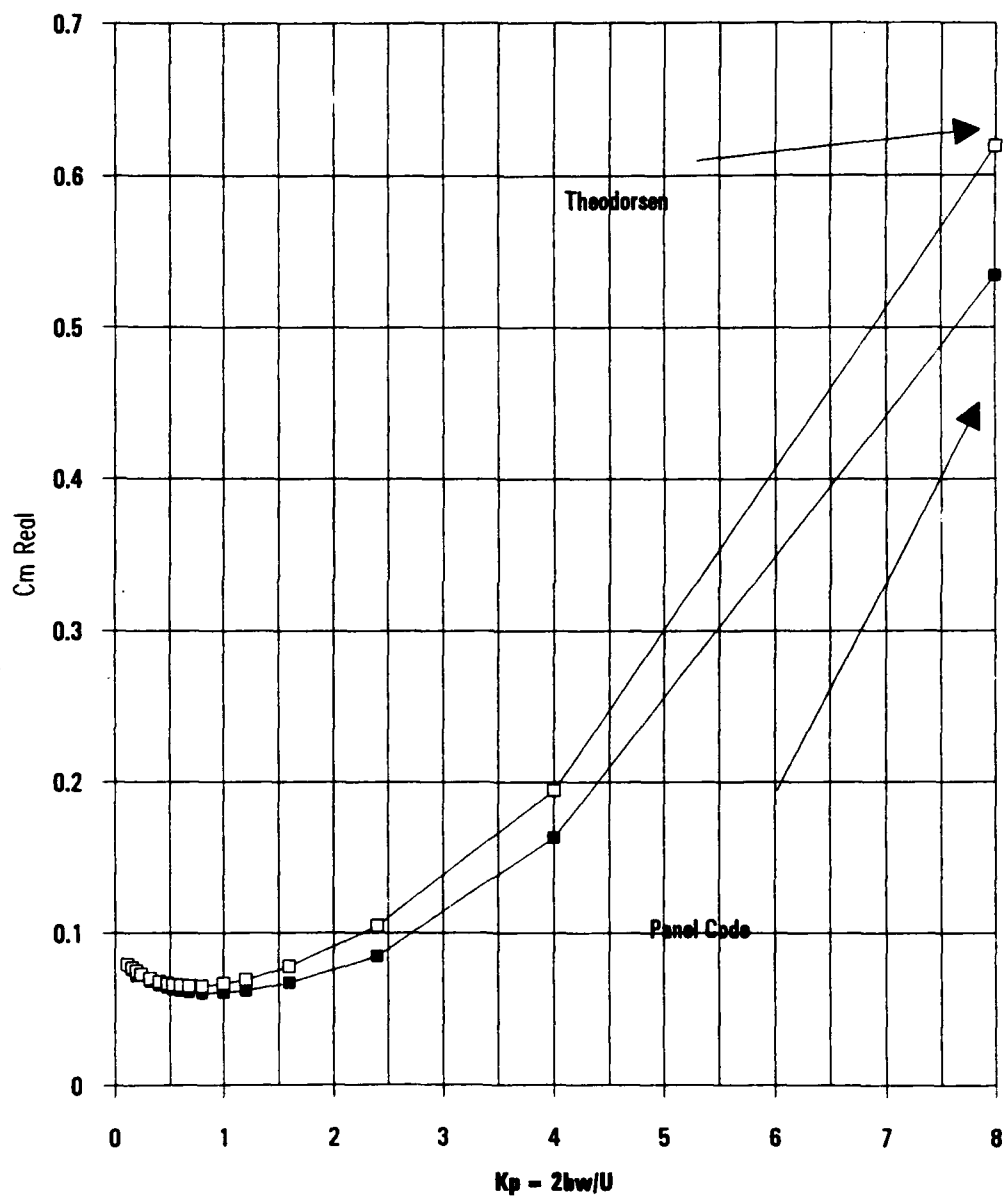


Figure 2.29 6.7 Degrees pitch $C_M \text{ Re}$

**Cm Real vs Kp Panel Code (pitch, 6.7deg, .37c, NACA 0007, 50
panels top and bottom)**

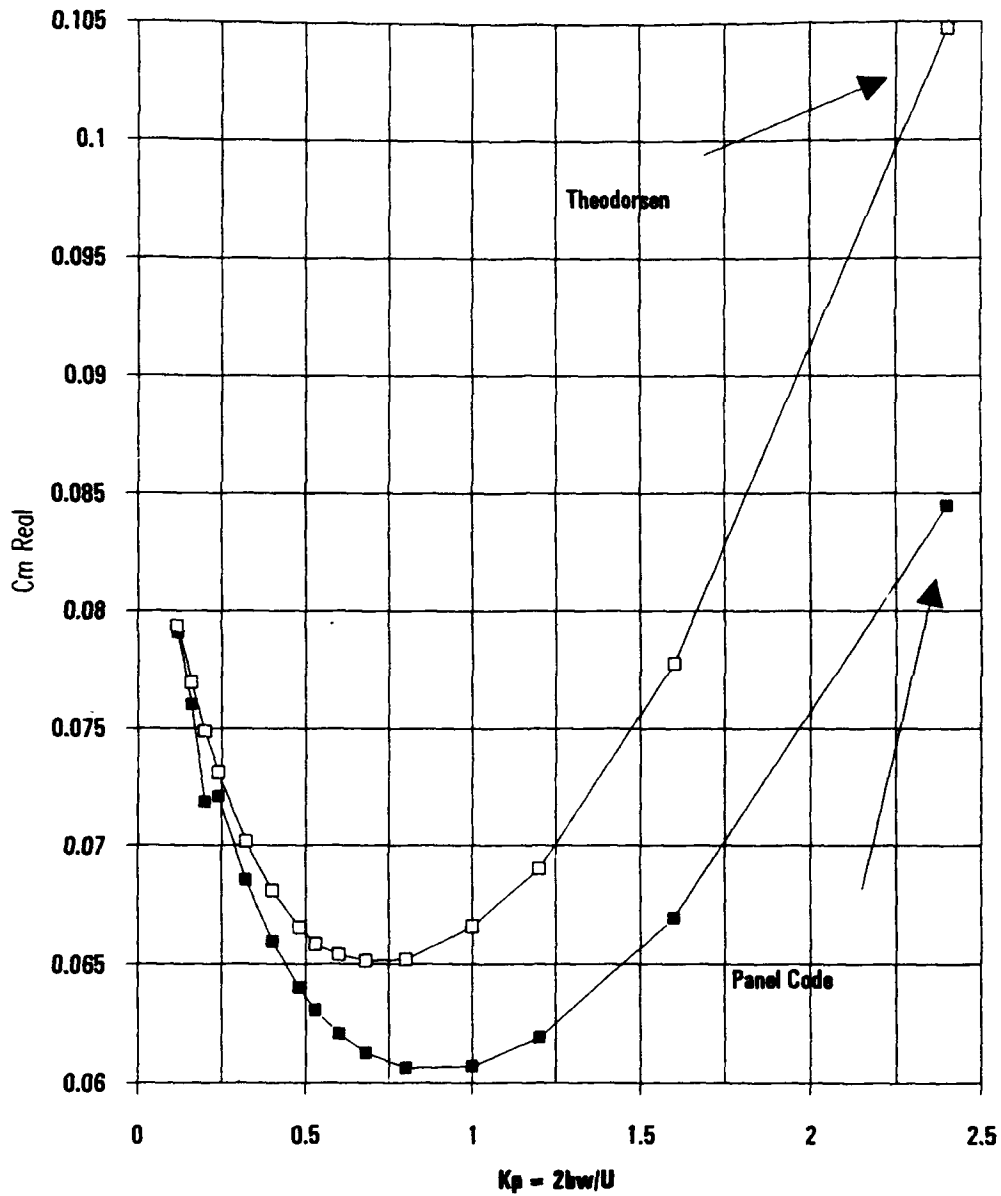


Figure 2.30 6.7 Degrees pitch C_M Re

**Cm Imaginary vs Kp Panel Code (pitch, 6.7deg, .37c,
NACA 0007, 50 panels top and bottom)**

$$Kp = 2bw/U$$

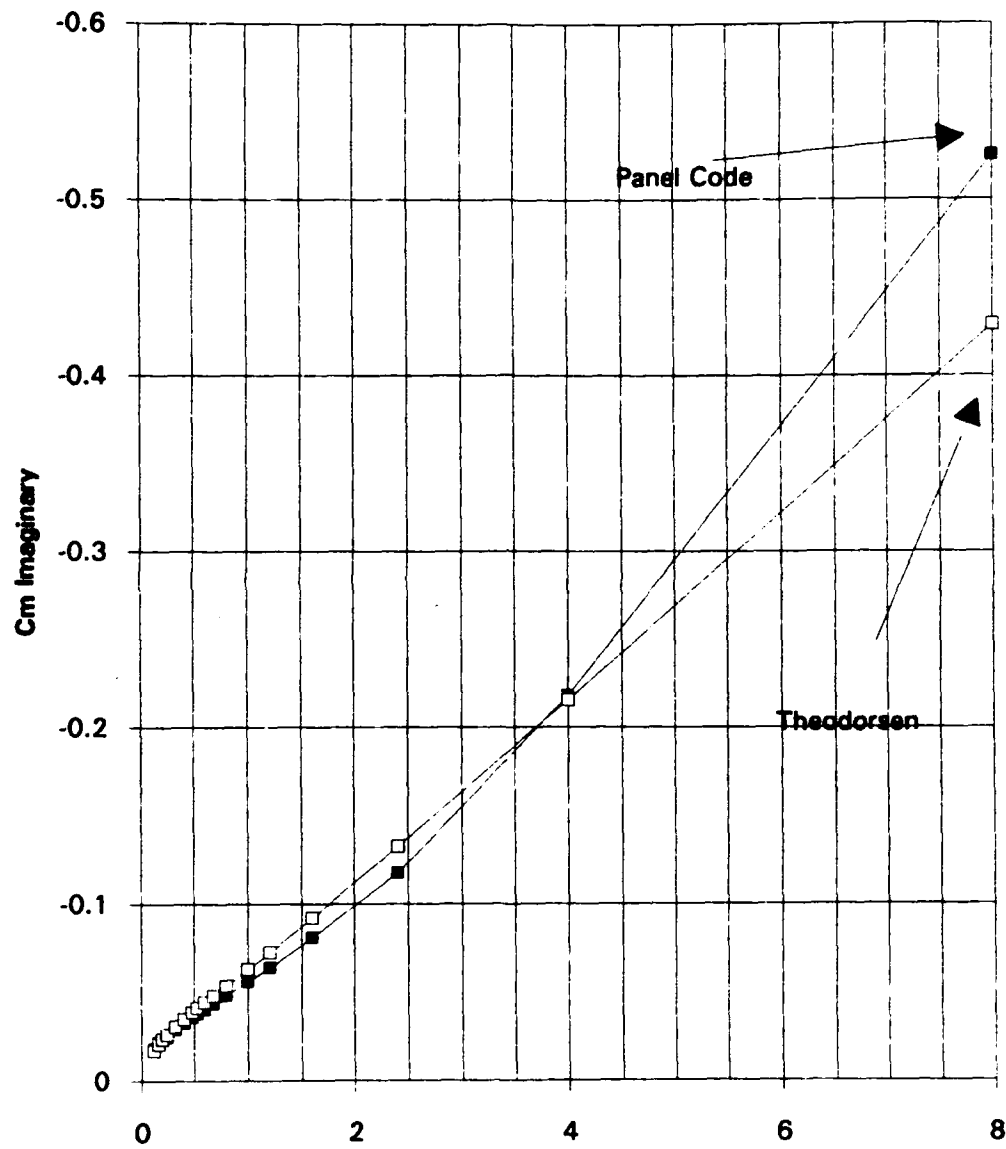


Figure 2.31 6.7 Degrees pitch C_m Im

**Cm Imaginary vs Kp Panel Code (pitch, 6.7deg,.37c,
NACA 0007, 50 panels top and bottom)**

$$Kp = 2bw/U$$

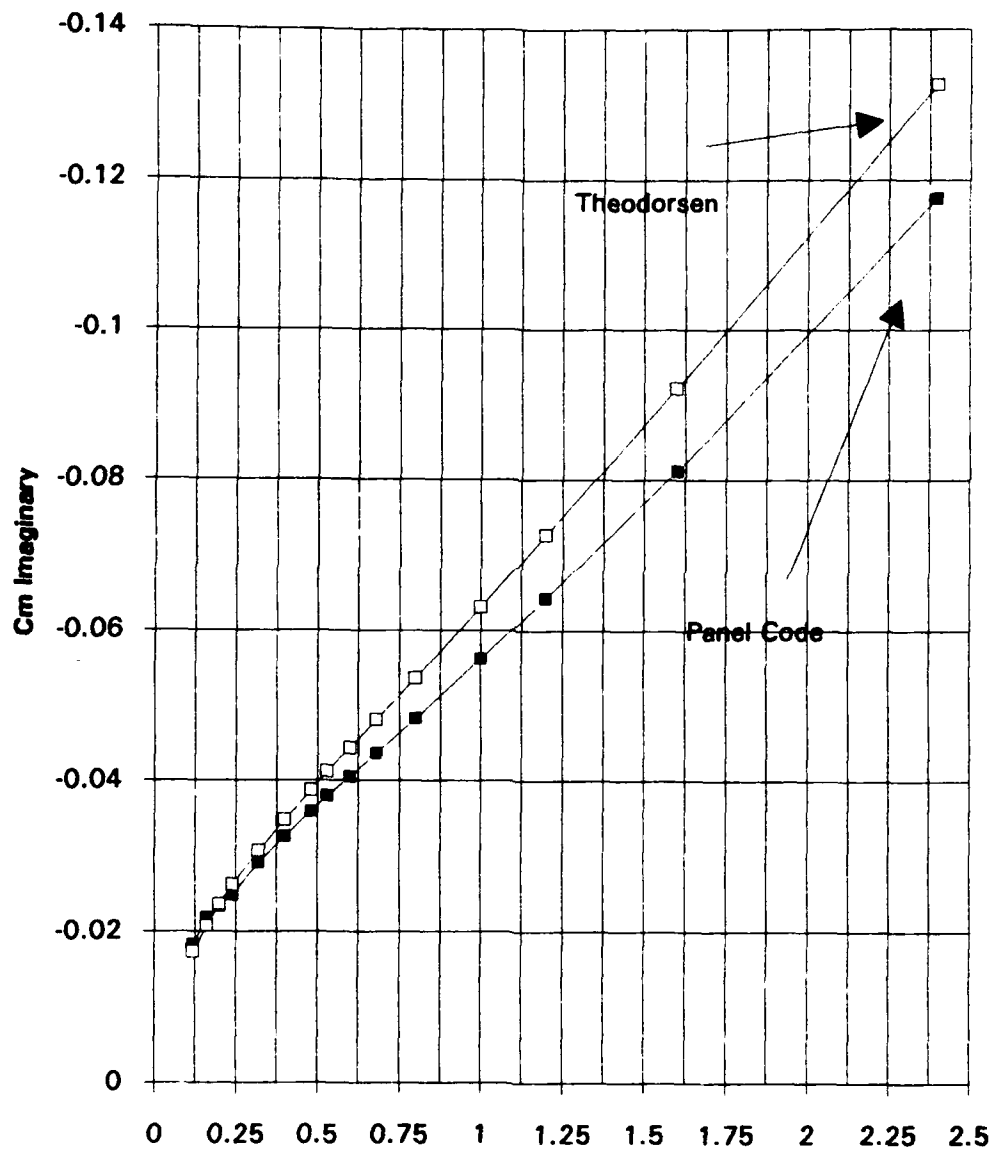


Figure 2.32 6.7 Degrees pitch C_m Im

**Cm Magnitude vs Kp Panel Code (pitch, 6.7deg, .37c,
NACA 0007, 50 panels top and bottom)**

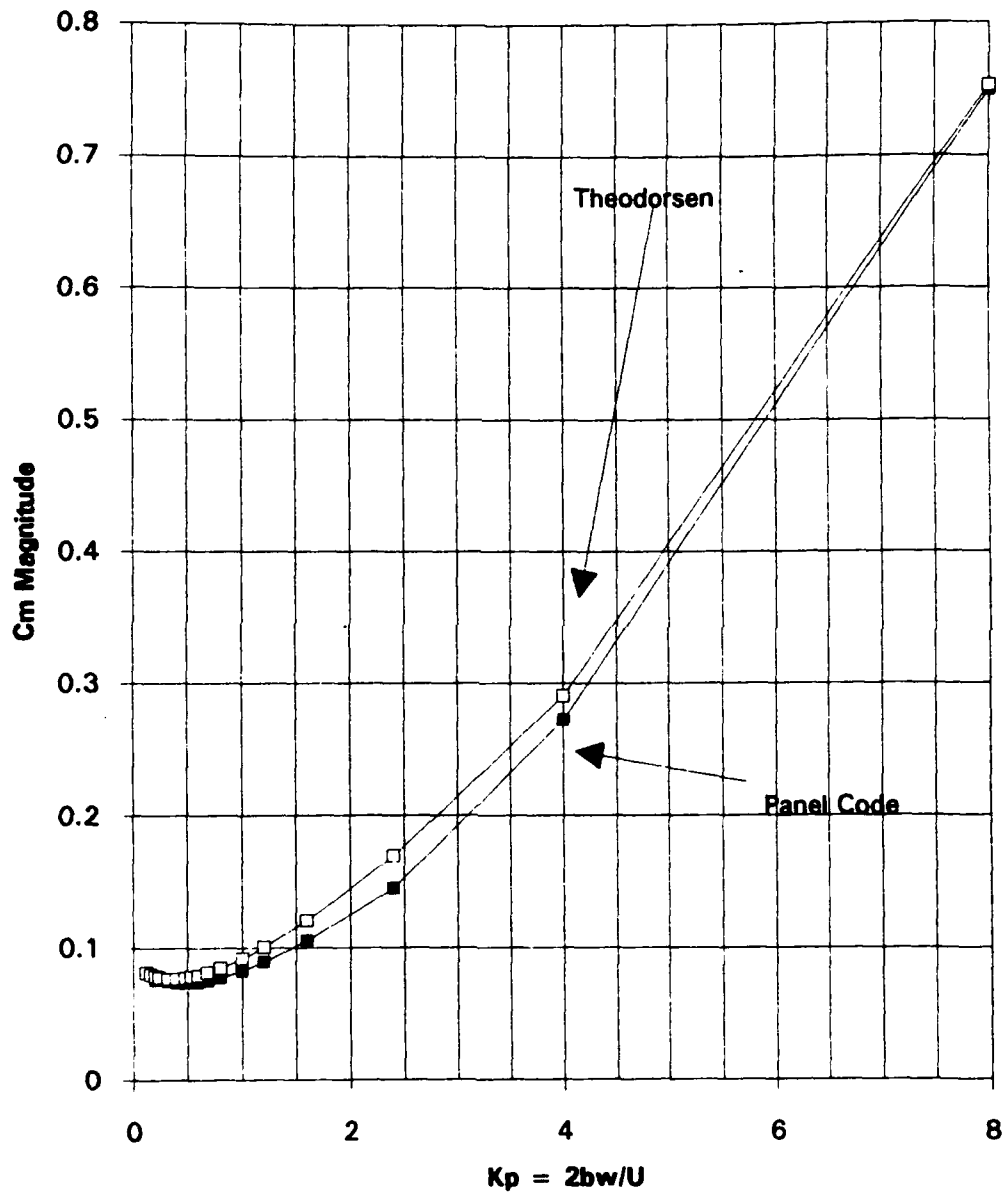


Figure 2.33 6.7 Degrees pitch C_m magnitude

**Cm Magnitude vs Kp Panel Code (pitch, 6.7deg, .37c,
NACA 0007, 50 panels top and bottom)**

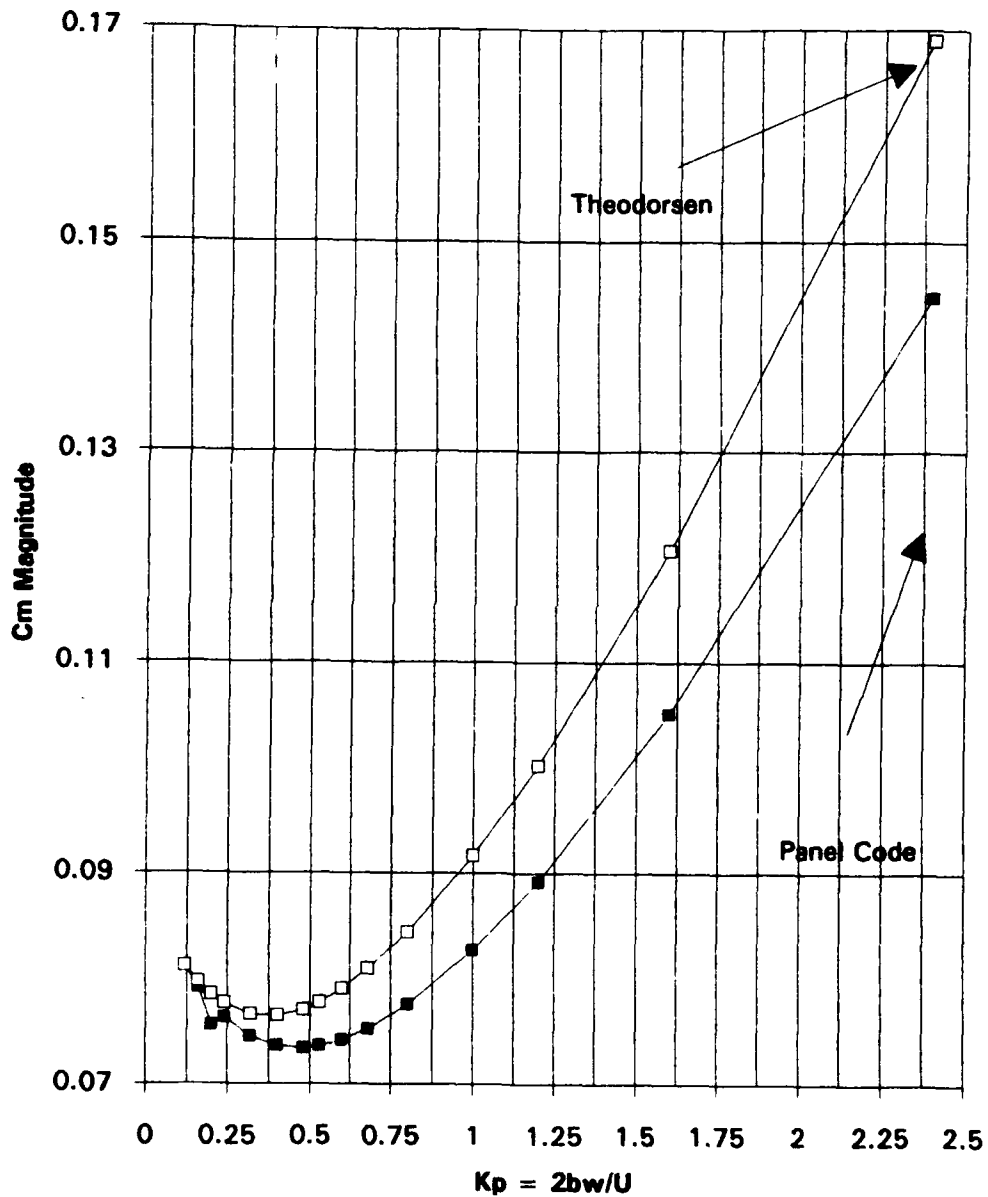


Figure 2.34 6.7 Degrees pitch C_m magnitude

**Cm Phase vs Kp Panel Code (pitch, 6.7deg, .37c,
NACA 0007, 50 panels top and bottom)**

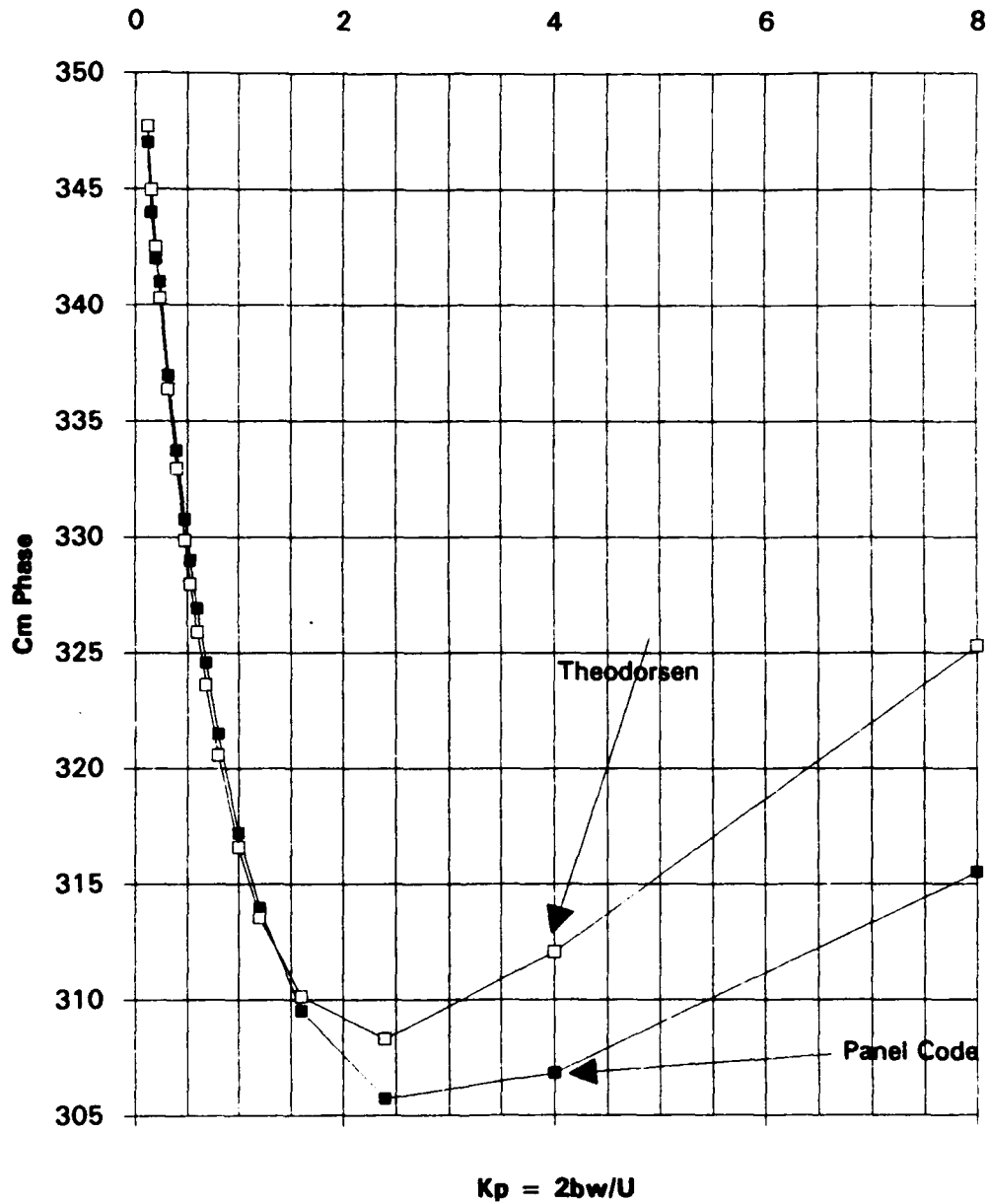


Figure 2.35 6.7 Degrees pitch C_M phase

**Cm Phase vs Kp Panel Code (pitch, 6.7deg, .37c,
NACA 0007, 50 panels top and bottom)**

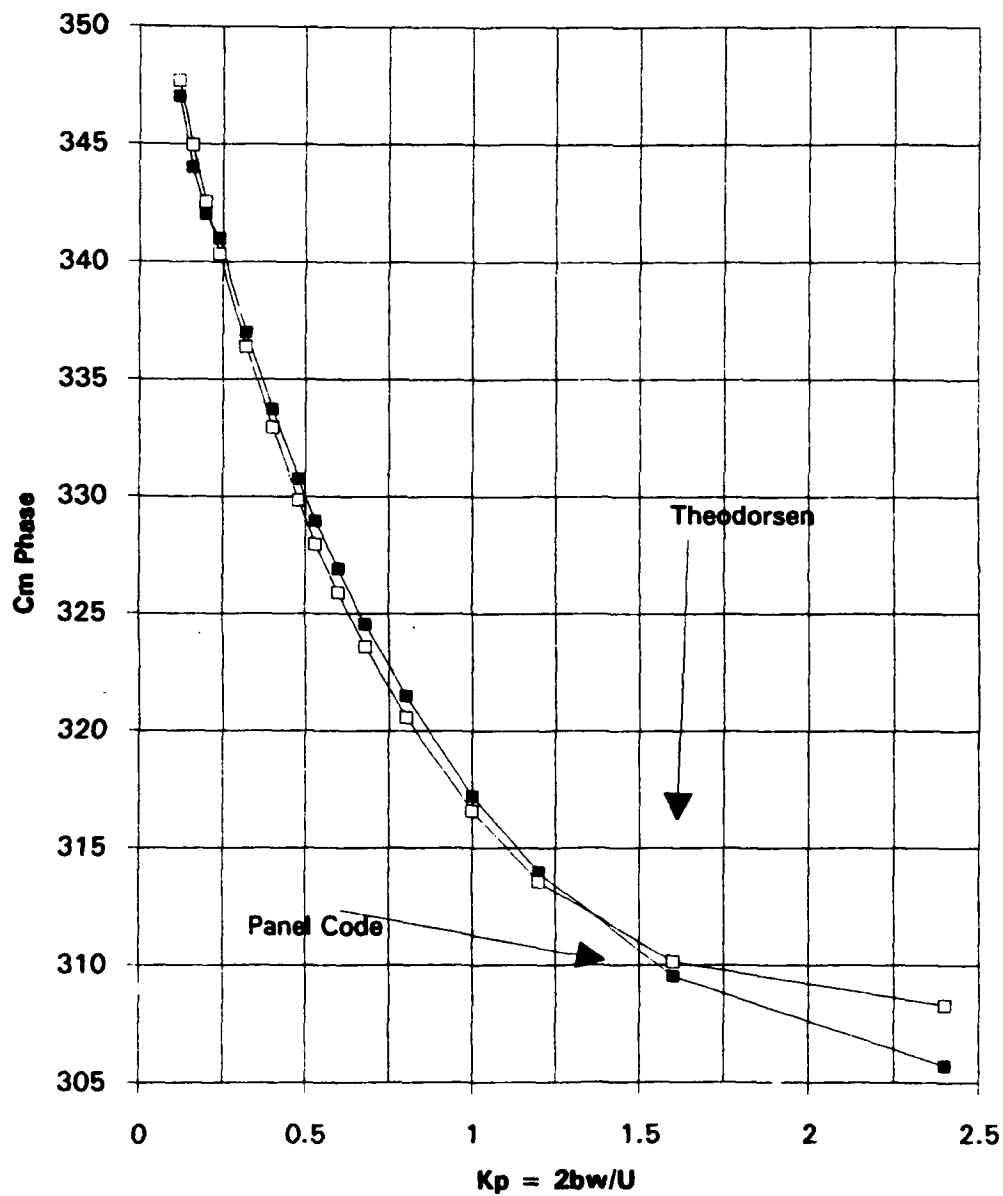


Figure 2.36 6.7 Degrees pitch C_M phase

Real Part of C_l for Panel and Theodorsen (plunge,
 $.0833 h/2b$, $.37c$, NACA0007,75 panels top and
bottom, 3cycles of 65 calculations)

