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CHAOTIC RESPONSE OF AEROSURFACES WITH STRUCTURAL NONLINEARITIES

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An analytical and experimental research activity is being performed to investigate the chaotic response behavior of aerosurfaces containing discrete structural nonlinearities. This investigation is being conducted by McDonnell Douglas Missile Systems Company with support from the University of Missouri-Rolla. This investigation expands on previous McDonnell Douglas studies investigating nonlinear aerosurface response which were sponsored by the Air Force Office of Scientific Research.

Following the previous AFOSR studies, McDonnell Douglas performed additional analyses for a nonlinear aerosurface to further define its dynamic response characteristics. These preliminary evaluations indicated that in certain regions aerosurface response appeared to be chaotic in nature. Chaos is the paradoxical emergence of random-like motion in completely deterministic —

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19. ABSTRACT (Continued)

nonlinear systems. During the present research program, the interrelated influence of aerosurface physical parameters, frequency content, magnitude of structural nonlinearities, and magnitude of initial disturbances on system dynamic response characteristics is being investigated. This research is developing an understanding of the chaotic response characteristics of a simple, but realistic nonlinear system -- an aerosurface containing discrete structural nonlinearities. Study results will extend the fundamental understanding of nonlinear system dynamics.

This is a three year research program to investigate chaotic response behavior for aerosurfaces containing discrete structural nonlinearities. The dynamic behavior of a rigid aerosurface has been investigated analytically and experimentally during the first year, or Basic Year. The rigid surface analysis and test activities are to be continued during the second, or Option I year. In addition, a flexible aerosurface will be designed and fabrication begun during the second year. The third or Option II year of the program will move to test and analysis of the flexible aerosurface.

This report presents the results of the completed Basic Year and plans for the upcoming Option I year. During the Basic Year analytical studies have been performed for a range of rigid aerosurface configurations and various root spring stiffnesses and nonlinearities. Test apparatus has been designed and fabricated to experimentally demonstrate the nonlinear behavior of a rigid aerosurface containing discrete structural nonlinearities. Wind tunnel testing for the rigid aerosurface configuration has been initiated and evaluation of the results of the wind tunnel tests is underway. Initial design and fabrication of the rigid aerosurface dynamic test setup was completed during the Basic Year.

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An analytical and experimental research activity is being performed to investigate the chaotic response behavior of aerosurfaces containing discrete structural nonlinearities. This investigation is being conducted by McDonnell Douglas Missile Systems Company (MDMSC) with support from the University of Missouri-Rolla (UMR). This investigation expands on previous McDonnell Douglas studies sponsored by the Air Force Office of Scientific Research (AFOSR).

Following the previous AFOSR studies, McDonnell Douglas performed additional analyses for a nonlinear aerosurface to further define its dynamic response characteristics. These preliminary evaluations indicated that in certain regions aerosurface response appeared to be chaotic in nature. Chaos is the paradoxical emergence of random-like motion in completely deterministic nonlinear systems. During the present research program, the interrelated influence of aerosurface physical parameters, frequency content, magnitude of structural nonlinearities, and magnitude of initial disturbances on system dynamic response characteristics is being investigated. This research is developing an understanding of the chaotic response characteristics of a simple, but realistic nonlinear system -- an aerosurface containing discrete structural nonlinearities. Study results will extend the fundamental understanding of nonlinear system dynamics.

The AFOSR Program Manager is Dr. Anthony Amos. The MDMSC principal investigator for this study is Dr. Robert M. Laurenson.
Mr. Anthony J. Hauenstein is co-investigator at MDMSC and Dr. Walter Eversman is co-principal investigator at UMR. This report presents the results of the Basic Year, or first year, of a three-year research program.

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1.0 INTRODUCTION

In two previous Air Force Office of Scientific Research (AFOSR) studies, References 1 and 2, McDonnell Douglas Corporation investigated the dynamic response of an aerosurface, Figure 1, in a subsonic airstream. Structural nonlinearities, in the form of discrete nonlinear root support springs K_θ and/or K_ϕ were present in the system. These studies addressed two types of nonlinear springs, Figure 2, which are characteristic of those encountered in missile systems with freeplay or deadband in the aerosurface root support.

The present research program is expanding on these previous studies for an aerosurface with discrete structural nonlinearities. The nonlinear system dynamic behavior is being investigated in detail through analytical and experimental activities. The research activity is led by McDonnell Douglas Missile Systems Company (MDMSC) with support from the University of Missouri-Rolla (UMR) and overall program direction from AFOSR. Nonlinear aeroelastic system dynamic analyses are being conducted by MDMSC. Design, fabrication, and testing of aerosurface models containing discrete structural nonlinearities is being done at UMR.

During the previous work, as discussed in References 2 and 3, it became apparent that there existed regions of flow dynamic pressure where the nature of the aerosurface dynamic response was not understood. These regions were most apparent for an aerosurface containing root spring freeplay plus preload nonlinearities, Figure 2(b). These regions appeared in a limited range of dynamic pressure as illustrated by the data presented in Figure 3. Additionally, frequency analyses, Reference 2, of the simulation results in these regions indicate that the nonlinear system time history response is comprised of several frequencies which are not multiples of each other.

Analyses performed with McDonnell Douglas funding, since the previous AFOSR studies, indicated that the response in these regions is probably chaotic in nature. Phase plane plots of root pitch response for dynamic pressures within and on either side of the region of unexpected dynamic response are shown in Figure 4. The changing nature of these phase plane plots over this range of dynamic pressures is characteristic of chaotic motion, Reference 4. Potential existence of chaos in a relatively simple dynamic system, such as the aerosurface configuration studied in these previous research programs, is very significant.

The present research program is expanding on these previous results. The dynamics of the nonlinear system shown in Figure 5 is being investigated both analytically and experimentally. This configuration is slightly different from that shown in Figure 1. This system has root support pitch (h) and plunge (α); degrees of freedom and is consistent with the classical two degree of freedom flutter model such as discussed in Reference 5.

During the completed Basic Year, analytical tools have been developed to investigate the time domain response of a rigid aerosurface having discrete nonlinearities in both root support degrees of freedom. These analytical methods are applicable to either steady or unsteady aerodynamic forcing function representations. An aerosurface root support mechanism has been designed and fabricated. This mechanism provides discrete, independent and adjustable nonlinear stiffness for the two aerosurface root support degrees of
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1
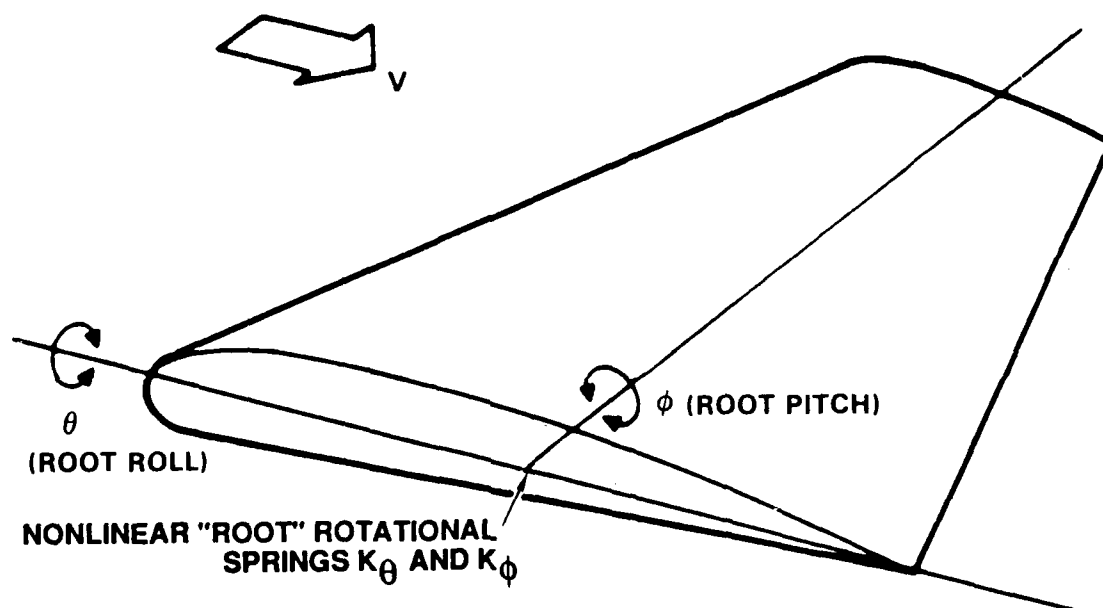
FIGURE 1. AEROSURFACE CONFIGURATION

11–2102

(a) – Freeplay nonlinearity

(b) – Preload nonlinearity
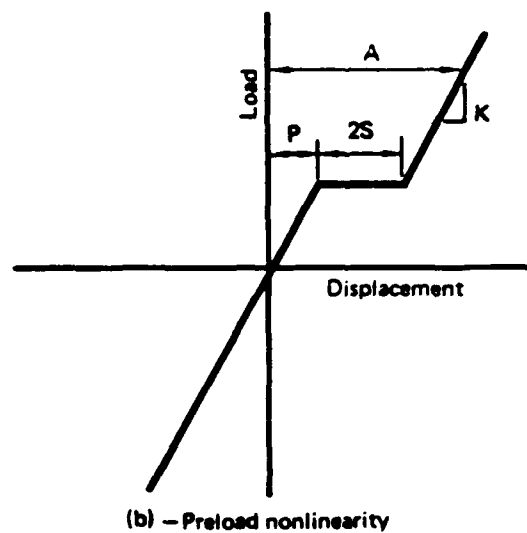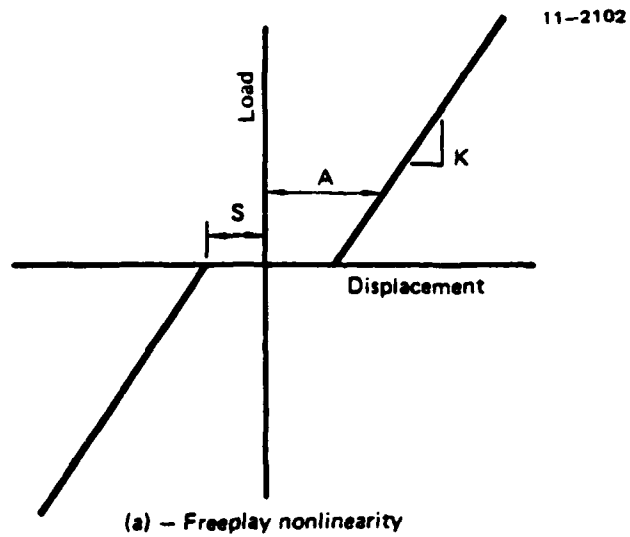
FIGURE 2. TYPES OF STRUCTURAL NONLINEARITIES

11-6085
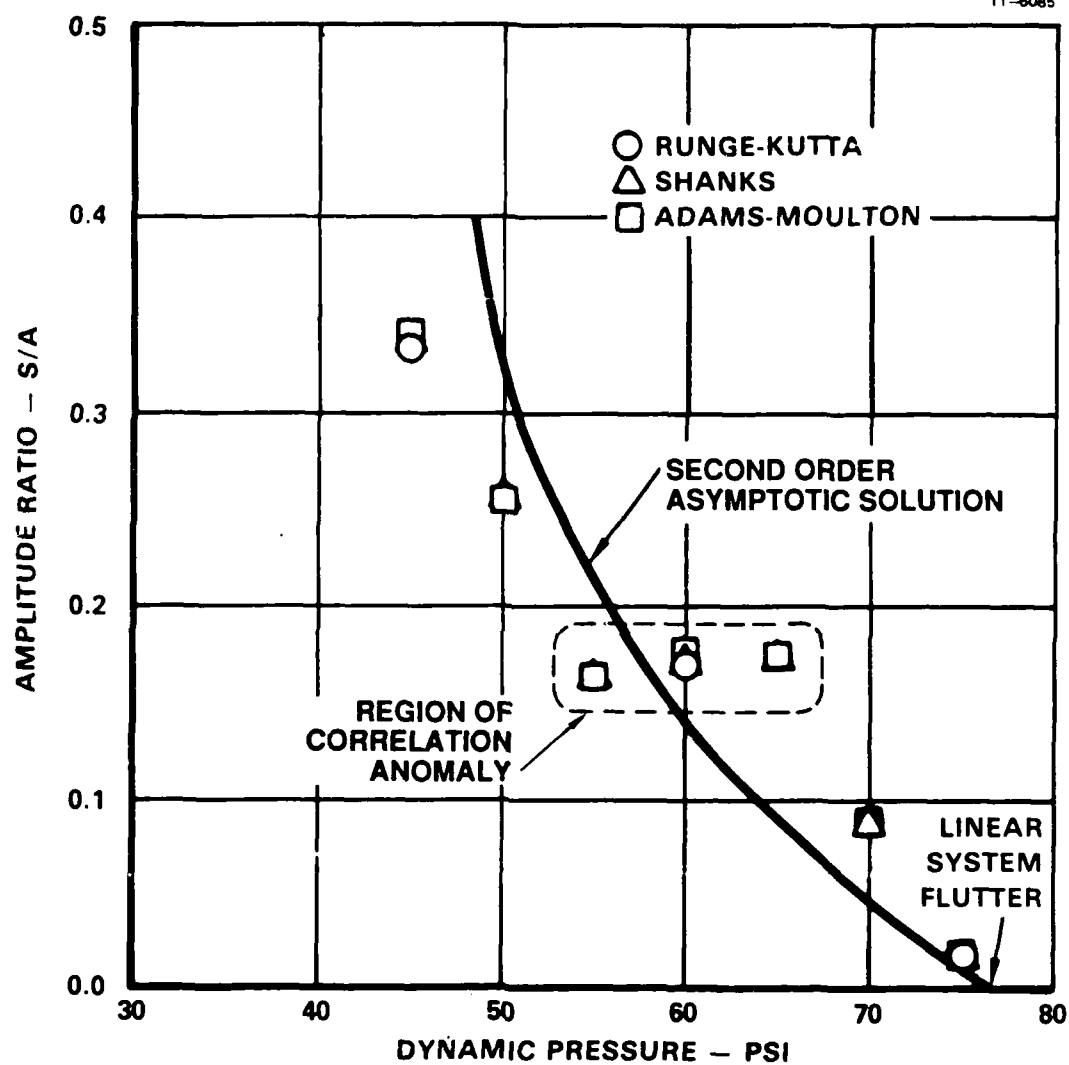
FIGURE 3. REGION OF "UNEXPECTED" DYNAMIC BEHAVIOR

FIGURE 4. ROOT PITCH PHASE PLANE PLOTS

11-15670

PLUNGE SPRING (k_h)

PITCH SPRING AT ROTATION POINT (k_α)

Midchord

b

E.A.

d

h

a

C.G.

α
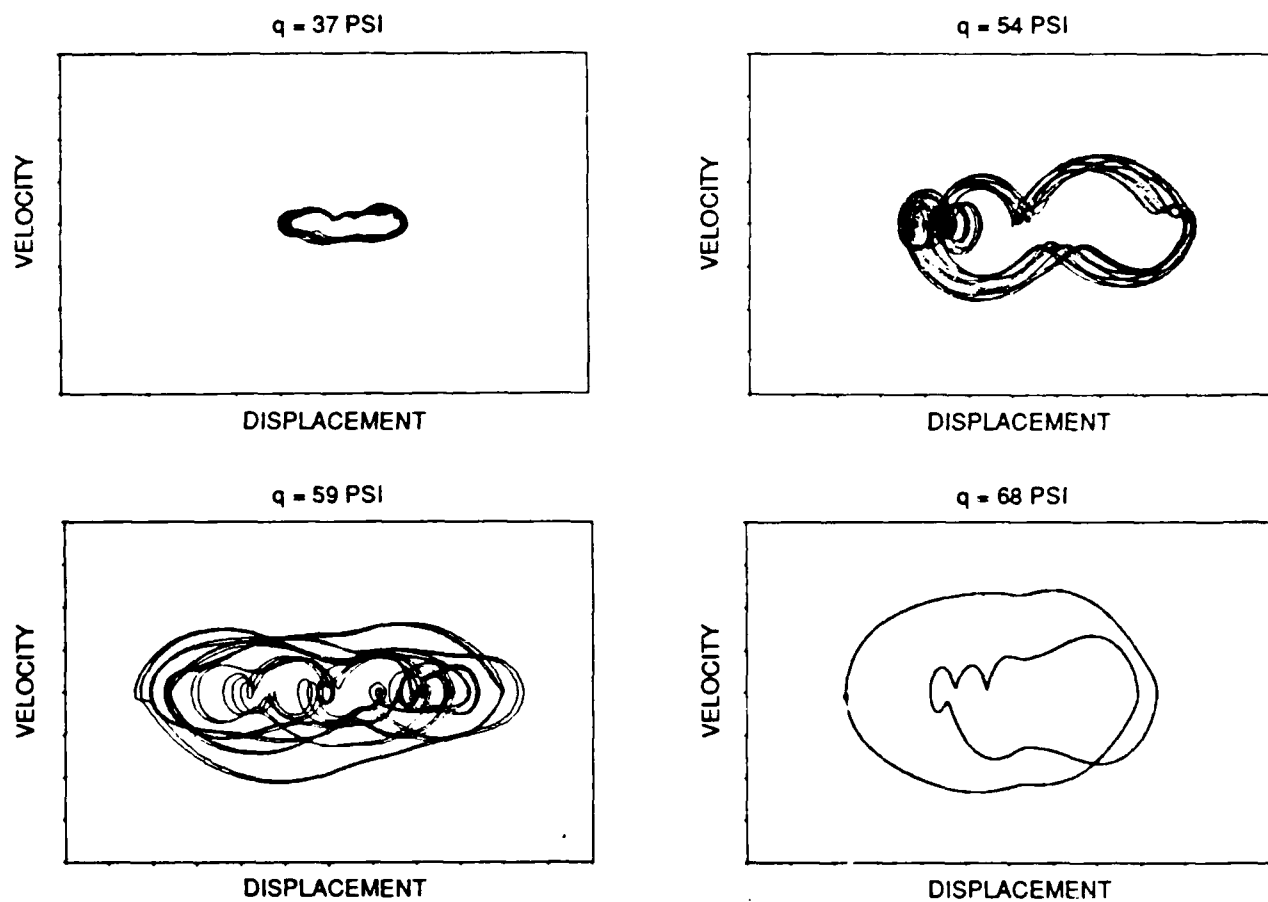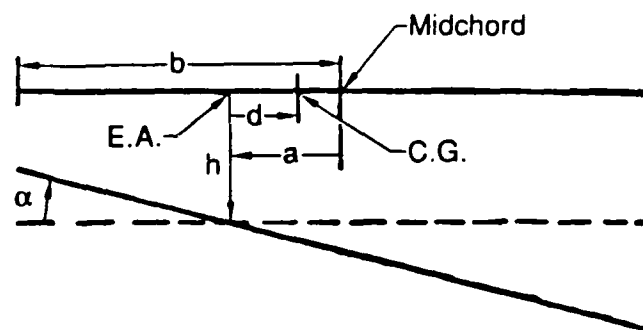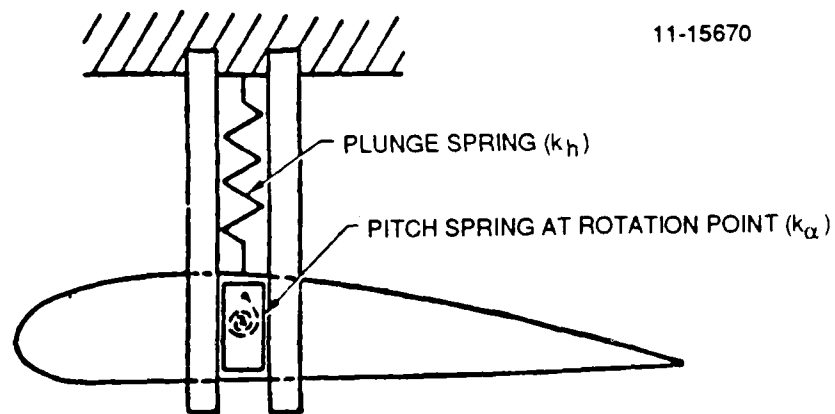
E.A. = ELASTIC AXIS
C.G. = CENTER OF GRAVITY
 b = SEMICHORD LENGTH
 a = DISTANCE FROM MIDCHORD TO E.A. (+ AFT)
 d = DISTANCE FROM E.A. TO C.G. (+ AFT)
 h = PLUNGE OF E.A. (+ DOWN)
 α = PITCH ABOUT E A. (+ LEADING EDGE UP)

FIGURE 5. TWO DEGREE OF FREEDOM SYSTEM

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freedom. A rigid aerosurface has been designed and fabricated. In this context, "rigid" indicates that the natural frequencies of the cantilevered aerosurface are well above the modes of the combined aerosurface and root support springs. Wind tunnel testing of the rigid aerosurface and nonlinear support mechanism combination has been initiated. Testing has identified linear system flutter points and demonstrated nonlinear system limit cycle responses for a number of root support stiffness combinations.

During the upcoming second program year, Option I, wind tunnel testing will be completed for the rigid aerosurface. Design of a flexible aerosurface will be completed and fabrication begun. Detailed analytical studies, for both the rigid and flexible aerosurface, will be performed during the coming year. In addition, dynamic testing of the rigid aerosurface is to be initiated. Test to analysis correlation studies will be completed for data obtained with the rigid aerosurface. These analytical and experimental studies will be directed toward identifying potential regions of chaotic response in the nonlinear aeroelastic system.

