# BT-2728 Comparison of Analytically and Experimentally Determined Dynamic Behavior of Tethered Balloons

Access Number

BT-2728

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**Responsible Organization** Goodyear Aerospace Corp.

**Funding Organization** Air Force Cambridge Research Labs.

**Date** 30 Mar 1973

**Report Number** AFCRL-TR-73-0284, GER 15932

**Repository Number** 

**Contract Number** F19628-72-C-0219

**Description** Scientific Report, 72 p, 11 refs

**Notes** Project 6665-09-01

**Key Words** Tethered balloons, aerodynamics, stability, tether cables

### Content

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made up of three discrete links. The tools consist of linearized characteristic equations incorporating the physical, aerodynamic and mass properties of the system and the dynamic simulation computer program which determines the response of the tethered balloon system to wind disturbances. A computer simulation of an actual tethered balloon system was compared with real flight data from that system which resulted in a reasonable match, allowing the conclusion that such modeling can become a powerful tool for design and analysis of tethered balloon systems.

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Goodyear Aerospace Corp.

Jerome J. Vorachek, George R. Doyle

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# COMPARISON OF ANALYTICALLY AND EXPERIMENTALLY DETERMINED DYNAMIC BEHAVIOR OF TETHERED BALLOONS

by

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Contract No. F19628-72-C-0219 Project No. 6665 Task No. 666509 Work Unit No. 66650901

> Scientific Report No. 1 30 March 1973

Contract Monitor: Don E. Jackson, Capt. USAF Aerospace Instrumentation Laboratory

Approved for public release; distribution unlimited

Prepared for

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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES AIR FORCE SYSTEMS COMMAND UNITED STATES AIR FORCE BEDFORD, MASSACHUSETTS 01730

#### ABSTRACT

Mathematical tools were developed previously to analyze the dynamic behavior of tethered balloon systems. The model for the tethered balloon system consists of the streamlined balloon and a tether made up of three discrete links. The tools consist of the linearized characteristic equations which incorporate the physical, aerodynamic and mass characteristics of the system and the dynamic simulation computer program which determines the response of the tethered balloon system to wind disturbances. Α tethered balloon system consisting of a 70,000 cubic foot aerodynamically shaped balloon and a 0.52 inch diameter Nolaro tether was flown at Fair Site on White Sands Missile Range to obtain experimental motion data. Experimental test conditions and test tethered balloon system characteristics were input in the computer programs and balloon dynamic behavior was predicted. A comparison of experimental and predicted dynamic characteristics of the tethered balloon showed a reasonable match although some discrepancies existed. In spite of these, it is concluded that the stability and dynamic simulation computer programs are a powerful tool for design and analysis of tethered balloon systems.

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#### SECTION I

#### INTRODUCTION

The objective of the present program is to compare actual flight data with analytically predicted data for a tethered balloon and to improve the mathematical model if required. A second objective is to study the dynamic behavior of two tethered balloon types

Mathematical tools have been developed on a previous program to analyze the dynamic behavior of tethered balloon systems. The techniques used are determination of the roots of the linearized characteristics equations which incorporate the physical, aerodynamic, and mass characteristics of the system, and dynamic simulation of the tethered balloon systems to determine response of the systems to wind disturbances. The techniques are complementary and each helps to obtain insight into the behavior of tethered balloon systems.

The model for the tethered balloon system consists of the streamlined balloon and a tether made up of three discrete links. The derivation of non-linear equations of motion for this system were devised in three dimensions. The equations are linearized for stability analysis and treated as uncoupled in the longitudinal and lateral degrees of freedom. Characteristic equations of the system are developed and solved for the roots which represent the frequency and damping qualities. References 1, 2, and 3 document the results of this program.

A tethered balloon system consisting of a 70,000 cubic foot aerodynamically shaped balloon and a .52 inch diameter Nolaro tether was flown by AFCRL at White Sands Missile Range to obtain experimental balloon motion data. These experimental data have been compared with those predicted by the mathematical model. The efforts to establish the validity of the analytical techniques are reported herein.

#### SECTION II

#### TECHNIQUES FOR STUDY OF DYNAMIC BEHAVIOR OF TETHERED BALLOONS

#### A. MATHEMATICAL MODELS

A system of differential equations was developed (see References 2 and 3) that describes the motion of the tethered balloon in three dimensions. The degrees of freedom associated with the motion are yaw, pitch and roll of the balloon about its dynamic mass center, and pitch and yaw (lateral rotation) of the tether. There are a total of 3 + 2N degrees of freedom where N is the number of links used to simulate the tether.