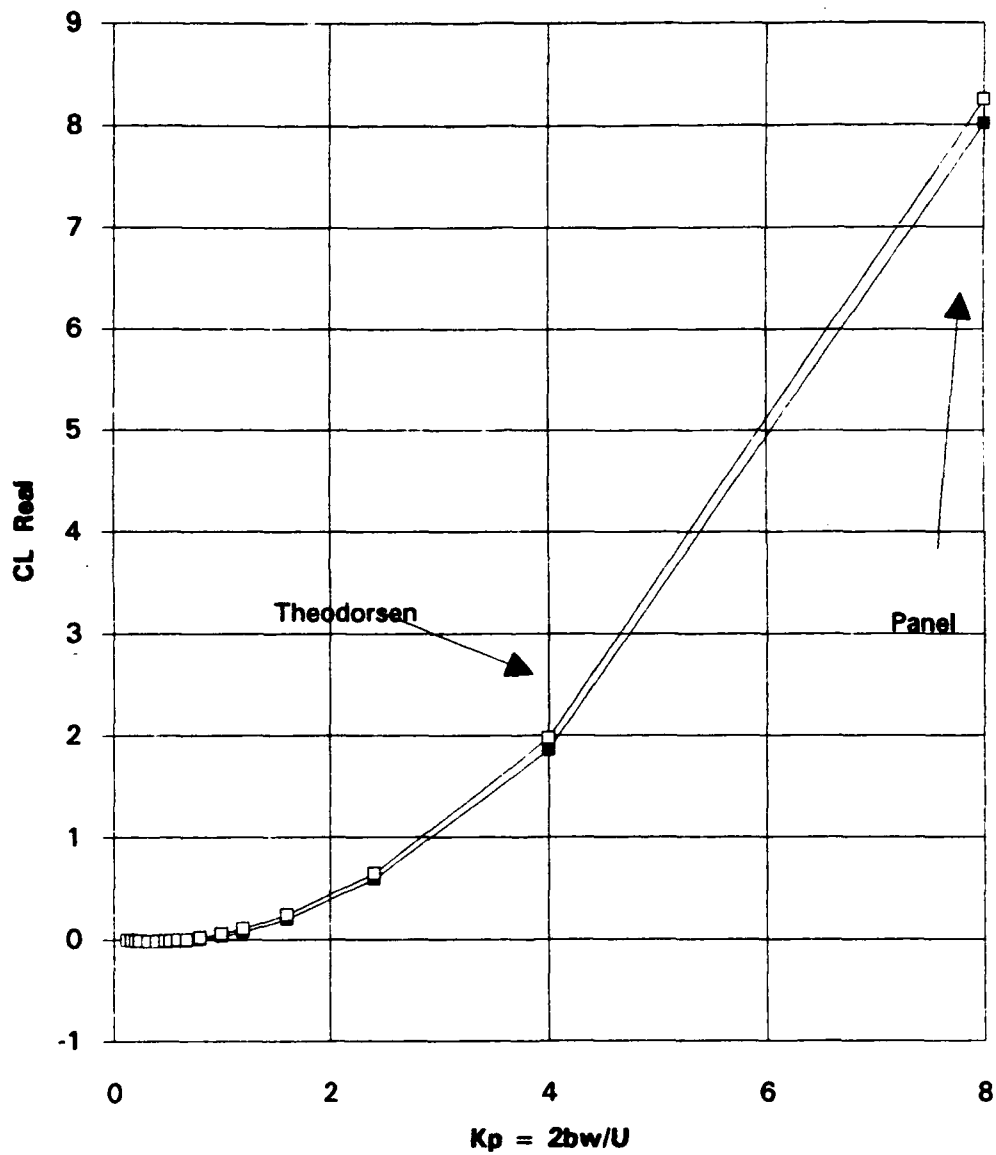


Figure 2.37 Plunge $h/2b=.0833$ C_L Re

Real Part of C_l for Panel and Theodorsen (plunge, .0833 $h/2b$, .37c, NACA0007,75 panels top and bottom, 3cycles of 65 calculations)

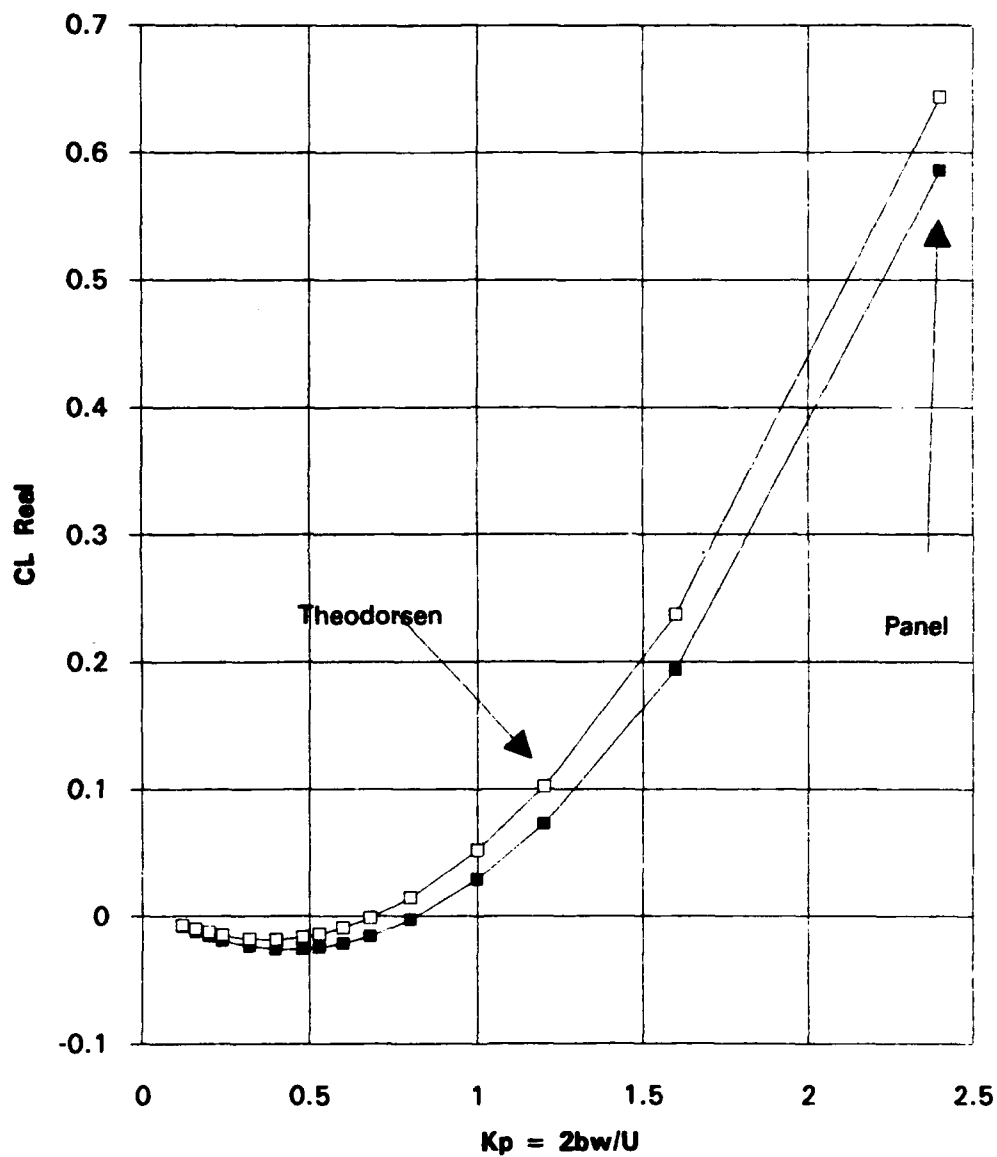


Figure 2.38 Plunge $h/2b=.0833$ $C_{l, \text{Re}}$

Imag Part of C_l for Panel and Theodorsen (plunge,
 $.0833 h/2b$, $.37c$, NACA0007,75 panels top and
bottom, 3cycles of 65 calculations)

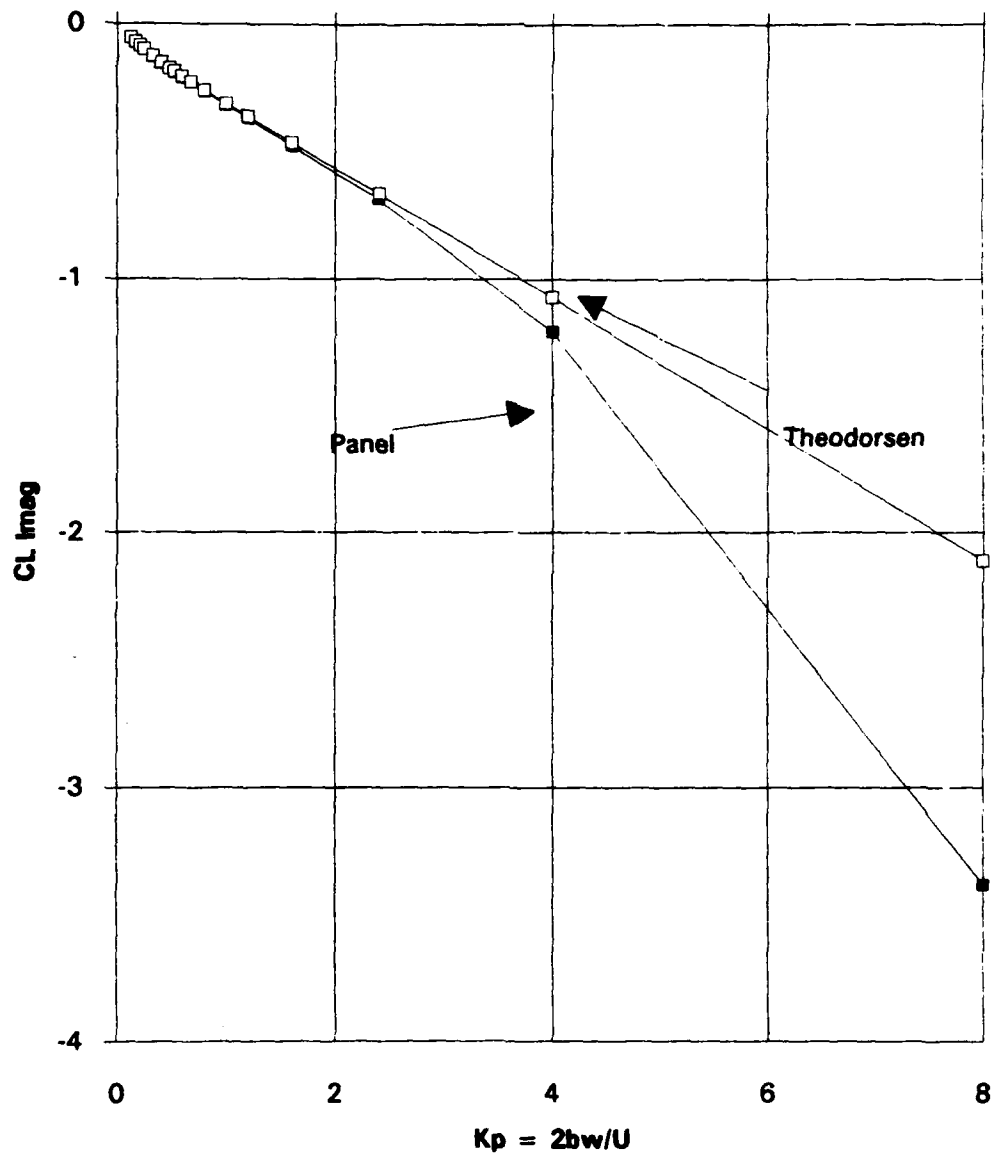


Figure 2.39 Plunge $h/2b=.0833$ $C_L \text{ Im}$

Imag Part of C_l for Panel and Theodorsen (plunge,
 $.0833 h/2b$, $.37c$, NACA0007,75 panels top and
bottom, 3cycles of 65 calculations)

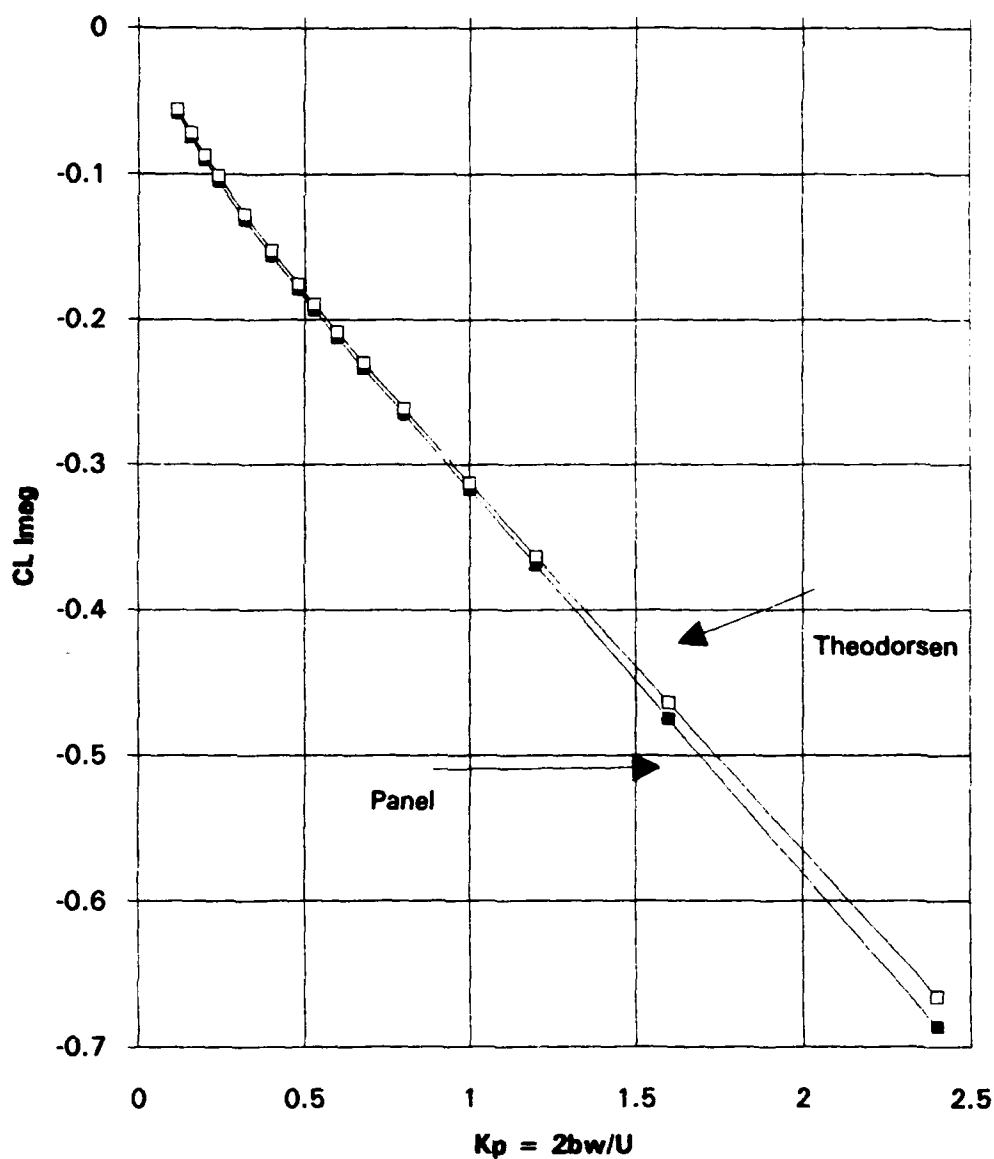


Figure 2.40 Plunge $h/2b=.0833$ $C_L \text{ Im}$

Magnitude of C_l for Panel and Theodorsen (plunge, .0833 $h/2b$, .37c, NACA0007,75 panels top and bottom, 3cycles of 65 calculations)

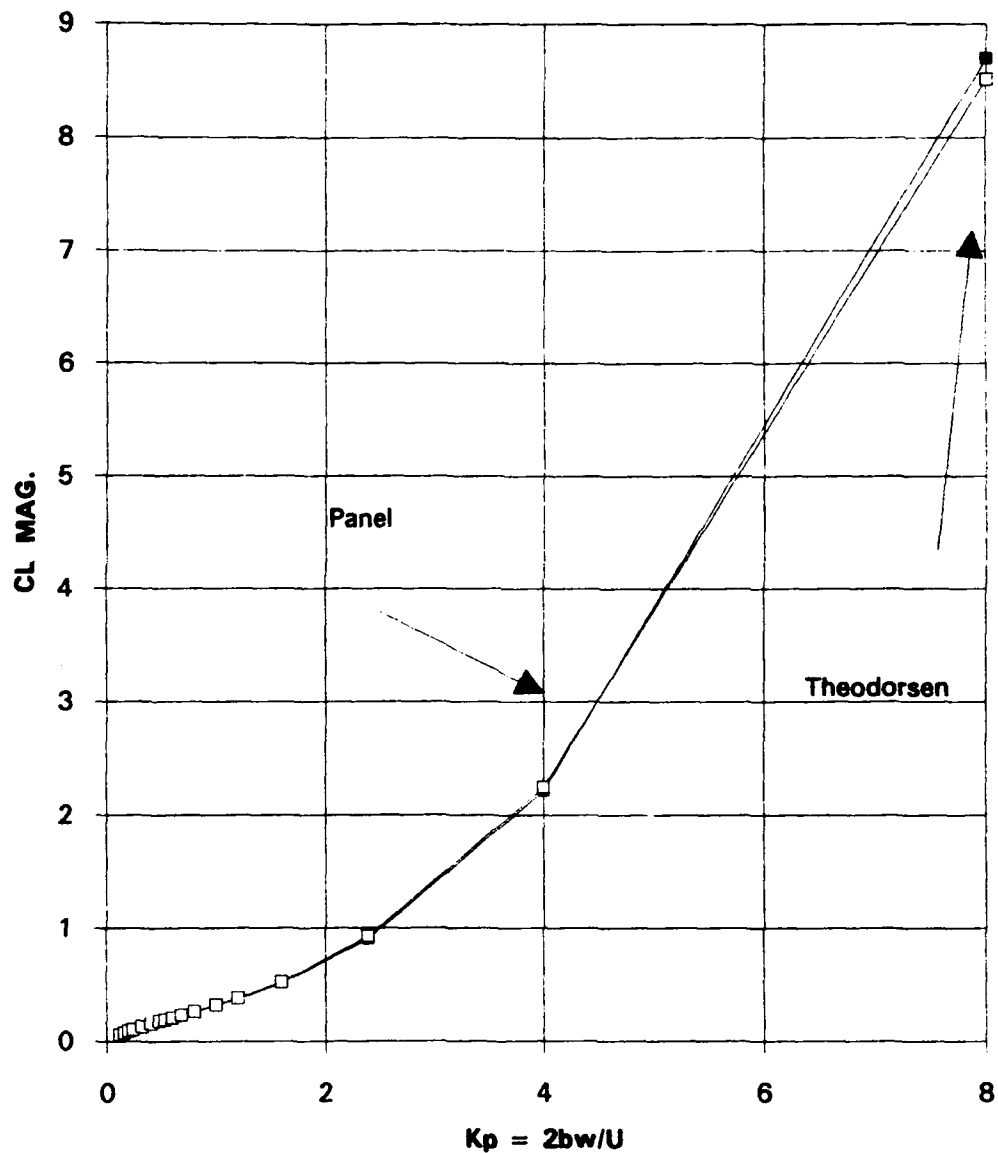


Figure 2.41 Plunge $h/2b=.0833$ C_L Magnitude

Magnitude of C_l for Panel and Theodorsen (plunge, .0833 $h/2b$, .37c, NACA0007,75 panels top and bottom, 3cycles of 65 calculations)

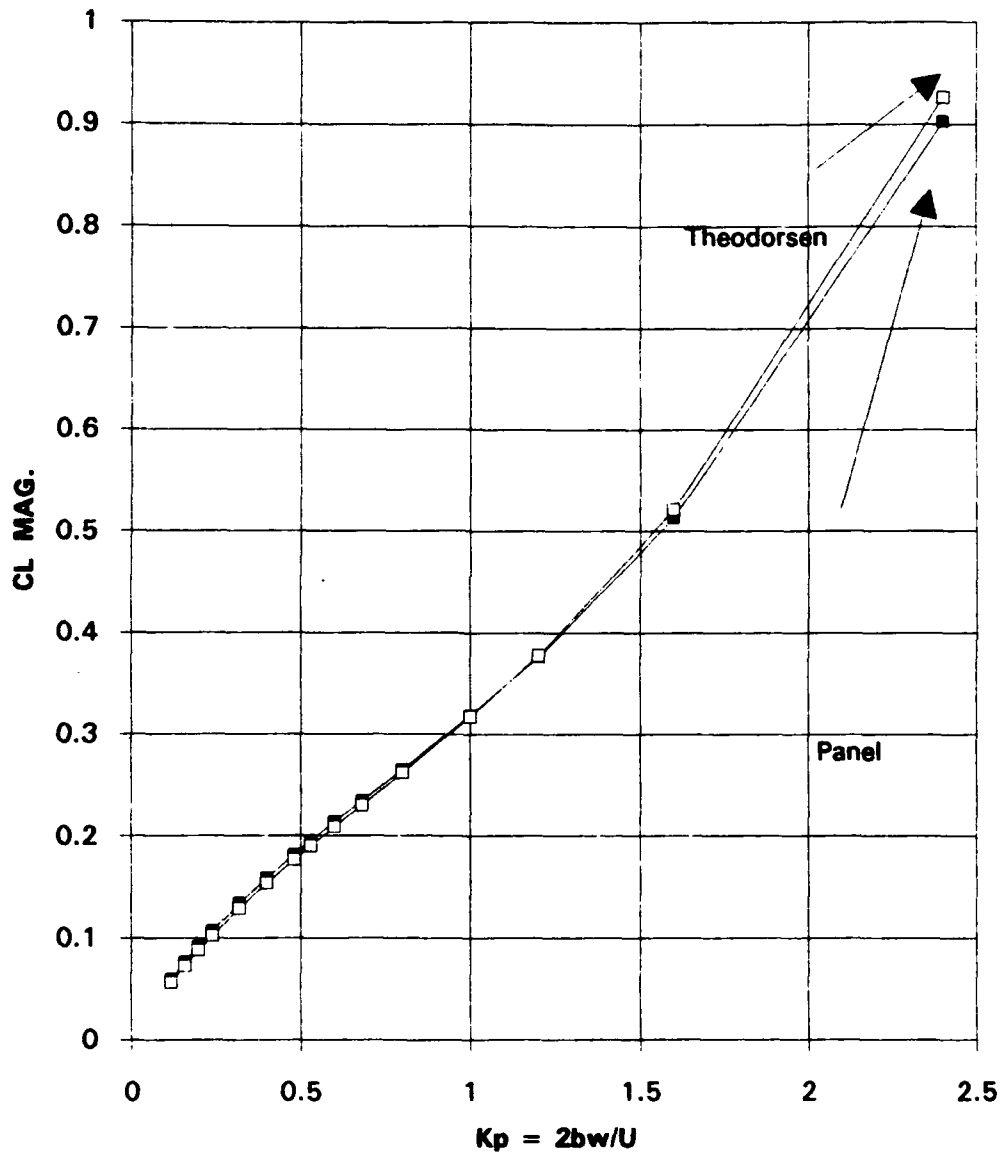


Figure 2.42 Plunge $h/2b=.0833$ C_L magnitude

Phase of C_l for Panel and Theodorsen (plunge, .0833
 $h/2b$, .37c, NACA0007,75 panels top and bottom,
 3cycles of 65 calculations)

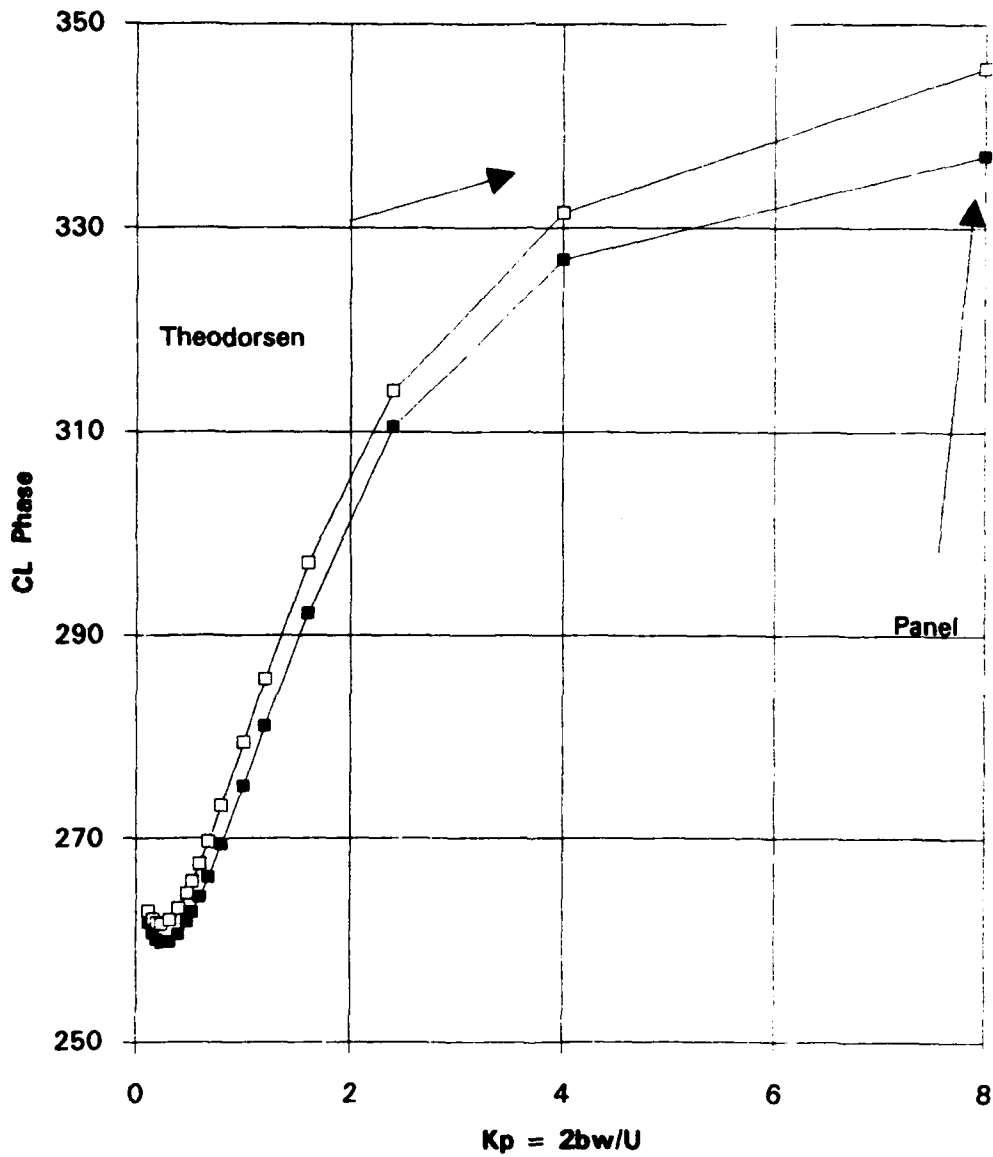


Figure 2.43 Plunge $h/2b=.0833$ C_l phase

Phase of C_l for Panel and Theodorsen (plunge, .0833
 $h/2b$, .37c, NACA0007.75 panels top and bottom,
 3cycles of 65 calculations)