A description of the overall research program is presented in the following section. Detailed discussions of the Basic Year accomplishments are provided in Section 3. This is followed by discussions of planned research for the second or Option I year, Section 4; conclusions reached to this point in the program, Section 5; a listing of research personnel and interactions, Section 6; and applicable references, Section 7.

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2.0 PROGRAM SUMMARY

This is a three year research program to investigate chaotic response behavior for aerosurfaces containing discrete structural nonlinearities. The program is an extension of previous AFOSR studies and contains both analytical and experimental activities.

The dynamic behavior of a rigid aerosurface has been investigated analytically and experimentally during the first year, or Basic Year. The rigid surface test and analysis activities are to be continued during the second, or Option I year. In addition, a flexible aerosurface will be designed and fabrication begun during the second year. The third or Option II year of the program will move to test and analysis of the flexible aerosurface. A description of the planned activities for each of these years follows. This is followed by a description of the approach being taken to accomplish these planned activities.

2.1 Program Plan

The activities performed, or to be performed, during each year of the research program are described in the following paragraphs. The overall objective through out the program is to obtain an increased understanding of the dynamic response phenomenon for aerosurfaces with discrete structural nonlinearities. The research is extending the fundamental understanding of nonlinear system dynamics and the potential characterization of this motion within the context of chaotic behavior.

Basic Year - Analytical studies have been performed for a range of rigid aerosurface configurations and various root spring stiffnesses and nonlinearities. Test apparatus has been designed and fabricated to experimentally demonstrate the nonlinear behavior of a rigid aerosurface containing discrete structural nonlinearities. Wind tunnel testing for the rigid aerosurface configuration has been initiated and evaluation of the results of the wind tunnel tests is underway. Initial design and fabrication of the rigid aerosurface dynamic test setup was completed during the Basic Year.

Option I Year - The wind tunnel testing for the rigid aerosurface configuration will be completed. A mechanically excited "feedback" system will be used to perform further dynamic testing of the rigid aerosurface configuration. The results of these wind tunnel and dynamic tests will be evaluated. Included in this evaluation will be test to analysis correlation studies. Analytical studies for a range of flexible aerosurface configurations and various root spring stiffnesses and nonlinearities will be performed. The design will be completed and fabrication initiated for test apparatus to experimentally demonstrate the nonlinear behavior of a flexible aerosurface containing discrete structural nonlinearities.

Option II Year - A mechanically excited "feedback" system will be used to test the flexible aerosurface configuration. Wind tunnel testing will be performed for the flexible aerosurfaces configuration and the results of the dynamic and wind tunnel tests will be evaluated. Included in this evaluation will be test to analysis comparisons and investigation of potential regions of chaotic response characteristics.

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2.2 Program Approach

As discussed in Section 1.0, the nonlinear system response of an aerosurface with discrete nonlinear structural elements is not thoroughly understood. The objectives of the program plan, Section 2.1, is to perform research to develop further understanding of this nonlinear response phenomenon. A thirty-eight month analytical and experimental research program, including documentation, is being performed to meet these objectives. As presented in Figure 6, the program schedule has been established to provide a logical flow of activities through the program.

MDMSC has responsibility for the overall program with UMR serving as a subcontractor to MDMSC. Roles and program activities for UMR and MDMSC are shown in Figure 7. In addition to overall program direction, MDMSC is performing the analytical studies and assisting with test data analysis. The design, fabrication, and testing of the aerosurface models is being performed by UMR.

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Basic Year | Option I | Option II

#	ACTIVITY
	RIGID AEROSURFACE
1	
2	Parametric Investigation
3	Model Design and Fabrication
4	Dynamic Testing
5	Evaluation of Dynamic Test Results
6	Wind Tunnel Testing
7	Evaluation of Wind Tunnel Test Results
8	**FLEXIBLE AEROSURFACE**
9	
10	Parametric Investigation
11	Model Design and Fabrication
12	Dynamic Testing
13	Evaluation of Dynamic Test Results
14	Wind Tunnel Testing
15	Evaluation of Wind Tunnel Test Results
16	
17	**DOCUMENTATION**
18	Reports
19	Research Progress and Forecast
20	Annual Technical
21	Final Technical
22	Oral Reviews
23	Kickoff
24	Year Midterm
25	Year Final
26	
27	
28	Note: Current contract is through
29	Option I year. Schedule
30	reflects full three year
31	program.
32	
33	
34	
35	

MONTHS AFTER GO-AHEAD | 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38

CALENDAR | M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A

1988 | 1989 | 1990 | 1991

28 February 1989

FIGURE 6. PROGRAM SCHEDULE

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ACTIVITY	ROLE	
	MDMSC	UMR
RIGID AEROSURFACE		
Parametric Investigations	Perform analyses to identify the rigid aerosurface model concept.	
Model Design & Fabrication	Define aerosurface model concept and approve UMR model design.	Develop detailed aerosurface model design and fabricate test hardware.
Dynamic Testing	Define requirements for dynamic testing. Monitor UMR test setup and progress of testing.	Define plan for dynamic testing, setup test, and perform testing.
Evaluation of Dynamic Test Results	Perform test-to-analysis comparisons to establish nature of nonlinear system response obtained during dynamic testing.	Perform data reduction and provide MDMSC with digitized test data for selected test conditions.
Wind Tunnel Testing	Define requirements for wind tunnel testing. Monitor UMR test setup and progress of testing.	Define plan for wind tunnel testing, setup test, and perform testing.
Evaluation of Wind Tunnel Test Results	Perform test-to-analysis comparisons to establish nature of nonlinear system response obtained during wind tunnel testing.	Perform data reduction and provide MDMSC with digitized test data for selected test conditions.
FLEXIBLE AEROSURFACE		
Parametric Investigations	Perform analyses to identify the flexible aerosurface model concept.	
Model Design & Fabrication	*Define aerosurface model concept and approve UMR model design.*	Develop detailed aerosurface model design and fabricate test hardware.
Dynamic Testing	Define requirements for dynamic testing. Monitor UMR test setup and progress of testing.	Define plan for dynamic testing, setup test, and perform testing.
Evaluation of Dynamic Test	Perform test-to-analysis comparisons to establish nature of nonlinear system response obtained during dynamic testing.	Perform data reduction and provide MDMSC with digitized test data for selected test conditions.
Wind Tunnel Testing	Define requirements for wind tunnel testing. Monitor UMR test setup and progress of testing.	Define plan for wind tunnel testing, setup test, and perform testing.
Evaluation of Wind Tunnel Test Results	Perform test-to-analysis comparisons to establish nature of nonlinear system response obtained during wind tunnel testing.	Perform data reduction and provide MDMSC with digitized test data for selected test conditions.
DOCUMENTATION		
Reports	Submit Research and Forecast, Annual Technical, and Final Technical reports to AFOSR detailing findings and accomplishment throughout the research program.	Provide MDMSC with data and information for incorporation in reports.
Oral Reviews	Oral reviews at UMR near middle of each year and year-end review at AFOSR each year. In addition a kick-off meeting at AFOSR early in the program.	Participate in review at UMR near mid-point of each year. Participate in kick-off meeting and end of year reviews at AFOSR.

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FIGURE 7. PROGRAM ACTIVITIES

3.0 BASIC YEAR ACCOMPLISHMENTS

Substantial progress has been made during the Basic Year towards achieving the overall research objectives. Several analysis techniques have been established and used to obtain further understanding of the nonlinear dynamic response characteristics of the rigid aerosurface system. Wind tunnel testing has begun for the rigid aerosurface and a majority of the equipment necessary for dynamic testing has been acquired. Comparison of analytical and wind tunnel test results has begun for the rigid aerosurface.

3.1 Analysis

A variety of analysis procedures have been developed during the Basic Year, or first year of the research program. These are: 1) a flutter stability analysis utilizing steady aerodynamic theory, 2) a transient response analysis using steady aerodynamic theory, and 3) a transient response analysis using unsteady aerodynamic theory. A program has been written which computes the correlation dimension for a given time history. In addition, the aerosurface system equilibrium points have been analytically determined for various combinations of linear and nonlinear root support springs.

All of these analysis activities are directed toward the objective of understanding the nature of the dynamic response of a aerosurface containing structural nonlinearities. These analysis accomplishments are discussed in detail in the following sections.

3.1.1 Stability Analysis With Steady Aerodynamics - A steady aerodynamic
flutter analysis was performed to size the rigid aerosurface and root support mechanism for eventual dynamic and wind tunnel testing. The sizing was performed to assure that the test article could flutter within the speed range of the UMR subsonic wind tunnel. Analysis results defined parametric relationships between rigid aerosurface weight, inertia, linear support spring stiffnesses, and location of the elastic axis, aerodynamic center, and center of gravity. Several combinations were found where flutter was predicted at speeds in the 100 to 150 ft/sec range, ideal for UMR wind tunnel testing. These results were used as guidelines in designing the test article.

The steady aerodynamic flutter method was chosen for use in the parametric sizing studies because the method has proven to be computationally efficient and reasonably accurate for aerosurface systems similar to the one of this study. The steady aerodynamic flutter method is discussed in References 6 through 8. The basic assumption made in this method is that the aerodynamic lift force is proportional to and in phase with the angle of attack. Flutter occurs at frequency coalescence for the two degree of freedom representation of the rigid aerosurface. This leads to a simple closed form definition of the flutter solution.

The system equations of motion for the rigid aerosurface in Figure 5 are

$$m_h \ddot{h} + T_\alpha \ddot{\alpha} + K_h h = -L$$
$$T_\alpha \ddot{h} + I_\alpha \ddot{\alpha} + K_\alpha \alpha = M \qquad (1)$$

The two degrees of freedom are aerosurface root pitch, α, and plunge, h, shown in Figure 5. The static unbalance T_α is:

$$T_\alpha = m_\alpha d \tag{2}$$

For low speed, incompressible steady aerodynamics, the aerodynamic lift force term is

$$L = qSC_{L\alpha}\,\alpha \tag{3}$$

where we have the dynamic pressure and lift-slope coefficient given as

$$q = 1/2\ \rho V^2$$
$$C_{L\alpha} = 2\pi \tag{4}$$

The aerodynamic moment is given as

$$M = L(a + 1/2b) \tag{5}$$

Here it has been assumed that the aerodynamic center is at the quarter chord, Figure 5.

Substituting the aerodynamic terms into the system equations, Equation (1) becomes

$$m_h \ddot{h} + T_\alpha\,\ddot{\alpha} + K_h h + 1/2\ \rho V^2 SC_{L\alpha}\alpha = 0 \tag{6}$$
$$T_\alpha \ddot{h} + I_\alpha\,\ddot{\alpha} + [K_\alpha - 1/2\ \rho V^2 SC_{L\alpha}(a + 1/2b)]\alpha = 0$$

Assuming harmonic motion and for non-trivial solutions, the determinant of coefficients of Equation (6) must be zero. Following the approach of Reference 8, and defining the following terms

$$A = \pi\ \rho V^2 S$$
$$B = m_h I_\alpha - T_\alpha^2$$
$$C = T_\alpha + m_h(a + 1/2b)$$
$$D = -K_h I_\alpha - K_\alpha m_h \tag{7}$$
$$E = -K_h\ (a + 1/2b)$$
$$F = K_h K_\alpha$$

we obtain the following expression for the parameter A at flutter

$$A_F = \frac{-\ (2CD - 4BE)\ \pm \sqrt{(2CD - 4BE)^2 - 4C^2(D^2 - 4BF)}}{2C^2} \tag{8}$$

Two values for A_F are obtained with the lower value being related to the system flutter velocity by

$$V_F = \sqrt{\frac{A_F}{\pi S \rho}} \tag{9}$$

Example results from the steady aerodynamic flutter solution are shown in Figures 8 through 11. For these cases, the aerosurface was modeled as a
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RIGID MODEL FLUTTER STUDY

2 PI AERO   EA=AC   5 LB

R 0.25 XA 0.500	[]	R 0.50 XA 0.333	×
R 0.25 XA 0.333	O	R 0.50 XA 0.167	◇
R 0.25 XA 0.167	Λ	R 0.75 XA 0.500	↑
R 0.50 XA 0.500	+	R 0.75 XA 0.333	⊠
		R 0.75 XA 0.167	Z
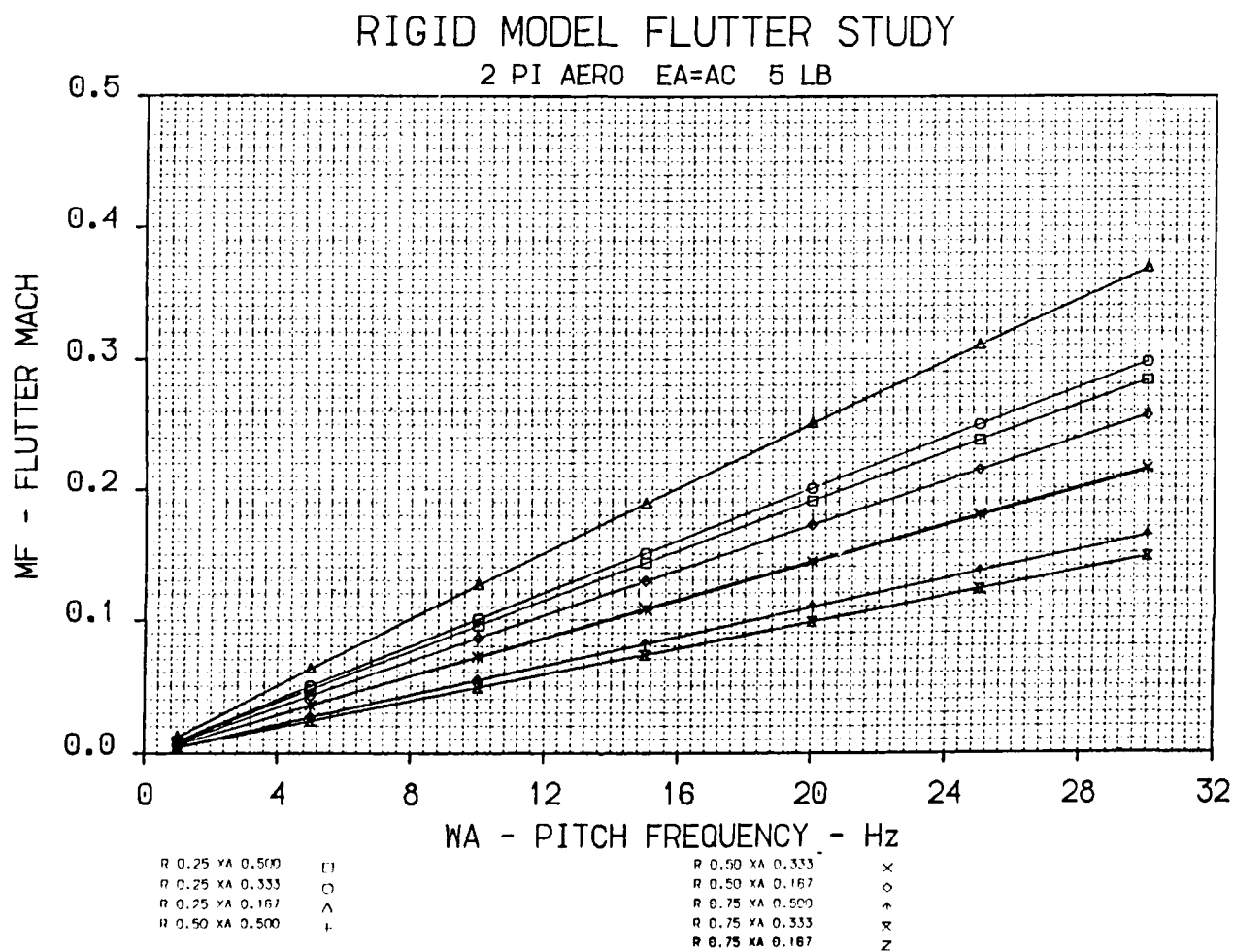
FIGURE 8. RIGID AEROSURFACE PARAMETRIC STUDY - FLUTTER MACH

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RIGID MODEL FLUTTER STUDY
2 PI AERO   EA=AC   5 LB

LIFT - LB/DEGREE

50
40
30
20
10
0

0   4   8   12   16   20   24   28   32

WA - PITCH FREQUENCY - Hz

R 0.25 XA 0.500   □
R 0.25 XA 0.333   ○
R 0.25 XA 0.167   △
R 0.50 XA 0.500   +

R 0.50 XA 0.333   ×
R 0.50 XA 0.167   ◇
R 0.75 XA 0.500   ▲
R 0.75 XA 0.333   ✕
R 0.75 XA 0.167   Z
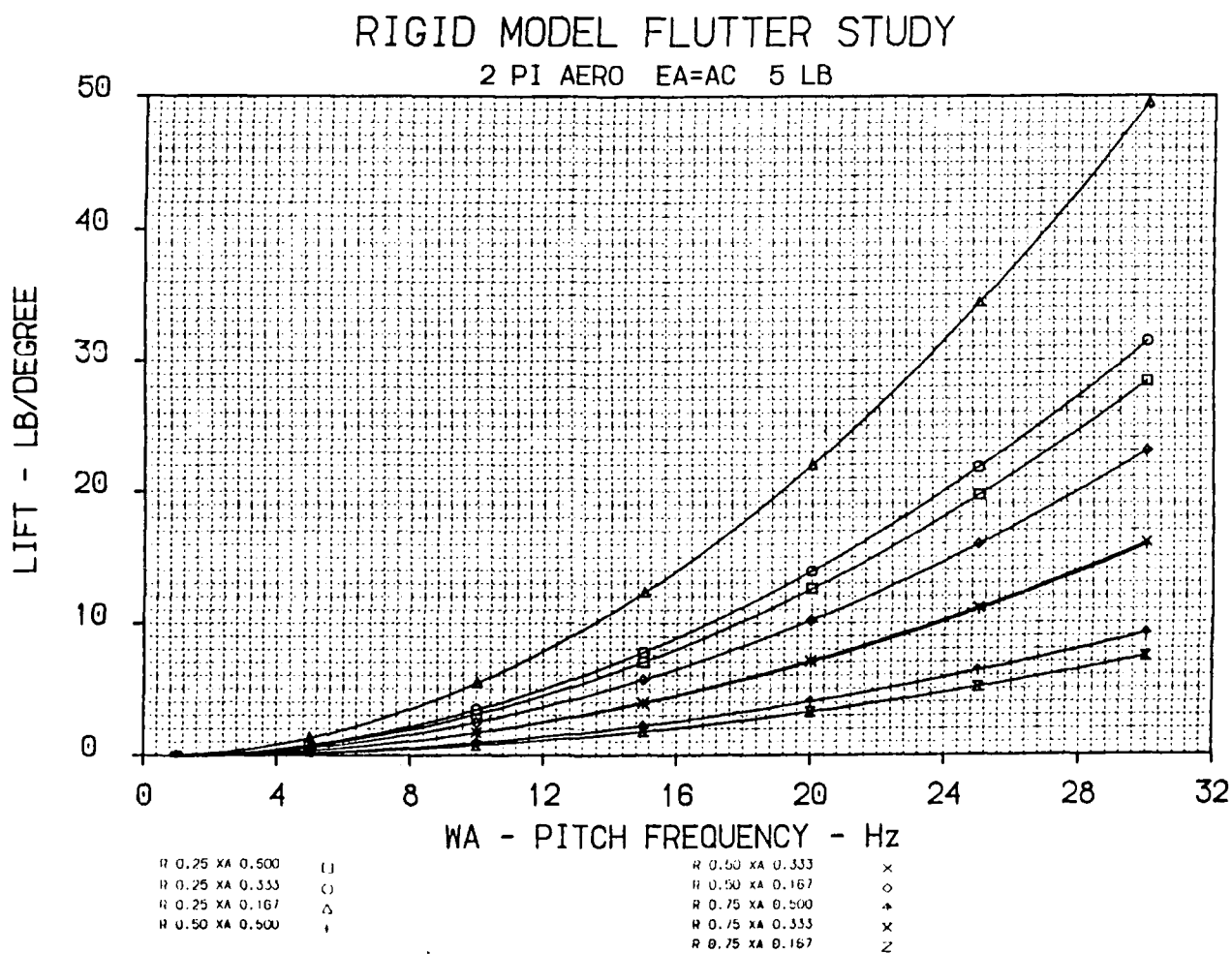
FIGURE 9. RIGID AEROSURFACE PARAMETRIC STUDY - LIFT FORCE