First consider the longitudinal degrees of freedom. The dependent variables shown in Figure 1 are  $\theta$  (pitch of the balloon) and  $\zeta_r$  (pitch of the "r"th link), where r is a particular link. All angles are shown positive.



Figure 1. Balloon Tether Model in Longitudinal Plane

In Figure 1  $V_{BR}$  is the relative velocity of the balloon's center of gravity with respect to the air and is the resultant of the steady wind, the wind gust, the balloon translational motion and the velocity due to rotation of the balloon about its center of mass. The angle of attack ( $\alpha$ ) is the angle that the relative wind forms with the longitudinal axis of the balloon.

The lateral degrees of freedom are displayed in Figure 2 which gives the front and top view of the tethered balloon. The lateral degrees of freedom are:  $\psi$ (yaw of balloon),  $\phi$  (roll of balloon), and  $\sigma_r$  (yaw of "r"th link). All angles are shown positive).



Figure 2. Balloon Tether Model in Lateral Plane

Pertinent geometry of the tethered balloon and applied forces are identified in Figure 3.

In order to separate the equations of motion into a longitudinal response and a lateral response, it was further assumed that the system was near equilibrium. This resulted in a set of equations describing the longitudinal motion which is coupled only in the pitching variables of the balloon and the pitching variables of the tether. However, the second set of equations for the lateral motion does not completely uncouple from the longitudinal degrees of freedom because the



Figure 3. Balloon Geometry and Applied Forces

equilibrium angles in the longitudinal plane are not zero. Therefore, when solving the lateral degrees of freedom, it must be assumed that the longitudinal variables remain constant and equal to their equilibrium values. In both the longitudinal and lateral cases, the tether is simulated by three rigid links. The number of uncoupled dynamic equations is four for the longitudinal response and five for the lateral response.

#### B. GENERAL STABILITY THEORY

The equilibrium configuration of a tethered balloon can be defined as that position which demands that the summation of all applied moments equals zero. The equilibrium is said to be stable if, for any small disturbance, the system ultimately returns to its equilibrium conditions. Two types of stability are of interest. In the first (statically stable), a small displacement of the system will create forces which tend to return the system to its equilibrium position. The second (dynamically stable) produces a motion which eventually restores equilibrium. If the motion is periodic, it is characterized by a damped frequency and a damping ratio. Similar definitions apply for statically and dynamically unstable motions. A third possibility is for the system to be neutrally stable during which the motion neither diverges nor converges.

Characteristic equations were derived for study of the stability of this system. The general approach was as follows:

- (1) Derive the nonlinear equations of motion in three dimensions for each degree-of-freedom
- (2) Assume the motion is near equilibrium so that the equations can be linearized and separated into a longitudinal motion and a lateral motion
- (3) Laplace transform the linear equations from the time domain to the "S" domain assuming that the initial condictions are zero. This establishes a matrix equation of the following form:

$$[A] \{X(S)\} = \{0\}$$
(1)

where  $\{X (S)\}\$  is the eigenvector and [A] is a square matrix whose elements are quadratics in S containing the physical properties of the system.

(4) Expand the determinant of [A] such that the characteristic polynominal is obtained.

Each root of the characteristic equation represents a term in the general solution of the form,  $A_i e^{Sit}$ , where  $S_i$ is the "i"th root and  $A_i$  is an amplitude, dependent on the initial conditions of the system. Both real and complex roots may appear where the complex roots occur in conjugate pairs. In general for "n" degrees of freedom, the characteristic equation will yield "2n" roots. Each pair of complex conjugate roots represents one oscillatory motion, while each real root represents one aperiodic motion.