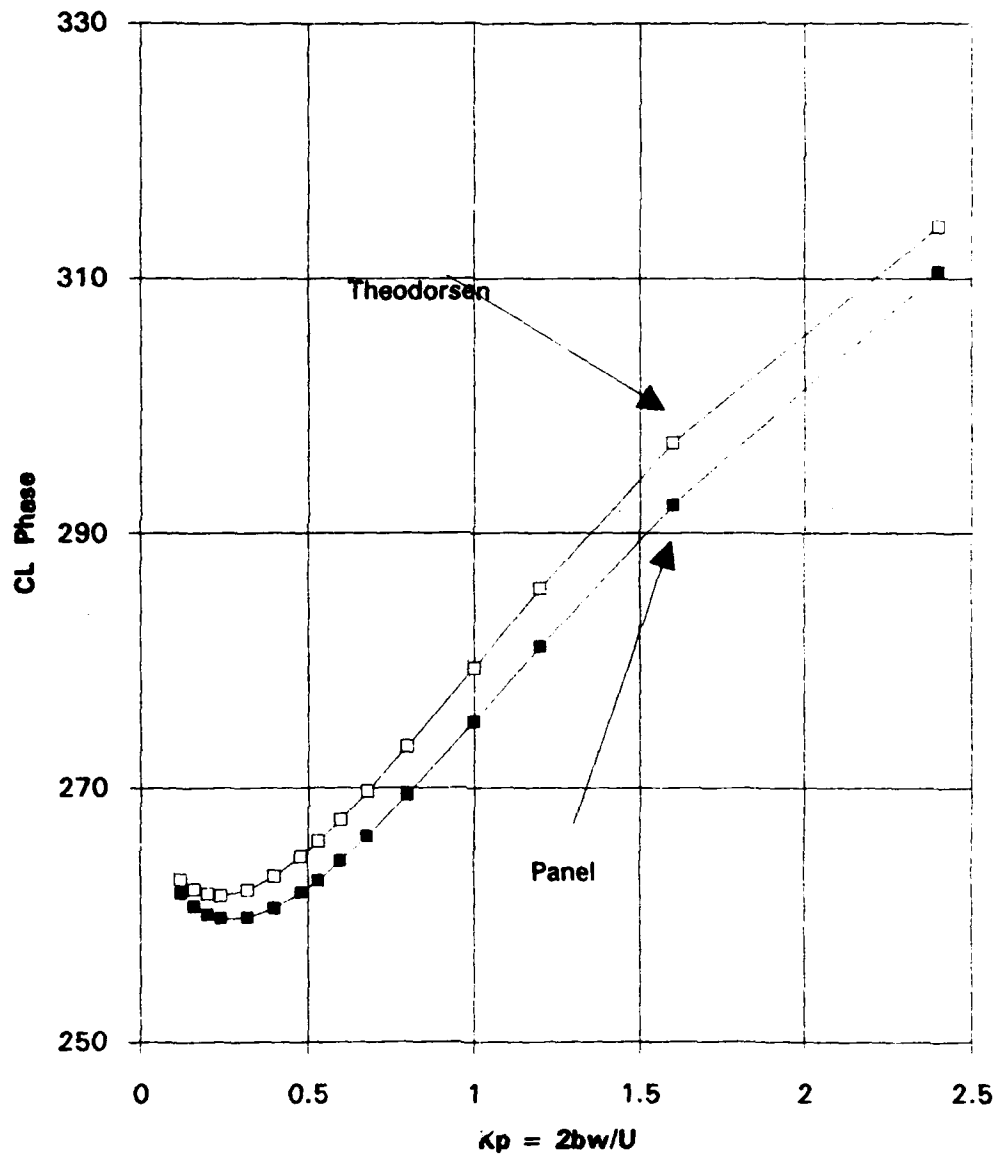


Figure 2.44 Plunge $h/2b=.0833$ C_L phase

Comparison of Panel Cn Values (Phuge) with Theodorsen Results											
(Phuge .0833b/c, .37c, NACA 0007, 75 panels, 3 cycles)											
Kpanel (equal to 2 x Theodorsen K)											
%DIFF taken wrt Theodorsen values.											
1/rt	Kpanel	Real pan.	Real theo.	% DIFF.	Imag Pan	Imag Theo	% DIFF.	Mag Pan.	Mag Theo.	% DIFF.	Phase Pa Phase Th % DIFF.
16.67	0.11998	0.00132	0.001319179	0.06%	0.00675	0.006721	0.44%	0.00687786	0.00684875	0.43%	78.9351 78.8945 0.05%
12.5	0.16	0.00202	0.00204733	1.33%	0.00865	0.008646	0.04%	0.00888273	0.00888531	0.03%	76.8555 76.6783 0.23%
10	0.2	0.00276	0.002844726	2.98%	0.01042	0.010451	0.30%	0.01077933	0.01083124	0.48%	75.1645 74.7732 0.52%
8.33	0.24	0.00354	0.00369484	4.19%	0.01209	0.012145	0.45%	0.01259761	0.01269456	0.76%	73.6798 73.0788 0.82%
6.25	0.32	0.00516	0.005512253	6.39%	0.0152	0.015331	0.85%	0.01605197	0.01629167	1.47%	71.249 70.2237 1.46%
5	0.4	0.00683	0.00745976	8.44%	0.01807	0.018279	1.14%	0.01931771	0.01974283	2.15%	69.2947 67.7996 2.21%
4.17	0.48	0.00857	0.009533759	10.11%	0.02081	0.02107	1.23%	0.02250558	0.02312655	2.69%	67.6171 65.6542 2.99%
3.75	0.53	0.0097	0.01098723	11.72%	0.02247	0.022787	1.39%	0.02447429	0.02529756	3.25%	66.6508 64.744 3.72%
3.33	0.6	0.01134	0.0128782	11.95%	0.02475	0.02506	1.24%	0.02722422	0.02817525	3.38%	65.3836 62.800 4.11%
2.94	0.68	0.01328	0.01528568	13.10%	0.02795	0.027628	1.21%	0.03035548	0.03157482	3.86%	64.0503 61.014 4.92%
2.5	0.8	0.01643	0.0191749	14.32%	0.03106	0.031403	1.09%	0.03513785	0.03679467	4.50%	62.1222 58.5917 6.03%
2	1	0.02232	0.026475126	15.69%	0.03722	0.037552	0.88%	0.04339943	0.04594666	5.54%	59.0498 54.8153 7.73%
1.67	1.2	0.02915	0.0348795	16.43%	0.04331	0.043623	0.72%	0.05220612	0.05585274	6.53%	56.0573 51.3552 9.16%
1.25	1.6	0.04591	0.05525155	16.91%	0.05529	0.055684	0.71%	0.07186593	0.0744436	3.39%	50.2955 45.2236 11.22%
0.83	2.4	0.09818	0.111201	11.71%	0.080021	0.079887	0.14%	0.12664811	0.13692186	7.50%	39.1748 35.6955 9.75%
0.5	4	0.26237	0.286658	8.47%	0.1095213	0.128854	15.00%	0.28431041	0.31428687	9.54%	22.6572 24.2042 6.39%
0.25	8	1.06271	1.10392	3.73%	-0.021611	0.253136	109%	1.062926	1.132711	6.15%	-1.165 12.915 109.02%
Values for Kp equal to 2.4, 4, and 8 above were calculated using 200 panels top and bottom and 4 cycles of 100 calculations.											
The below values were calculated using 75 panels and 3 cyc of 65 calc.											
0.83	2.4	0.09315	0.111201	16.23%	0.07777	0.079887	2.65%	0.121347	0.13692186	11.37%	39.8582 35.6955 11.67%
0.5	4	0.24712	0.28665824	13.79%	0.10401	0.128854	19.28%	0.26811635	0.31428709	14.69%	22.8257 24.2042 5.70%
0.25	8	0.9993	1.1039244	9.48%	-0.04788	0.253136	119%	1.00044639	1.13257539	11.67%	-2.7431 12.915 121.24%
Kp of 4 and 8 for CM ing were redone using b/b = .01, .02, .04, .06 to better understand why the imag values became so different.											
These values of b/b were made smaller to account for the very high Kp (NACA 0007, 100 panels, 3 cycles, .37c)											
b/b = .01, Imag, Imag Th, %diff b/b = .02, Imag p, Imag Th, %diff b/b = .04, Imag p, Imag Th, %diff b/b = .06, Imag, Imag Th, %diff											
0.01536	0.01546	0.65%	0.0304	0.030937	1.74%	0.05862	0.06187	5.25%	0.08291	0.09281	10.67%
0.0734	0.03039	10%	0.04886	0.060768	20%	0.06019	0.12107	50%	0.03441	0.18235	81%

TABLE 2.7 PLUNGE $h/2b = .0833$ C_M COMPARISON

Real Part of CM for Panel and Theodorsen (plunge,
 .0833 $h/2b$, .37c, NACA0007,75 panels top and
 bottom, 3cycles of 65 calculations)

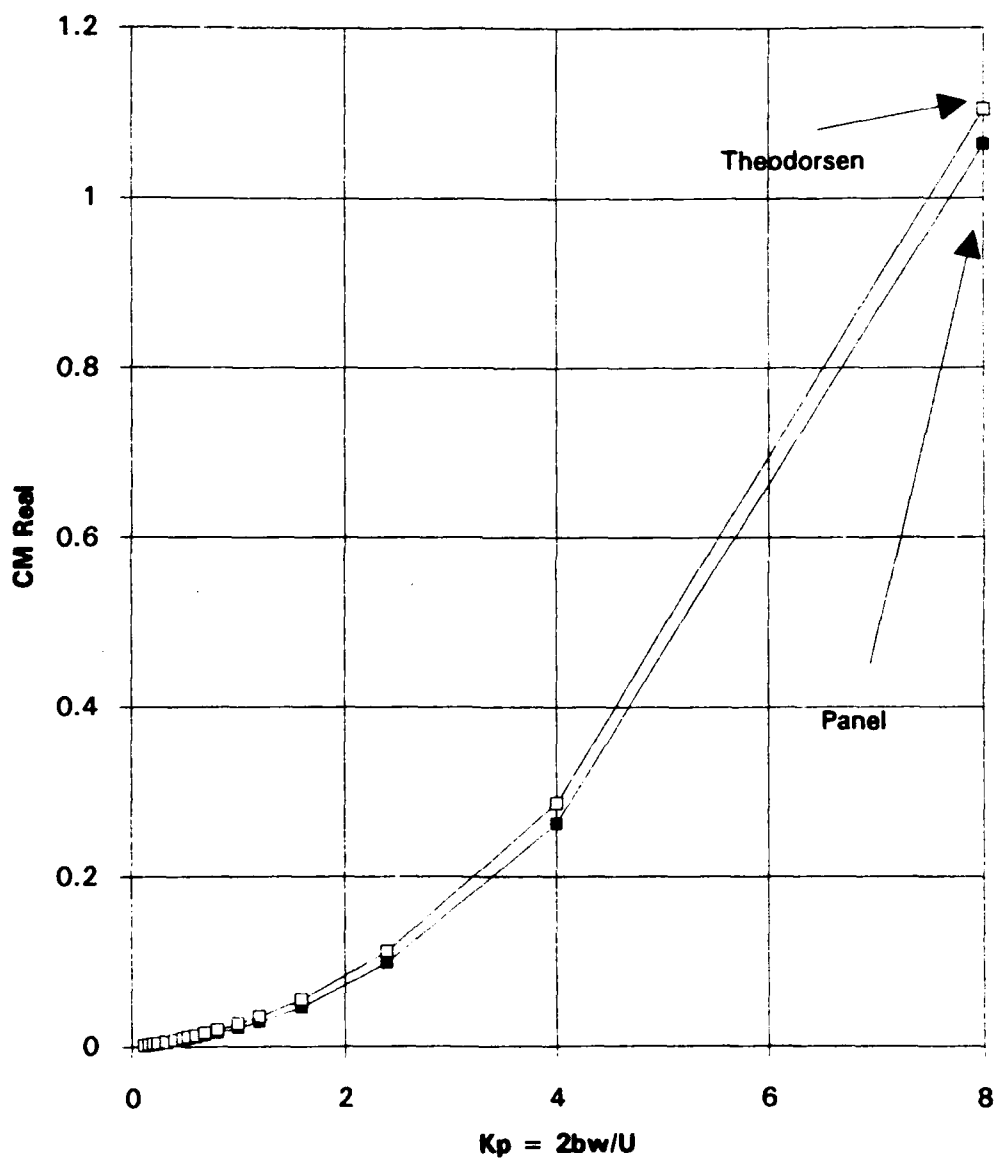


Figure 2.45 Plunge $h/2b=.0833$ C_M Re

Real Part of CM for Panel and Theodorsen (plunge, .0833 h/2b, .37c, NACA0007,75 panels top and bottom, 3cycles of 65 calculations)

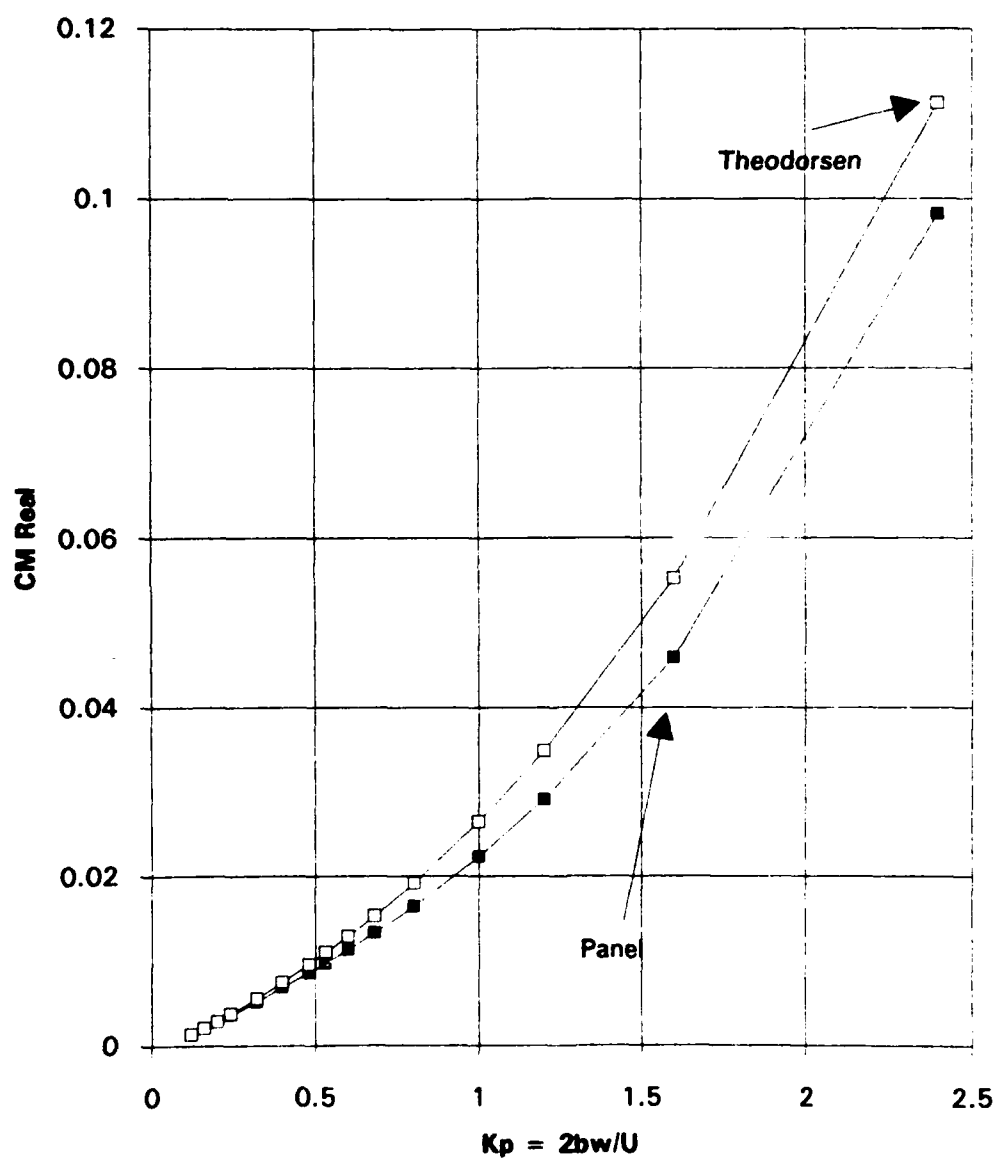


Figure 2.46 Plunge $h/2b=.0833$ C_M Re

Imag. Part of CM for Panel and Theodorsen (plunge,
 .0833 $h/2b$, .37c, NACA0007,75 panels top and
 bottom, 3cycles of 65 calculations)

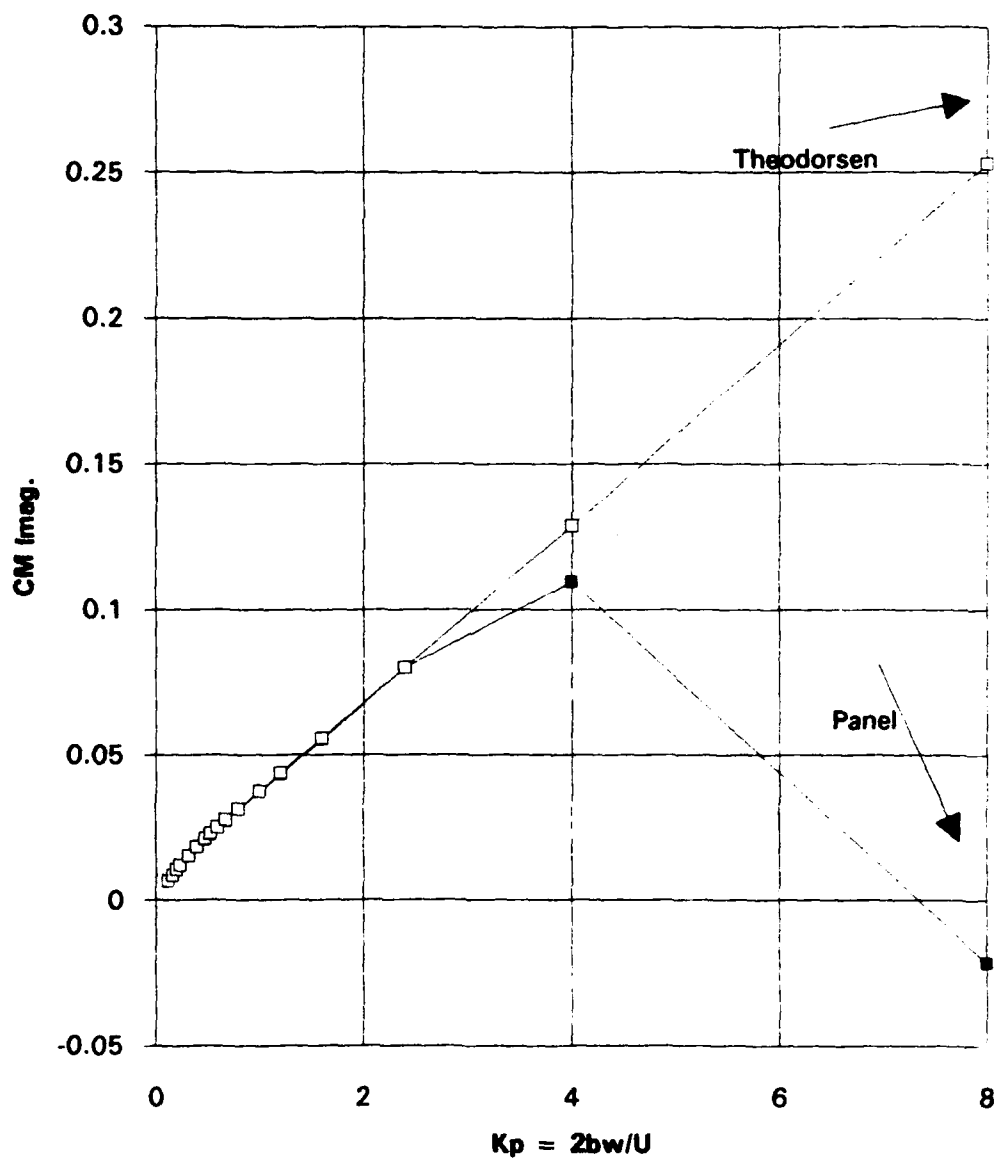


Figure 2.47 Plunge $h/2b=.0833$ C_M Im

Imag. Part of CM for Panel and Theodorsen (plunge,
 .0833 $h/2b$, .37c, NACA0007.75 panels top and
 bottom, 3cycles of 65 calculations)

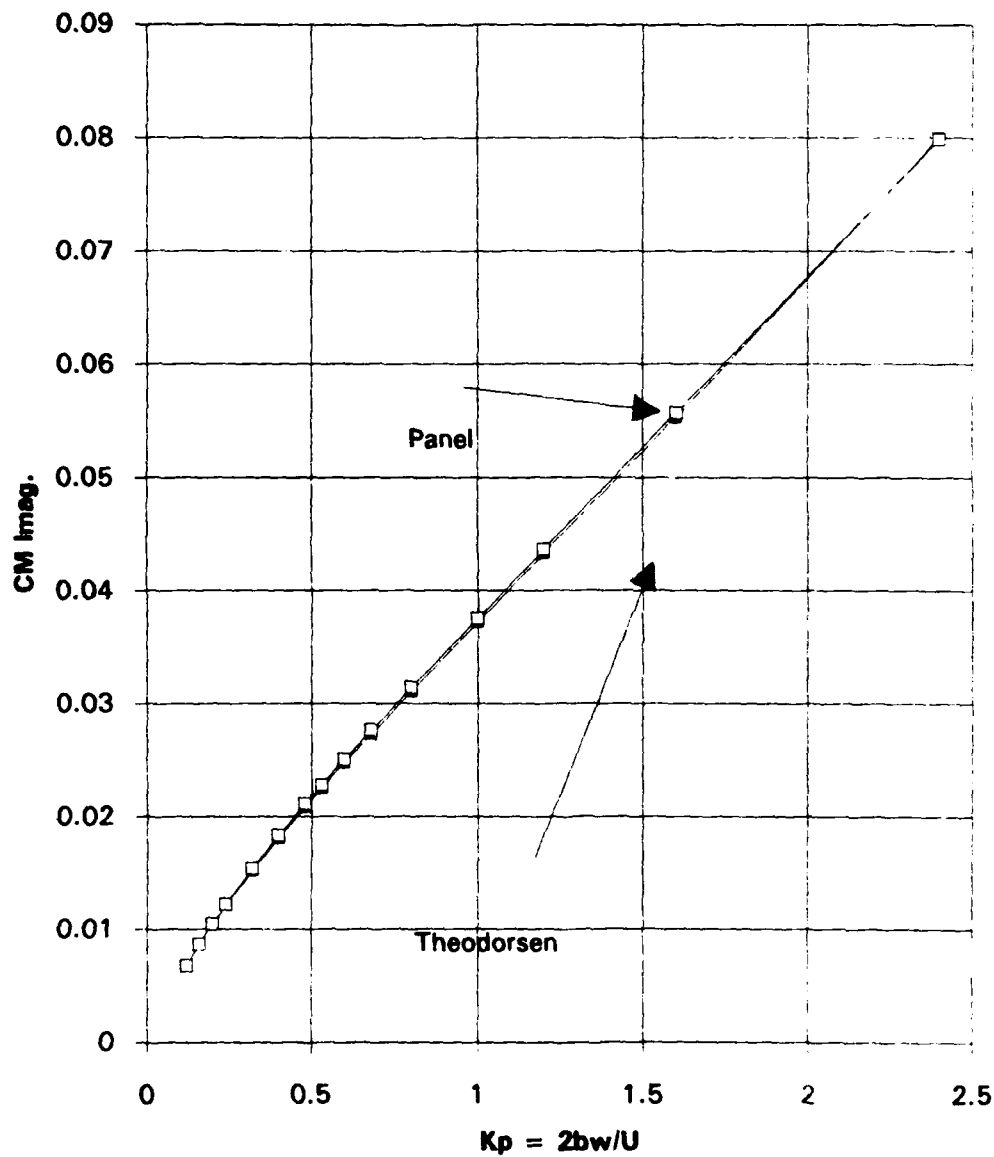


Figure 2.48 Plunge $h/2b=.0833$ C_M Im

**Magnitude of CM for Panel and Theodorsen (plunge,
.0833 $h/2b$, .37c, NACA0007,75 panels top and
bottom, 3cycles of 65 calculations)**

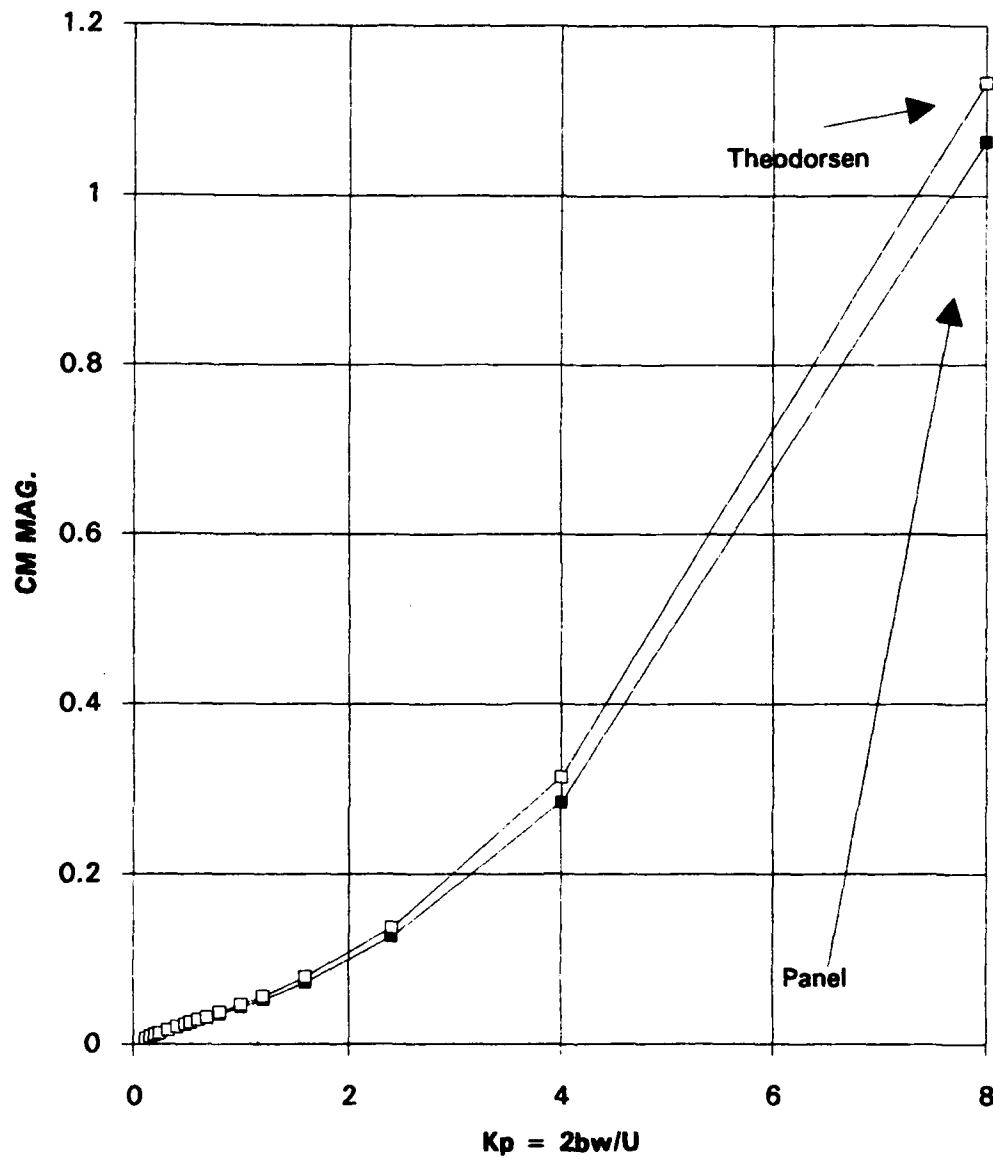


Figure 2.49 Plunge $h/2b=.0833$ C_M Magnitude

Magnitude of CM for Panel and Theodorsen (plunge, .0833 h/2b, .37c, NACA0007,75 panels top and bottom, 3cycles of 65 calculations)