RIGID MODEL FLUTTER STUDY
2 PI AERO   EA=AC   5 LB

R - 0.75

R - 0.50

R - 0.26

KH - PLUNGE SPRING CONSTANT - LB/FT ,10³

WA - PITCH FREQUENCY - Hz

R 0.25 XA 0.500	[]	R 0.50 XA 0.333	×
R 0.25 XA 0.333	○	R 0.50 XA 0.167	◇
R 0.25 XA 0.167	∧	R 0.75 XA 0.500	*
R 0.50 XA 0.500	*	R 0.75 XA 0.333	×
		R 0.75 XA 0.167	z
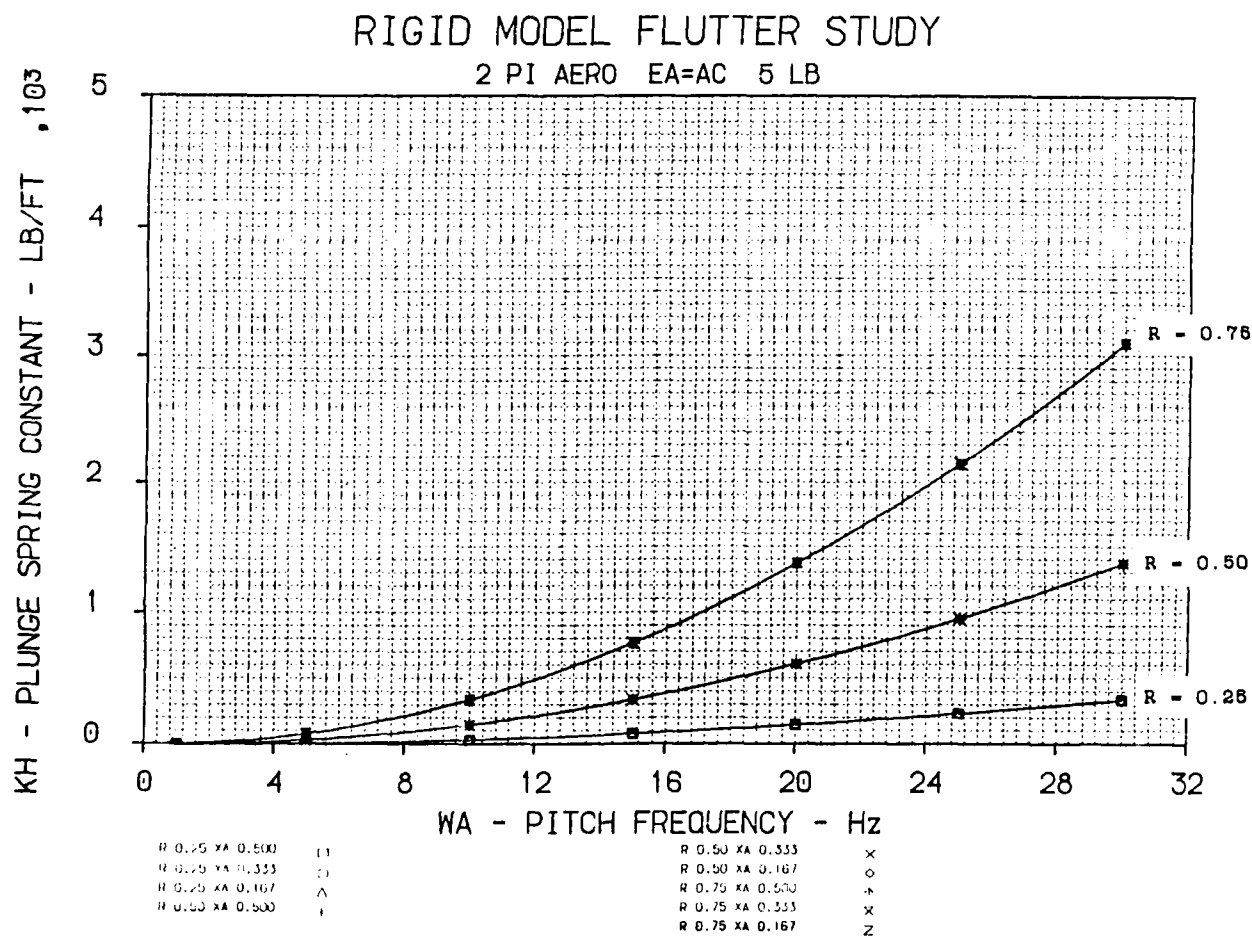
FIGURE 10. RIGID AEROSURFACE PARAMETRIC STUDY - PLUNGE SPRING CONSTANT

RIGID MODEL FLUTTER STUDY

2 PI AERO   EA=AC   5 LB

Plot axes:
- Y-axis: KA – PITCH SPRING CONSTANT – FT-LB/DEG (0 to 5)
- X-axis: WA – PITCH FREQUENCY – Hz (0 to 32)

Curve labels:
- XA – 0.500
- XA – 0.333
- XA – 0.167

Legend:

R 0.25 XA 0.500	□	R 0.50 XA 0.333	×
R 0.25 XA 0.333	○	R 0.50 XA 0.167	◇
R 0.25 XA 0.167	∧	R 0.75 XA 0.500	✦
R 0.50 XA 0.500	+	R 0.75 XA 0.333	☒
		R 0.75 XA 0.167	Z
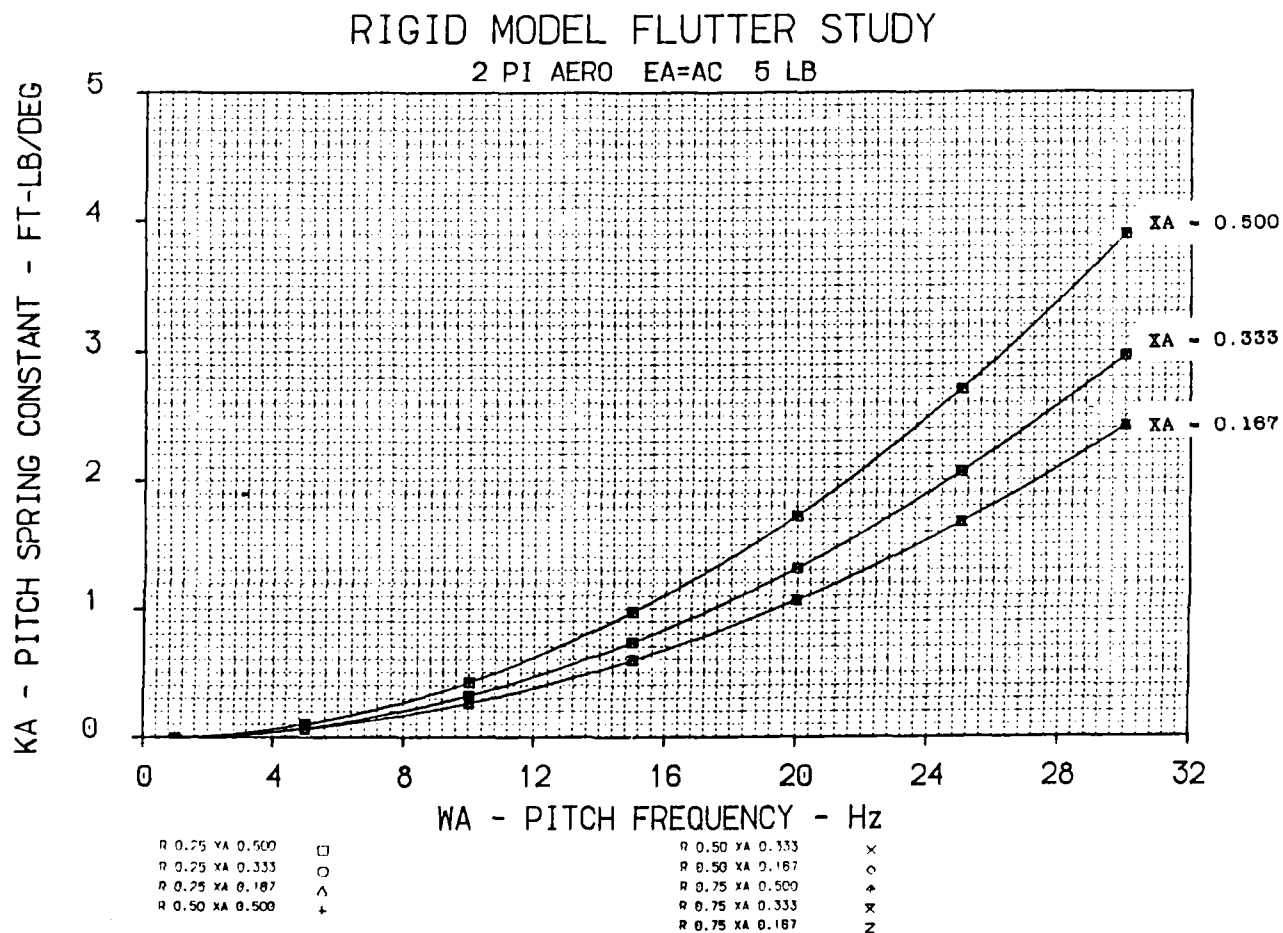
FIGURE 11. RIGID AEROSURFACE PARAMETRIC STUDY - PITCH SPRING CONSTANT

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rigid plate. The center of gravity was held constant at the half-chord. The total weight of the aerosurface and the support mechanism was assumed to be 5 pounds. The aerodynamic center was coincident with the elastic axis. The aerodynamic center and elastic axis move from the quarter-chord aft towards the half-chord. The parameter x_α is a nondimensional form of d, Figure 5, such that

$$d = b \ x_\alpha \tag{10}$$

The term R is the zero airspeed frequency ratio defined by

$$R = \omega_h/\omega_\alpha \tag{11}$$

Based on operational characteristics of the UMR wind tunnel, the goal for wind tunnel testing was in the 0.1 to 0.2 Mach number range. From the results shown in Figures 8 through 11, a rigid aerosurface test article weighing about 5 pounds with pitch and plunge frequencies in the 8 to 12 Hz range seemed ideal for purposes of this study. These results formed the basis of the eventual definition of the rigid aerosurface configuration.

3.1.2 Transient Analysis With Steady Aerodynamics - A steady aerodynamic transient response simulation has been developed. The program has been exercised using the physical properties of a preliminary aerosurface test article design. The program will be used in the upcoming Option I year to establish conditions for dynamic testing and to obtain results for comparison with the dynamic test results. The simulation performs transient analysis of the two degree of freedom rigid aerosurface, Figure 5, with nonlinear root supports and assuming steady aerodynamics. The simulation uses the ACSL (Advanced Continuous Simulation Language) routine, Reference 9.

The governing second order equations of motion, Equation (6), are transformed to first order equations using the state variable transformation

$$X = \begin{Bmatrix} h \\ \dot{h} \\ \alpha \\ \dot{\alpha} \end{Bmatrix} \tag{12}$$

The system of first order equations are then given as

$$M \ \dot{X} + K \ X = 0 \tag{13}$$

where we have

$$M = \begin{bmatrix} 0 & m_h & 0 & T_\alpha \\ 0 & T_\alpha & 0 & I_\alpha \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{14}$$

$$K = \begin{bmatrix} K_h & C_h & A & 0 \\ 0 & 0 & K_\alpha - A(a + 1/2b) & C_\alpha \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

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Note that velocity proportional damping terms C_h and C_α has been included in these equations.

The ACSL routine is used to numerically integrate Equation (13). A flow velocity is assumed and the system is given a prescribed set of initial conditions. The resulting time solution is then examined for stability and chaos. In this analysis, the root springs K_h and K_α are no longer constants, but due to assumed nonlinearities are dependent on aerosurface response. During a simulation, the instantaneous values of these stiffnesses follow the relationships shown in Figure 2.

Due their relationship with the dynamic testing, results from the steady aerodynamic transient response analysis will be included in the Option I year technical report.

3.1.3 Transient Analysis With Unsteady Aerodynamics - An unsteady aerodynamic transient response simulation has also been developed. The simulation has been used to establish conditions for wind tunnel testing and to obtain results for comparison with the wind tunnel test results. The simulation performs transient analysis of the two degree of freedom rigid aerosurface, Figure 5, with nonlinear root supports and assuming unsteady aerodynamics. The simulation uses the ACSL (Advanced Continuous Simulation Language) routine.

Two-dimensional, incompressible Theodorsen aerodynamics, References 10 and 11, are used for this transient response analysis. Since the unsteady aerodynamic coefficients are known only at discrete values of reduced frequency, an approximate transfer function is used to develop the continuous function necessary for transient analysis. Additional modifications are incorporated so that the transient flutter solution is applicable to arbitrary motion as opposed to the commonly assumed simple harmonic motion. This method is described in detail in References 12 and 13.

For unsteady aerodynamics, the equations of motion for the rigid aerosurface, Equation (1), are expressed as

$$m_h \, \ddot{h} + T_\alpha \, \ddot{\alpha} + C_h \, \dot{h} + K_h \, h = L$$
$$T_\alpha \, \ddot{h} + I_\alpha \, \ddot{\alpha} + C_\alpha \, \dot{\alpha} + K_\alpha \, \alpha = M \qquad (15)$$

$$\begin{Bmatrix} L \\ M \end{Bmatrix} = q \begin{bmatrix} C_{hh} & C_{h\alpha} \\ C_{\alpha h} & C_{\alpha\alpha} \end{bmatrix} \begin{Bmatrix} h_o \\ \alpha_o \end{Bmatrix} e^{i\omega t}$$

where the C_{xx} terms are the unsteady Theodorsen coefficients. The aerodynamics are approximated by Roger's transfer function, Reference 14, which consists of a second order polynomial in terms of reduced frequency k with a finite series of poles.

$$[C(k)] = [A_1] + [A_2](ik) + [A_3](ik)^2 + \sum_{m=4}^{M+3} \frac{[A_m](ik)}{(ik) + k_m} \qquad (16)$$

where in the above A_1 is the noncirculatory static aerodynamics, $A_2(ik)$ is the aerodynamic damping, $A_3(ik)^2$ is the apparent mass, and the summation terms are circulatory aerodynamic lags.

The value of m can be 1, 2, 3, or 4, depending on the required accuracy. All analysis performed to date for this study has used a value of m equal to 1. The transfer function circulatory aerodynamic lag terms, k_m's, are computed from a best fit of the Theodorsen function. The A_m coefficients are computed by the least-squares error method for the reduced frequencies at which the transfer function is defined.

For the aerosurface system in this study we have:

$$\underline{X} = \begin{Bmatrix} h \\ \alpha \end{Bmatrix}$$

$$[M] = \begin{bmatrix} m_h & T_\alpha \\ T_\alpha & I_\alpha \end{bmatrix}$$

$$[C] = \begin{bmatrix} C_h & 0 \\ 0 & C_\alpha \end{bmatrix} \tag{17}$$

$$[K] = \begin{bmatrix} K_h & 0 \\ 0 & K_\alpha \end{bmatrix}$$

The following definitions are used.

$$\dot{\underline{X}} = \underline{V}$$

$$\ddot{\underline{X}} = \dot{\underline{V}}$$

$$[\hat{M}] = [M] - q \left(\frac{b}{V}\right)^2 [A_3]$$

$$[\hat{C}] = [C] - q \frac{b}{V} [A_2]$$

$$[\hat{K}] = [K] - q [\bar{A}_1] \tag{18}$$

$$[\hat{A}_4] = qP_4 [A_4]$$

$$[\bar{A}_1] = [A_1] + [A_4]$$

$$P_4 = \frac{V}{b} k_4$$

A set of six first order differential equations are then obtained by utilizing the inverse Laplace transform, the response to a unit impulse, and the convolution integral. The $\underline{Z}$ terms are the generalized aerodynamic lags.

$$\begin{Bmatrix} \dot{\underline{V}} \\ \dot{\underline{X}} \\ \dot{\underline{Z}} \end{Bmatrix} = \begin{bmatrix} -[\hat{M}]^{-1}[\hat{C}] & -[\hat{M}]^{-1}[\hat{K}] & -[\hat{M}]^{-1}[\hat{A}_4] \\ [I] & 0 & 0 \\ 0 & [I] & -P_4[I] \end{bmatrix} \begin{Bmatrix} \underline{V} \\ \underline{X} \\ \underline{Z} \end{Bmatrix} \tag{19}$$

The system equations, Equation (19) have been programmed in ACSL in a manner similar to that for steady aerodynamics. Aerosurface transient response is obtained for varying combinations of stiffness nonlinearities,

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initial conditions, and flow conditions. As with the steady aerodynamic simulation, K_α and K_h are variable and functions of the aerosurface response. Results for these simulations are compared to wind tunnel test results in Section 3.3.

3.1.4 Correlation Dimension - An automated method for computing the correlation dimension of a phase space trajectory has been developed to aid in identifying chaotic behavior. The correlation dimension is a probabilistic measure which can be used to classify attractors as being either simple or chaotic. Simple attractors have integer dimensions while chaotic attractors have fractional dimensions.

The correlation dimension formulation used in this study is taken from Reference 15. For a discretized phase space trajectory of N points, a correlation function is defined as

$$C(r) = \lim_{N \to \infty} \left(\frac{1}{N^2}\right) N_r$$

where N_r is the number of pairs of points $\underline{X}_i$ and $\underline{X}_j$ such that $|\underline{X}_i - \underline{X}_j| < r$. This function exhibits a power law dependence on r as r approaches zero for many attractors such that

$$\lim_{r \to 0} C(r) = ar^d \qquad (21)$$

for some constant a. The correlation dimension d_c is defined using the slope of the log C(r) versus log r curve

$$d_c = \lim_{r \to 0} \frac{\log C(r)}{\log r} \qquad (22)$$

The correlation dimension of the Henon map has been computed as a test case for these calculations. The Henon map is defined as

$$x_{n+1} = 1.0 - ax_n^2 + y_n \qquad (23)$$
$$y_{n+1} = b \, x_n$$

For this test case, a has been defined as 1.4 and b as 0.3.

A total of 5000 points, N, in the x-y phase space were computed and are shown in Figure 12. The log C(r) versus log r plot is shown in Figure 13. Clearly there is a limited range where the slope is approximately constant and only this range is used when computing the correlation dimension. Computing the slope via a least squares fit for values of log r between 52 and 64 yields a correlation dimension of 1.22. This compares to the value established in Reference 16 of 1.21 $\pm$ 0.01.

The usefulness of the correlation dimension in classifying attractors for the aerosurface system being used in this study will be investigated during Option I year. The current plan is to use the embedding technique, also known as the pseudo-phase space approach, as described in Reference 17. This technique has proven to work well with experimental data, Reference 18. Instead of measuring $\underline{X}_i$, only a single component X_i is measured. A new n-dimensional phase space is constructed as:
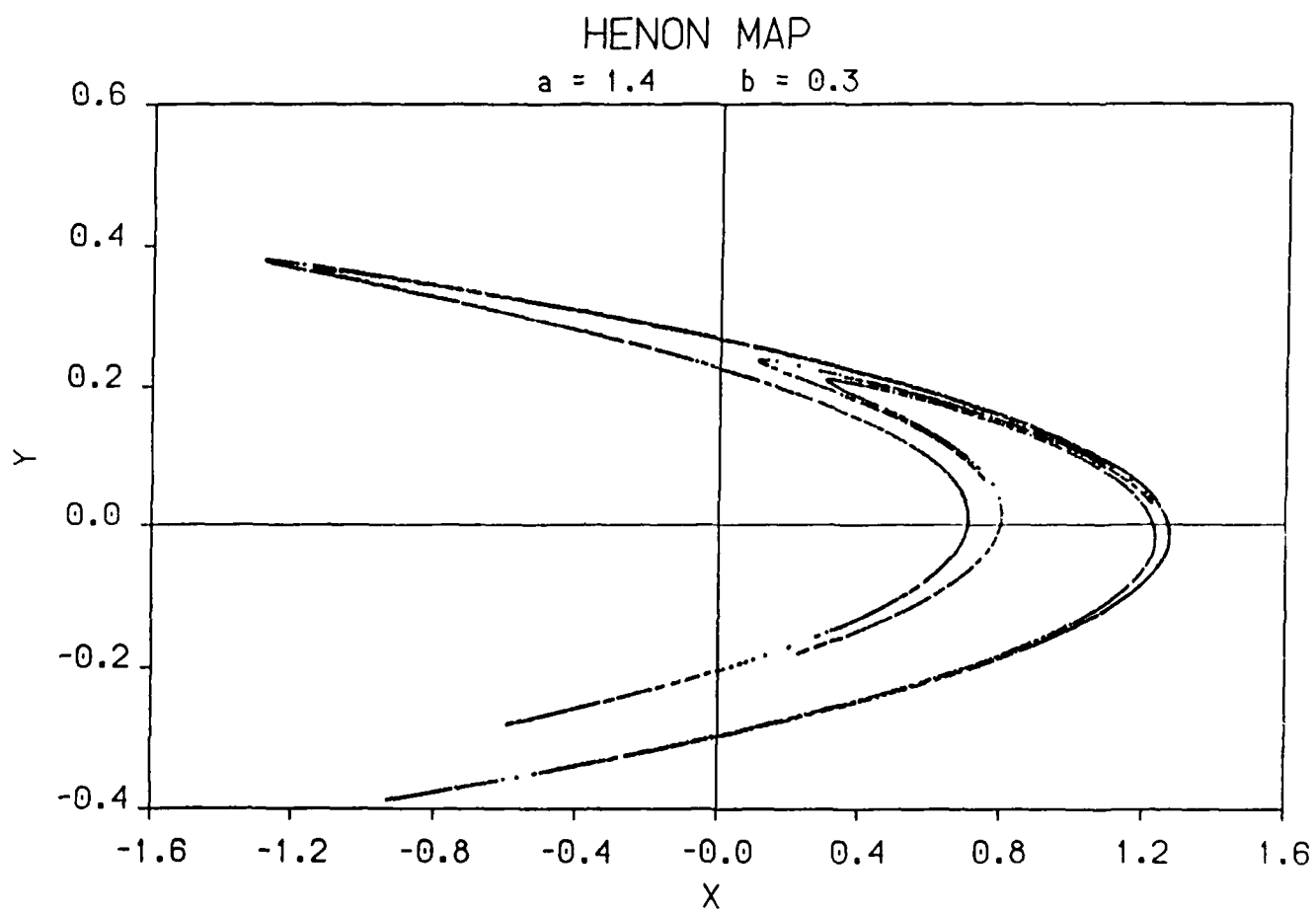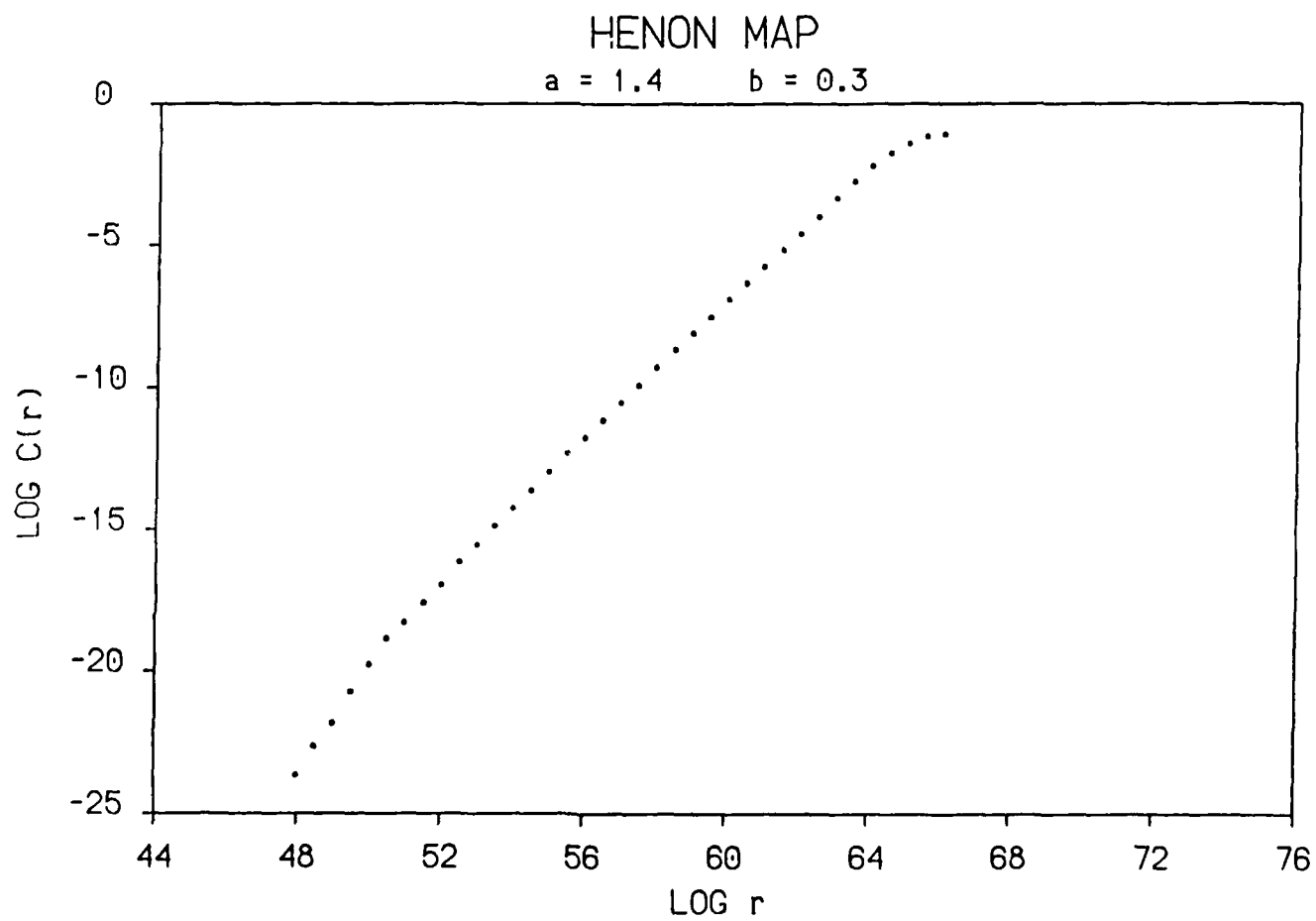
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HENON MAP