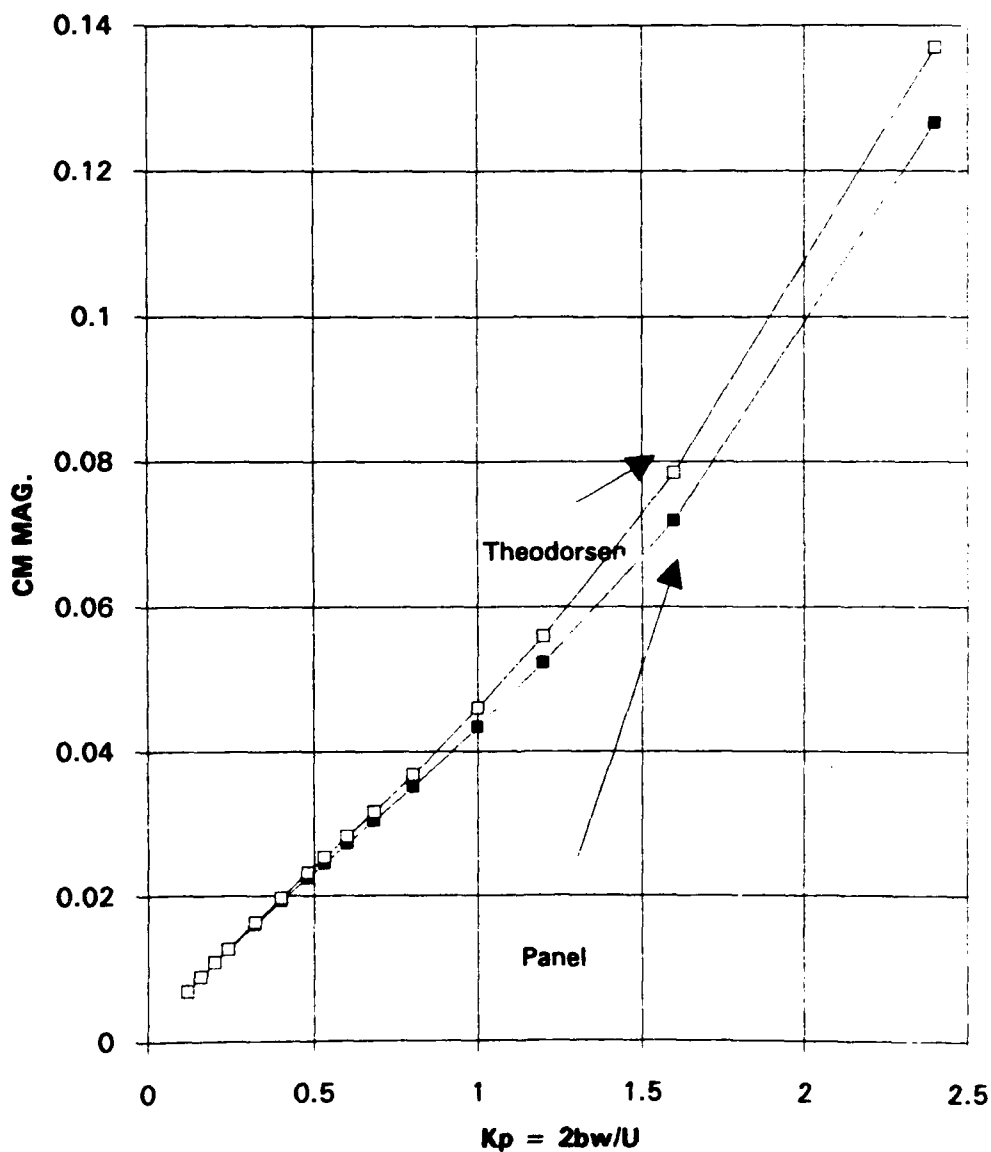


Figure 2.50 Plunge $h/2b=.0833$ C_M Magnitude

Phase of CM for Panel and Theodorsen (plunge, .0833 h/2b, .37c, NACA0007,75 panels top and bottom, 3cycles of 65 calculations)

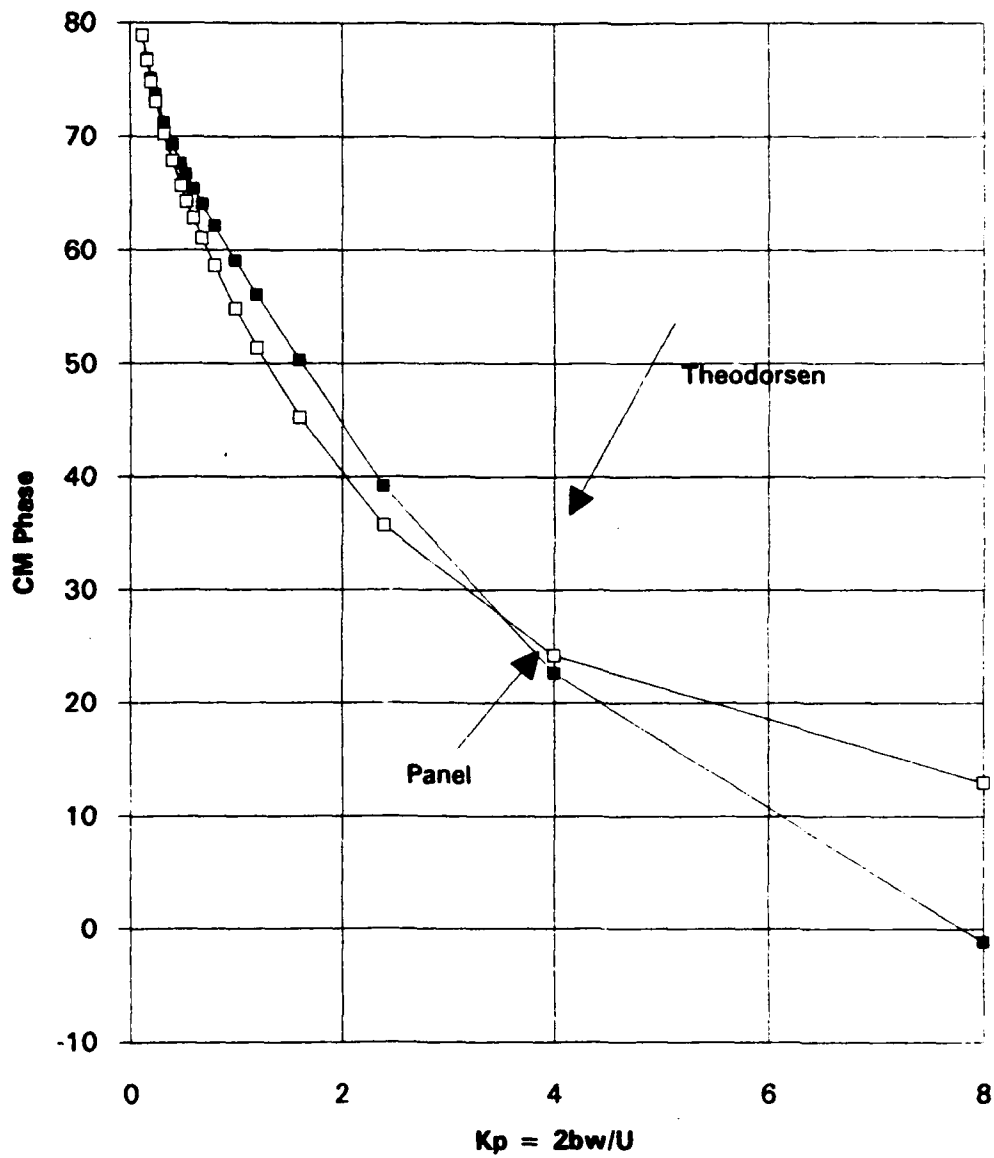


Figure 2.51 Plunge $h/2b=.0833$ C_M Phase

Phase of CM for Panel and Theodorsen (plunge,
 .0833 $h/2b$, .37c, NACA0007,75 panels top and
 bottom, 3cycles of 65 calculations)

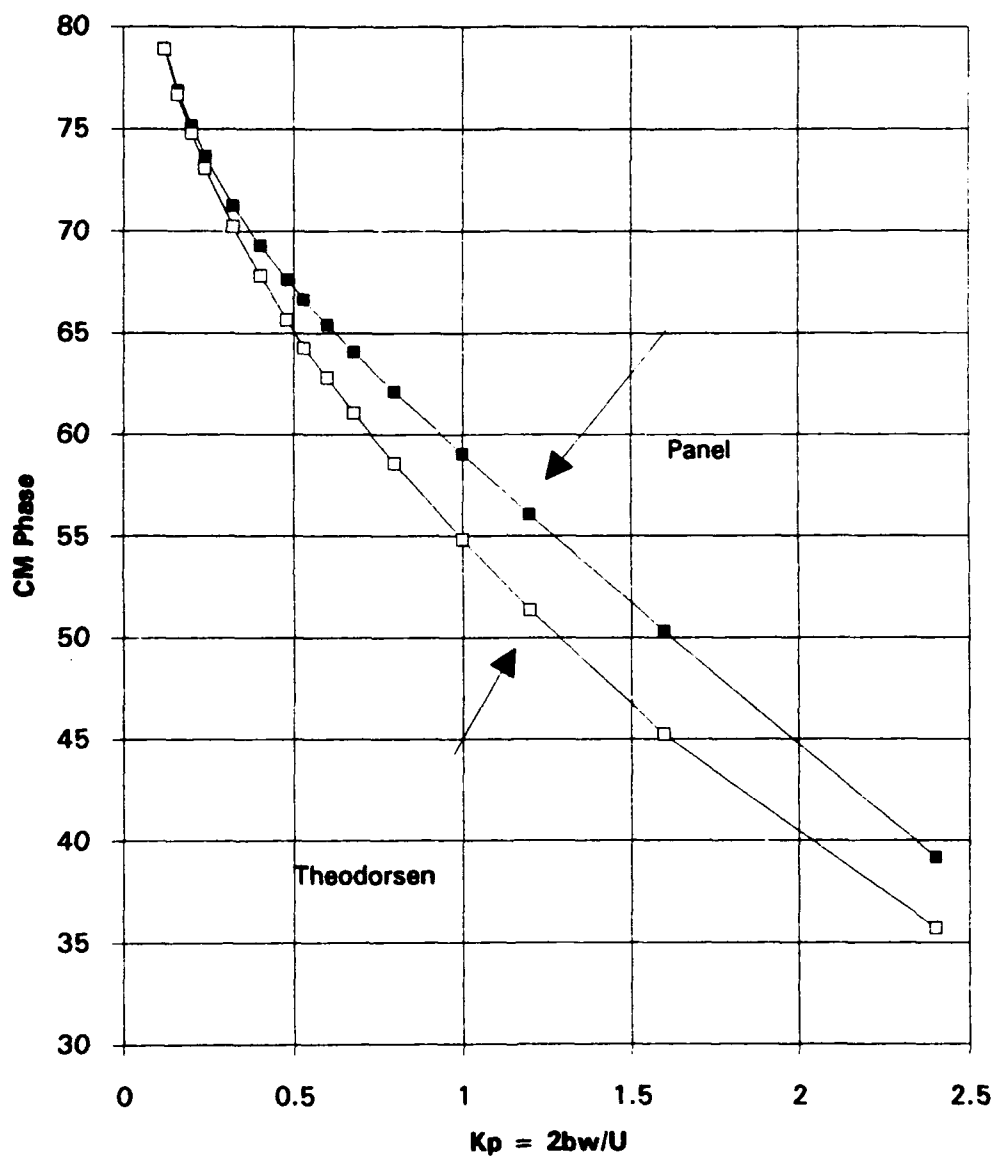


Figure 2.52 Plunge $h/2b=.0833$ C_M Phase

Comparison of Panel Cm Values (Plunge) with Theodolite Results													
(plunge .01 h/2b .37c, NACA 0007, 100 panels, 3 cycles)													
Kpanel (equal to 2 x Theodolite Kt)													
%DIFF taken wrt Theodolite values.													
1/Kt	Kpanel	Real pan.	Real theo.	% DIFF.	Imag Pan	Imag Theo.	% DIFF.	Mag Pan.	Mag Theo.	% DIFF.	Phase Pn.	Phase T % DIFF.	
18.67	0.11988	0.00016	0.000158365	1.03%	0.00081	0.00080678	0.40%	0.000826	0.000822	0.42%	78.826182	78.89	0.09%
12.5	0.16	0.00001	0.000248778	98.93%	0.00001	0.00103796	99.04%	1.41E-06	0.001067	98.87%	45	78.88	41.31%
10	0.2	0.00033	0.000341504	3.37%	0.00125	0.00126482	0.37%	0.001283	0.0013	0.67%	76.211322	74.77	0.69%
8.33	0.24	0.00043	0.000443658	3.06%	0.00145	0.00146798	0.55%	0.001612	0.001624	0.76%	73.482188	73.08	0.55%
6.25	0.32	0.00063	0.000681735	4.80%	0.00183	0.00184043	0.57%	0.001835	0.001866	1.04%	71.003346	70.22	1.11%
5	0.4	0.00083	0.00088653	7.32%	0.00216	0.00218438	1.57%	0.002314	0.00237	2.37%	68.980268	67.8	1.74%
4.17	0.48	0.00104	0.001144509	9.13%	0.00249	0.00252841	1.56%	0.002688	0.002776	2.80%	67.331136	66.66	2.55%
3.75	0.53	0.00117	0.001319886	11.30%	0.00269	0.00273553	1.66%	0.002833	0.003037	3.41%	65.483846	64.28	3.48%
3.33	0.6	0.00137	0.00154804	11.39%	0.00289	0.00300837	1.61%	0.003282	0.003382	3.57%	65.163615	62.8	3.76%
2.94	0.68	0.00161	0.001835016	12.26%	0.00327	0.00331671	1.41%	0.003646	0.00378	3.84%	63.788462	61.06	4.49%
2.5	0.8	0.00189	0.002301909	13.60%	0.00372	0.00376881	1.37%	0.004218	0.004417	4.51%	61.83111	58.59	5.53%
2	1	0.002704	0.003178288	14.93%	0.00448	0.00450808	1.06%	0.006216	0.006516	5.43%	58.77842	54.82	7.23%
1.67	1.2	0.00363	0.004187215	16.70%	0.0062	0.00623883	0.73%	0.008284	0.008706	6.28%	55.82521	51.36	8.70%
1.25	1.6	0.00553	0.00632792	16.28%	0.0087	0.00888475	0.19%	0.00988	0.009417	7.82%	50.22754	45.22	11.08%
0.83	2.4	0.011207	0.01334946	16.05%	0.00981	0.00968028	0.25%	0.014768	0.016437	10.17%	40.62587	35.69	13.82%
0.5	4	0.029326	0.034412725	14.78%	0.01536	0.0164887	0.71%	0.033104	0.03773	12.26%	27.6416	24.2	14.20%
0.25	8	0.115247	0.132523408	13.04%	0.02734	0.0303886	10.02%	0.118447	0.136983	12.88%	13.34888	12.92	3.34%

TABLE 2.8 PLUNGE $h/2b=.01$ C_M COMPARISON

Real Part of CM for Panel and Theodorsen (plunge,
 .01 $h/2b$, .37c, NACA0007, 100 panels top and
 bottom, 3 cycles of 65 calculations)

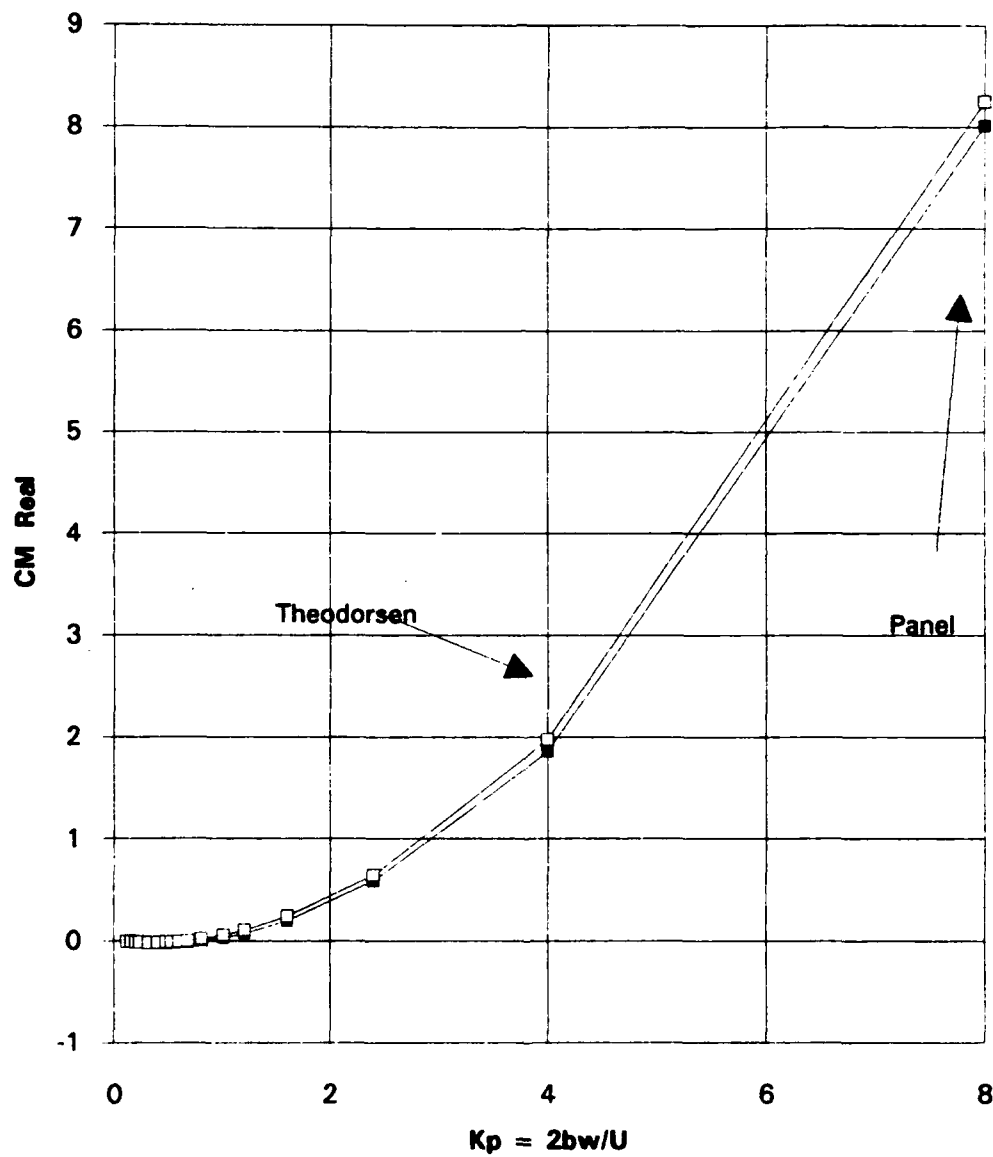


Figure 2.53 Plunge $h/2b=.01$ C_M Re

Imag Part of CM for Panel and Theodorsen (plunge, .01
h/2b, .37c, NACA0007,100 panels top and bottom,
3cycles of 65 calculations)

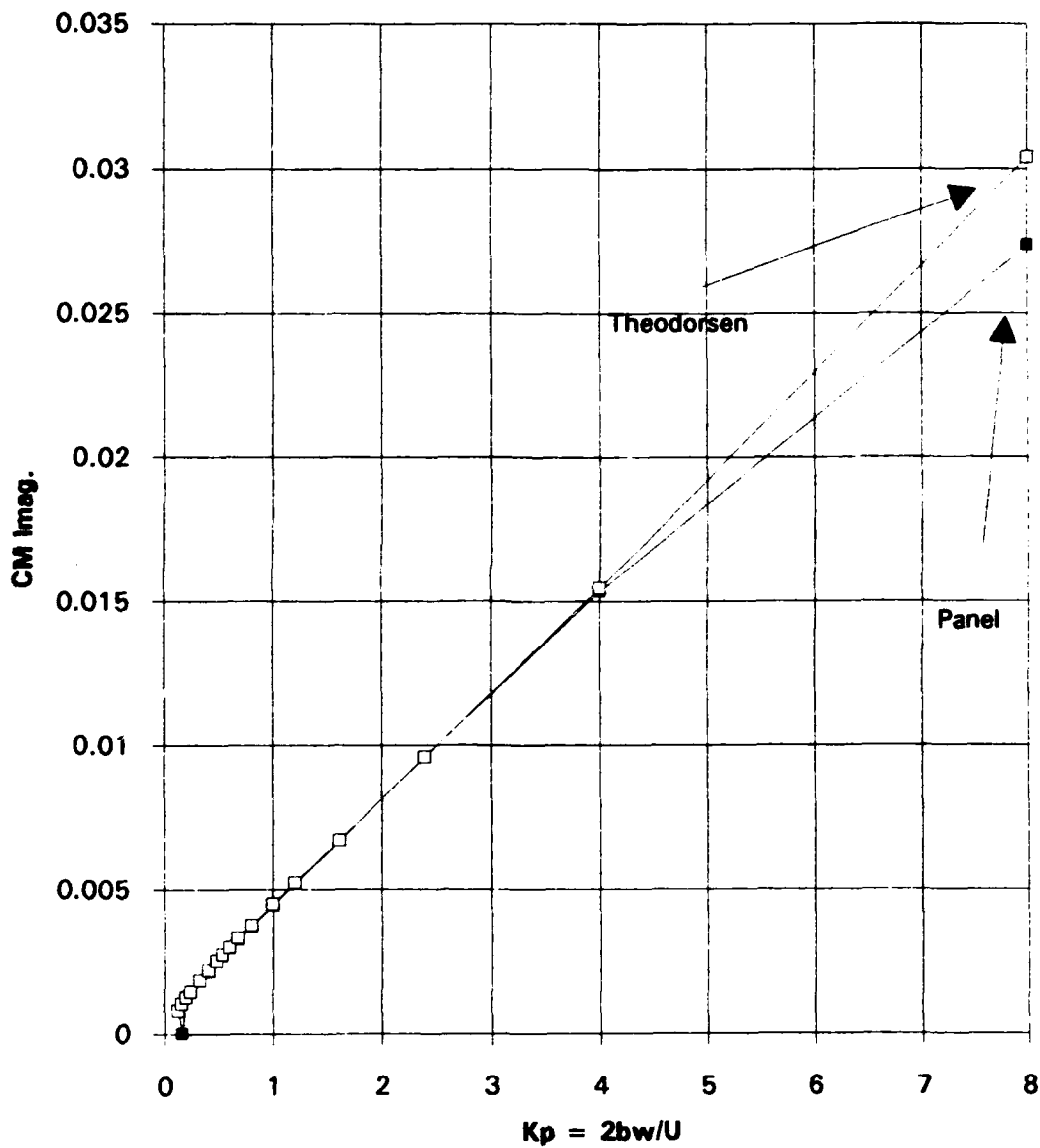


Figure 2.54 Plunge $h/2b=.01$ C_M Im

Magnitude of CM for Panel and Theodorsen (plunge, .01
h/2b, .37c, NACA0007,100 panels top and bottom,
3cycles of 65 calculations)

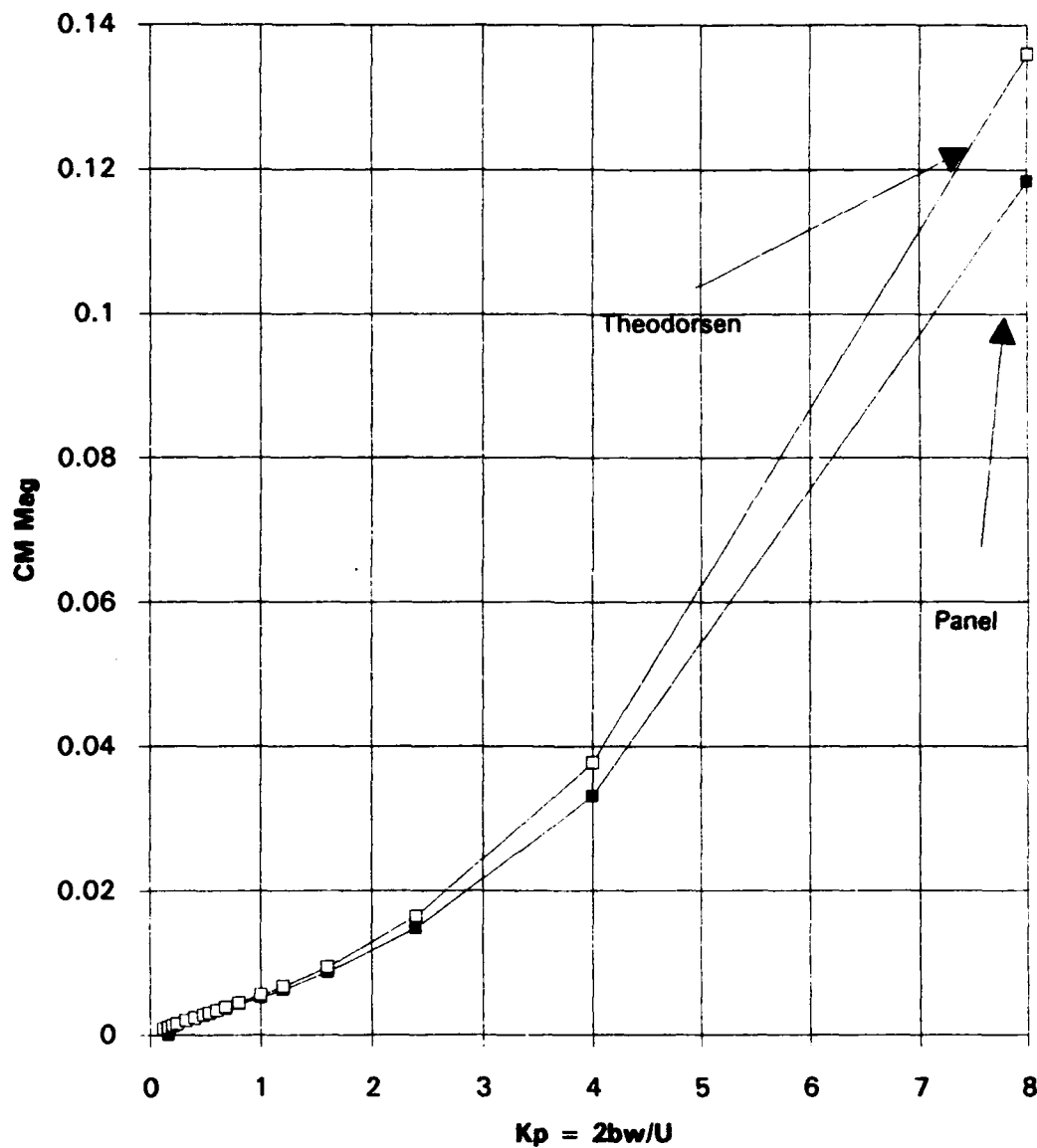


Figure 2.55 Plunge h/2b=.01 C_M Magnitude

Phase of CM for Panel and Theodorsen (plunge, .01
 $h/2b$, .37c, NACA0007, 100 panels top and bottom,
 3 cycles of 65 calculations)

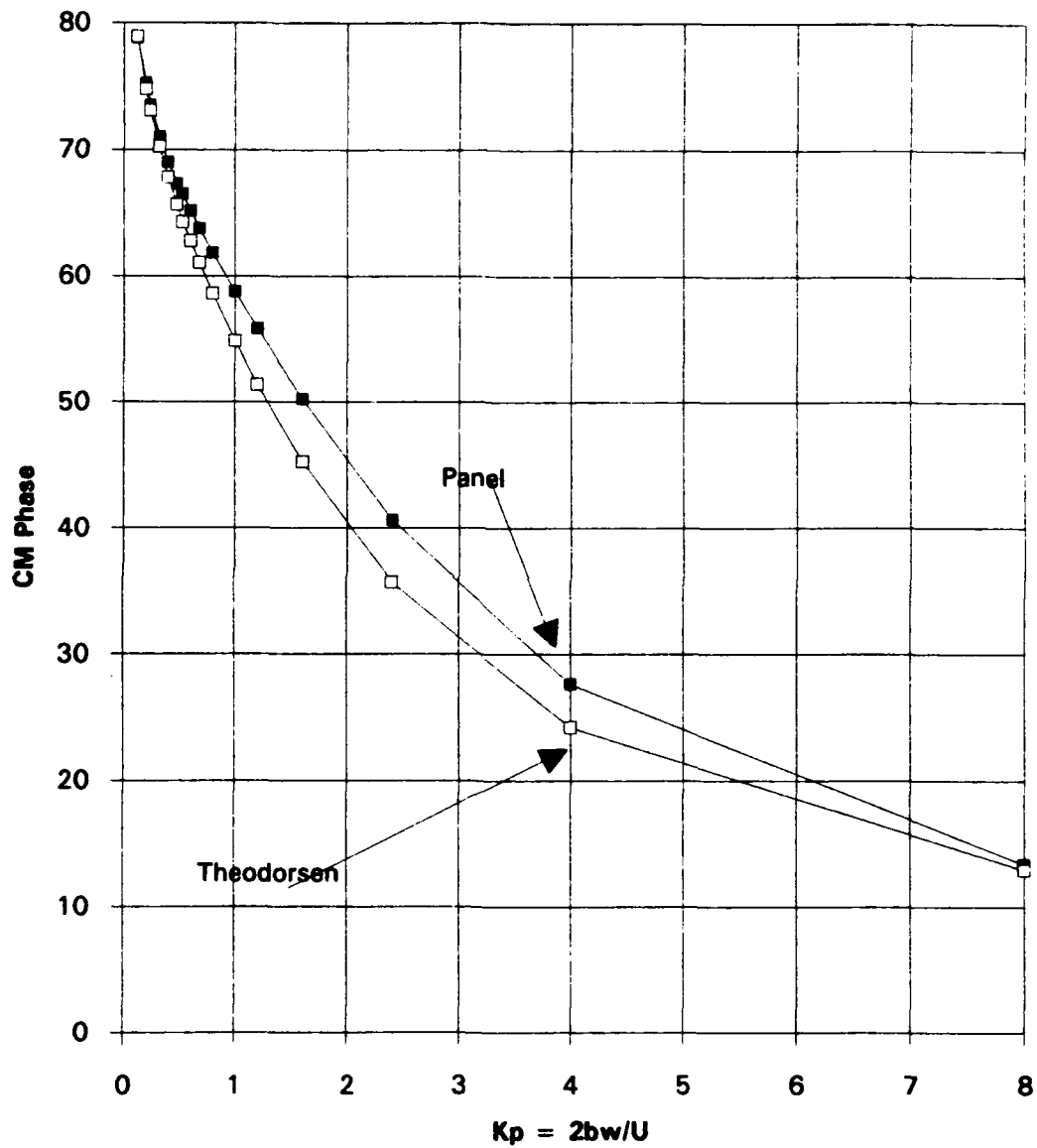


Figure 2.56 Plunge $h/2b=.01$ C_M Phase

Comparison of CM Imag vs Kp for Various Values of Pitch
(NACA0007, 100 panels, 1, 3 and 6.7 deg. pitch, 3 cyc 65)(0c.)