FIGURE 12. HENON MAP PHASE SPACE

FIGURE 13. HENON MAP CORRELATION DIMENSION

$$\underline{Z}_i = (X_i, X_{i+t}, X_{i+2t}, \ldots, X_{i+nt}) \tag{24}$$

where t is an almost arbitrarily chosen time constant. The main restriction on choosing t is to avoid the system's basic oscillation period.

The correlation dimension is computed using the $\underline{Z}_i$ vectors. The value of the embedding dimension, n, is increased until a constant value of the correlation dimension is obtained. This procedure will be used to assess the possibility of chaos in both the analytical transient response results and the experimental data.

3.1.5 Equilibrium Point Identification - The equilibrium points for systems with various nonlinear root spring combinations and aerodynamic center locations have been analytically determined. Chaotic behavior of the aerosurface system would seem to be caused by the response jumping from one equilibrium point to another. Several nonlinear root spring and aerodynamic center location combinations yielding multiple system equilibrium points were found. The analytical and experimental search for chaotic response will be focused on these combinations.

Starting with the equations of motion for the aerosurface, such as Equation (1), the dynamic terms are set equal to zero to determine the equilibrium points. Thus we are looking for solutions to the following relationships

$$F_{sh}(h) = -L(\alpha)$$
$$M_{s\alpha}(\alpha) = M(\alpha) \tag{25}$$

where F_{sh} and $M_{s\alpha}$ are the forces in the root plunge and pitch springs.

To simplify the analysis, steady aerodynamics are assumed. The lift force at the elastic axis is given as

$$L = q\ S\ C_{L\alpha}\ \alpha \tag{26}$$

where

$$q = 1/2\ \rho\ (a_0 M)^2$$
$$C_{L\alpha} = 2\pi \tag{27}$$

Combining Equations (26) and (27), we define A as the aerodynamic constant

$$A = \pi S \rho a_0^2 \tag{28}$$

The aerodynamic moment at the elastic axis is thus expressed as:

$$M = Lr = ArM^2\alpha \tag{29}$$

where r is the distance from the aerodynamic center to the elastic axis (positive aft). To simplify the analysis, no negative r values are considered. This corresponds to a system where the elastic axis is coincident with the aerodynamic center (r = 0) or the elastic axis is behind the aerodynamic center (r > 0). The system equations become

$$F_{sh}(h) = -AM^2\alpha$$
$$M_{s\alpha}(\alpha) = ArM^2\alpha \tag{30}$$

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The nonlinear spring force and moment terms, $F_{sh}(h)$ and $M_{s\alpha}(\alpha)$, are now considered. For the nonlinear springs used in this study, the load displacement relationship can be broken into linear segments as shown in Figure 2. For the linear spring we have

$$L = kx \qquad \text{for} \qquad -\infty \leq x \leq \infty \tag{31}$$

For the freeplay spring, we have

$$
\begin{aligned}
L &= k(x + S) & \text{for} & \quad -\infty \leq x \leq -S \\
L &= 0 & \text{for} & \quad -S \leq x \leq S \\
L &= k(x - S) & \text{for} & \quad S \leq x \leq \infty
\end{aligned}
\tag{32}
$$

and for the preload spring, this becomes

$$
\begin{aligned}
L &= kx & \text{for} & \quad -\infty \leq x \leq P \\
L &= kP & \text{for} & \quad P \leq x \leq P + 2S \\
L &= k(x - 2S) & \text{for} & \quad P + 2S \leq x \leq \infty
\end{aligned}
\tag{33}
$$

In order to determine the equilibrium points, all possible displacement combinations are considered for a given pair of springs. For example, a system with two freeplay springs has the following possible displacement combinations.

1) $-\infty \leq \alpha \leq -S_\alpha$ $-\infty \leq h \leq -S_h$
2) $-S_\alpha \leq \alpha \leq S_\alpha$ $-\infty \leq h \leq -S_h$
3) $S_\alpha \leq \alpha \leq \infty$ $-\infty \leq h \leq -S_h$
4) $-\infty \leq \alpha \leq -S_\alpha$ $-S_h \leq h \leq S_h$
5) $-S_\alpha \leq \alpha \leq S_\alpha$ $-S_h \leq h \leq S_h$
6) $S_\alpha \leq \alpha \leq \infty$ $-S_h \leq h \leq S_h$
7) $-\infty \leq \alpha \leq -S_\alpha$ $S_h \leq h \leq \infty$
8) $-S_\alpha \leq \alpha \leq S_\alpha$ $S_h \leq h \leq \infty$
9) $S_\alpha \leq \alpha \leq \infty$ $S_h \leq h \leq \infty$

There are three possibilities for each displacement combination: 1) a unique equilibrium point exists (the system is determinate), 2) an infinite number of equilibrium points exist (the system is indeterminate), or 3) no equilibrium point exists (the system is undefined).

A second assumption used in this analysis was that only air stream velocities below the system divergence velocity are considered. Divergence is a special case of an equilibrium point where the displacement is equal to infinity. At divergence, the aerodynamic moment equals the spring moment. That is

$$K_\alpha = ArM^2 \tag{34}$$

The equilibrium points for several spring combinations are summarized in Figure 14. The details of establishing these characteri·tics are presented in Appendix A.

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SUPPORT TYPE	EQUILIBRIUM POINTS		
	DETERMINATE	INDETERMINATE	UNDEFINED
2 LINEAR/NO AERO MOMENT	1	0	0
2 LINEAR/WITH AERO MOMENT	1	0	0
2 PRELOAD/NO AERO MOMENT	1	0	8
2 PRELOAD/WITH AERO MOMENT	3	0	6
2 FREEPLAY/NO AERO MOMENT	2	3	4
2 FREEPLAY/WITH AERO MOMENT	4	1	4

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FIGURE 14. SYSTEM EQUILIBRIUM POINT SUMMARY

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3.2 Experimentation

The majority of test activity during the Basic Year dealt with wind tunnel testing of the rigid aerosurface. The emphasis of this report will be on this testing. For completeness, a summary is given of the design and initial fabrication of the rigid aerosurface dynamic testing equipment. The dynamic testing will be performed during the upcoming Option I year.

3.2.1 Wind Tunnel Testing - The overall wind tunnel test facility is shown in Figure 15. The UMR subsonic wind tunnel is a closed circuit, single return tunnel. The test section has an internal width of 4 feet, height of 3.67 feet, and a length of 11 feet. It is constructed of plywood with Plexiglas sides. The tunnel has a settling chamber with a counteraction ratio of 9 to 1 and two screens to equalize the tunnel velocity profile and reduce turbulence intensity. Both screens are a square 14 mesh (14 wires per inch across the mesh) with a wire diameter of 0.020 inch for the upstream screen and 0.022 inch for the downstream screen. Open area of the screen is about 70% of total area. Both the open area ratio of the screens and the counteraction ratio follow Bradshaw's recommendations for boundary layer testing.

The power plant for the wind tunnel is a 350 horsepower diesel engine. This engine drives a variable displacement hydraulic pump which in turn drives a fixed displacement hydraulic motor. The motor is directly connected to the wind tunnel fan through a driveshaft provided with universal-joint couplings at each end. The airflow power system, through its variable pitch fan blade settings and variable speed hydraulic transmission, provides a wide range of tunnel velocities with variable control of velocity within a range allowed by the fan pitch. Feedback command control of fan speed is performed by a Moog controller and a D.C. tachometer. A speed range from near zero to in excess of 200 miles per hour is possible.

As seen in Figure 15, a support frame is attached to the floor and extended around the outside of the tunnel. The aerosurface is supported at the top of the wind tunnel by a root support mechanism mounted to the support frame. Additional details of the aerosurface installation are shown in Figures 16 and 17. The aerosurface support shaft, Figure 16, extends through the tunnel ceiling to the support mechanism shown in Figure 17. The support mechanism is free to move in the horizontal direction on four linear bearings supported by two precision shafts. This horizontal motion, aerosurface plunge degree of freedom h, is monitored by a LVDT as shown in Figure 18. Rotational motion of the aerosurface support shaft corresponds to the pitch degree of freedom α. A RVDT, Figure 18, monitors this degree of freedom.

Output from these transduces go to signal conditioners and then to a digital processing oscilloscope, Figure 19. With this oscilloscope, the digitized response data may be displayed as time history information. In addition, phase planes and/or frequency domain information may be obtained for these time history data. The digitized data may be down-loaded to the data storage personal computer for paper plotting and/or further analysis.

The aerosurfaces root stiffness and associated nonlinearities may be varied through features incorporated in the design of the support mechanism, Figure 20. Steel leaf spring material of varying thicknesses are used for the pitch, K_h, and plunge, K_α, springs. Various magnitudes of freeplay gaps
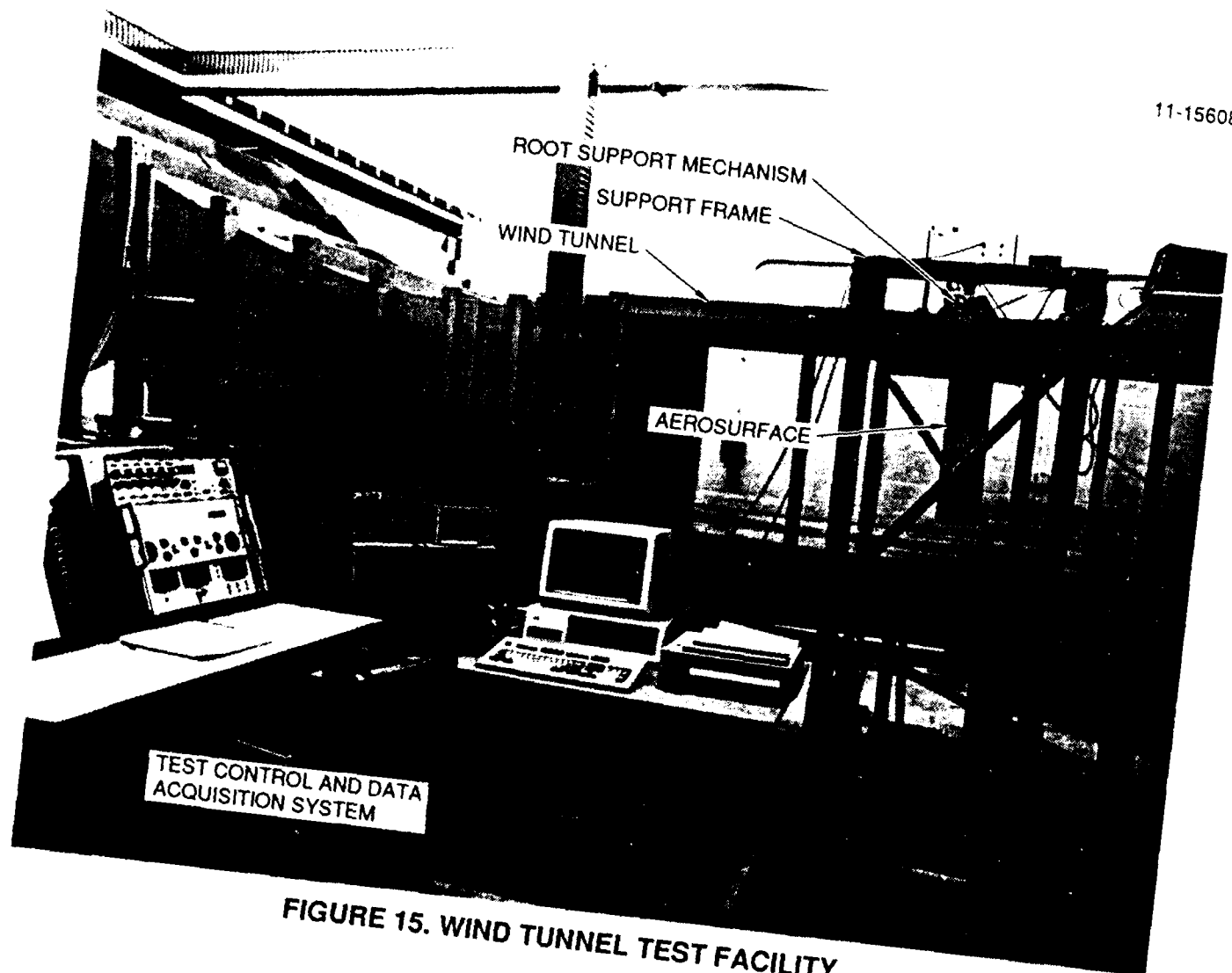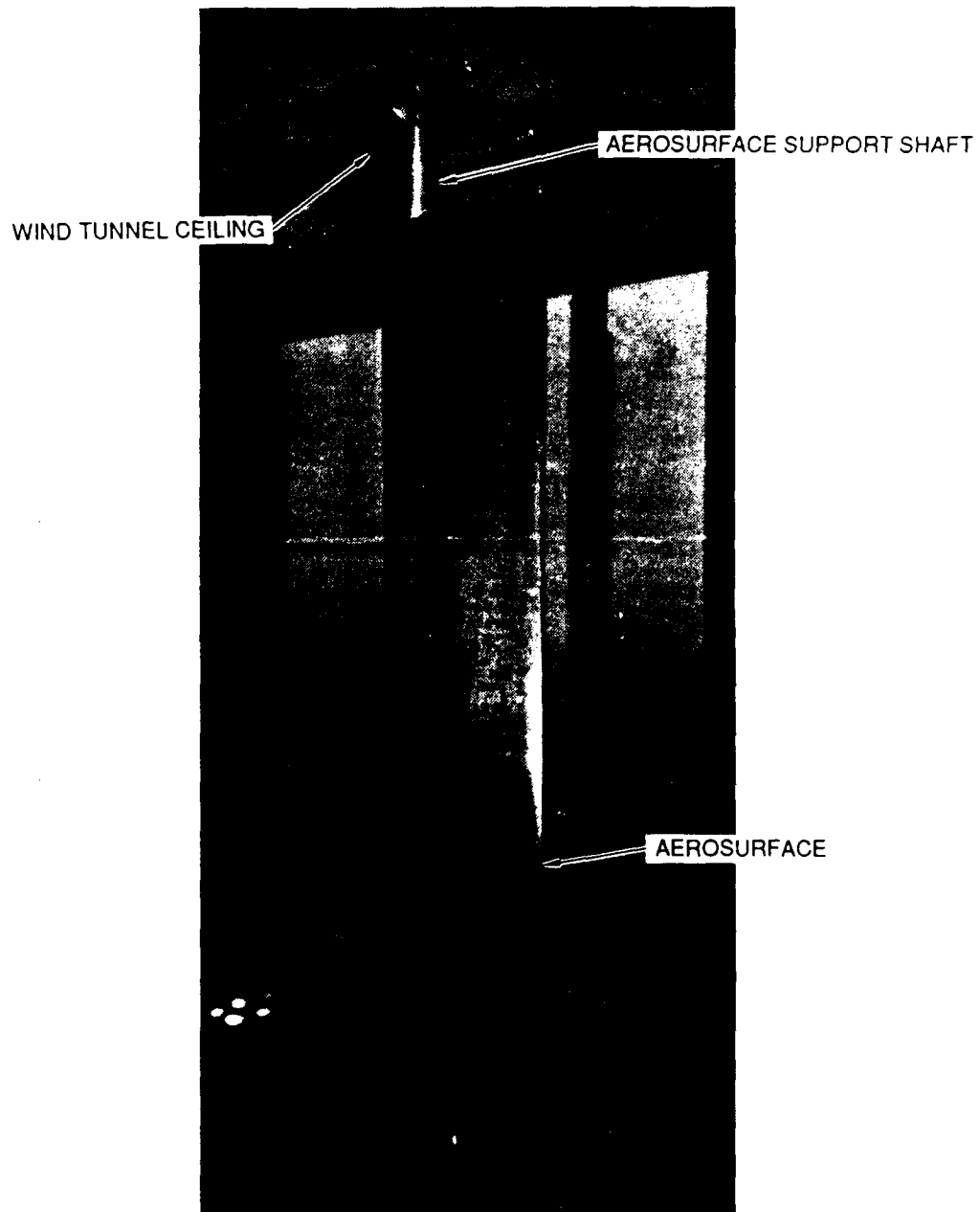5470D/8

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ROOT SUPPORT MECHANISM

SUPPORT FRAME

WIND TUNNEL

AEROSURFACE

TEST CONTROL AND DATA
ACQUISITION SYSTEM

FIGURE 15. WIND TUNNEL TEST FACILITY

11-15609

**FIGURE 16. AEROSURFACE
INSTALLED IN WIND TUNNEL**
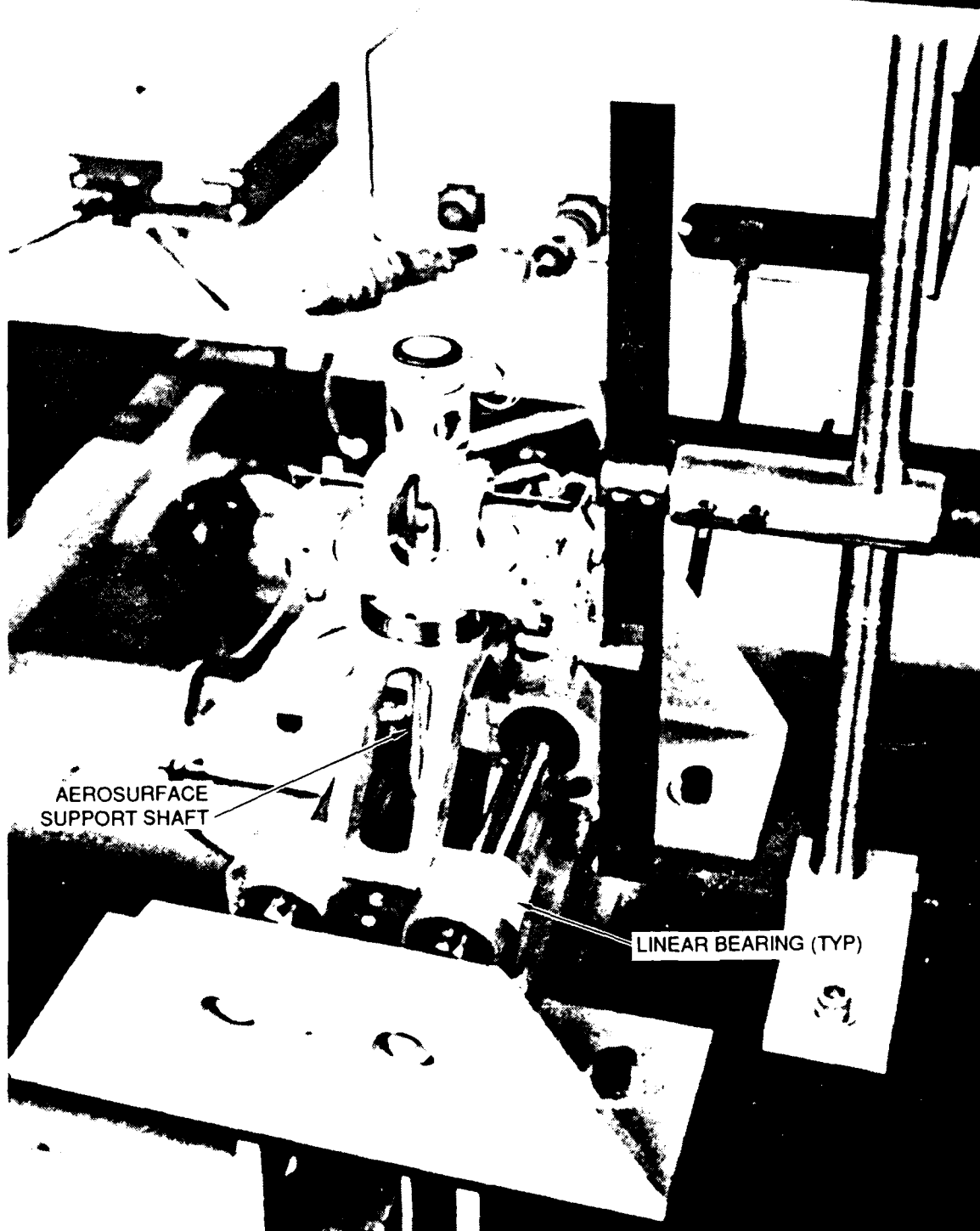
AEROSURFACE
SUPPORT SHAFT

LINEAR BEARING (TYP)

FIGURE 17. ROOT SUPPORT MECHANISM
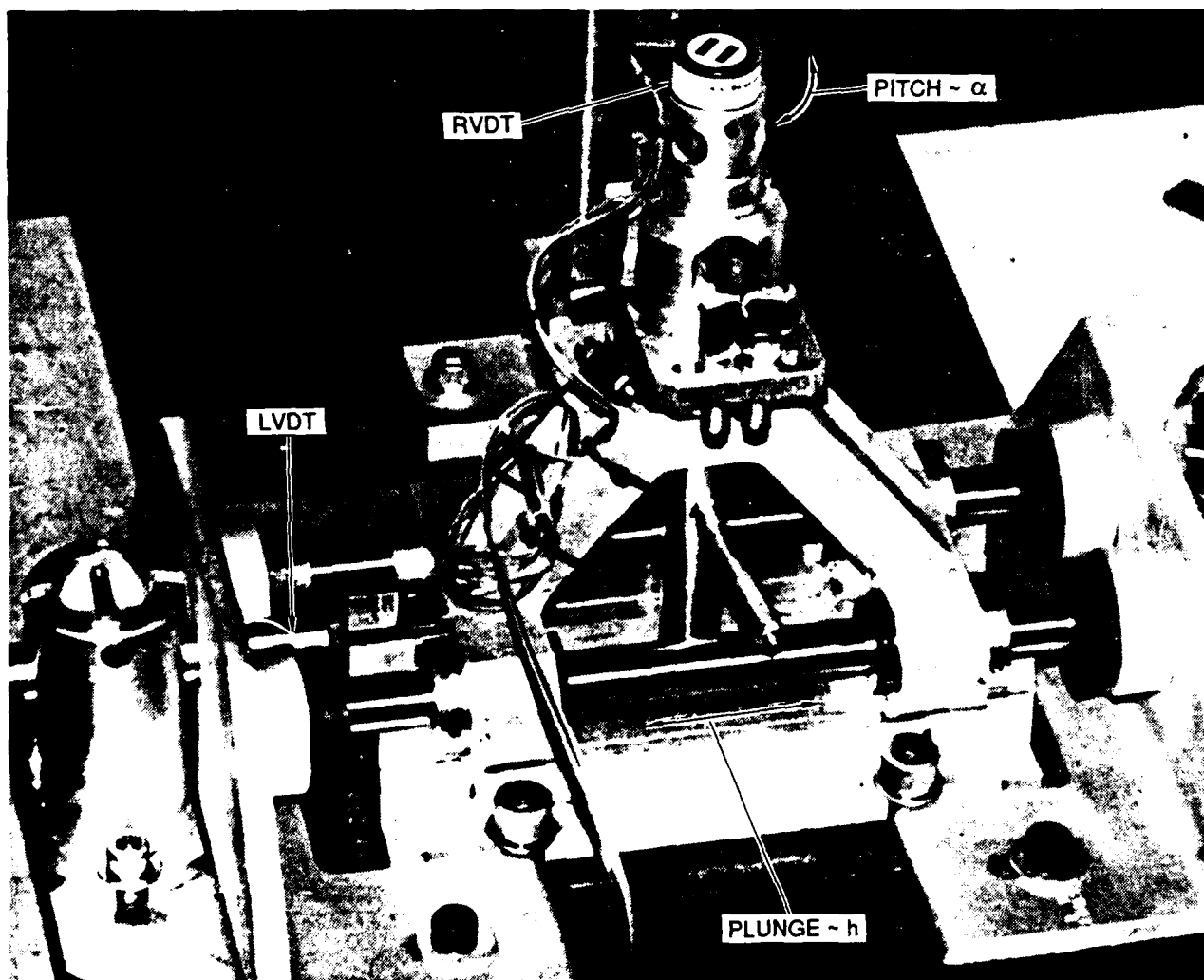
FIGURE 18. INSTRUMENTATION
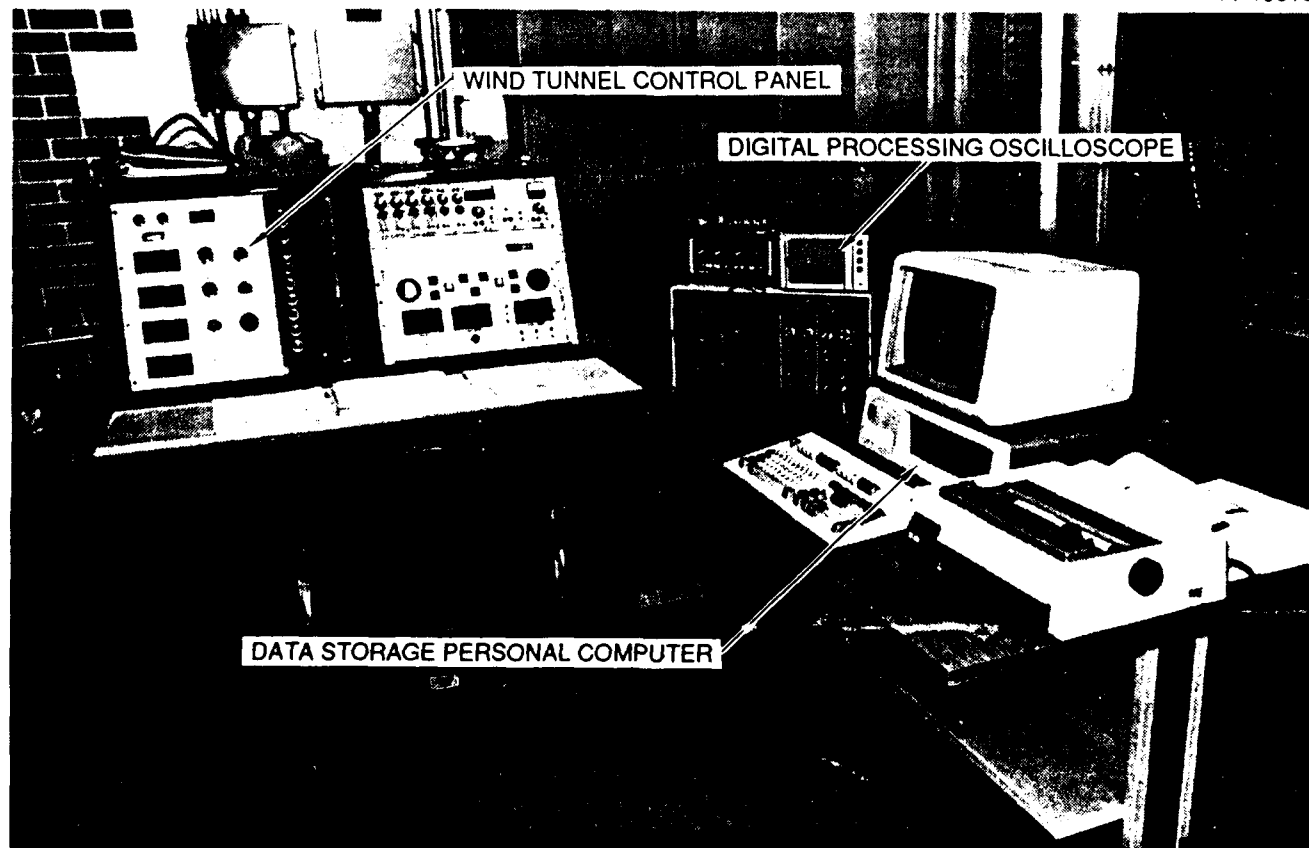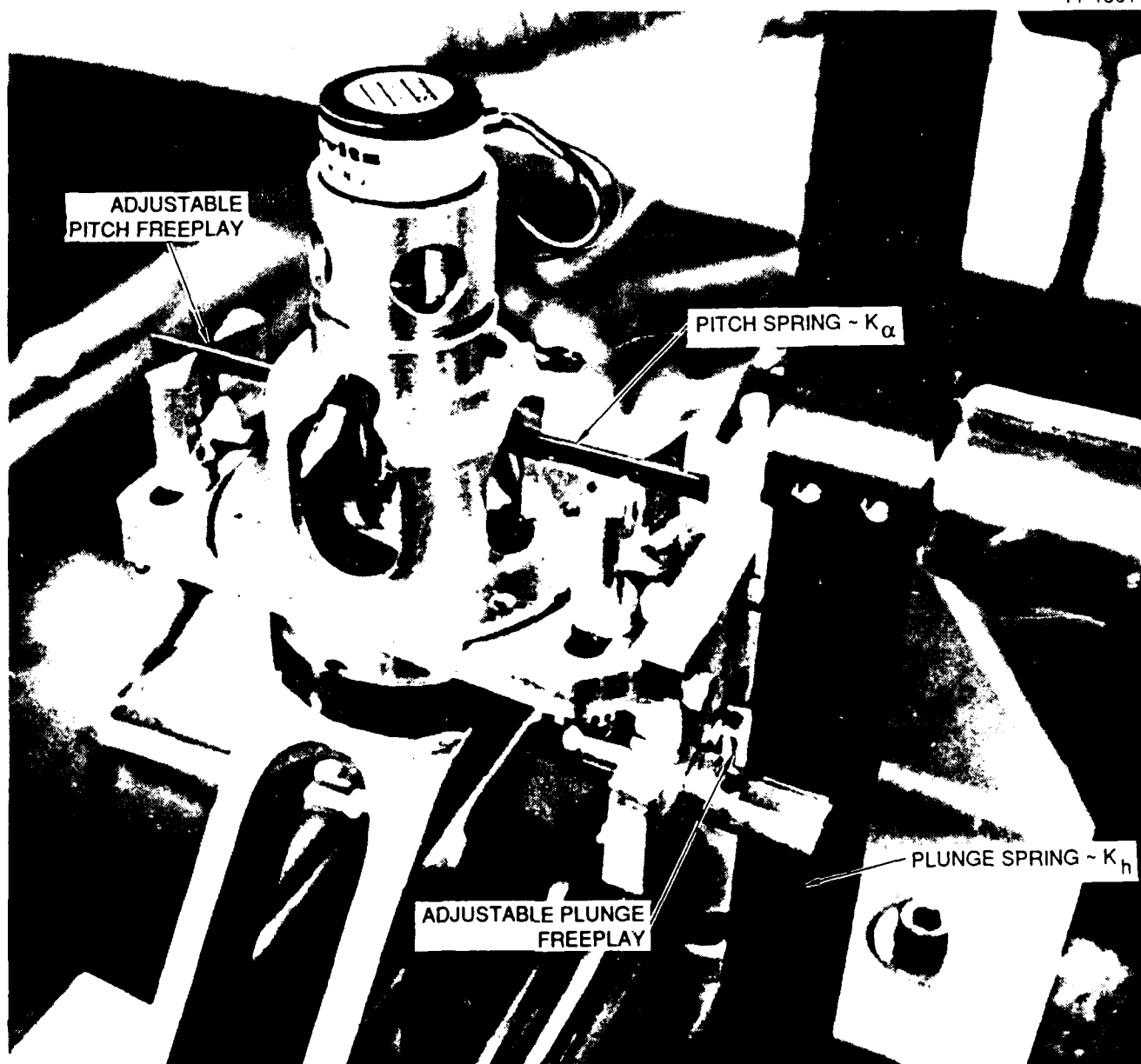
FIGURE 19. TEST CONTROL AND DATA ACQUISITION SYSTEM

ADJUSTABLE
PITCH FREEPLAY

PITCH SPRING ~ K_α

PLUNGE SPRING ~ K_h

ADJUSTABLE PLUNGE
FREEPLAY

FIGURE 20. ROOT SUPPORT STIFFNESSES

are obtained by adjusting the pitch and/or plunge support stops shown in Figure 20. A linear stiffness is obtained by tightly securing the stops against the leaf spring.

Mass and inertia properties of the moving portions of the aerosurface and support mechanism have been determined. Several different combinations of spring elements are available to obtain various combinations of root support stiffnesses. A summary of this mass and stiffness information, in addition to other aerosurface data, is given in Figure 21.

3.2.2 Dynamic Testing - Dynamic testing is planned during the Option I year to obtain additional data to complement the wind tunnel data for the nonlinear system. The dynamic testing will employ an equivalent, mechanically excited system. During this testing, excitation will be controlled by a "feed back" system, in a manner analogous to the aerodynamic forcing function associated with aerosurface motion in a subsonic airstream.

In the experimental approach for dynamic testing, Figure 22, a transducer will measure the root pitch parameter α and feed this information back as the controlling function for a mechanical actuator. The signal from the pitch degree of freedom RVDT goes to a signal conditioner and then to the actuator controller. Also fed to the controller is the output from a load cell on the actuator drive shaft. The controller maintains an actuator load which is equal to the aerodynamic lift associated with the pitch response for an assumed flow condition.

A hydraulic actuator configuration has been selected for this testing. Thus, the controller governs a servovalue which controls the hydraulic flow to a piston. A majority of individual items have been assembled for this test setup. The hydraulic servovalve is on order and the actuator piston is being procured from an outside machine shop. There has been a delay in the delivery of these items. Therefore the rigid aerosurface dynamic testing will be performed later in Option I year following the wind tunnel testing.

3.3 Test to Analysis Comparison

Wind tunnel testing of the rigid aerosurface system has begun with several preliminary cases having been run. A number of these cases are described in this section. Time histories of the experimental data are shown. The experimental results are compared with analytical results from the transient response simulations using unsteady aerodynamics as described in Section 3.1.3. The preliminary test results will be used to determine the matrix of conditions for the rigid aerosurface complete test program to be completed during the Option I year. Lessons learned while performing these initial tests will be used to refine the test procedure prior to performing the complete test program.

All of the test results described in this section have a plunge spring constant of 37.8 lb/in and a pitch spring constant of 704.4 in-lb/rad. These values correspond to a plunge frequency of 8.21 Hz and a pitch frequency of 10.2 Hz.

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Property	Symbol	Value
Semichord length	b	3.5 in
Span	-	24.5 in
Distance from midchord to elastic axis (+ aft)	a	-1.75 in
Distance from elastic axis to center of gravity (+ aft)	d	0.84 in
Pitch mass	m_α	$5.037(10^{-3})$ lb-sec^2/in
Plunge mass	m_h	$14.22(10^{-3})$ lb-sec^2/in
Pitch moment of inertia about elastic axis	I_α	0.1715 lb-sec^2 - in
Pitch linear spring constant range	k_α	732-1831 in-lb/rad
Plunge linear spring constant range	k_h	13.7-215 lb/in
Pitch spring deadband (max)	$\pm S_\alpha$	11 degrees
Plunge spring deadband (max)	$\pm S_h$	0.56 in

FIGURE 21. RIGID AEROSURFACE PROPERTIES

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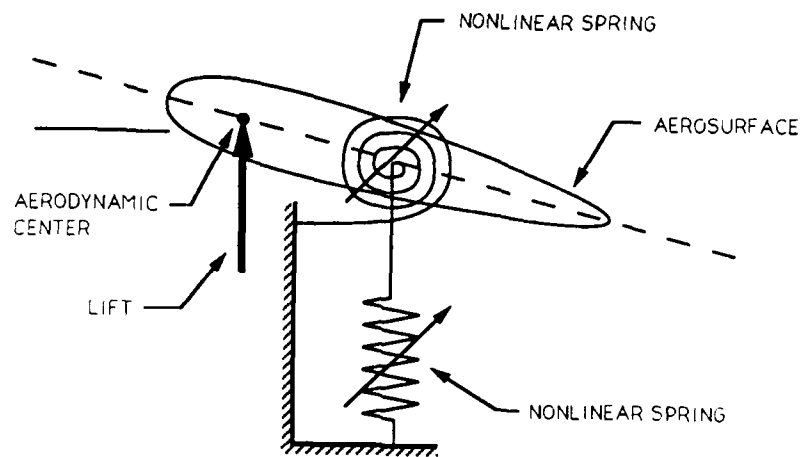
(a) IDEALIZATION
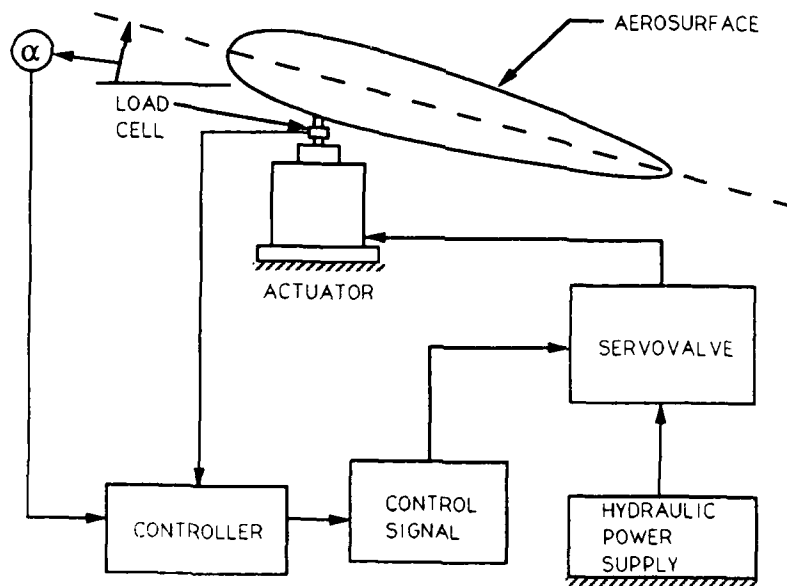
(b) IMPLEMENTATION

FIGURE 22. DYNAMIC TEST IMPLEMENTATION

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The first case is for a linear system. Time histories of the experimental data are shown in Figure 23. This data is for a velocity of 122 ft/sec. The system is close to flutter at this velocity, as can be seen from the relatively low damping in the experimental time histories. Additional experimentation has determined the flutter speed to be between 125 ft/sec and 130 ft/sec. Analytical results for this case are shown in Figures 24 and 25. From these results it is evident that analytical flutter occurs between 110 and 115 ft/sec. Work is in progress to determine why the analytically determined flutter speed is lower than the flutter speed obtained from testing. One possible reason is that zero mechanical damping was included in the analysis. An appropriate value for mechanical damping will be determined and incorporated in the analysis during subsequent analyses.

The second set of experimental data is for a system which has a linear plunge spring and a ±2.5 degree freeplay deadband in the pitch degree of freedom. Time histories for the experimental data are shown in Figure 26. The system is experiencing a stable limit cycle oscillation of approximately ±15 degrees pitch and ±1 inch plunge motion. These data are shown at a time following the startup transient in the test system. The analytical time histories are shown in Figure 27. After a startup transient the analysis also predicts stable limit cycle response. In this case the analysis predicts limit cycle oscillation of approximately ±23 degrees pitch and ±1.6 inches plunge. Reasons for the difference between the amplitudes of limit cycle oscillations for the experimental and analytical data are being investigated. A possibility is that as in the linear case, zero mechanical damping was used in the analysis. This will be studied during the Option I year. To aid in understanding the relation between experimental and analysis results, the frequency content of the data will also be compared.