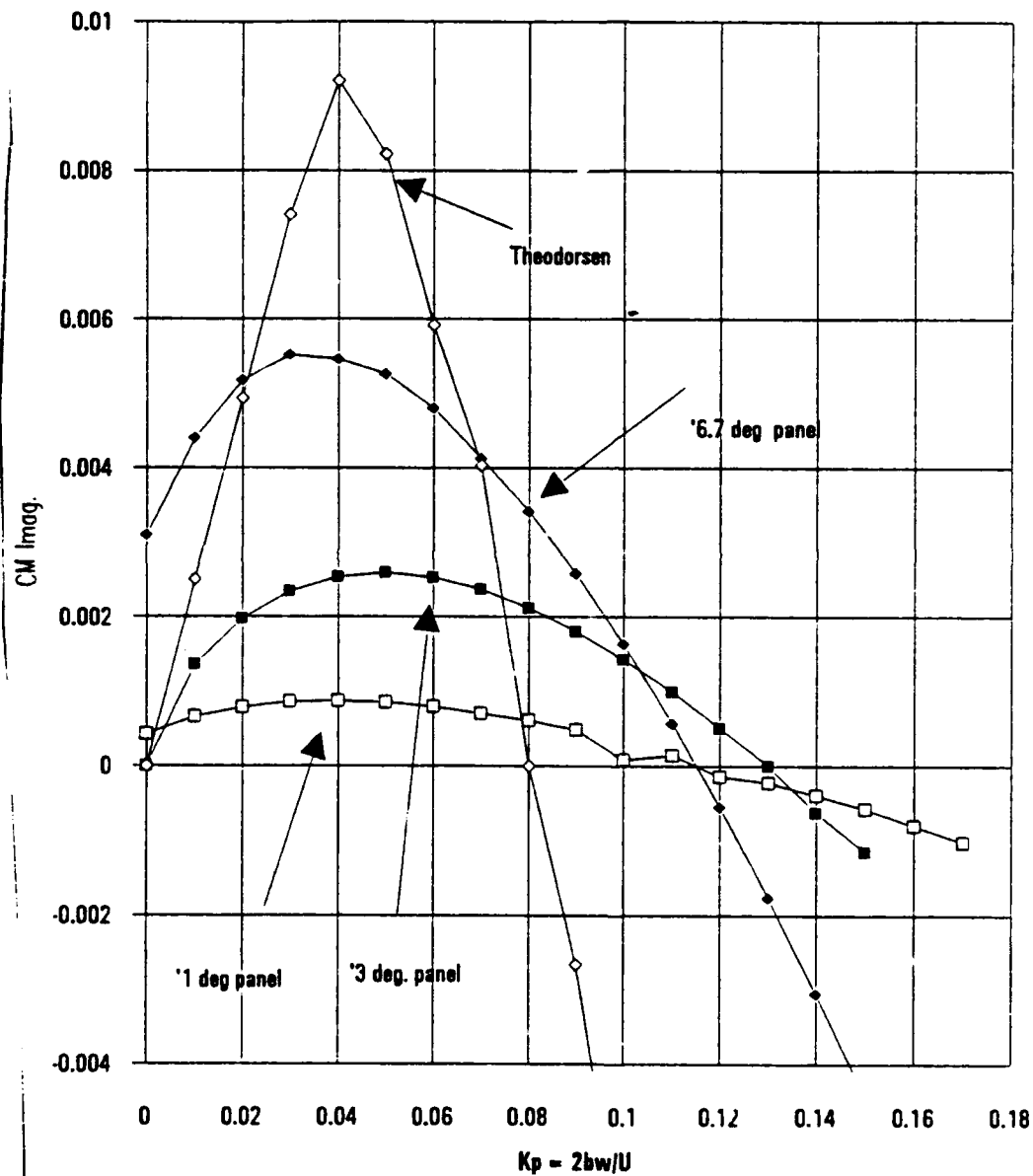


Figure 2.57 Pitch 0c. 1.0, 3.0, and 6.7 degrees vs Theodorsen

'Comparison of Imaginary Dimensionless Aerodynamic Coefficient ($Im\ My = 8 \cdot Im\ C_{m\alpha} / (\alpha \cdot \pi \cdot K_p^2)$) (NACA0007, 100 panels, 1, 3, 6.7 deg. pitch, 3cyc65, 0c.)

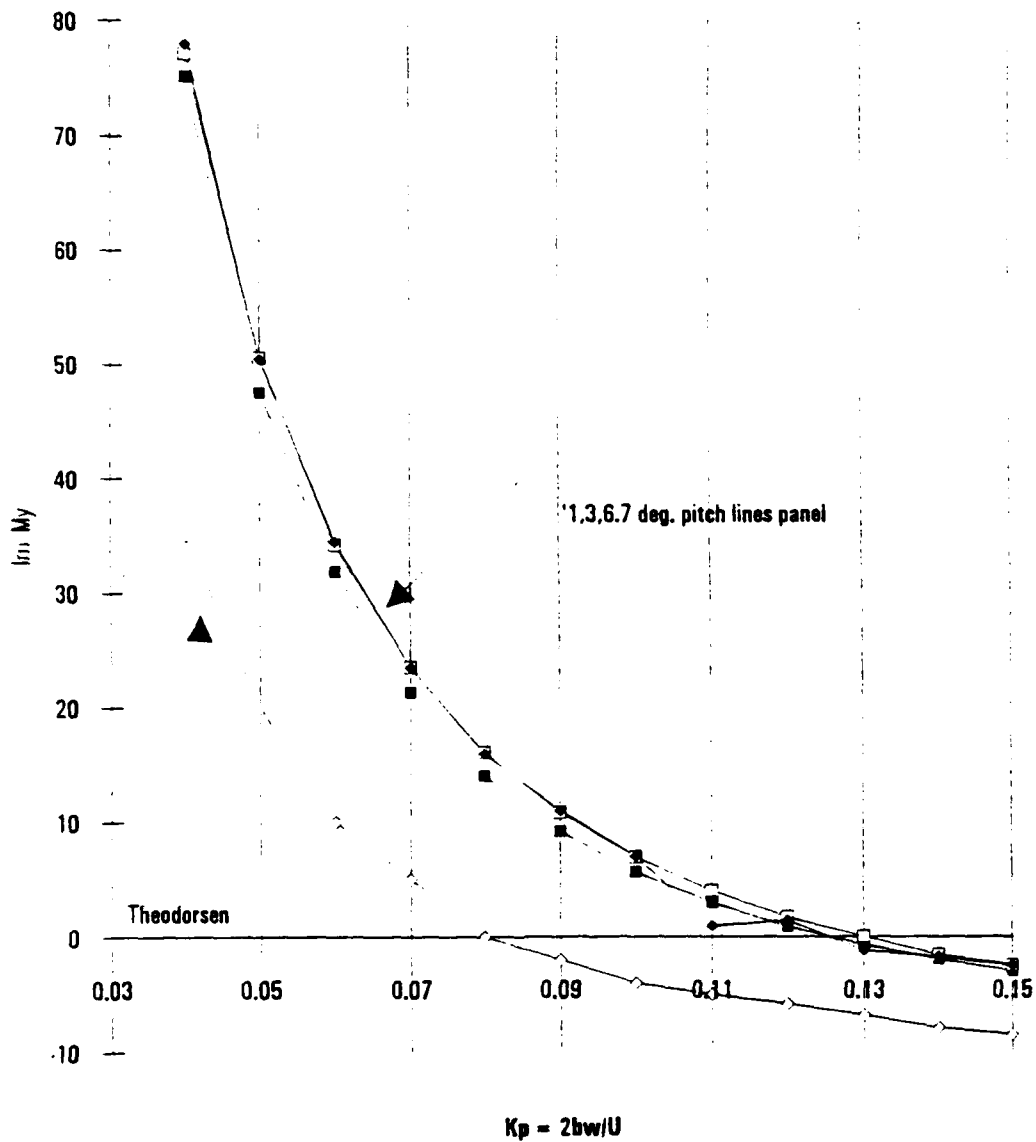


Figure 2.58 Dimensionless Aerodynamic Coefficient for 1.0, 3.0, and 6.7 degrees

III. FLUTTER DETERMINANT

The proven accuracy of the UPOT Code enabled it to be used for the solution of the flutter determinant.

A. FLUTTER THEORY

In order to analyze the phenomenon of flutter, it is necessary to obtain the equations of motion of the system. To simplify the problem the assumption is made that the actual motion of the system can be considered a combination of fundamental wing bending, and fundamental wing torsion. The system can then be replaced by an equivalent system containing an airfoil section of unit span restrained by springs against independent vertical motion (bending), and torsion as illustrated in Figure 3.1. This paper will not consider the aileron hinge case so β and c are set equal to zero. According to the class notes of M. Platzer [ref.1] the formulation proceeds as follows:

Consider the balance of the elastic, inertial and aerodynamic forces on a mass element:

- Total Inertial force: $-\int dm(h'' + r\alpha'') = -(Mh'' + S_a\alpha'')$
Mass: $M = \int dm$
Static Moment about the elastic axis: $S_a = \int r dm$
- The moments about the elastic axis are:

$$- \int r(h'' + r\alpha'') dm = -(I_\alpha \alpha'' + S_\alpha h'') \quad (3.1)$$

Mass moment of inertia about elastic axis

$$I_\alpha = \int r^2 dm$$

- Elastic restoring forces are: $-hC_h$ $-\alpha C_\alpha$
The Equations of motion therefore become:

$$\begin{aligned} h''M + \alpha''S_\alpha + hC_h &= L \\ \alpha''I_\alpha + h''S_\alpha + \alpha C_\alpha &= M \end{aligned} \quad (3.2)$$

Where: C_α = Torsional stiffness of the wing

C_h = Stiffness of the wing in translation (plunge)

M = Mass of the wing per unit span

These equations can be written in a different way by expressing the spring constants in terms of the natural frequencies. Consider the airfoil to be so restrained that only one degree of freedom is permitted. The equations of motion become:

$$\begin{aligned} Mh'' + hC_h &= 0 \quad \text{so that} \quad \omega_h = \sqrt{\frac{C_h}{M}} \\ I_\alpha \alpha'' + \alpha C_\alpha &= 0 \quad \text{so that} \quad \omega_\alpha = \sqrt{\frac{C_\alpha}{I_\alpha}} \end{aligned} \quad (3.3)$$

$$\text{Hence: } C_h = M\omega_h^2 \quad C_\alpha = I_\alpha \omega_\alpha^2$$

The small structural damping of metal aircraft may be approximated by a force that opposes the motion and is in phase with the velocity. One assumes therefore that the

magnitude of the damping is proportional to the elastic restoring force. Since the motion of the airfoil is harmonic at the critical flutter condition, the structural damping can be accounted for by replacing the terms:

$$hC_h \text{ with } hC_h(1+ig_h)$$

$$\alpha C_\alpha \text{ with } \alpha C_\alpha(1+ig_\alpha)$$

Where g_h and g_α are damping constants multiplied by i to ensure that the damping force is in phase with the velocities in the simple harmonic motion.

From equation 3.3 with:

$$h(t) = he^{i\omega t} \quad \text{and} \quad \alpha(t) = \alpha e^{i\omega t}$$

We have:

$$h'' = -\omega^2 he^{i\omega t} \quad \text{and} \quad \alpha'' = -\omega^2 \alpha e^{i\omega t}$$

And the equations of motion become:

$$e^{i\omega t}(-\omega^2 hM - \omega^2 \alpha S_\alpha + hC_h) = L \quad (3.4)$$

$$e^{i\omega t}(-\omega^2 \alpha I_\alpha - \omega^2 hS_\alpha + \alpha C_\alpha) = M \quad (3.5)$$

The equations for the aerodynamic forces were given by Fung [ref.5] and are shown here:

$$L = \pi \rho b^3 \omega^2 (L_h \frac{h}{b} + [L_\alpha - (\frac{1}{2} + a) L_h] \alpha) e^{i\omega t} \quad (3.6)$$

Equating equation 3.4 to 3.6 and 3.5 to 3.7 yields:

Substituting into equation 3.8 and 3.9 for C_h and C_α and using the following dimensional terms:

$$M = \pi \rho b^4 \omega^2 \left([M_h - (\frac{1}{2} + a) L_h] \frac{h}{b} + \right. \\ \left. [M_\alpha - (\frac{1}{2} + a) (L_\alpha + M_h) + (\frac{1}{2} + a)^2 L_h] \alpha \right) e^{i\omega t} \quad (3.7)$$

$$(-\omega^2 M h - \omega^2 \alpha S_\alpha + h C_h) = \pi \rho b^3 \omega^2 (L_h \frac{h}{b} + [L_\alpha - (\frac{1}{2} + a) L_h] \alpha) \quad (3.8)$$

$$(-\omega^2 \alpha I_\alpha - \omega^2 h S_\alpha + \alpha C_\alpha) = \pi \rho b^4 \omega^2 \left([M_h - (\frac{1}{2} + a) L_h] \frac{h}{b} + \right. \\ \left. [M_\alpha - (\frac{1}{2} + a) (L_\alpha + M_h) + (\frac{1}{2} + a)^2 L_h] \alpha \right) \quad (3.9)$$

$$\mu = \frac{M}{\pi \rho b^2} \quad x_\alpha = \frac{S_\alpha}{M b} \quad r_\alpha = \sqrt{\frac{I_\alpha}{M b^2}} \quad (3.10)$$

The equations simplify and after bringing all terms to the left result in:

$$A \frac{h}{b} + B \alpha = 0 \\ D \frac{h}{b} + E \alpha = 0 \quad (3.11)$$

This is a homogeneous equation whose solution is obtained if the flutter determinant is zero.

$$\begin{bmatrix} A & B \\ D & E \end{bmatrix} = 0 \quad (3.12)$$

Where:

$$\begin{aligned}
A &= \mu \left[1 - \left(\frac{\omega_a}{\omega} \right)^2 \left(\frac{\omega h}{\omega_a} \right)^2 (1 + i g_h) \right] + L_h \\
B &= \mu X_a + L_a - L_h (\frac{1}{2} + a) \\
D &= \mu X_a + \frac{1}{2} - L_h (\frac{1}{2} + a) \\
E &= \mu r_a^2 \left[1 - \left(\frac{\omega_a}{\omega} \right)^2 (1 + i g_a) \right] - \frac{1}{2} (\frac{1}{2} + a) + M_a - L_a (\frac{1}{2} + a) + L_h (\frac{1}{2} + a)^2
\end{aligned} \tag{3.13}$$

μ is the ratio of the mass of the wing to the mass of a cylinder of air of a diameter equal to the chord of the wing. ω_a and ω_h are the natural angular frequency (rad/sec) of torsional vibration around "a" (elastic axis) and the natural frequency in deflection, respectively. x_a is the location of center of gravity of the wing measured from a. ω is the circular frequency of wing vibration.

The relationships between the code and Theodorsen derived earlier in Chapter II can be used here to simplify the equations: (note: no damping in this case $g_a = g_h = 0$)

For A: manipulating equation 2.20,

$$L_h = \frac{2C_{Lh}}{\pi K_p^2 \left(\frac{h}{2b} \right)} \tag{3.14}$$

resulting in:

$$A = \mu \left[1 - \left(\frac{\omega_a}{\omega} \right)^2 \left(\frac{\omega h}{\omega_a} \right)^2 \right] + \frac{2C_{La}}{\pi K_p^2 \left(\frac{h}{2b} \right)} \tag{3.15}$$

For B: manipulating equation 2.14,

$$L_a - L_h (1/2 + a) = \frac{4 C_{La}}{\pi K_p^2 \alpha} \quad (3.16)$$

resulting in:

$$B = \mu X_a + \frac{4 C_{La}}{\pi K_p^2 \alpha} \quad (3.17)$$

For D: manipulating equation 2.28

$$L_a - L_h (1/2 + a) = \frac{4 C_{Mh}}{\pi K_p^2 \left(\frac{h}{2b} \right)} \quad (3.18)$$

resulting in:

$$D = \mu X_a + \frac{4 C_{Mh}}{\pi K_p^2 \left(\frac{h}{2b} \right)} \quad (3.19)$$

For E: manipulating equation 2.24

$$-1/2 (1/2 + a) + M_a - L_a (1/2 + a) + L_h (1/2 + a)^2 = \frac{8 C_{Ma}}{\alpha \pi K_p^2} \quad (3.20)$$

resulting in:

$$E = \mu r_a^2 \left[1 - \left(\frac{\omega_a}{\omega} \right)^2 \right] + \frac{8 C_{Ma}}{\alpha \pi K_p^2} \quad (3.21)$$

The determinant is expanded to $AE - BD = 0$, and the real and imaginary parts are set equal to zero. Substituting $(\omega_a/\omega)^2 = X$ and solving the real (2 roots) and imaginary (1 root) equations for values of X corresponding to each reduced frequency value. These X values can be plotted as $\text{SQRT}(X)$

against K_p and any intersections of real and imaginary parts signify a flutter point.

Knowing that :

$$K_p = \frac{2b\omega}{U} \quad \text{and} \quad \sqrt{X} = \left(\frac{\omega_a}{\omega} \right) \quad (3.22)$$

solve for $U_{critical}$

$$U_{critical} = \frac{2b\omega_a}{K_p\sqrt{X}} \quad (3.23)$$

which is the critical flutter speed.

B. UPOTFLUT CODE

1. FORMULATION AND INPUT

The equations derived in the flutter theory section above were programmed into a FORTRAN subroutine and attached to the UPOT.f code. The UPOT code was modified first to enable it to conduct a frequency sweep of pitch and plunge simultaneously. The resulting frequency sweep pitch and plunge array data is then sent to the flutter subroutine which provides the values of $SQRT(x)$ and K_p for plotting. The program also gives a best guess for the $U_{critical}$ based on the difference between the real and imaginary $SQRT(X)$ values. The input file UPOTFLUT.IN is very similar to the regular UPOT.IN file with the addition of actual physical properties of the system being analyzed. The user should start the

analysis in the pitch mode first (IOSCIL =1, ITRANS =0) to ensure complete coverage of all frequencies of interest. The following relations were taken from NACA TR-685 [ref.8] and should prove helpful in determining the physical properties needed for program operation.

$$\kappa = \text{mass ratio} = \pi \rho b^2 / M$$

$$\kappa = 1/\mu$$

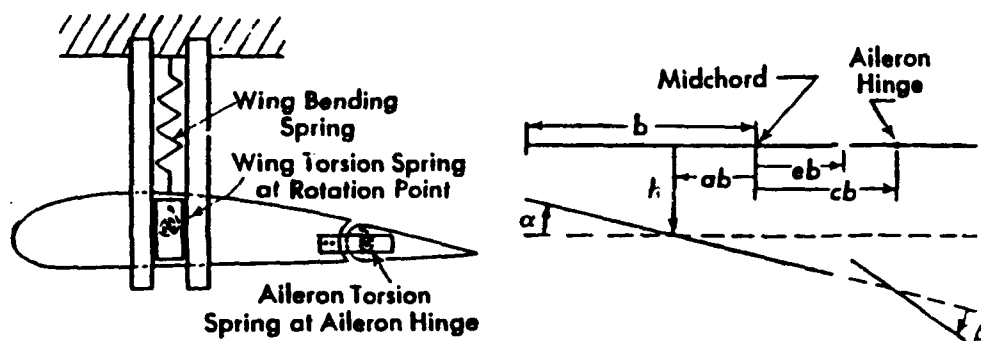
$$x_\alpha = S_\alpha / Mb$$

$$r_\alpha^2 = I_\alpha / Mb^2$$

2. OUTPUT

Outputs from the code have been limited to reduce the amount of computer space taken up by the code operation. A sample input and output file are contained in Figure 3.2. The following list describes the input/output files and the data they contain:

- a. UPOTFLUT.IN The input file figure 3.2a
- b. CL.d Same as UPOT.f output
- c. CM.d Same as UPOT.f output
- d. PHASE.d Same as UPOT.f output
- e. CPSS.d Same as UPOT.f output
- f. CPU005.d Same as UPOT.f output
- g. PHZSWP.d This file contains $K_p, \phi_L, \phi_M, C_{L\alpha}, C_{M\alpha}$
- h. PLHZSWP.d This file contains $K_p, \phi_L, \phi_M, C_{Lh}, C_{Mh}$
- i. PITCH.in This file contains $K_p, C_{L\alpha} \text{ Re}, C_{L\alpha} \text{ Im}, C_{M\alpha} \text{ Re}, C_{M\alpha} \text{ Im}$



- b = semichord (ft.)
- cb = distance between midchord and aileron hinge, positive if aft of midchord (ft.)
- eb = distance between midchord and aileron leading edge, positive aft of midchord (ft.)
- ab = distance between rotation point (elastic axis) and midchord, positive if aft of midchord (ft.)
- h = bending deflection of rotation point (elastic axis), positive downward (ft.)
- α = angular deflection about rotation point (elastic axis), positive for leading edge up (radians)
- β = angular deflection of aileron about aileron hinge relative to wing chord, positive for aileron leading edge up (radians)

Figure 3.1 Simplified System Geometry

```

4
.....
      AIRFOIL TYPE : NACA 0012 AIRFOIL
      NLOWER = 50 , NUPPER = 50
.....
IFLAG  NLOWER  NUPPER
0      50      50
AIRFOIL TYPE
1
IRAMP  IOSCIL  ALPI  ALPMAX  PIVOT
0      1      -3.0   3.0      0.1
FREQ   RFOSCP  RFQENL
.85    .01     .95
IGUST  UGUST   VGUST
0      0.      0.
ITRANS DELHX   DELHY  DELI  PHASE
0      0.00   .0833  -.0833 0.00
CYCLE  NTCYCLF  TOL
3      65      0.005
naot & naot X aoa values multiplied by 10 (integer)
2      05 10 20 25 39 50
Semi-chord  Walpha  Wh  Mass
6           90      72.0  .53789
Ialpha      Salpha  Density
4.84102     .645468 .002378
Comments...

IRAMP 0: n/a          RFREQ is based on full chord
      1: Straight ramp
      2: Modified ramp

IOSCIL 0: n/a          RFREQ is based on full chord
      1: Sinusoidal pitch, motion starts at min Aoa

ITRANS 0: n/a
      1: Translational harmonic oscillation

CYCLE : # of cycles for oscillatory motions
      -In case of ramp, cycle=1.5 denotes airfoil is held
        at max aoa for the duration of .5 cycle
      -For steady state solution set it to 0

NTCYCLE: # of time steps for each cycle
      CYCLE*NTCYCLE is limited to 200 currently.

NAOT: # of input aoa for cp output
      - angles should be in increasing order,
      - for oscillatory motions angles should increase
        first, then decrease. Decreasing angles are for
        the return cycle..

SEMI-CHORD Half Chord in feet.

Walpha,Wh, uncoupled natural frequencies of the system in question.
      Walpha is pitch and Wh is plunge(HZ).

Mass      specific mass of the system in slugs/foot of span

Ialpha    Moment of Inertia of system about the elastic axis(a)
           per unit span length.

Salpha    Static moment of wing-alleron per unit span length

Density   Mass of air per unit of volume(slugs per ft^3)

```

Figure 3.2a UPOTFLUT.in example input file

```

stdln
Page 1
*****
AIRFOIL TYPE : NACA 0012 AIRFOIL
NLOWER = 50 , NUPPER = 50
*****
OSCILLATORY MOTION, IOSCIL = 1

FREQ SWEEP
FREQ = 0.850000

      PHASE SHIFT ANALYSIS
      FREQ = 0.8500000
w 0.8500000
kp= 0.8500000 ifreq 1
AMPLITUDE; clamp, cmamp : 0.2316691 2.9221054E-02
ioscil = 0itrans = 0
PHASE; clp, cmp : 202.4033 -63.70797
AVERAGE DRAG, TOTAL DRAG : 1.5930884E-03 0.1051438
ETAS, WBAR : -0.1430808 -1.1134184E-02

      PHASE SHIFT ANALYSIS
      FREQ = 0.8500000
w 0.8500000
kp= 0.8500000 ifreq 1
AMPLITUDE; clamp, cmamp : 0.2779089 2.2117507E-02
ioscil = 0itrans = 1
PHASE; clp, cmp : 270.5030 37.10253
AVERAGE DRAG, TOTAL DRAG : -6.2051453E-03 -0.4095396
ETAS, WBAR : 0.1050769 -0.1181067

FREQ SWEEP
FREQ = 0.860000

      PHASE SHIFT ANALYSIS
      FREQ = 0.8600000
w 0.8600000
kp= 0.8600000 ifreq 2
AMPLITUDE; clamp, cmamp : 0.2317267 2.9490557E-02
ioscil = 0itrans = 0
PHASE; clp, cmp : 202.8760 -63.85251
AVERAGE DRAG, TOTAL DRAG : 1.5921656E-03 0.1050829
ETAS, WBAR : -0.1398697 -1.1383206E-02

      PHASE SHIFT ANALYSIS
      FREQ = 0.8600000
w 0.8600000
kp= 0.8600000 ifreq 2
AMPLITUDE; clamp, cmamp : 0.2804866 2.2494521E-02
ioscil = 0itrans = 1
PHASE; clp, cmp : 270.7843 36.79393
AVERAGE DRAG, TOTAL DRAG : -6.3188463E-03 -0.4170439
ETAS, WBAR : 0.1047920 -0.1205979

FREQ SWEEP
FREQ = 0.870000

      PHASE SHIFT ANALYSIS
      FREQ = 0.8700000
w 0.8700000

```

Figure 3.2b UPOTFLUT example output file

```

sidin Page 2
kp= 0.8700000 ifreq 3
AMPLITUDE: clamp, cmamp : 0.2317936 2.9765518E-02
ioscil = Oitrans = 0
PHASE: clp, cmp : 203.3604 -64.02047
AVERAGE DRAG, TOTAL DRAG : 1.5893428E-03 0.1048966
ETAS, WBAR : -0.1365460 -1.1639614E-02

PHASE SHIFT ANALYSIS
FREQ = 0.8700000
w 0.8700000
kp= 0.8700000 ifreq 3
AMPLITUDE: clamp, cmamp : 0.2830637 2.2874046E-02
ioscil = Oitrans = 1
PHASE: clp, cmp : 271.0655 36.47753
AVERAGE DRAG, TOTAL DRAG : -6.4334869E-03 -0.4246101
ETAS, WBAR : 0.1045149 -0.1231114

FREQ SWEEP
FREQ = 0.8800000

PHASE SHIFT ANALYSIS
FREQ = 0.8800000
w 0.8800000
kp= 0.8800000 ifreq 4
AMPLITUDE: clamp, cmamp : 0.2318744 3.0037180E-02
ioscil = Oitrans = 0
PHASE: clp, cmp : 203.8330 -64.15525
AVERAGE DRAG, TOTAL DRAG : 1.5880425E-03 0.1048108
ETAS, WBAR : -0.1335113 -1.1894441E-02

PHASE SHIFT ANALYSIS
FREQ = 0.8800000
w 0.8800000
kp= 0.8800000 ifreq 4
AMPLITUDE: clamp, cmamp : 0.2856959 2.3258235E-02
ioscil = Oitrans = 1
PHASE: clp, cmp : 271.3546 36.17284
AVERAGE DRAG, TOTAL DRAG : -6.5488103E-03 -0.4322215
ETAS, WBAR : 0.1042214 -0.1256711

FREQ SWEEP
FREQ = 0.8900000

PHASE SHIFT ANALYSIS
FREQ = 0.8900000
w 0.8900000
kp= 0.8900000 ifreq 5
AMPLITUDE: clamp, cmamp : 0.2319494 3.0311935E-02
ioscil = Oitrans = 0
PHASE: clp, cmp : 204.3115 -64.29196
AVERAGE DRAG, TOTAL DRAG : 1.5859993E-03 0.1046759
ETAS, WBAR : -0.1304959 -1.2153637E-02

PHASE SHIFT ANALYSIS
FREQ = 0.8900000
w 0.8900000
kp= 0.8900000 ifreq 5
AMPLITUDE: clamp, cmamp : 0.2883391 2.3644408E-02

```

Figure 3.2c UPOZFLOT example output file

```

                                stdin                                Page 3

ioscil =                      Oitrans =          1
PHASE;      clp,      cmp      : 271.6436      35.87401
AVERAGE DRAG, TOTAL DRAG : -6.6649993E-03 -0.4398900
ETAS, WBAR      : 0.1039310      -0.1282581

FREQ SWEEP
FREQ = 0.900000

                                PHASE SHIFT ANALYSIS
                                FREQ = 0.9000000
w 0.9000000
kp= 0.9000000      ifreq      6
AMPLITUDE; clamp, cmamp : 0.2320280      3.0592278E-02
ioscil =                      Oitrans =          0
PHASE;      clp,      cmp      : 204.7803      -64.43259
AVERAGE DRAG, TOTAL DRAG : 1.5828811E-03 0.1044701
ETAS, WBAR      : -0.1274617      -1.2418482E-07

                                PHASE SHIFT ANALYSIS
                                FREQ = 0.9000000
w 0.9000000
kp= 0.9000000      ifreq      6
AMPLITUDE; clamp, cmamp : 0.2909827      2.4039967E-02
ioscil =                      Oitrans =          1
PHASE;      clp,      cmp      : 271.9288      35.58691
AVERAGE DRAG, TOTAL DRAG : -6.7821071E-03 -0.4476191
ETAS, WBAR      : 0.1036481      -0.1308680

FREQ SWEEP
FREQ = 0.910000

                                PHASE SHIFT ANALYSIS
                                FREQ = 0.9100000
w 0.9100000
kp= 0.9100000      ifreq      7
AMPLITUDE; clamp, cmamp : 0.2321466      3.0865142E-02
ioscil =                      Oitrans =          0
PHASE;      clp,      cmp      : 205.2529      -64.61227
AVERAGE DRAG, TOTAL DRAG : 1.5800473E-03 0.1042831
ETAS, WBAR      : -0.1245367      -1.2687406E-02

                                PHASE SHIFT ANALYSIS
                                FREQ = 0.9100000
w 0.9100000
kp= 0.9100000      ifreq      7
AMPLITUDE; clamp, cmamp : 0.2936268      2.4440434E-02
ioscil =                      Oitrans =          1
PHASE;      clp,      cmp      : 272.2159      35.29980
AVERAGE DRAG, TOTAL DRAG : -6.9000078E-03 -0.4554005
ETAS, WBAR      : 0.1033707      -0.1335003

FREQ SWEEP
FREQ = 0.920000

                                PHASE SHIFT ANALYSIS
                                FREQ = 0.9200000
w 0.9200000
kp= 0.9200000      ifreq      8

```

Figure 3.2d UPOTFLUT example output file

```

AMPLITUDE: clump, cump : 0.2322159      3.1136697E-02
ioscil = Oitrons = 0
PHASE: clp, cmp : 205.1373      -64.69626
AVERAGE DRAG, TOTAL DRAG : 1.5182372E-03      0.1041637
ETAS, WBAR : -0.1218763      -1.2949497E-02

```

PHASE SHIFT ANALYSIS
FREQ = 0.9200000

```

w 0.9200000
kp 0.9200000 ifreq 8
AMPLITUDE: clump, cump : 0.2962705      2.4841581E-02
ioscil = Oitrons = 1
PHASE: clp, cmp : 272.5011      35.01268
AVERAGE DRAG, TOTAL DRAG : -7.0186830E-03      -0.4632331
ETAS, WBAR : 0.1030987      -0.1161546

```

FREQ SHEFF
FREQ = 0.9300000

PHASE SHIFT ANALYSIS
FREQ = 0.9299999

```

w 0.9299999
kp 0.9299999 ifreq 9
AMPLITUDE: clump, cump : 0.2324548      3.1417310E-02
ioscil = Oitrons = 0
PHASE: clp, cmp : 206.2080      -64.82713
AVERAGE DRAG, TOTAL DRAG : 1.5755624E-03      0.1039871
ETAS, WBAR : -0.1191657      -1.3221607E-02

```

PHASE SHIFT ANALYSIS
FREQ = 0.9299999

```

w 0.9299999
kp 0.9299999 ifreq 9
AMPLITUDE: clump, cump : 0.2989171      2.9250172E-02
ioscil = Oitrons = 1
PHASE: clp, cmp : 272.7901      34.72948
AVERAGE DRAG, TOTAL DRAG : -7.1382108E-03      -0.4711219
ETAS, WBAR : 0.1028326      -0.1388317

```

FREQ SHEFF
FREQ = 0.9400000

PHASE SHIFT ANALYSIS
FREQ = 0.9399999

```

w 0.9399999
kp 0.9399999 ifreq 10
AMPLITUDE: clump, cump : 0.2324474      3.1699074E-02
ioscil = Oitrons = 0
PHASE: clp, cmp : 206.6846      -64.94821
AVERAGE DRAG, TOTAL DRAG : 1.5715322E-03      0.1037211
ETAS, WBAR : -0.1164358      -1.3496989E-02

```

PHASE SHIFT ANALYSIS
FREQ = 0.9399999

```

w 0.9399999
kp 0.9399999 ifreq 10
AMPLITUDE: clump, cump : 0.3015640      2.5659467E-02
ioscil = Oitrons = 1

```

```

PHASE: clp, cmp : 273.0192      34.44823
AVERAGE DRAG, TOTAL DRAG : -7.2587137E-03      -0.4790751
ETAS, WBAR : 0.1025746      -0.1415304
Number of Kp Values = 10
Plunge Value/Full Chord (h/2h) = 0.0833
Alpha = 3.0000
PIVOT POINT (a) Of Elastic Axis = -0.4000
Half Chord (b) = 6.0000
Alpha Uncoupled Nat. Freq. = 90.0000
Plunge Uncoupled Nat. Freq. = 72.0000
I alpha = 4.8410
S alpha = 0.6455
Mass = 0.5379
Air Density = 0.0024
Mass Ratio = 2.0000
Dist. To Wing CG Aft of Elae. Axis = 0.2000
-----
Kp crit = 0.9000000
DIFF = 1.150723E-03
SORTX = 0.9519428
U crit = 1252.484

```

Figure 3.2e UPOTFLUT example output file

- j. PLUNGE.in This file contains K_p , C_{Lh} RE, C_{Lh} IM, C_{mh} RE, C_{mh} IM
- k. FLUTPLOT.d This file contains K_p , SQRT(x) Re, SQRT(X) RE, SQRT(X) IM

3. VALIDATION

The program was tested against some sample cases to check for code validity. The first case was taken from reference 6 example #1, p. 236. Figures 3.3 and 3.4 show plots of the FLUTPOT.d file. Figure 3.3 shows the initial look over a wide range of K_p and after finding the approximate flutter location Figure 3.4 shows a closer look at the K_p range of interest. This example calculated a $U_{critical}$ of 161.985 ft/sec. which compares favorably to the example value of 162 ft/sec. The next example was taken from NACA TR-685 [ref.8] case #1 p. 8. Figures 3.5 and 3.6 again show the initial and final looks for this analysis. The example called for a $U_{critical}$ of 567 miles/hr and the program returned a value of 570 miles/hr. Next, the code was tested over a range of ω_h/ω_α ratios as done in NACA TR-685, p11., graph I-A(a). Figure 3.7 shows the comparison between the two methods.

Flutloop Example sec. 6.11 (NACA0007,2cyc60,75pan,.5c,.083

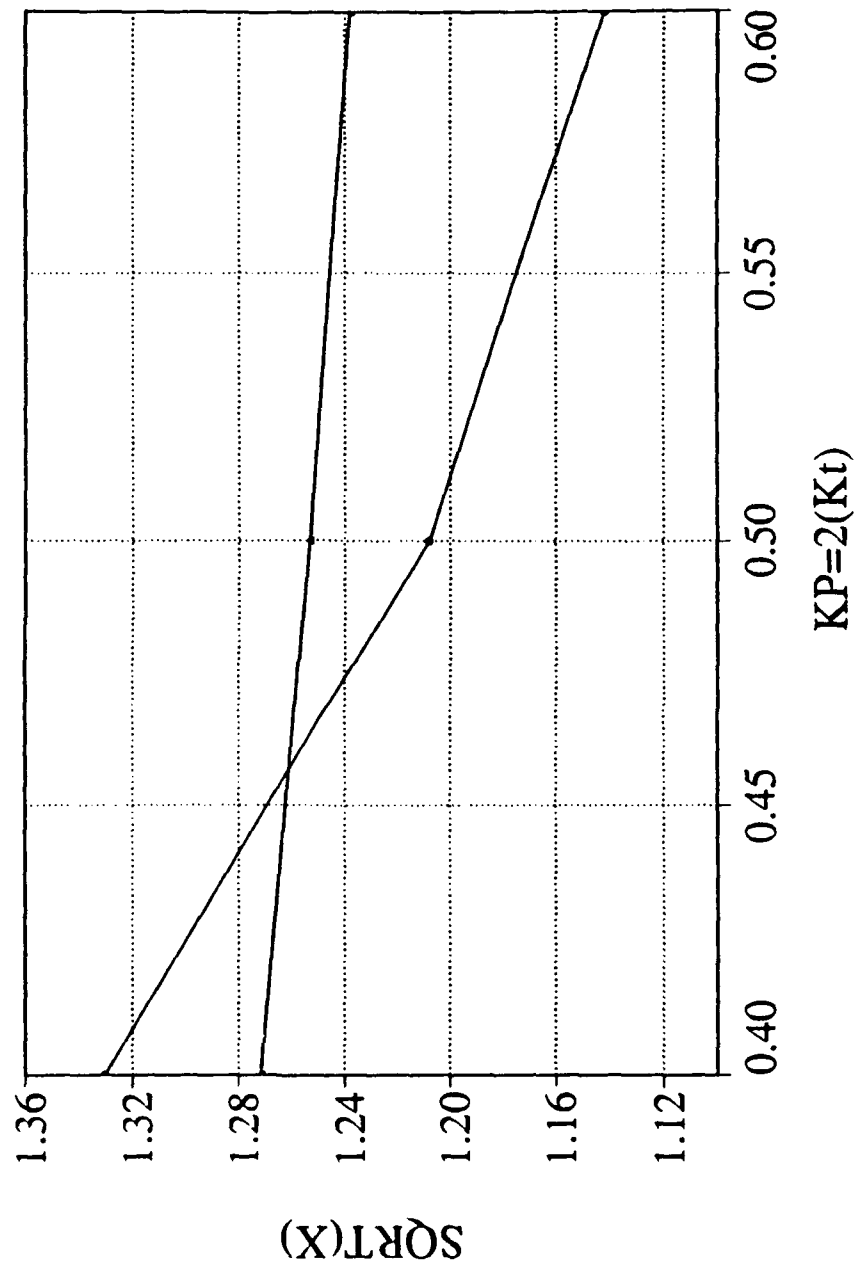


Figure 3.3 Initial look at flutter, example 1

Flutloop Example Sec. 6.11 (N0007,3cyc65,75pan,.5c,.0833,3d

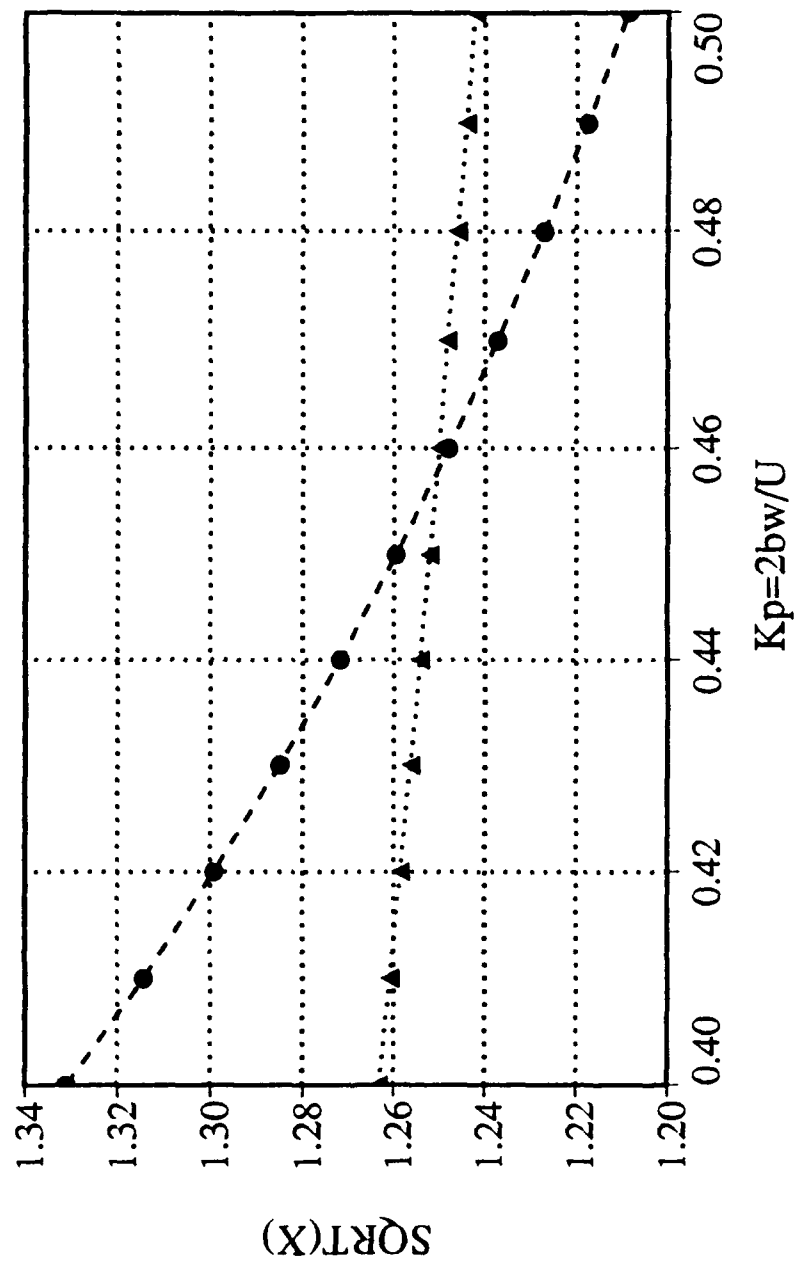


Figure 3.4 Final look at flutter, example 1

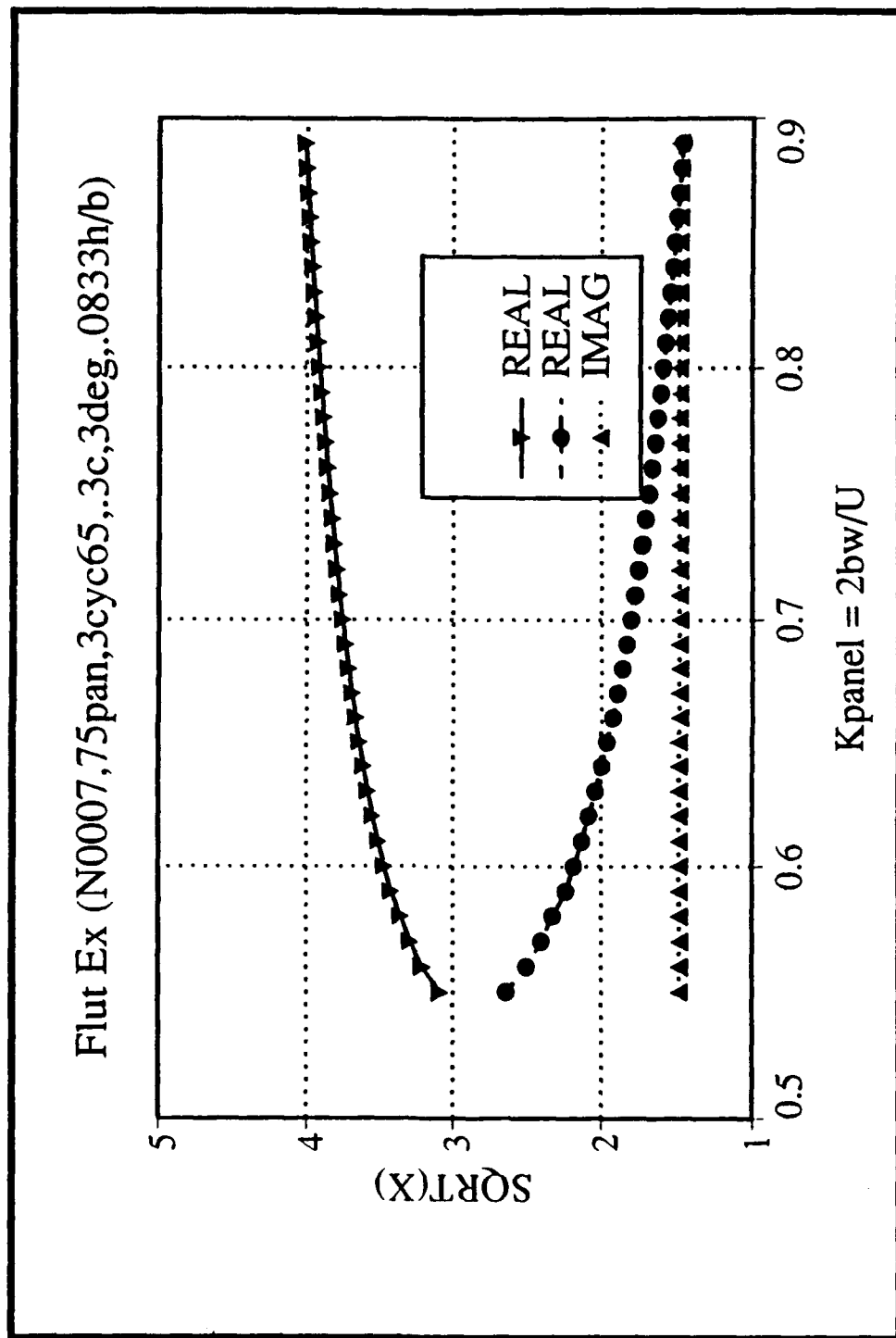


Figure 3.5 Initial look at flutter, example 2

Flutter Ex. (N0007,75pan,3cyc65,3c,3deg)

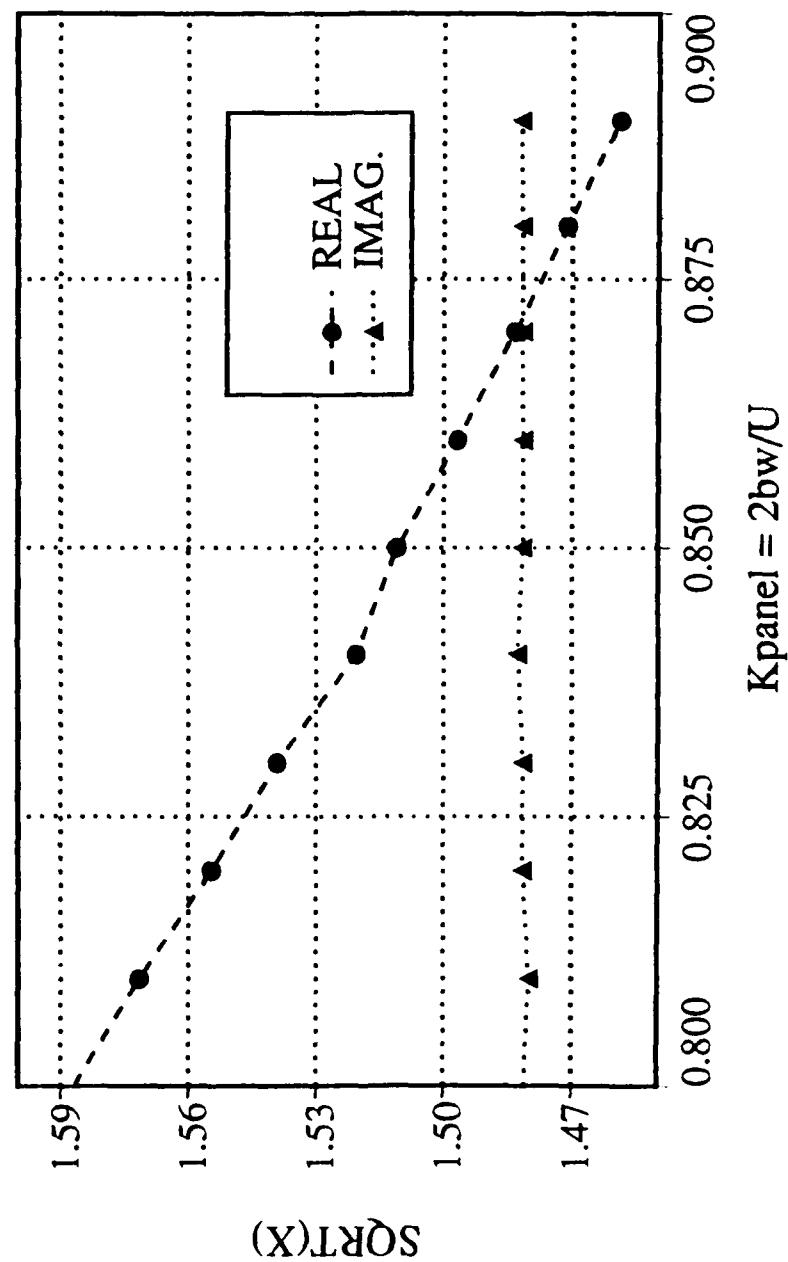


Figure 3.6 Final look at flutter, example 2

Mechanism of Flutter .The effects of changing the ratio of plunge and pitch natural frequencies.				
Panel code vs Theo.		(NACA0007, 50panels, 3deg, h/2b = .0833, 3cyc66calc..)		
(Mass = .53789 slug/ft, lalpha=4.84102, Salpha = .645468,b = ft, std day air density)				
Wh/Walpha	Panel Ucrit.(ft/sec)	Panel (-Ucrit/bWalpha)	Theo (-Ucrit/bWalpha)	%Diff wrt Theo.
0.0111	886.6013	-1.66	-1.7	2.35%
0.2	926.5668	-1.713994	-1.72	0.35%
0.4	960.3143	-1.7783598	-1.8	1.20%
0.5	994.4232	-1.84162	-1.9	3.08%
0.6	1036.167	-1.9168	-2.04	5.84%
0.7	1107.237	-2.060438	-2.22	7.64%
0.8	1262.889	-2.32016	-2.42	4.13%

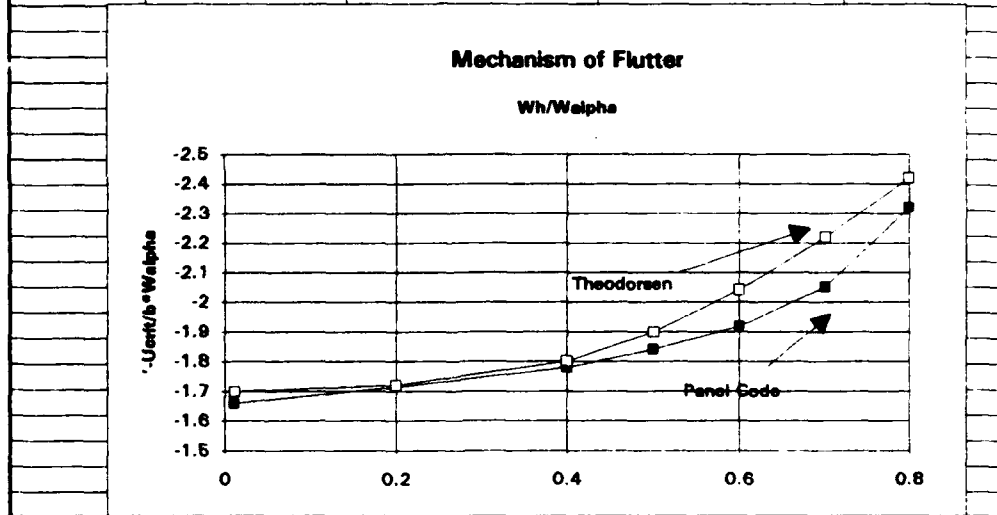


Figure 3.7 ω_h/ω_α Calculations

IV. FLOW VISUALIZATION EXPERIMENT

A. INTRODUCTION

The purpose of this experiment was to document the production of thrust by a plunging airfoil. This was a preliminary experiment to better understand the vortex pattern produced by a plunging airfoil, and to examine the production of thrust using smoke flow visualization techniques.

An explanation of what constitutes a propulsive vortical signature along with smoke flow visualization of the propulsive vortical patterns is given in Reference 7. In this reference, the explanation is given by contrasting the vortical pattern produced by a cylinder (drag) with the vortical pattern produced by a plunging airfoil (thrust). The cylinder produced a vortical sheet where the top row of vortices rotated clockwise and the bottom row of vortices rotated counterclockwise. This pattern induces a velocity component in the upstream direction (Biot-Savart law). In contrast, the plunging airfoil produced a clockwise rotating vortex sheet on the bottom row. This pattern induces a velocity component in the downstream direction. Reproduction of the flow visualization data from Reference 7 is shown in Figure 4.1.



Figure 4.1 View of flow over cylinder (top) and plunging airfoil (bottom) [Ref. 7]

B. THEORY

A comparison was done using the incompressible panel code, U2DIIF. The purpose of this study was to examine the vortical pattern produced by the panel code, and determine if the vortical signature matched experimental results. The input to the panel code was set up to best match the conditions of the experiment described in the next section. The panel code was run using a plunge amplitude, $h/2b$ equal to .1977, a reduced frequency of 1.8 and a zero mean AOA. The results of the vortical pattern are shown in Figure 4.2. Aside from the starting vortex, this is clearly a thrust producing vortical sheet. Furthermore, the vortical pattern is similar to that produced by the experiment shown in Figures 4.10 and 4.11.

C. EXPERIMENTAL SETUP

1. Plunging Airfoil

The plunging airfoil used in this paper was originally a wing taken from the rotor of a model helicopter. The wing was attached to a MB250 Shaker Table as shown in Figure 4.3. The wing was made from a NACA0007 airfoil section and consisted of a 2.45" chord and a 22" span. The wing was built from a foam core and finished with a layer of graphite epoxy composite for added fatigue strength. The airfoil's drive mechanism was a MB 250 Shaker Table capable of 1" total

Wake Pattern (plunge.h/2b=.1977,N0007,Kp=1.8,.25c,3cyc65)

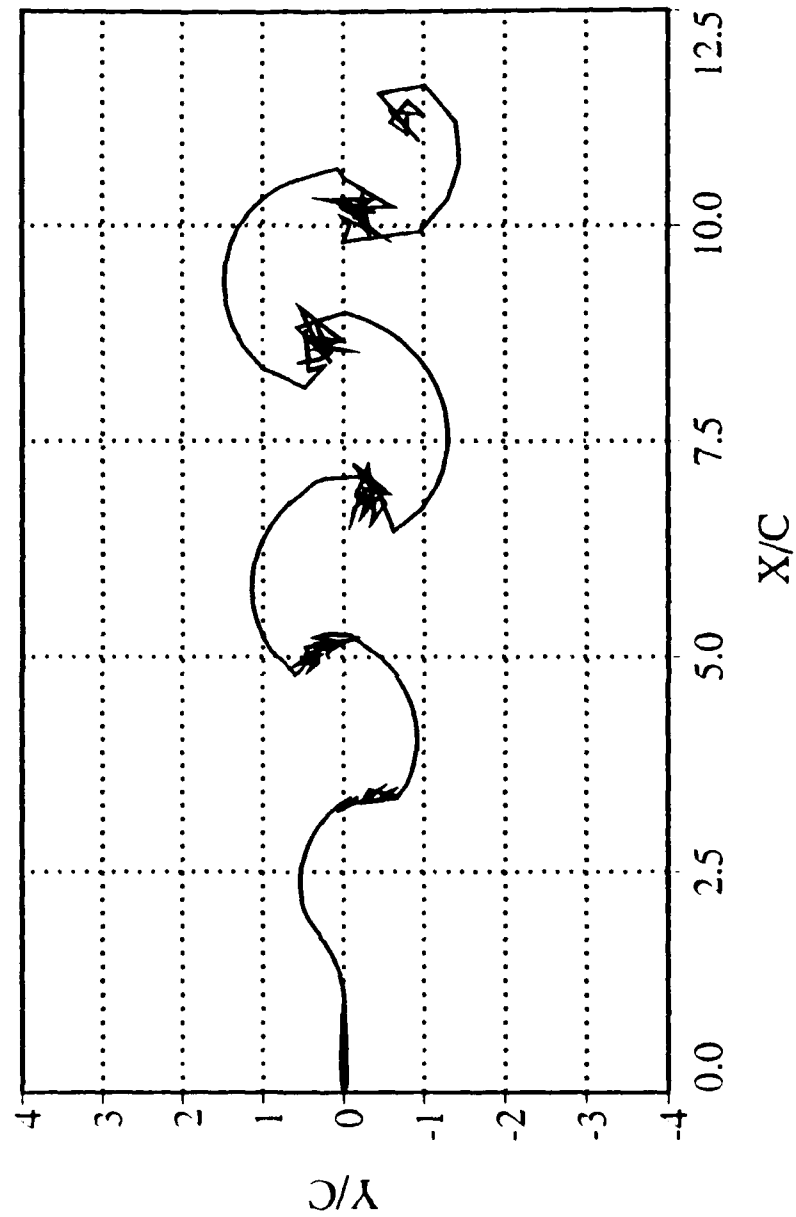


Figure 4.2 Wake pattern produced by U2DIIF code

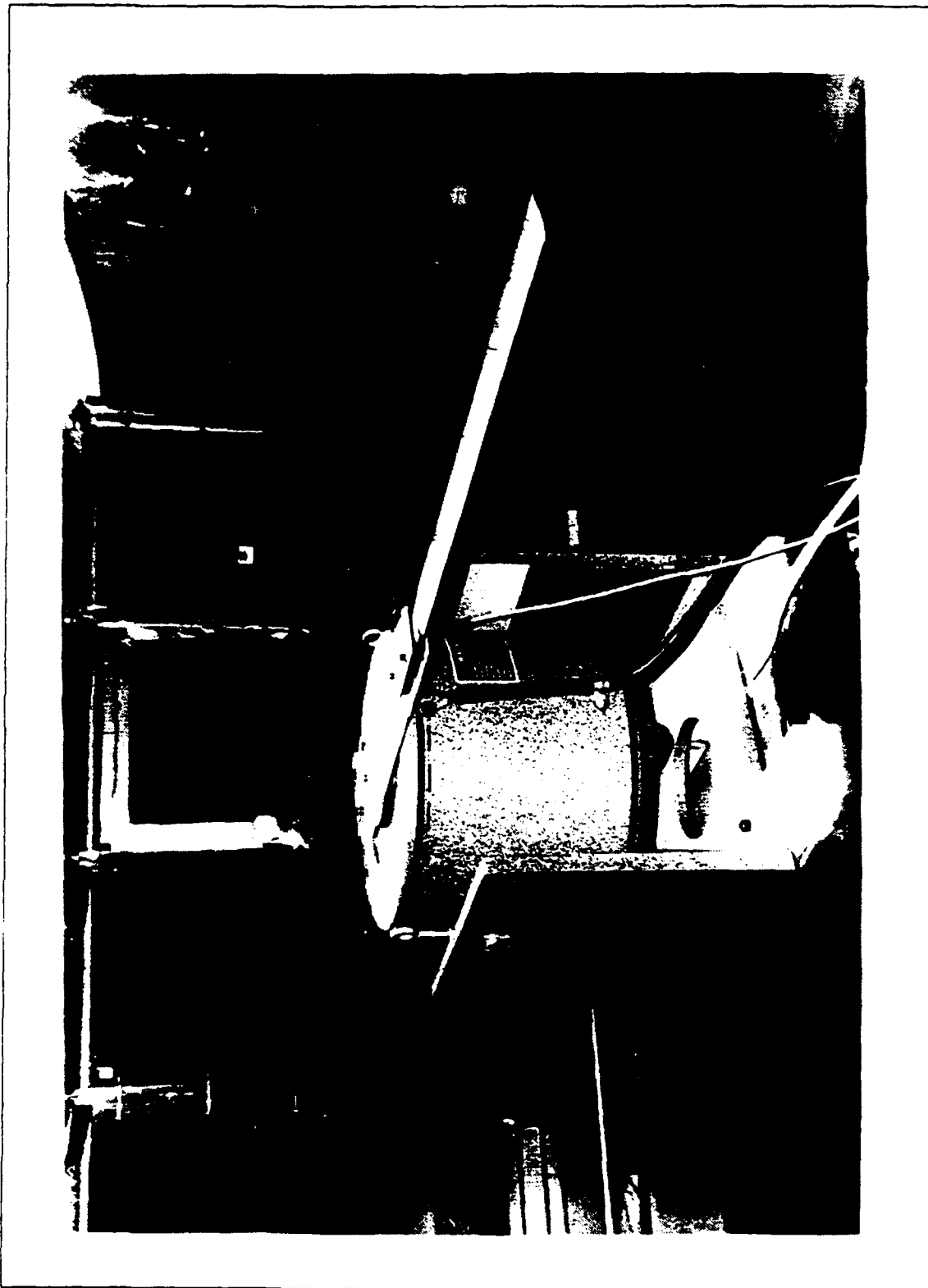


Figure 4.3 Shaker table with wing

deflection. The Shaker Table was limited only by resonance frequencies of the wing which occurred around 20 Hz or 1200 rpm.