The third set of data is for a system with a ±2.5 degree freeplay deadband in pitch and a ±0.25 inch freeplay deadband in plunge. Experimentally obtained time histories are shown in Figures 28 and 29. At the lower velocity of 61 ft/sec, the system is damped and the response dies out. A stable limit cycle oscillation is obtained for the higher velocity of 81 ft/sec. The analytical time histories for the 81 ft/sec case are shown in Figure 30. As can be seen the nature of the experimental and analytical response is different. In particular, the analytical response seems to be beating in both degrees of freedom with a slight indication of beating in the experimental pitch degree of freedom. The cause of this phenomena is not understood and will be investigated during the next year.
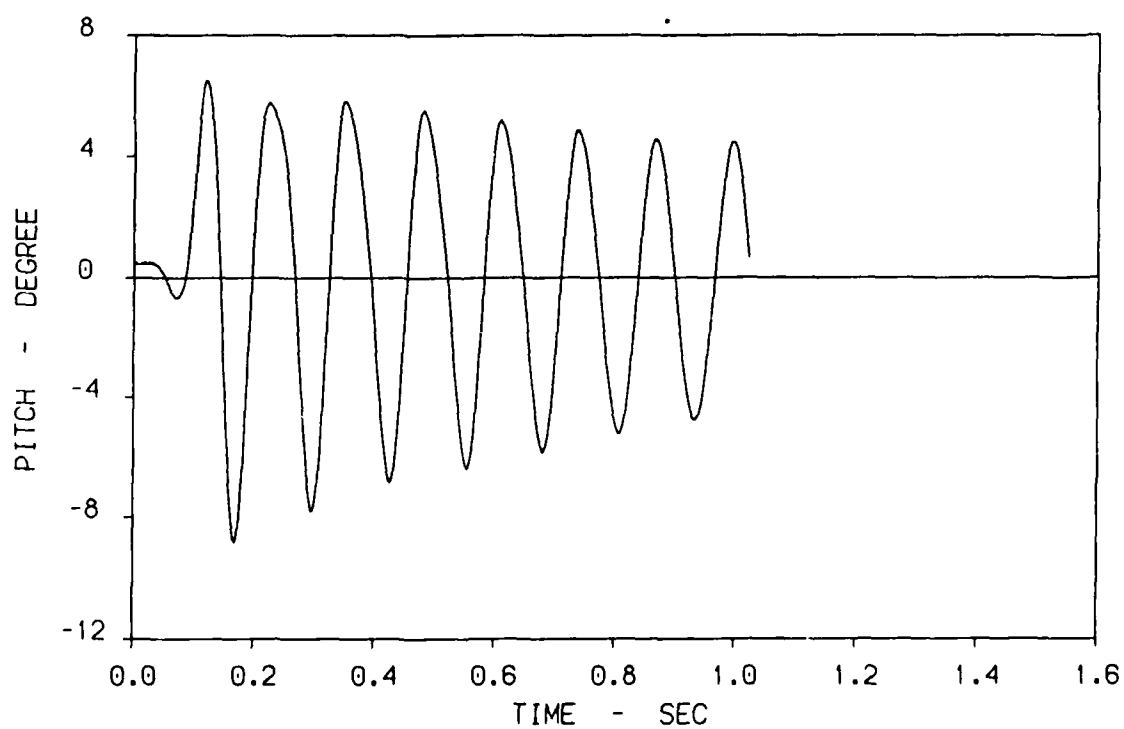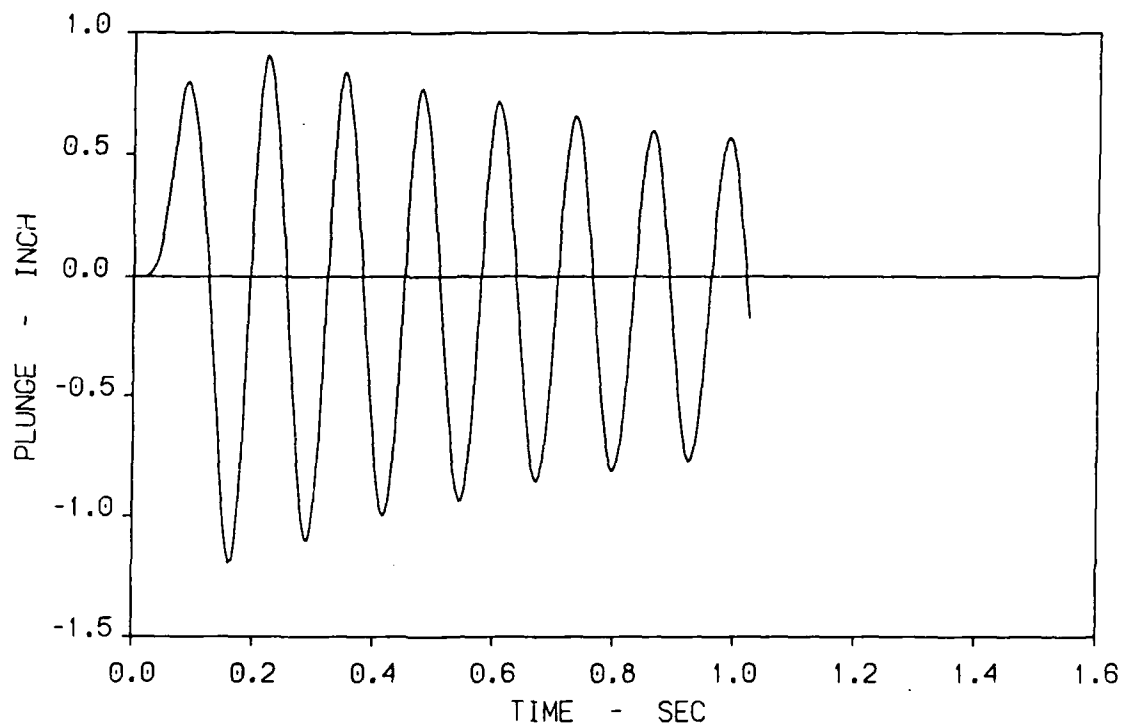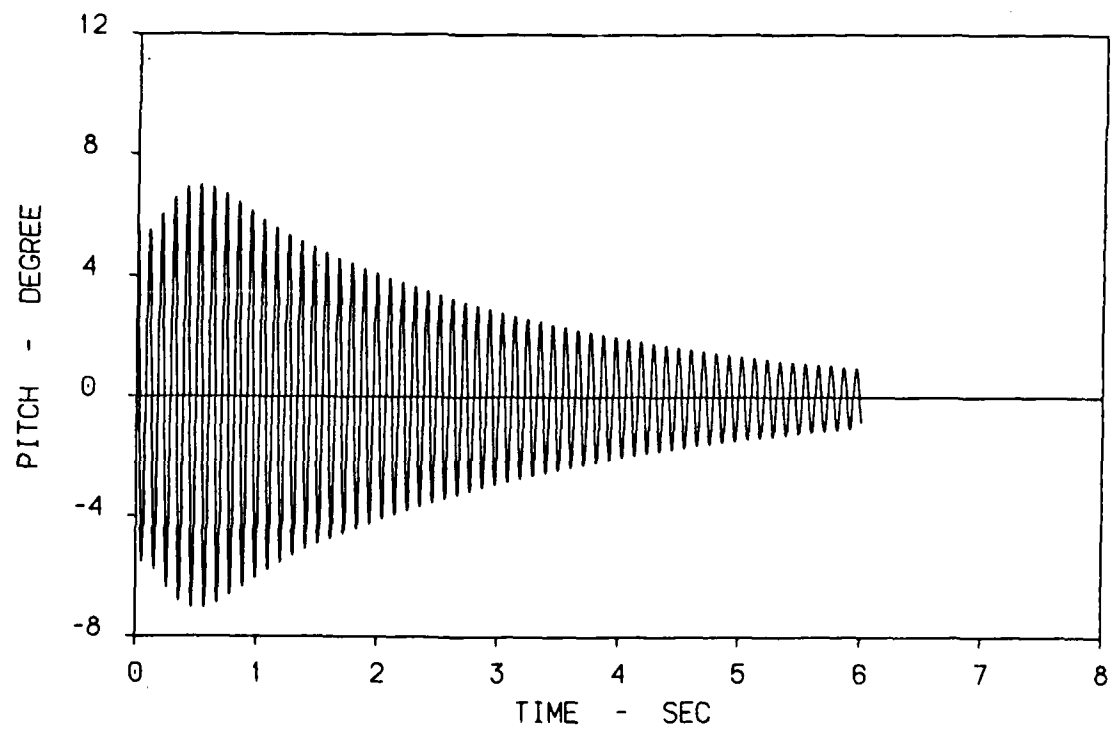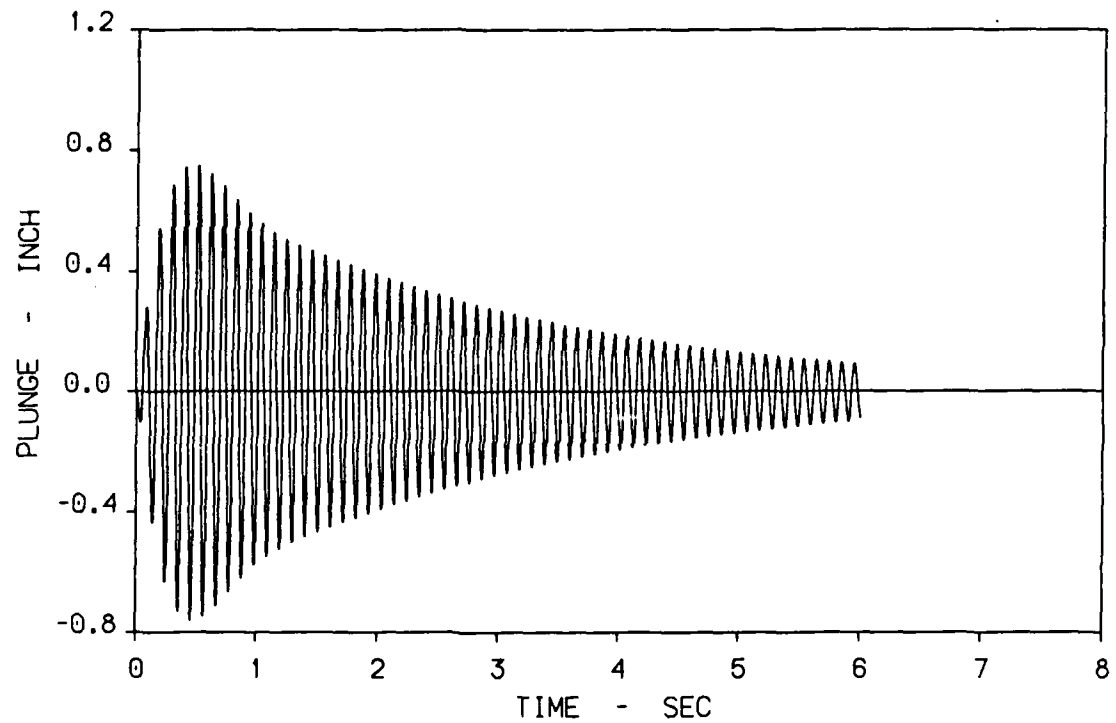
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FIGURE 23. EXPERIMENTAL DATA - 122 FT/SEC

FIGURE 24. ANALYTICAL RESULTS - 110 FT/SEC

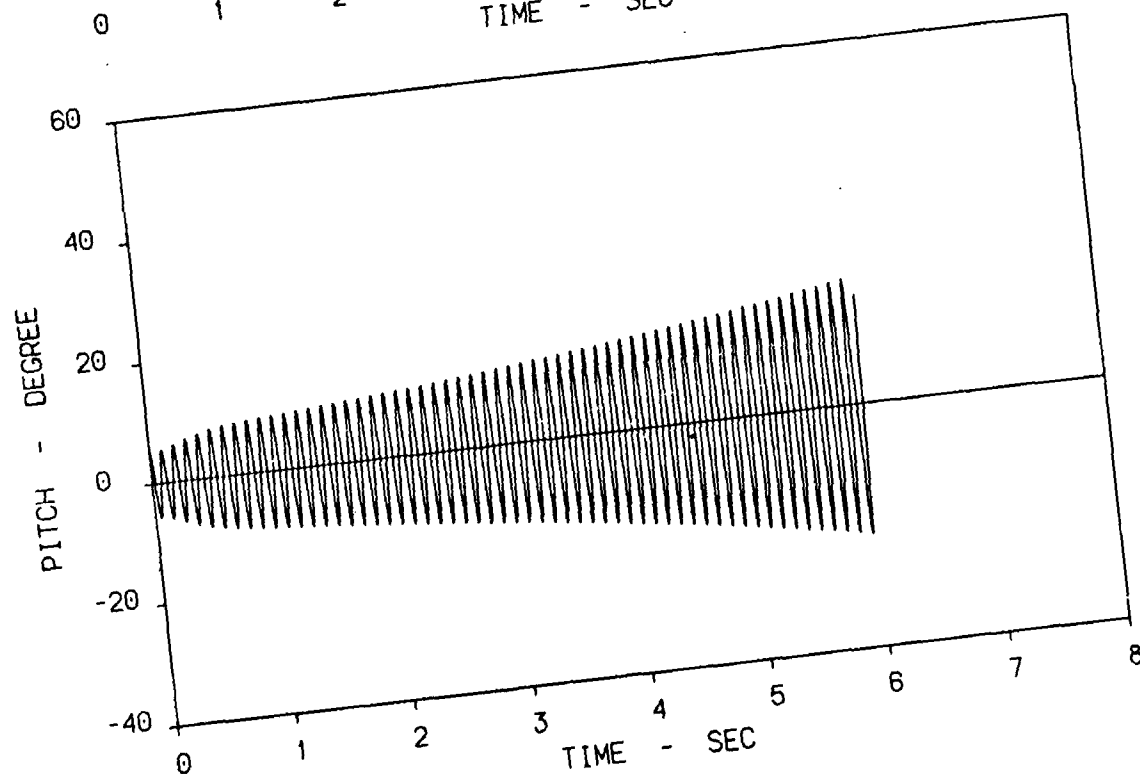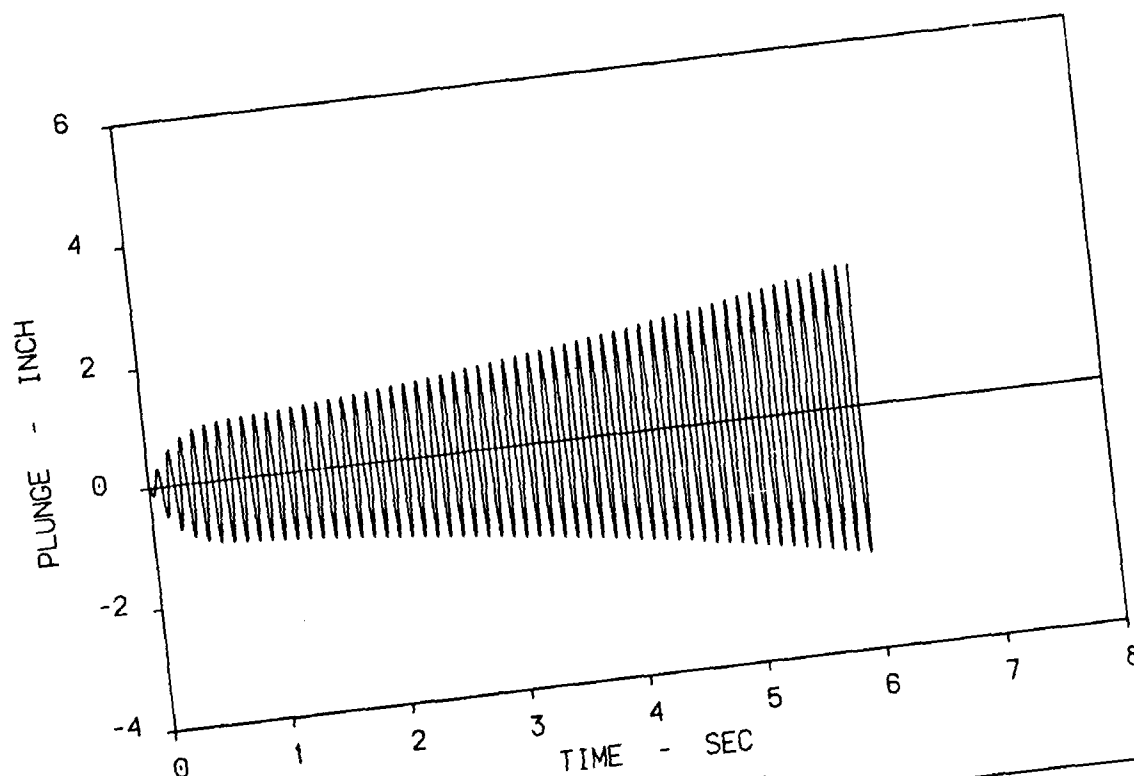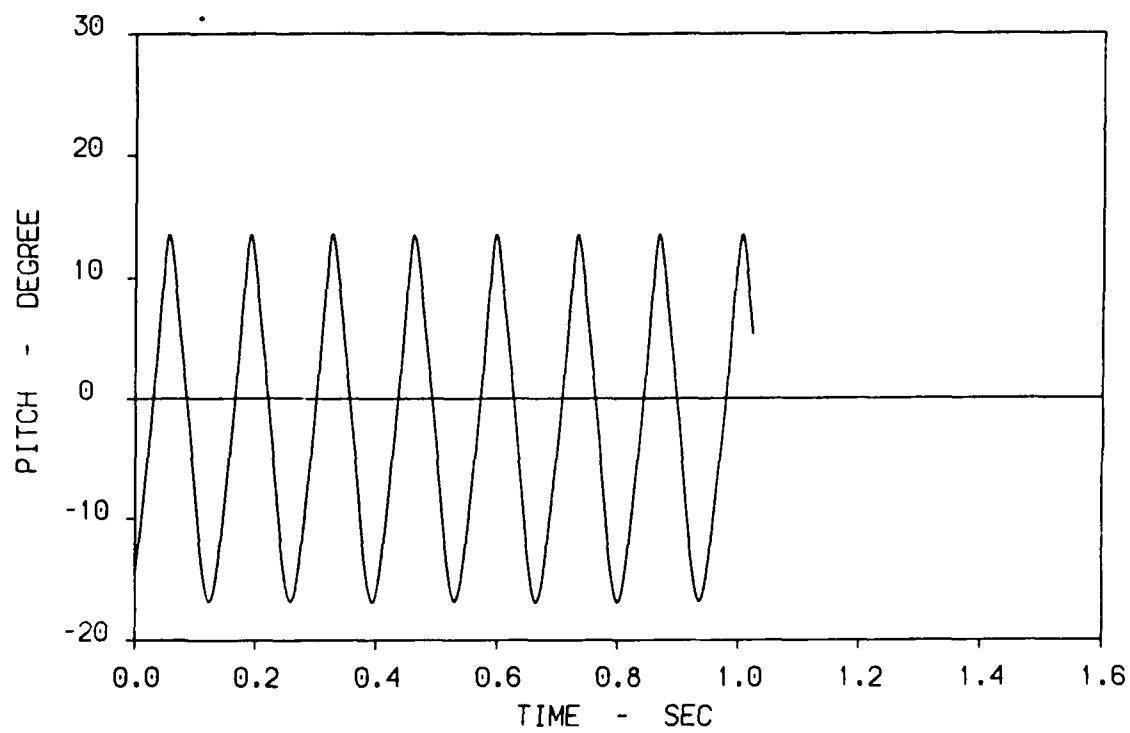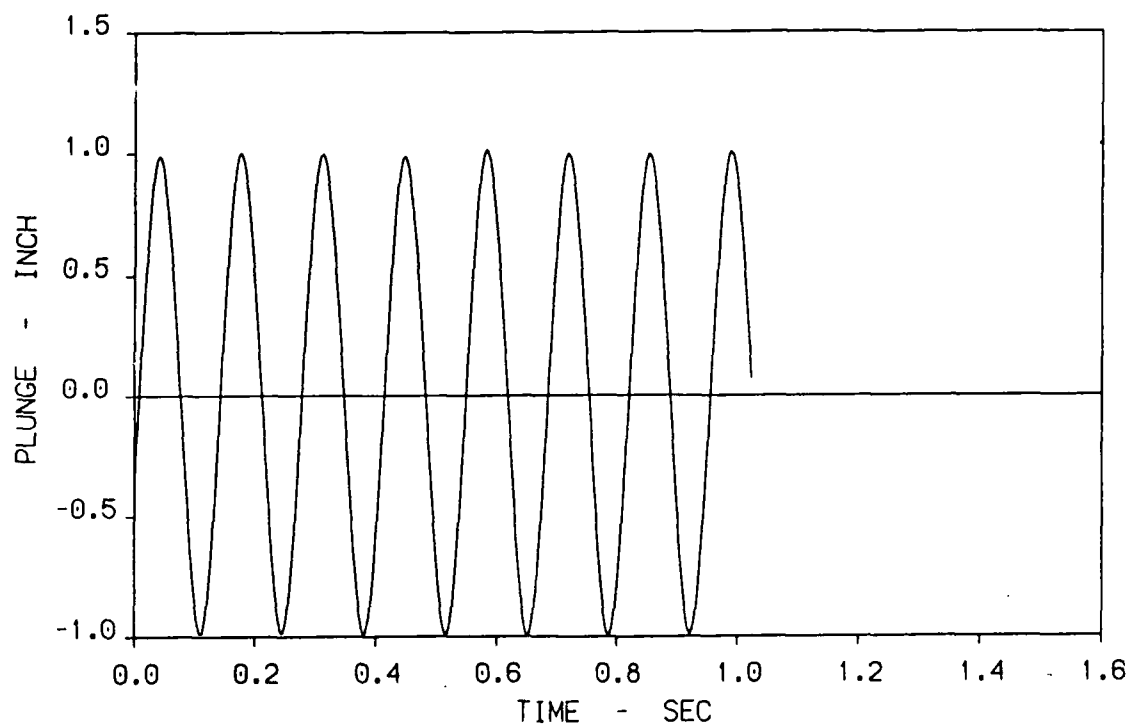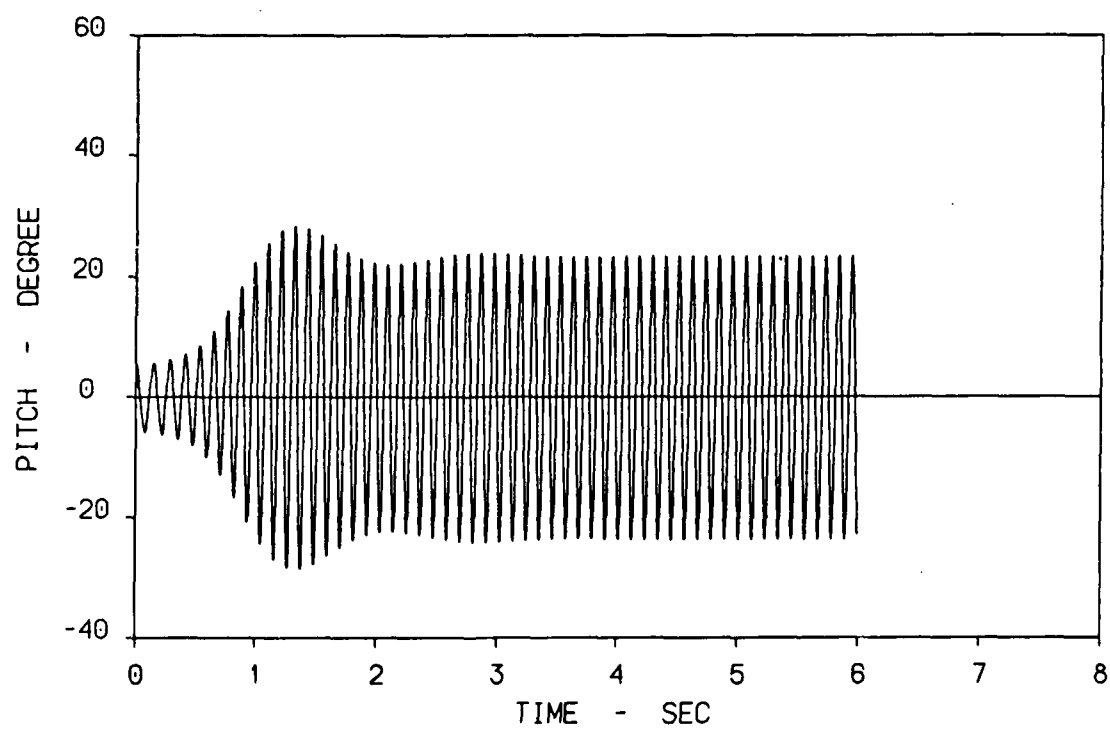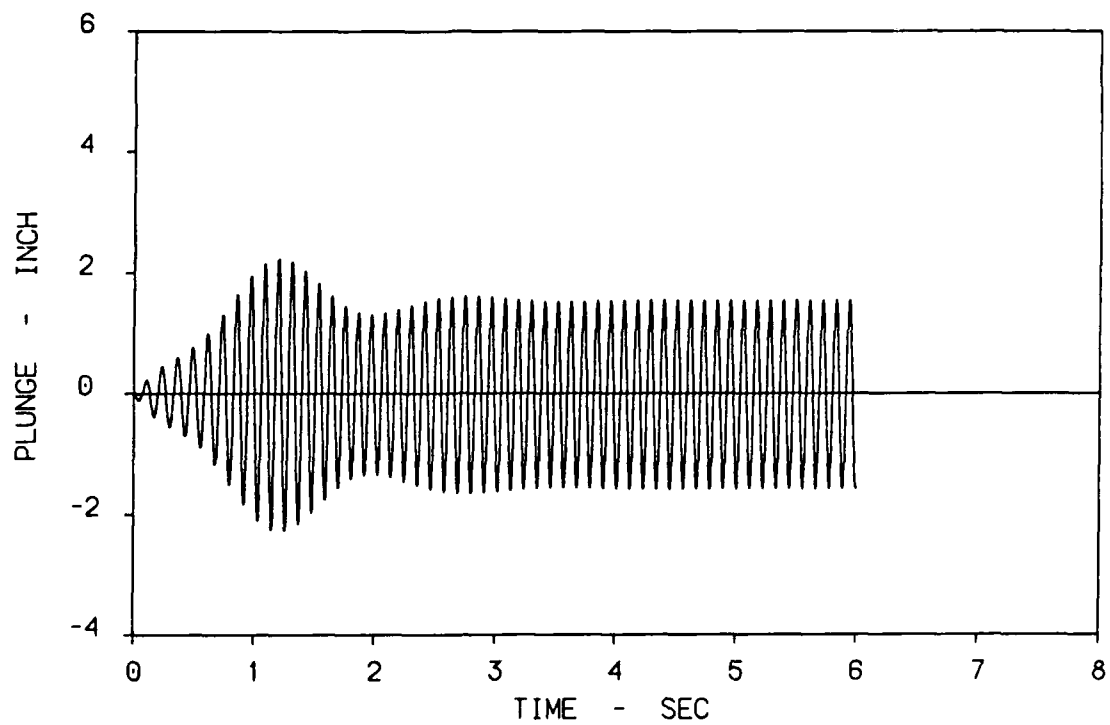FIGURE 25. ANALYTICAL RESULTS - 115 FT/SEC