2. WIND TUNNEL

The wind tunnel used in this experiment was a very low speed, low turbulence smoke tunnel. It is made of plexiglass walls and a contraction ratio of 2.8:1. The motor provides wind tunnel velocities between 0 and 10 feet per second (fps). The smoke was created using a Rosco smoke generator and piped into the tunnel in the test section using a small seven tube smoke rake constructed for this experiment. Figure 4.4 is a photograph of the wind tunnel and smoke rake used in this experiment.

D. TEST PROCEDURE

Testing was conducted in the low speed smoke tunnel under several different conditions. The speeds of the tunnel were approximately 1.04 fps, 1.47 fps, and 1.56 fps (measured visually). These low speeds allowed good pictures and the ability to get higher reduced frequencies without calling for too high a load on the wing. The actual plunging harmonic frequencies ranged from 1 to 15 Hz and amplitudes from 1/16" to 1" peak to peak. The tunnel was initially turned off and the Shaker Table turned on with stagnant smoke in the tunnel. The purpose was to see if the plunging airfoil would draw the smoke through the tunnel like



Figure 4.4 Tunnel and smoke rake

a fan, thus showing the production of thrust by the plunging airfoil.

Photos were taken using a Nikon 35mm camera and Kodak TMAX-400 ASA black and white film. The shutter speed was set to 1/125 seconds with an aperture setting of 4.0 for the light conditions. Film developing time was optimized at 9 minutes at 75 degrees F.

E. RESULTS AND DISCUSSION

The result for the tunnel off condition flow visualization experiment was as expected. The wing in fact accelerated the smoke in its vicinity.

The result of the additional rake flow visualization experiments are shown in Figures 4.5-4.14. Figure 4.5 shows the stationary airfoil at zero degree AOA. The Reynolds number (based on airfoil chord) is 10,000. It can be seen that the airfoil produces a small wake with the boundary layer mostly attached. Figures 4.6 through 4.14 show the vortical wake flow patterns produced by plunge oscillations at various frequencies as indicated. Most of these pictures reveal the propulsive vortical street pattern discovered in Reference 7. Previous experiments by Neace, [ref.9] found that the tunnel was too small for the airfoil size used, but the airfoil size for the present experiment seemed to be optimum, as seen by the long trail of vortices. The vortical patterns show that the bottom vortex is rotating clockwise, and the top vortex is