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FIGURE 26. EXPERIMENTAL DATA - 81 FT/SEC
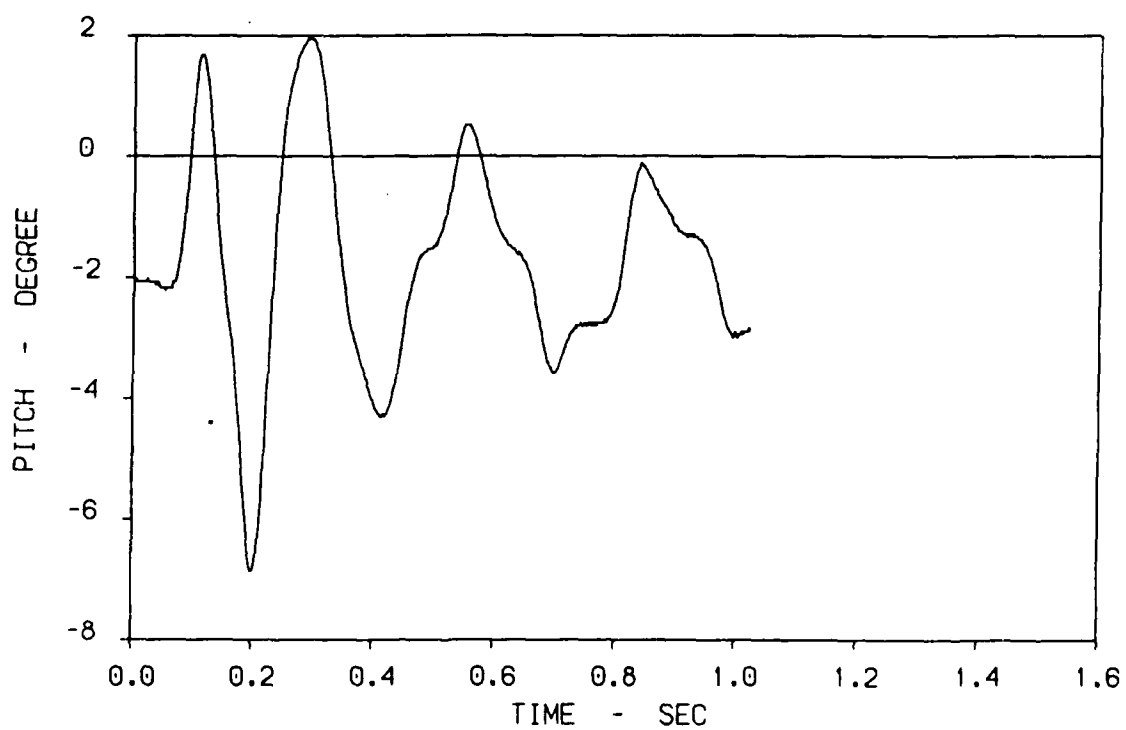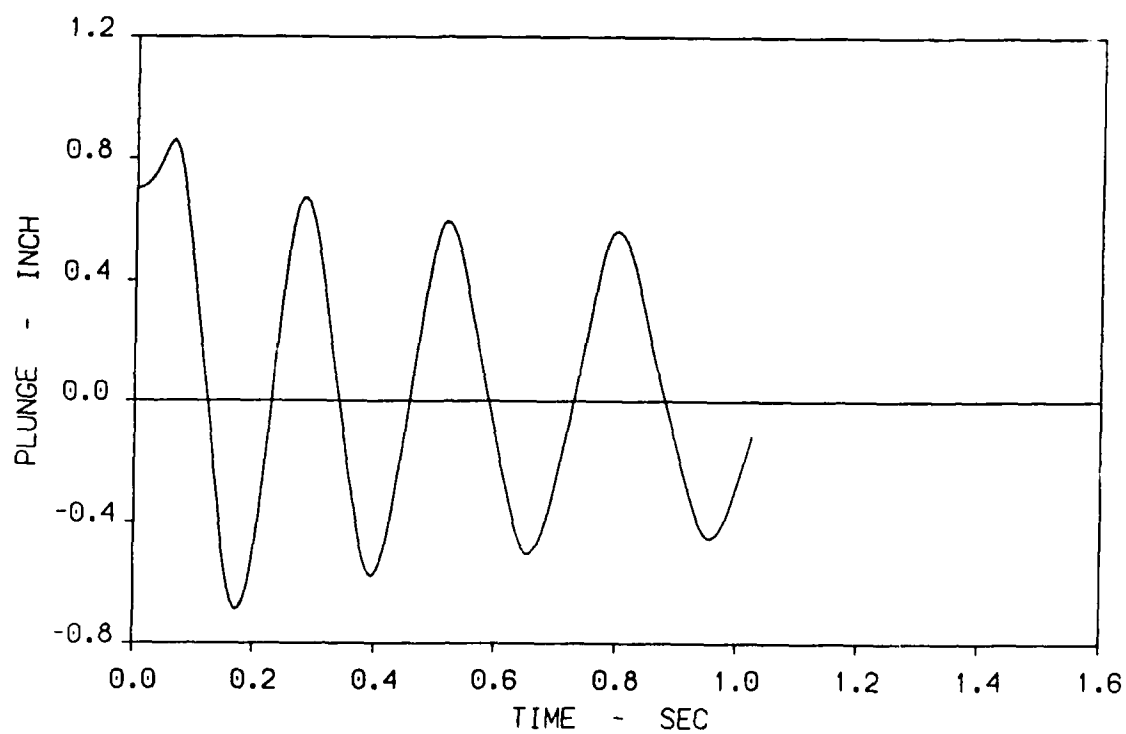
42

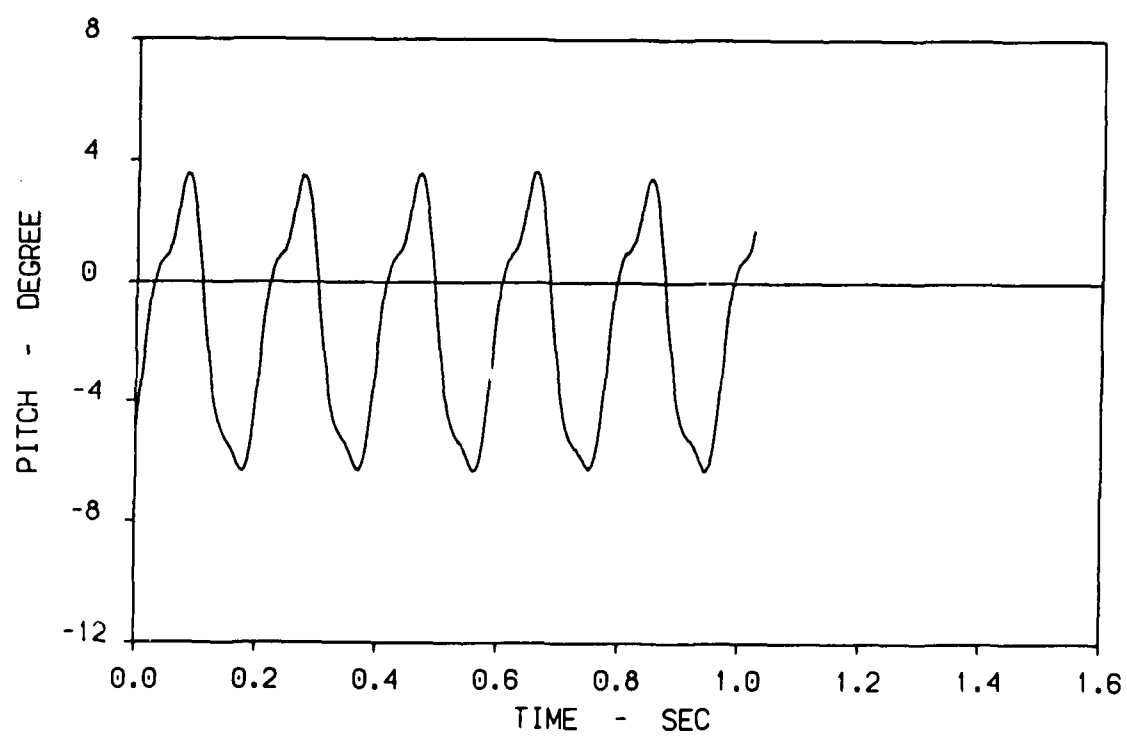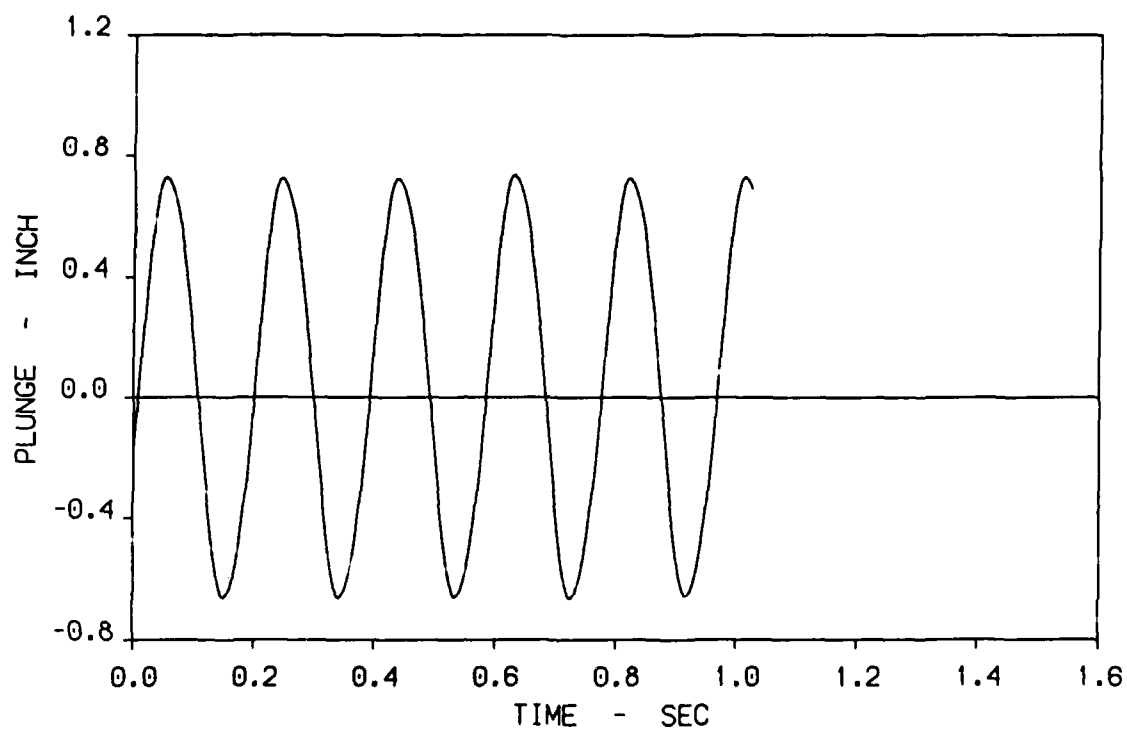**FIGURE 27. ANALYTICAL RESULTS - 81 FT/SEC**

FIGURE 28. EXPERIMENTAL DATA - 61 FT/SEC
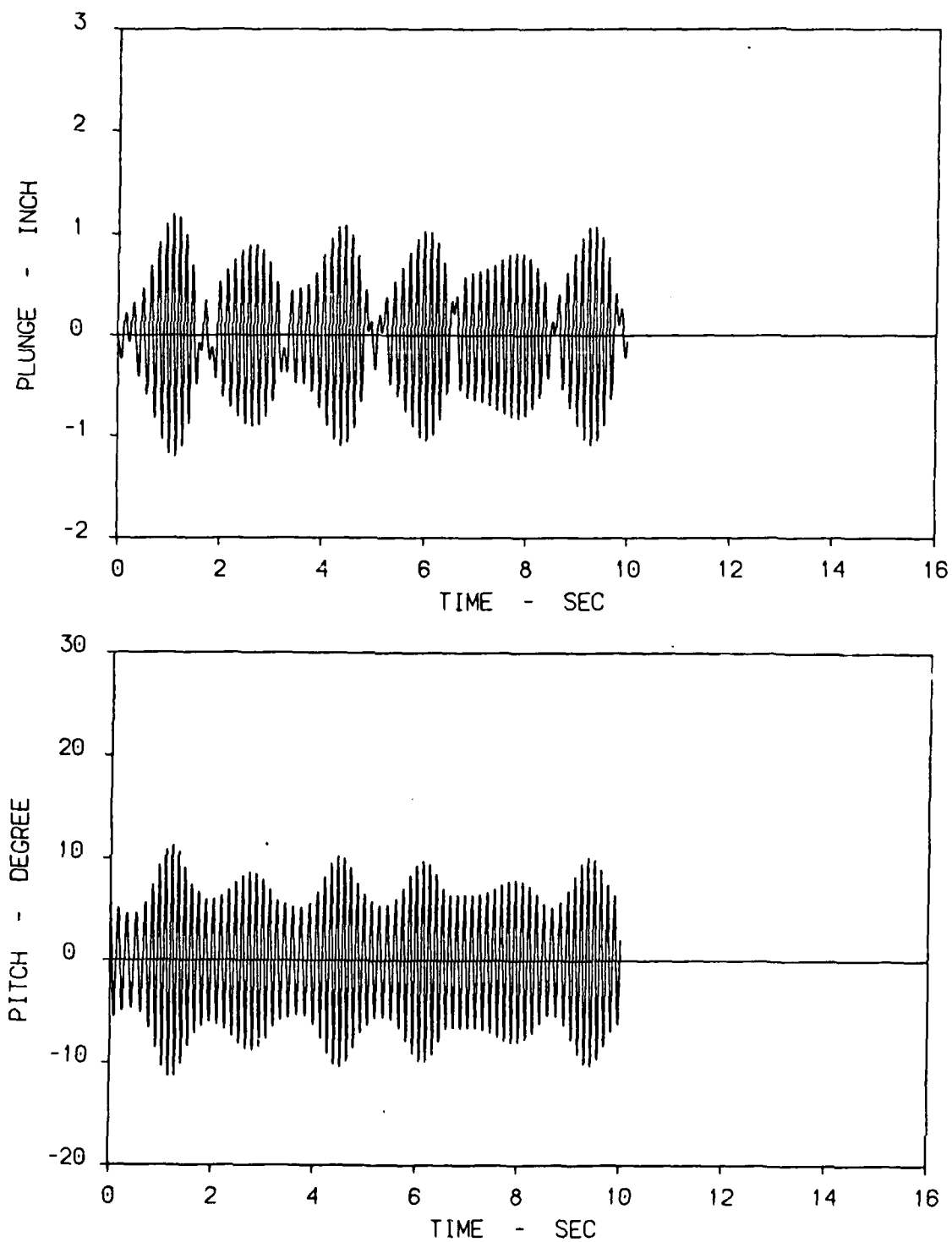
44

FIGURE 29. EXPERIMENTAL DATA - 81 FT/SEC

45

FIGURE 3ΰ. ANALYTICAL DATA - 81 FT/SEC

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4.0 OPTION I YEAR PLANS

During the upcoming Option I year, this research program will build on the accomplishments of the completed Basic Year. A schedule of these activities is presented in Figure 6, Section 2.2.

Extensive wind tunnel testing will be conducted for the rigid aerosurface with varying combinations of root support nonlinearities. Aerosurface response characteristics will be determined as a function of air speed, magnitude and type of nonlinearities, and initial conditions. Post-test analysis of measured response will focus on identifying potential regions of chaotic response. Included will be frequency and power spectral density analyses, plotting of phase planes and Poincare' maps, and determination of the associated correlation dimension.

Numerical simulations of the nonlinear dynamics problem will be conducted in parallel with the wind tunnel testing. These simulations will employ the unsteady aerodynamic representation, Section 3.1.3. Aerosurface response characteristics will be evaluated numerically to determine the nature of this response in terms of initial conditions, air speed, and nonlinearities. Results from these numerical studies will aid in defining wind tunnel test conditions. In addition, these simulation results will be evaluated for the potential of chaotic behavior in a maneuver similar to that used for the wind tunnel test data.

In reviewing results from the wind tunnel testing, it became apparent that there was slippage in the root spring of the pitch degree of freedom. For the current design, this leaf spring, Figure 20, is held in place with set screws. During testing there appeared to be relative motion through this attachment. Early in the Option I year the attachment of the pitch spring will be modified to ensure a positive support at this point.