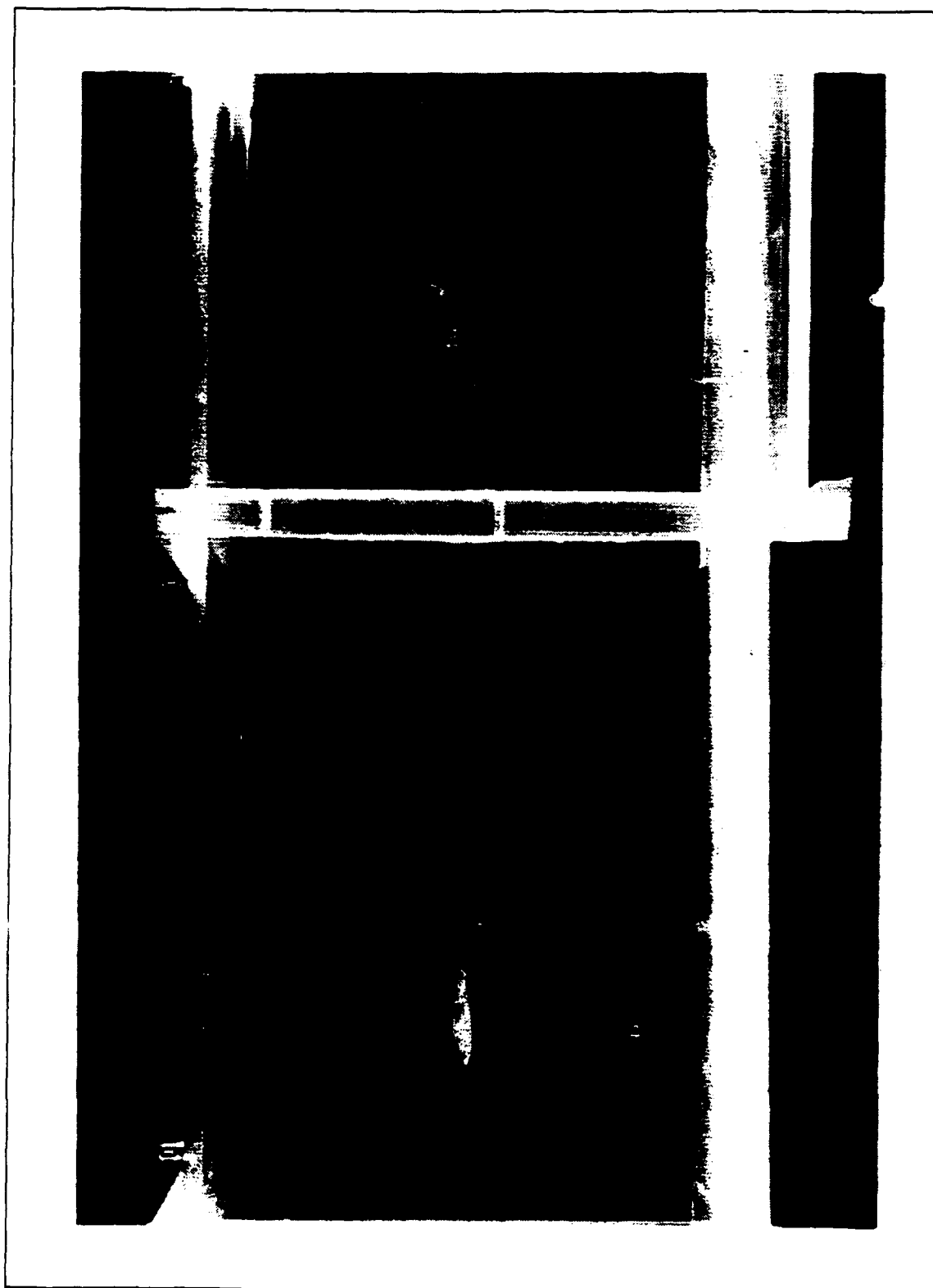


Figure 4.5 Steady airfoil 1.56 ft/s



Figure 4.6 $K_p = 1.8008$, $r/2b = .1977$, 1.56 ft/s

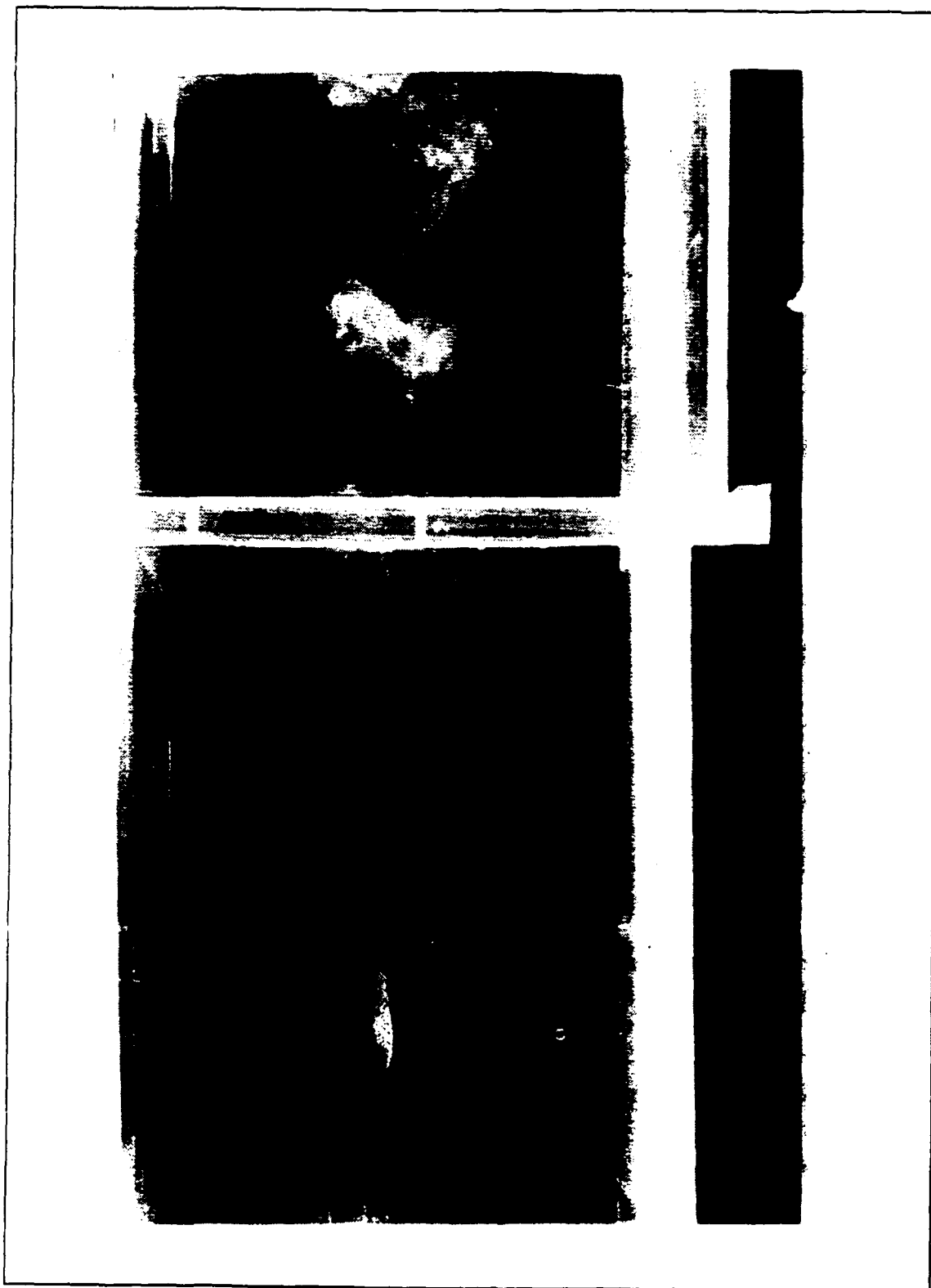


Figure 4.7 $K_p = 2.467$, $h/2b = .10204$, 1.56 ft/s

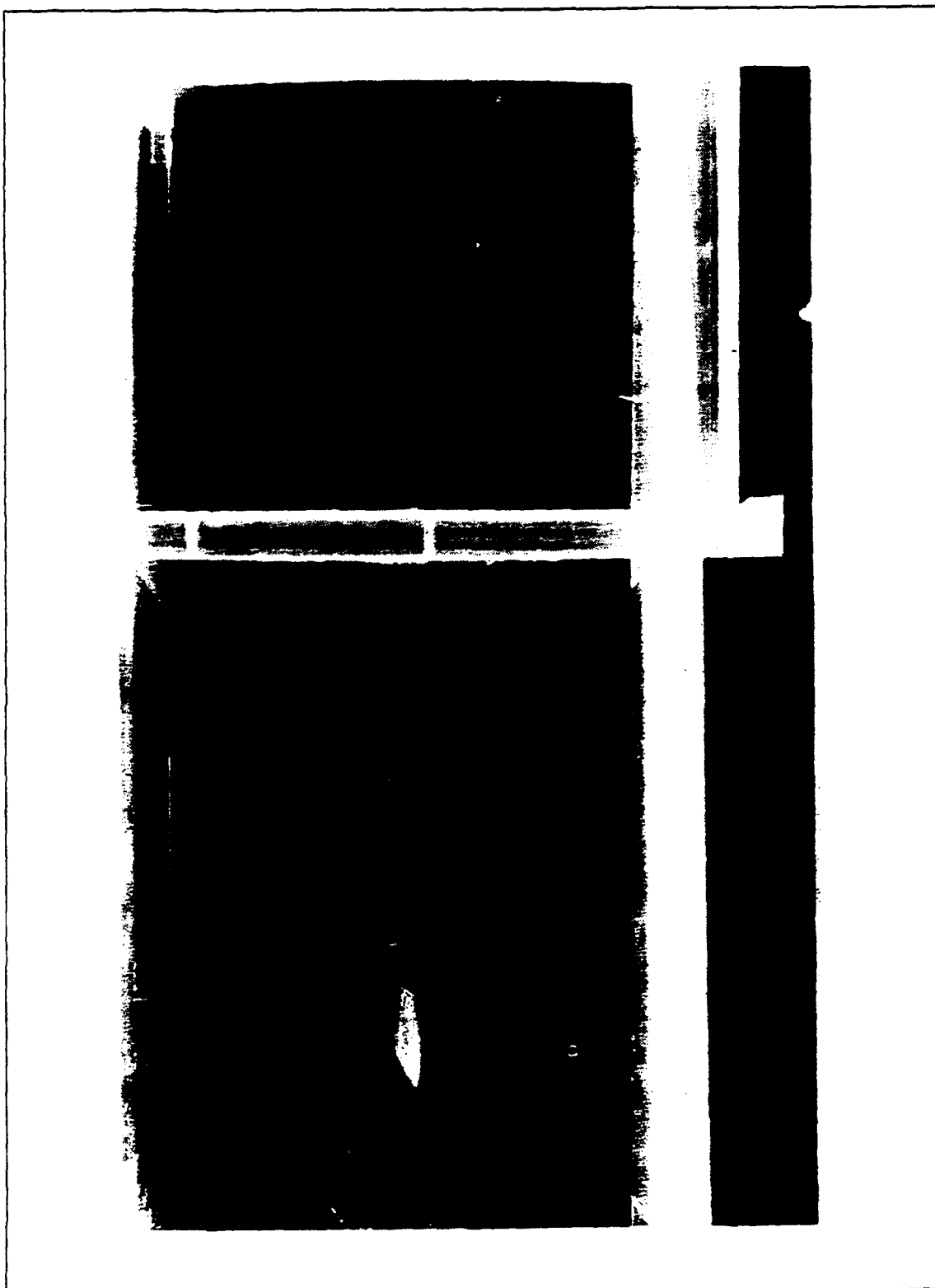


Figure 4.8 $K_p = 2.467$, $h/2b = .1913$, 1.56 ft/s

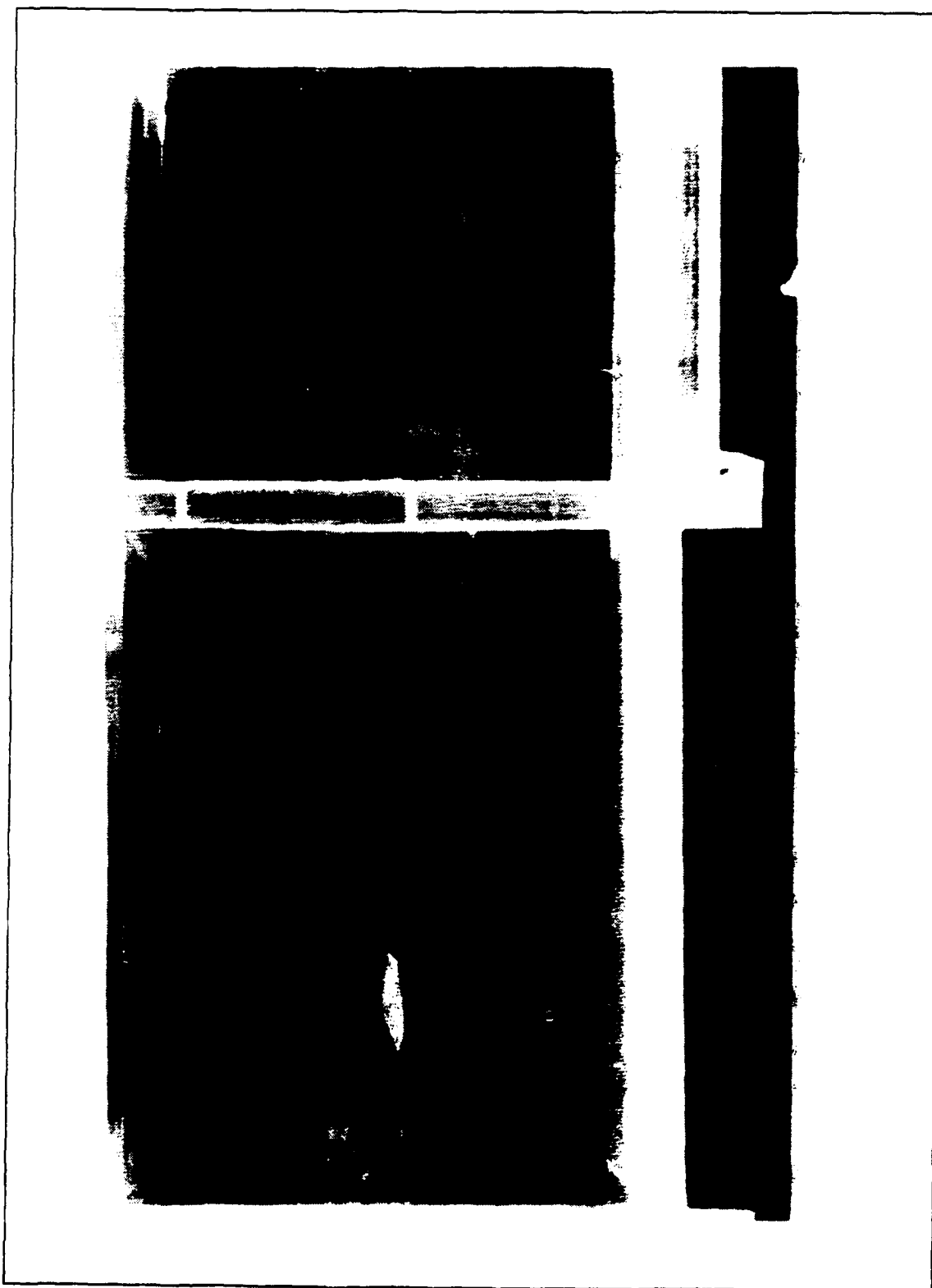


Figure 4.9 $K_p = 4.112$ $h/2b = .14031$, 1.56 ft/s

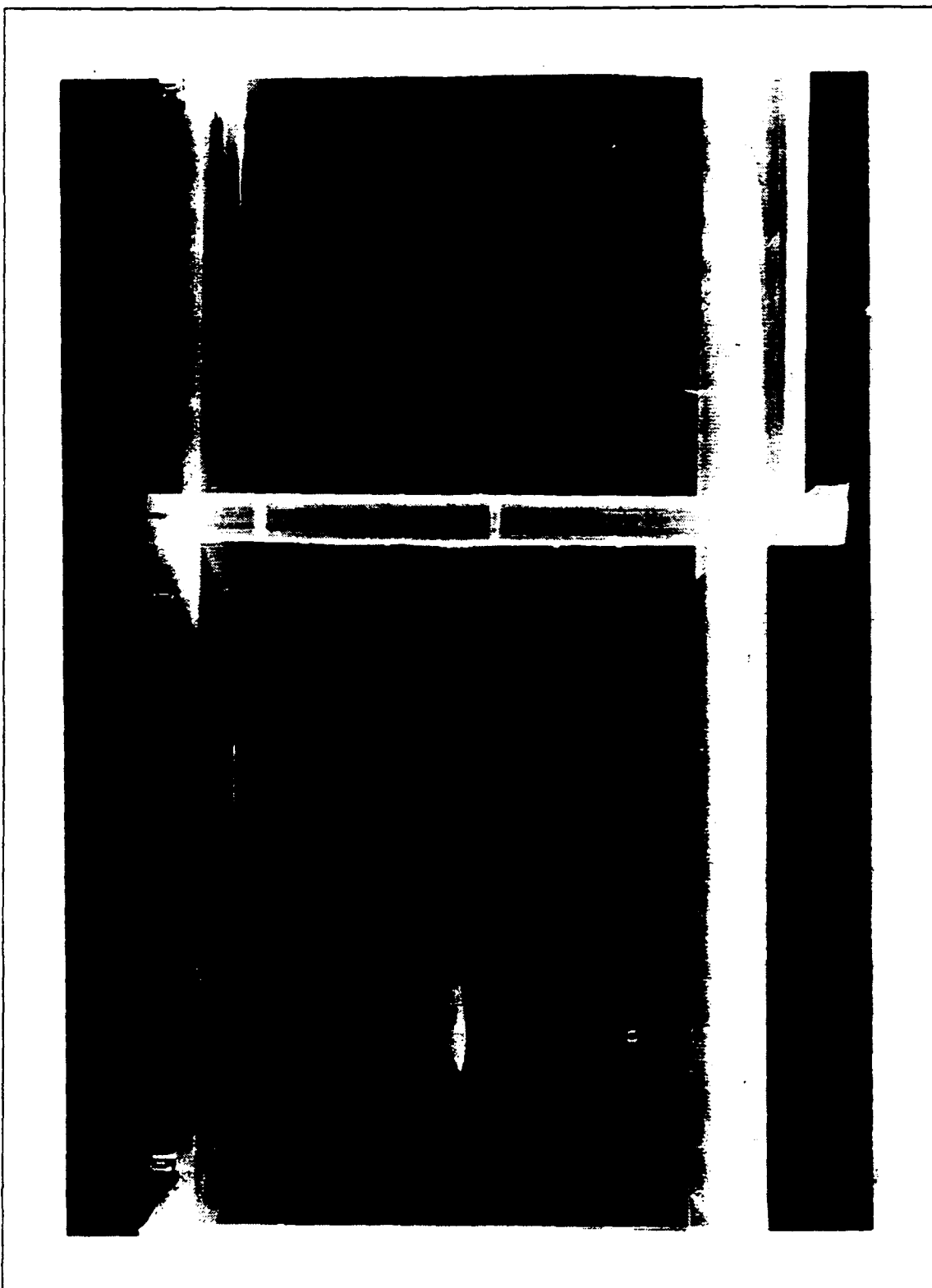


Figure 4.10 $K_p = 6.167$, $h/2b = .05102$, 1.56 ft/s



Figure 4.11 $R_p = 6.753$, $h/2b = .1084$, 1.56 ft/s

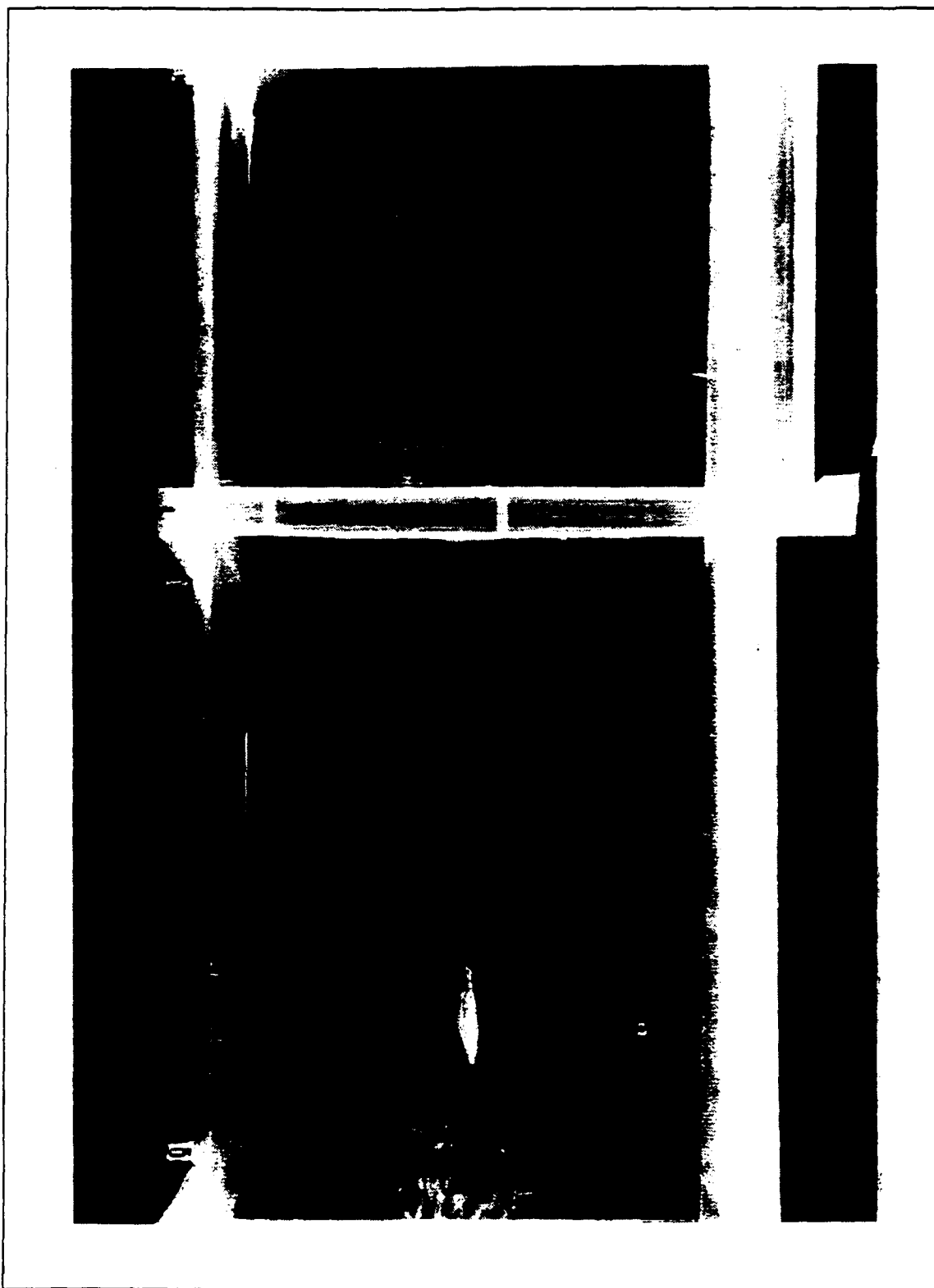


Figure 4.12 $K_p = 7.401$, $h/2b = .03826$, 1.56 ft/s

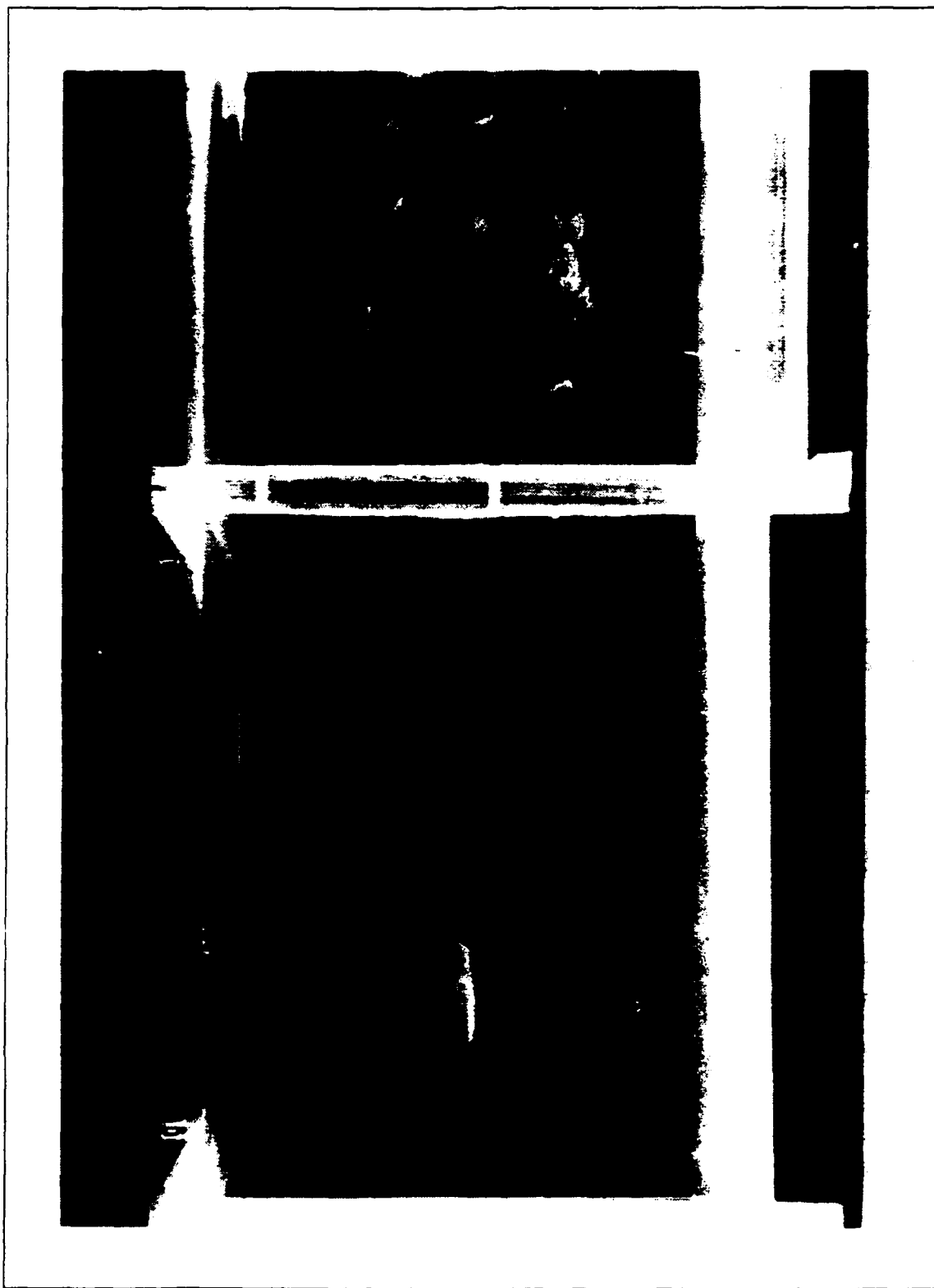


Figure 4.13 $K_p = 8.223$, $h/2b = .01913$, 1.56 ft/s

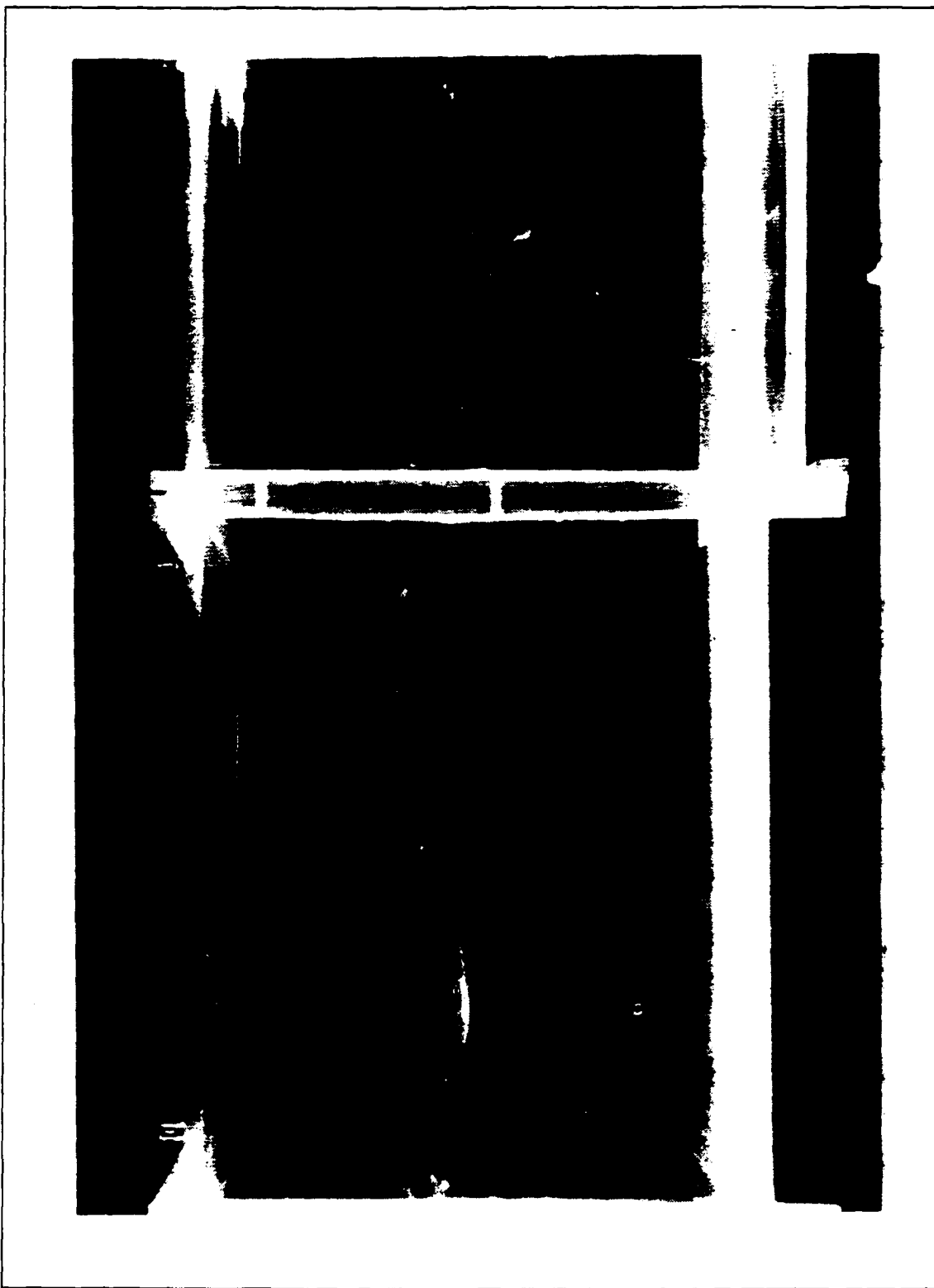


Figure 4.14, $K_p=12.335$, $h/2b=.01775$, 1.56 ft/s

rotating counterclockwise, which is a thrust producing vortical sheet. It can be seen in the pictures that the frequency greatly affects the vortical strength (size). Increasing the frequency leads to an increase in wake vorticity.

V. LIFT ENHANCEMENT PRODUCED BY A PLUNGING AIRFOIL

A. THEORY

Chapter IV demonstrated the propulsive capability of a plunging airfoil. The production of thrust implies the generation of a jet flow which, in turn, may be utilized as a boundary layer control device. Therefore, an additional test was conducted in the NPS smoke tunnel in order to explore the feasibility of this concept.

B. SETUP

The same NACA0007 plunging wing was used as in chapter IV with a different driving mechanism. The wing was mounted to an ELECTRO-SEIS Model 113 Shaker Table by APS Dynamics, Inc. The shaker was located below the test section of the NPS smoke tunnel (Figure 5.1). The plunging airfoil was mounted to struts at both ends to prevent excessive bending while plunging. The large airfoil is a cambered profile taken from the rotor of a full size helicopter (13" chord, 2" Thickness, modified NACA airfoil, Reynolds Number of 52,000). The wing is suspended from the tunnel ceiling as shown in the flow pictures. The design allowed for full movement of the big wing to position it in the vicinity of the plunging airfoil.

C. WIND TUNNEL

This study used the Naval Postgraduate School's flow visualization wind tunnel. The tunnel is an open-circuit one, with air entering an inlet that measures 4.5 m X 4.5 m (15'X15'). As the air enters the tunnel, it passes through a 7.5-cm long honeycomb. A 9:1 ratio square contraction cone directs the flow into a test section that is 1.5 m X 1.5 m (5'X5'), and 6.7 m (22') long, as seen in Figure 5.2. The flow is then exhausted into the atmosphere through a fan, which uses variable pitch blades to control the speed of the flow. The speed control toggle switch is located right below the red and green on/off switch located in the left side of the tunnel control room. The tunnel speed was determined using a digital manometer which was verified for accuracy (Figure 5.3).

An observation booth is located on the side of the tunnel. A glass window, 1.6 m X 1.1 m (5.2' X 3.4'), provides the primary viewing area from the observation room and a second one, 0.4 m X 1.23 m (1.33'X4'), is located in the tunnel's roof. The main viewing window had sufficient area for most of the photography, with the top window used for illumination. A circular turntable was located on the floor of the test section [ref.11] which allowed for easy access to the shaker table. The walls and floor of the test section were flat black for low light reflectivity.



Figure 5.1 Shaker table setup below tunnel

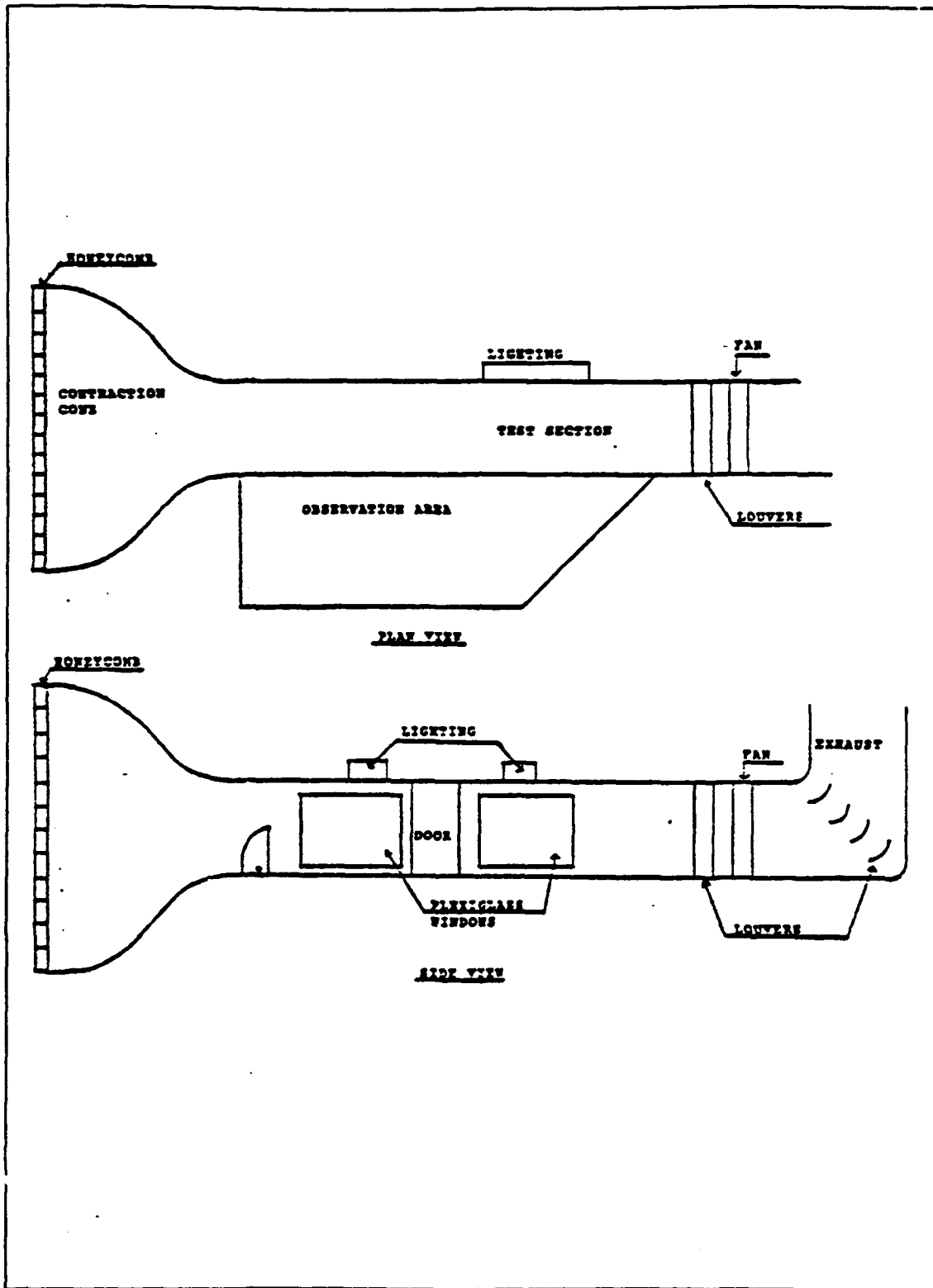


Figure 5.2 Tunnel Layout

Tunnel Velocity Speed Check					
Comparing the digital manometer speed indications against known					
Aerolab Wind Tunnel readings (3 readings taken at each value)					
Digital reading (in H ₂ O)	Aerolab reading (cm H ₂ O)	Dig. Vel. ft/s	Aero. Vel. ft/s	% Diff fm Acad.	
0.0175	0.05	9.2815	9.845	5.72%	
0.04	0.1	14.0338	13.9229	0.80%	
0.0835	0.2	20.2735	19.69	2.96%	
0.131	0.3	25.397	24.115	5.32%	
0.173	0.4	29.1845	27.8459	4.81%	
0.22	0.5	32.912	31.132	5.72%	
0.263	0.6	35.985	34.1	5.53%	
0.343	0.8	41.095	39.38	4.36%	
0.43	1	46.013	44.028	4.51%	
0.662	1.5	57.09	53.92	5.88%	

Figure 5.3 Tunnel speed check

D. SMOKE GENERATION

The smoke was generated in the Rosco smoke/fog machine. Many different smoke injection techniques were tried but with less than satisfactory results. Smoke rakes were first tried outside the tunnel with the tube number varying from 2 to 30 tubes. The tubes were inserted in the honeycomb and also separated different distances from the inlet of the tunnel. The rake was also tried inside the test section with very bad results (smoke dispersed immediately). Problems ranged from lack of smoke and turbulence when enough smoke was present. The Rosco machine at its lowest setting was producing a very high smoke volume and whenever the flow was restricted by a smoke rake the smoke production went way down. The final technique adopted was very simple. The smoke output was sent directly from the machine to a 1" nozzle which was manually waved at the entrance of the tunnel to make a steady cloud. The steady cloud was gradually pulled into the tunnel, producing a thick smoke sheet in the test section.

E. PHOTOGRAPHY

Photos were taken using a Nikon 35mm camera and Kodak TMAX-400 ASA black and white film. The film speed was set to 1/250 seconds with an aperture setting of 4.0 for the light conditions. Film developing time was optimized at 9 minutes at 75 degrees F.

F. EXPERIMENTAL PROCEDURES

The first step involved a look at the large airfoil to verify normal flow patterns (Figure 5.4 and 5.5) and find the AOA for initial trailing edge separation (Figure 5.6). Next, the plunging airfoil was placed in the tunnel by itself and a run was made to verify the propulsive capability in the larger tunnel at higher speeds. As seen in Figure 5.7, the airfoil produced a drag vortical flow. Figure 5.8 and 5.9 shows the propulsive pattern of the propulsive airfoil. Finally, the two airfoils were placed in close relative position to see the interference effect between the two airfoils.

G. RESULTS AND DISCUSSION

Several airfoil position combinations were studied, as shown in Figures 5.10 through 5.15. Figure 5.10 and 5.11 show the plunging airfoil located at approximately .65 chord of the large airfoil. Figure 5.12 through 5.15 show the plunging airfoil located at approximately .75 chord.

The differences between the plunging on and off condition were not easy to see with the eye but pictures indeed showed some differences between the two conditions. A shortcoming of this experiment was the inability of the plunging airfoil to run parallel with the large airfoil. Additionally, sizing of and relative positioning of the two airfoils was not optimized to give best results. The two airfoils were chosen from the resources available and time constraints prevented a more



Figure 5.4 Large airfoil at zero AOA



Figure 5.5 Large airfoil at 10 degrees AOA



Figure 5.6 Large airfoil at 12 degrees AOA (stall)



Figure 5.7 Plunge airfoil steady

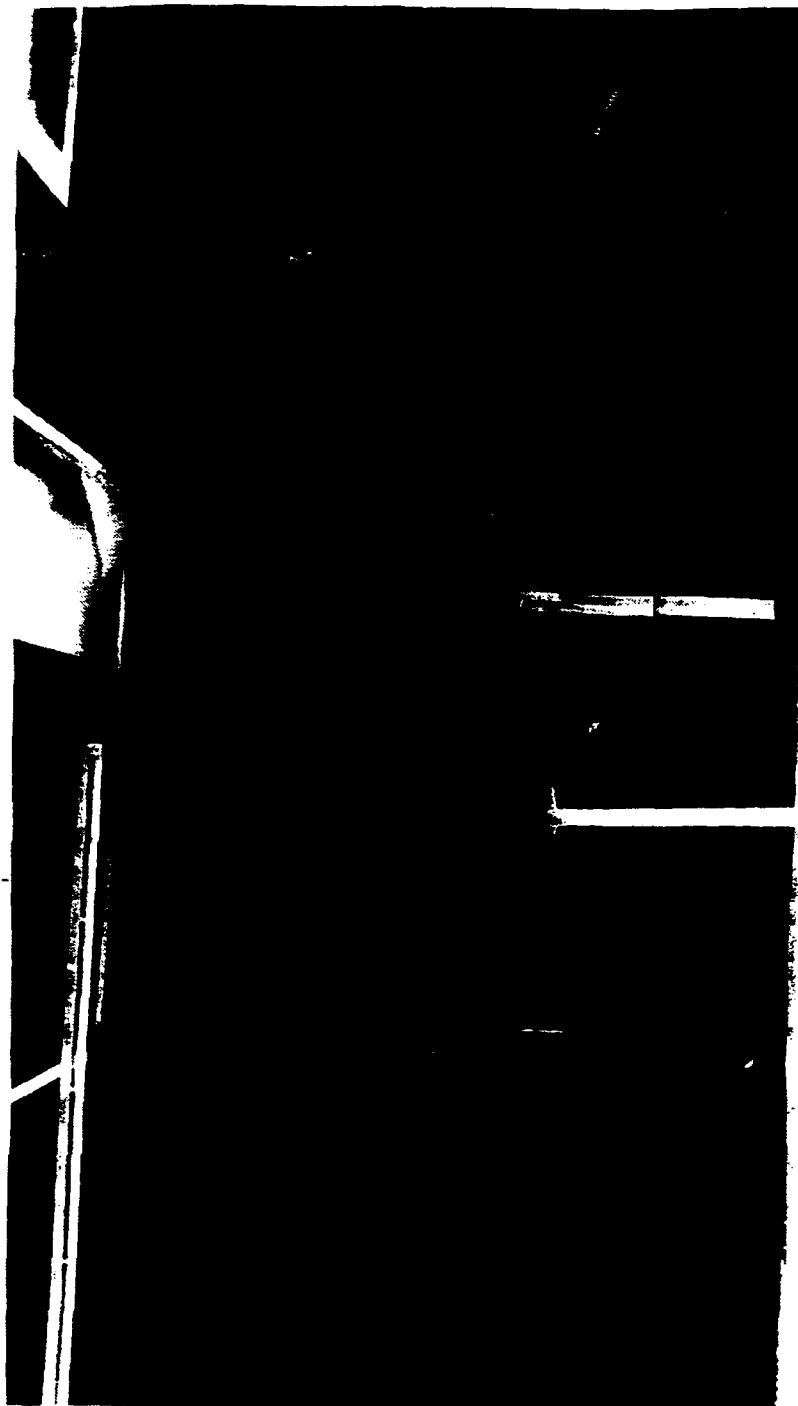


Figure 5.8 Plunging airfoil $K_p=1.71$

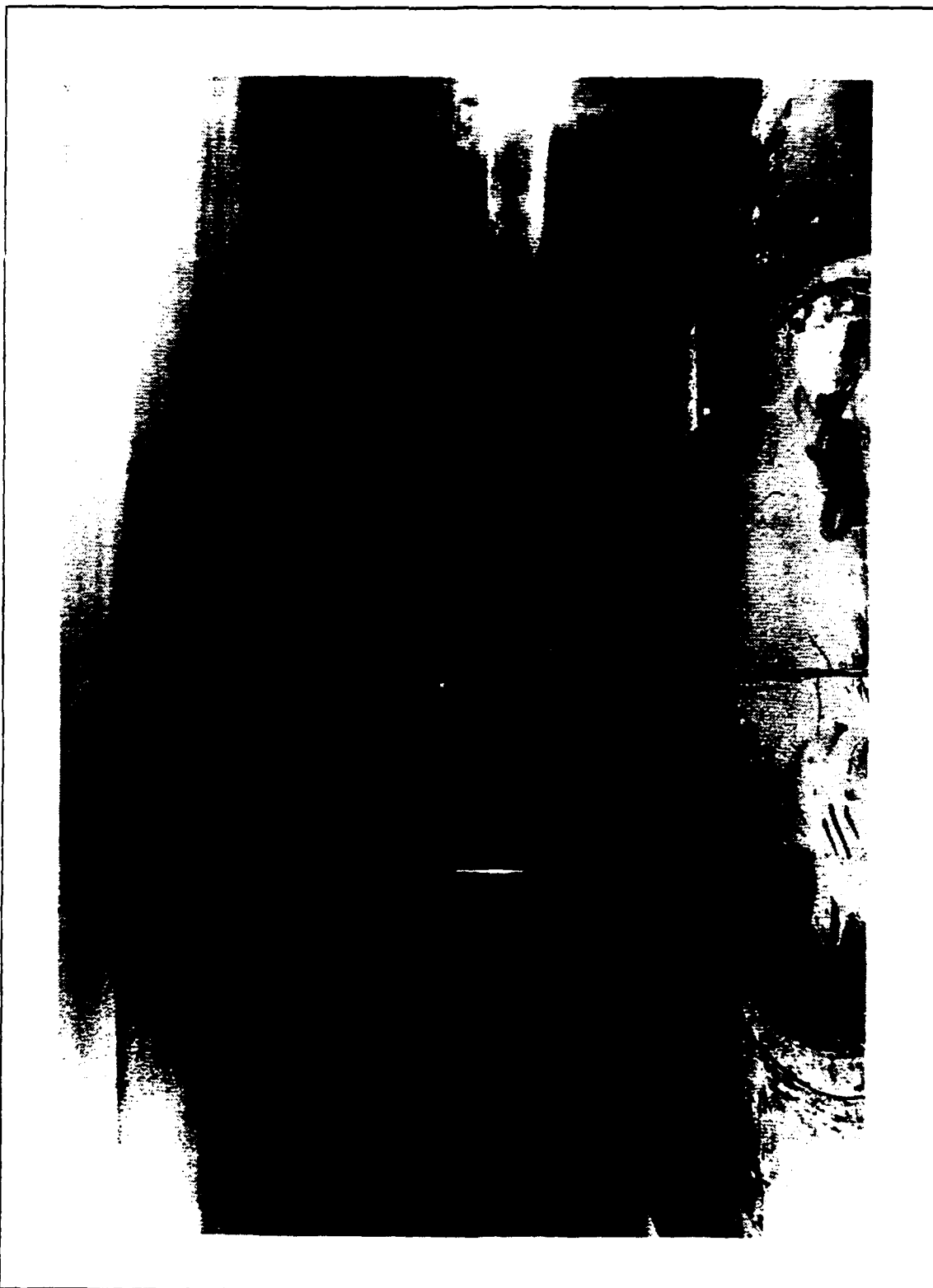


Figure 5.9 Plunging airfoil $K_p=3.42$



Figure 5.10 Large airfoil at 12 degrees AOA, steady plunging
airfoil position 1

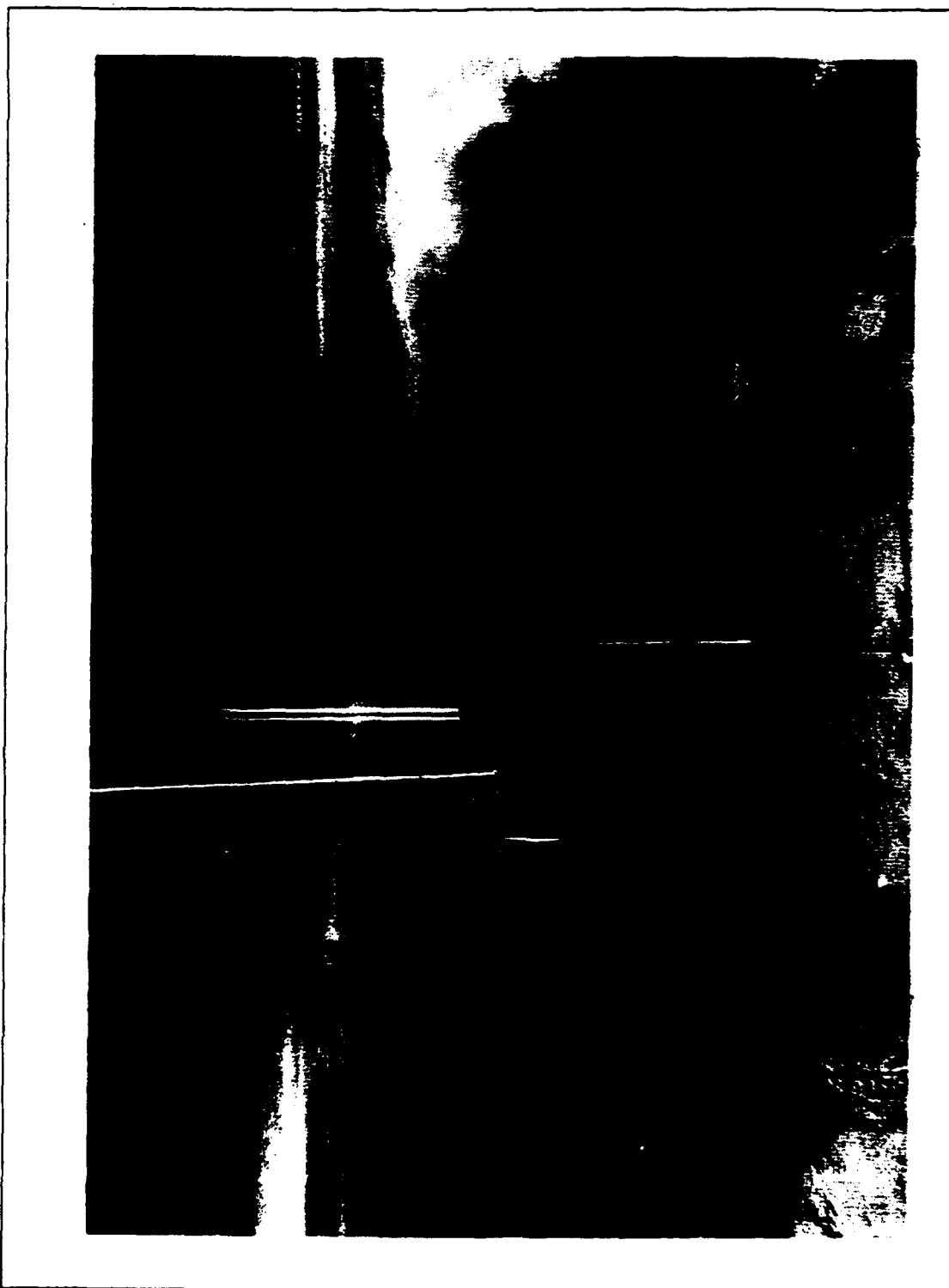


Figure 5.11 Large airfoil at 12 degrees AOA, plunging
airfoil $K_p=3.42$, position 1



Figure 5.12 Large airfoil at 12 degrees AOA, plunging
airfoil steady, position 2



Figure 5.13 Large airfoil at 12 degrees AOA, plunging
airfoil $K_p=3.42$, position 2



Figure 5.14 Large airfoil at 14 degrees AOA, plunging
airfoil steady, position 2



Figure 5.15 Large airfoil at 14 degrees AOA, plunging
airfoil $K_p=3.42$, position 2

detailed investigation of the interference effects between the two airfoils.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. SINGLE AIRFOIL ANALYSIS

The modified version of U2DIIF (UPOT) can perform aerodynamic calculations over any range of reduced frequencies. The nonlinear theory presented here for harmonic motion, and the phase relationships that exist between the airfoil motion and the aerodynamic forces have been extensively verified by comparison with Theodorsen's linear theory. Furthermore, this panel code was applied to the analysis of incompressible bending-torsion airfoil flutter. Again, excellent agreement with the classical Theodorsen analysis was obtained.

Access to faster computational means is recommended to shorten the time needed to predict the flutter points. The code should be modified to incorporate three-dimensional calculations which would help solve more difficult flutter problems.

B. FLOW VISUALIZATION EXPERIMENTS

The flow visualization experiment successfully showed the development of thrust produced by a plunging airfoil. The enhanced lift experiment, on the other hand, was not a complete success. The smoke visualization presented difficulties that were not satisfactorily overcome. As a

result, the pictures taken were somewhat inconclusive. Furthermore, the angle of attack of the oscillating airfoil could not be changed thus making it difficult to achieve a flow condition conducive to lift enhancement.

It is recommended that further experiments be conducted in the low speed smoke tunnel with a shaker table capable of moving an airfoil at harmonic frequencies near 40 HZ. Additionally, the airfoil must be modified to allow change of AOA. Finally, the Rosco smoke machine output volume must be modified to permit much lower smoke output. This final point proved to be the single largest detriment to the visualization experiment.

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