During the coming year, the dynamic test setup will be completed and dynamic testing begun for the rigid aerosurface. This testing is to obtain data to augment the information obtained during wind tunnel testing. This information will enhance the understanding of the behavior of the nonlinear aeroelastic system. In conjunction with this testing, numerical simulation studies will be performed using the techniques discussed in Section 3.1.2. These analyses will employ a steady aerodynamics representation which is consistent with the planned dynamic test techniques discussed in, Section 3.2.2.

UMR has completed an initial design and assembled a prototype model for the flexible aerosurface. This is well ahead of the scheduled milestones shown in Figure 6. The initial design/fabrication activities were the result of a senior design project under the direction of Dr. Eversman. At this time, Dr. Galecki has begun fabrication of an improved prototype of the flexible aerosurface spar. In all likelyhood, final fabrication and initiation of wind tunnel testing for the flexible aerosurface will be accomplished during the Option I year. The probability of this activity occuring during Option I has been reflected in the Figure 6 Program Schedule.
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5.0 CONCLUSIONS

Substantial progress has been made during the Basic Year towards achieving the overall research objectives. These objectives are to obtain an increased understanding of the dynamic response phenomenon for aerosurfaces with discrete structural nonlinearities within the context of chaotic behavior.

Several analysis techniques have been established and used to obtain further understanding of the nonlinear dynamic response characteristics of the rigid aerosurface system. Wind tunnel testing has begun for the rigid aerosurface and a majority of the equipment necessary for dynamic testing has been acquired. Comparison of analytical and wind tunnel test results has begun for the rigid aerosurface.

For the rigid aerosurface, similar type motion; damped decay, stable limit cycle, and flutter; has been observed in both the analysis and experimental results. A number of response characteristics seen in the analysis results need experimental confirmation. These include beat phenomenon, dependance on initial conditions, and indications of chaotic response. In addition, the influence of mechanical damping on analysis results requires further investigation. These topics will be addressed during the coming year.

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6.0 PERSONNEL AND INTERACTIONS

A summary of the professional personnel associated with the research program is presented in the following section. This is followed by a discussion of interactions with other organizations.

6.1 Personnel

Dr. Robert M. Laurenson of MDMSC is Principal Investigator and is responsible for overall program management and performance including cost and schedule control. Mr. Anthony J. Hauenstein is Co-Investigator reporting directly to Dr. Laurenson and is responsible for MDMSC program technical performance. Dr. Walter Eversman is Co-Principal Investigator and directs all program activities accomplished at UMR. Assisting Dr. Eversman at UMR are Dr. Grzegorz Galecki, Dr. Richard T. Johnson, and Mr. Iyad Khalil Qumei.

During the research project Dr. Laurenson reports to Dr. John L. Gubser who is head of the Structures Department at MDMSC. Due to his background as Principal Investigator during the previous two AFOSR studies, References 1 and 2, Dr. Gubser serves as a Consultant during this study. In this capacity he participates in program reviews.

Summary information for these individuals follows.

ROBERT M. LAURENSON
Principal Investigator

Position: Branch Chief
           Structures Department
           McDonnell Douglas Missile Systems Company (MDMSC)
           St. Louis, Missouri

Education: 1961; B.S., Mechanical Engineering, University of Missouri-Rolla,
                 Rolla, MO
           1962; M.S., Mechanical Engineering, University of Michigan,
                 Ann Arbor, MI
           1969; Ph.D., Mechanical Engineering, Georgia Institute of
                 Technology Atlanta, GA
                 Thesis Title: "Dynamic Characteristics of Nonlinearity
                                Damped System"

ANTHONY J. HAUENSTEIN
Co-Investigator

Position: Engineer
           Structures Department
           McDonnell Douglas Missile Systems Company (MDMSC)
           St. Louis, Missouri

Education: 1984; B.S., Aerospace Engineering, Iowa State University, Ames, IA

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WALTER EVERSMAN
Co-Principal Investigator

Position: Curators' Professor
             Mechanical and Aerospace Engineering and Engineering
               Mechanics Department
             University of Missouri-Rolla (UMR)
             Rolla, Missouri

Education: 1959; B.S., Aerospace Engineering; Purdue University,
                   West Lafayette, IN
            1961; M.S., Engineering Mechanics; Stanford University,
                   Stanford, CA
            1964; Ph.D., Aeronautics & Astronautics, Stanford University
                   Stanford, CA

JOHN L. GUBSER
Program Consultant

Position: Manager
             Structures Department
             McDonnell Douglas Missile Systems Company (MDMSC)
             St. Louis, Missouri

Education: 1958; B.S., Mechanical Engineering; Washington University,
                   St. Louis, MO
            1959; M.S., Engineering Mechanics; University of Illinois,
                   Urbana, IL
            1961; Ph.D., Engineering Mechanics; University of Illinois,
                   Urbana, IL
            1961; Fullbright Fellowship, Technological University, Delft in
                   the Netherlands

RICHARD T. JOHNSON
Test Instrumentation

Position: Professor
             Mechanical and Aerospace Engineering and Engineering Mechanics
               Department
             University of Missouri-Rolla (UMR)
             Rolla, Missouri

Education: 1962; B.S., Mechanical Engineering; University of Missouri-Rolla,
                   Rolla, MO
            1964; M.S., Mechanical Engineering; University of Missouri-Rolla,
                   Rolla, MO
                   Thesis Title: "The Design, Construction and Operation
                   of a Conducting Field Analog Computer"
            1968; Ph.D., Mechanical Engineering; University of Iowa,
                   Iowa City, IA
                   Thesis Title: "Fluid Jet Transmission of a Pressure
                   Signal from a Rotating Shaft to a Fixed Receiver"

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GRZEGORZ GALECKI
Mechanical Hardware Fabrication

Position: Visiting Scholar
Rock Mechanics & Explosives Research Center
High Pressure Waterjet Laboratory
University of Missouri-Rolla
Rolla, Missouri

Education: 1974; B.S., Master of Mechanical Engineering, Wroclaw Technical
University, Wroclaw, Poland
1978; Ph.D. in Technical Sciences, Wroclaw Technical University,
Wroclaw, Poland
Thesis Title: "Mechanism of Cutting of a Material by
High Speed Water Jet"

IYAD KHALIL QUMEI
Coordination of Hardware Fabrication and Testing

Position: Graduate Student
Mechanical and Aerospace Engineering Mechanics Department
University of Missouri-Rolla
Rolla, Missouri

Education: 1986; B.S., Mechanical Engineering, Yarmouk University,
Irbid, Jordan
1986; Graduate Student, Mechanical and Aerospace Engineering,
University of Missouri-Rolla, Rolla, MO

6.2 Interactions

During the performance of this research program, industry/university
information exchange has developed in addition to that required by the
research objectives. This experience has been selected for incorporation in
the proceedings of the ASME 1989 Mechanical Engineering Department Heads
Conference which was held March 8-10, 1989 in Orlando, Florida. A description
of this interaction is contained in Appendix B.

Dr. Eversman has obtained $25K in research funding from the state of
Missouri under the Missouri Research Assistance Act (MRAA). These monies are
available for faculty members at Missouri institutions who are doing research
for Missouri firms. This funding is a direct augmentation of the AFOSR funds
that UMR is receiving via their subcontract with MDMSC.

Briefings have been made to a number of organizations which included a
review of the work being done in this research program. A listing of the
briefings held during the Basic Year is presented in Figure 31. A review of
the research program objectives/results was recently held with members of the
Structural Dynamics and Loads Department from McDonnell Aircraft Company. In
addition, periodic status briefings have been made to MDMSC management
including the Vice President of Engineering and the Director of Design and
Technology Engineering.

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DATE	INDIVIDUAL(S)	ORGANIZATION
14 April 1988	Dr. Gerald Seidel J.V. Marron Jay Schneider Michelle Finegan Alkis Koutsiouroubas Robert Hay	Structural Design & Analysis Branch Code 6041 Naval Air Development Center Warminister, PA 18974

12 July 1988	Dr. Daniel R. Mulville	Office of Aeronautic & Space
		    Technology
		National Aeronautics & Space
		    Administration
		Washington, D.C. 20546

17 August 1988	Randall C. Davis John Shideler H. Neale Kelly (PRC) Wayne Sawyer Charles Camarda Jim Robinson Vic Spain (PRC) Jeff Cerro (PRC) Stuart Jones (PRC) Shawn Birchenough Kevin Rivers Steve Scotti Lynn Bownan David Glass	Thermal Structures Branch NASA Langley Research Center Hampton, VA 23665
31 August 1988	Dr. Craig Porter Michael Munson Jim McManigal Ted Hicks Linda Finco	Thermal/Structures Branch Code 3242 Naval Weapons Center China Lake, CA 93555

FIGURE 31. BASIC YEAR SUMMARY BRIEFINGS

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7.0 REFERENCES

1. R. P. Briley and J. L. Gubser, "Investigation of Limit Cycle Response of Aerodynamic Surfaces with Structural Nonlinearities," Final Report, AFOSR Contract F49620-82-C-0043, November 1982.

2. A. J. Hauenstein, R. M. Laurenson, and J. L. Gubser, "Investigation of an Asymptotic Expansion Technique to Analyze Limit Cycle Response of Aerodynamic Surfaces with Structural Nonlinearities," Final Report, AFOSR Contract F49620-84-C-0123, 8 July 1985.

3. A. J. Hauenstein, R. M. Laurenson, and J. L. Gubser, "Effects of Structural Nonlinearities on Limit Cycle Response of Aerodynamic Surfaces," AIAA paper 86-899-CP, AIAA/ASME/ASCE/AHS 27th Structures, Structural Dynamics, and Materials Conference, San Antonio, TX, 19-21 May 1986.

4. E. H. Dowell, "Observations and Evolution of Chaos for an Autonomous System," Journal of Applied Mechanics, Vol. 51, September 1984, pp. 664-673.

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8. N.H. Zimmerman, "Elementary Static Aerodynamics Adds Significance and Scope in Flutter Analyses," Proceedings of AIAA Symposium on Structural Dynamics of High Speed Flight, Los Angeles, CA, 24-26 April 1961.

9. Advanced Continuous Simulation Language (ACSL) User Guide/Reference Manual, Mitchell and Gauthier Associates Inc., Concord, MA 1981.

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12. L.O. Brase, "The Application of Transient Aerodynamics to the Structural Nonlinear Flutter Problem," Master's Thesis, University of Missouri-Rolla, July 1986.

13. L.O. Brase and W. Eversman, "The Application of Transient Aerodynamics to the Structural Nonlinear Flutter Problem," AIAA Paper 87-0908, 1987.

14. I. Abel, "An Analytical Technique for Predicting the Characteristics of a Flexible Wing Equipped with an Active Flutter Suppression System and Comparison With Wind Tunnel Data," NASA TP 1367, 1979.

15. T.S. Parker and L.O. Chua, "Chaos: A Tutorial For Engineers," Proceedings of the IEEE, Vol. 75, No. 8, August 1987.

16. P. Grassberger and I. Procaccia, "Characterization of Strange Attractors," Physical Review Letters, Vol. 50, No. 5, January 1983.

17. N.H. Packard, J.P. Crutchfield, J.D. Farmer, and R.S. Shaw, "Geometry from a Time Series," Physical Review Letters, Vol. 45, No. 9, September 1980.

18. S. Ciliberto and J.P. Gollub, "Chaotic Mode Competition in Parametrically Forced Surface Waves," J. Fluid Mech., Vol. 158, 1985.

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APPENDIX A

EQUILIBRIUM POINT IDENTIFICATION

This Appendix contains examples which demonstrate how the equilibrium points discussed in Section 3.1.5 were identified. All the displacement combinations for the two cases of: 1) two linear springs with no aerodynamic moment and 2) two freeplay springs with an aerodynamic moment are shown. Equilibrium points for systems with other spring combinations may be defined in a similar manner. Figure 2 from Section 1.0 is repeated here as Figure A-1.

Case 1 - Two Linear Springs With No Aerodynamic Moment

This case has one possible set of displacement combinations defined as

$$- \infty \leq \alpha \leq \infty \text{ and } - \infty \leq h \leq \infty$$

For this case the system equations, obtained from Equation (30), are

$$K_h = -AM^2\alpha$$
$$K_\alpha \, \alpha = 0$$

Solving the above for h and α yields:

$$\alpha = 0 \text{ and } h = 0$$

This is a unique equilibrium point and the system is determinate.

Case 2 - Two Freeplay Springs With An Aerodynamic Moment

This case has nine possible displacement combinations. Each of these combinations are individually considered.

o **Combination 1:**

$$- \infty \leq \alpha \leq -S_\alpha \text{ and } - \infty \leq h \leq -S_h$$

The system equations for this situation are

$$K_h \, h + K_h \, S_h = -AM^2\alpha$$
$$K_\alpha \, \alpha + K_\alpha \, S_\alpha = AM^2 r\alpha$$

Solving for h and α yields

$$\alpha = -K_\alpha \, S_\alpha/(K_\alpha - AM^2 r)$$
$$h = -AM^2\alpha/K_h - S_h$$

From the displacement assumption, α is always negative. This causes h to always be greater than S_h, which violates the displacement assumption for h. Thus, Combination 1 has no equilibrium point and the system is undefined.

o **Combination 2:**

$$-S_\alpha \leq \alpha \leq S_\alpha \text{ and } - \infty \leq h \leq -S_h$$

The system equations are

$$K_h h + K_h S_h = -AM^2\alpha$$
$$0 = AM^2 rd$$

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(a) — Freeplay nonlinearity
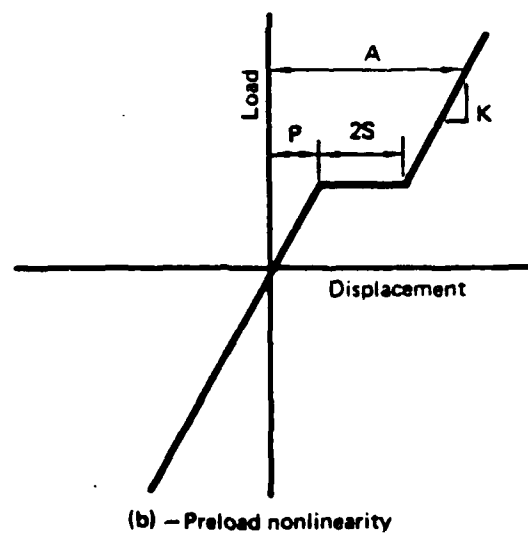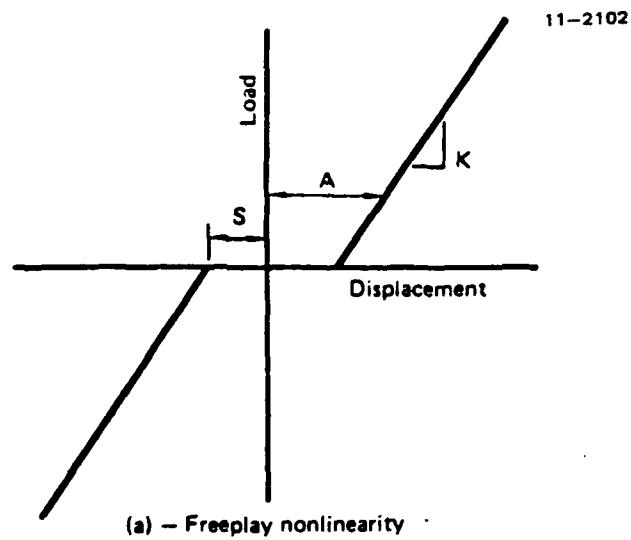
(b) — Preload nonlinearity

FIGURE A-1. TYPES OF STRUCTURAL NONLINEARITIES

Solving for h and α yield

$$\alpha = 0 \text{ and } h = -S_\alpha$$

This is a unique equilibrium point and the system is determinate.

o **Combination 3:**

$$S_\alpha \leq \alpha \leq \infty \text{ and } -\infty \leq h \leq -S_h$$

The system equations are

$$K_h h + K_h S_h = -AM^2\alpha$$
$$K_\alpha \alpha - K_\alpha S_\alpha = AM^2 \, rd$$

Solving for h and yields

$$\alpha = K_\alpha S_\alpha/(K_\alpha - AM^2 r)$$
$$h = -AM^2\alpha/K_h - S_h$$

This is a unique equilibrium point and the system is determinate.

o **Combination 4:**

$$-\infty \leq \alpha \leq -S_\alpha \text{ and } -S_h \leq h \leq S_h$$

The system equations are

$$0 = -AM^2\alpha$$
$$K_\alpha\alpha + K_\alpha S_\alpha = AM^2 r\alpha$$

These equations yield two solutions for α which are

$$\alpha = 0$$
$$\alpha = -K_\alpha S_\alpha/(K_\alpha - AM^2 r)$$

and thus this combination has no solution and the system is undefined.

o **Combination 5:**

$$-S_\alpha \leq \alpha \leq S_\alpha \text{ and } -S_h \leq h \leq S_h$$

The system equations are

$$0 = -AM^2\alpha$$
$$0 = AM^2 r\alpha$$

Solving for α yields

$$\alpha = 0$$

The only restriction on h is that it be within the displacement assumption

$$-S_h \leq h \leq S_h$$

Thus this combination has an infinite number of equilibrium points and is indeterminate.

o <u>Combination 6</u>:

$$S_\alpha \leq \alpha \leq \infty \text{ and } -S_h \leq h \leq S_h$$

The system equations are

$$0 = -AM^2\alpha$$
$$K_\alpha \ \alpha - K_\alpha S_\alpha = AM^2 r\alpha$$

Solving for α yields two solutions

$$\alpha = 0$$
$$\alpha = K_\alpha S_\alpha / (K_\alpha - AM^2 r)$$

This combination has no solution and is therefore undefined.

o <u>Combination 7</u>:

$$- \infty \leq \alpha \leq -S_\alpha \text{ and } S_h \leq h \leq \infty$$

The system equations are

$$K_h h - K_h S_h = -AM^2\alpha$$
$$K_\alpha \alpha + K_\alpha S_\alpha = AM^2 \ r\alpha$$

Solving for h and α yields

$$\alpha = -K_\alpha S_\alpha / (K_\alpha - AM^2 r)$$
$$h = -AM^2\alpha / K_h + S_h$$

This is a unique equilibrium point and the system is determinate.

o <u>Combination 8</u>:
$$-S_\alpha \leq \alpha \leq S_\alpha \text{ and } S_h \leq h \leq \infty$$

The system equations are

$$K_h h - K_h S_h = -AM^2\alpha$$
$$0 = AM^2 r\alpha$$

Solving for h and α yields

$$\alpha = 0$$
$$h = S_h$$

This is a unique equilibrium point and the system is determinate.

o <u>Combination 9</u>:

$$S_\alpha \leq \alpha \leq \infty \text{ and } S_h \leq h \leq \infty$$

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The system equations are

$$K_h h - K_h S_h = -AM^2 \alpha$$

$$K_\alpha \alpha - K_\alpha S_\alpha = AM^2 r \alpha$$

Solving for h and α yields

$$\alpha = K_\alpha S_\alpha (K_\alpha - AM^2 r)$$

$$h = -AM^2 \alpha / K_h + S_h$$

This combination has no equilibrium point which satisfies the displacement assumptions and thus the system is undefined.

o **Summary**

For the case of two freeplay springs with an aerodynamic moment there exist four determinate equilibrium points, one indeterminate point, and four undefined points. These results are reflected in the data shown in Figure 14, Section 3.1.5.

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APPENDIX B

UNIVERSITY/INDUSTRY INTERACTION

BENEFITS OF UNIVERSITY/INDUSTRY COOPERATIVE RESEARCH
ASME 1989 Mechanical Engineering Department Heads Conference

Walter Eversman
Curators' Professor
Mechanical & Aerospace Engineering and Engineering Mechanics Department
University of Missouri-Rolla
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(314) 341-4670

ABSTRACT

The University of Missouri-Rolla is currently involved with McDonnell Douglas Missile Systems Company, St. Louis, MO, in a cooperative research program for the Air Force. Of significance is the added benefit of information exchange with this type relationship -- in addition to the obvious goal of doing good research work. This university/industry interaction has developed during the course of the research activity and demonstrates the benefit of cooperative research programs.

· DESCRIPTION

McDonnell Douglas Missile Systems Company is currently under contract to the Air Force Office of Scientific Research (AFOSR) for a research program entitled "Chaotic Response of Aerosurfaces With Structural Nonlinearities." This is a joint program involving McDonnell Douglas and the University of Missouri-Rolla (UMR). Dr. Robert M. Laurenson is Principal Investigator at McDonnell Douglas and Dr. Walter Eversman of the Mechanical and Aerospace Engineering and Engineering Mechanics Department is the Co-Principal Investigator at UMR. McDonnell Douglas is doing nonlinear aeroelastic analysis development work while UMR is designing, building, and testing wind tunnel models.

Early in the project, the wind tunnel model design was used as a project for a Mechanical Engineering senior design team at UMR. This model was to have a rigid airfoil with adjustable nonlinear root support springs. The students established a configuration and fabricated a prototype model. McDonnell Douglas engineers attended the student's oral presentation of their design project. This allowed them to obtain a much better understanding of UMR's design concept and to provide suggestions for modification to the final model design. In addition, the students gained experience in presenting their design work to an outside "customer." The students' prototype has subsequently been refined and has been used in wind tunnel tests to investigate limit cycles which occur in nonlinear aeroelasticity.

As the result of discussions on McDonnell Douglas analytical work, UMR was provided with "quick and dirty" flutter analysis techniques McDonnell Douglas uses during advanced design/concept formulation studies. These methods have proven useful in the teaching environment to introduce various aspects of the flutter phenomenon to students. They have been used as an introduction to the more rigorous development of dynamic aeroelastic theory.

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