First consider an oscillatory system. This motion is characterized by two roots of the form  $S_1 = X + i Y$ , where X and Y are real numbers and  $i = \sqrt{-1}$ . <sup>i</sup> Several important quantities can be found from the root. The natural frequency associated with this motion is  $\omega_n = \sqrt{X^2 + Y^2}$ . The damping ratio is  $\zeta = \frac{-X}{\omega_n}$ . The damping frequency is  $\omega_d = \omega_n \sqrt{1 - \zeta^2} = Y$ . It is also of interest to know the time to half amplitude for a stable root or the time to double amplitude for an unstable root. This quantity can easily be found by considering one oscillatory motion. The general solution for free vibration is

$$Z = Ce^{-\zeta \omega n t} \sin (\omega_{d} t + \beta)$$
 (2)

where  $\emptyset$  is the phase angle dependent upon initial conditions

C is a constant dependent upon initial conditions

The half amplitude time is

$$t_2 - t_1 = \frac{0.693}{\zeta \omega_n}$$
 (3)

The second possibility is an aperiodic motion given by the expression

$$z = Ce^{Xt}$$
(4)

where X is the real part of one root and the imaginary part (Y) is zero

If X is negative, Z approaches zero as time increases indefinitely and the motion is said to be overdamped. Like the oscillatory motion, roots which give overdamped motions will also occur in pairs. However, unlike the complex conjugate roots which result in one oscillatory motion, each real root is a distinct motion. Therefore, it is possible for an "n" degree-of-freedom system to have "2n" distinct motions if the system is so heavily damped that all the roots to the characteristic equation are real. There is a third possible motion which is a borderline case. If two roots are real and equal, the system is said to be critically damped. The motion will be aperiodic and both roots will give the same motion.

The general solution to the motion of the system is a linear combination of all the motions defined by the roots to the characteristic equation. Associated with each root is a mode shape which gives the relative amplitudes of each degree of freedom when the system is responding to one particular root. It is of interest to establish these mode shapes so that each stability curve can be associated with a definite motion of the whole system. For example, one mode shape may show that the pitching motion of the balloon is very large compared to the motion of the tether.

#### C. STABILITY ANALYSIS

Derivations of the equations of motion of the tethered balloon system and development of the characteristic equations for a tethered balloon system approximated with a three-link tether are given in Reference 2.

The four linearized longitudinal equations are Laplace transformed, and an eighth order characteristic equation generated which specifies stability characteristics of the system. In like manner, the five linearized lateral equations can be reduced to a tenth order equation which gives stability information in the lateral degrees-of-freedom. The roots of these characteristic equations identify the natural frequencies, damped frequencies and damping ratios.

#### D. DYNAMIC RESPONSE ANALYSIS

The calculations of the balloon system response to specific disturbances is the subject of the dynamic response analysis. The most general motion the system can have is a linear superposition of the normal modes.

Each aperiodic or non-oscillatory normal mode has one arbitrary constant (the initial value of any one of the variables) associated with it; and each periodic or oscillatory normal mode has two arbitrary constants (the amplitude and phase angle of any one of the variables) associated with it. The total number of arbitrary constants is then equal to the number of aperiodic modes plus twice the number of periodic modes; i.e. to the degree of the characteristic equation, or the order of the system. A specific disturbance will excite the normal modes in varying degrees and establish the values of the arbitary constants. The dynamic response of tethered balloon systems to various wind disturbances is obtained by integrating numerically the longitudinal and lateral equations of motion to produce a time history of the dynamics. The start conditions, or equilibrium conditions for the dynamic response computer programs are obtained from the linearized stability computer programs (Reference 2). This approach to analysis has the advantage that wind gusts can be produced and the actual motion of the system can be observed. The major disadvantage is that a greater amount of computer time is required when compared to evaluation of stability by investigating the roots of the characteristic equations.

The equations of motion for the longitudinal dynamics of a tethered balloon system were initially derived in two forms (see Reference 3):

- inertia terms which contain products of angular velocities are neglected,
- (2) inertia terms which contain products of angular velocities are included.

The concept of neglecting products of angular velocities is associated with the assumption that angular velocities are small; and therefore, products of angular velocities are negligible.

Numerical integrations were made with the computer to determine the effect of neglecting the inertia terms containing products of angular velocities. Although an effect is obviously present, the overall differences between the results of the two sets of equations is small as shown in Reference 3.

It was decided that dynamic simulation studies would be conducted with a model which neglects products of angular velocities for three reasons. First, the equations containing products of angular velocities are shown to give only slightly different results. Second, it is desirable to keep the dynamic equations compatible to the equations used in the stability study (the stability study used linearized equations). Third, it is desirable to keep the longitudinal equations compatible to the lateral equations (to derive the lateral equations of motion containing products of angular velocities in the inertia terms would be a very difficult task because of the number of terms involved.)

#### SECTION III

#### TEST BALLOON DESCRIPTION

#### A. GENERAL

The tethered balloon system which was flown to obtain experimental motion data consisted of a 70,000 cubic foot aerodynamically shaped balloon produced by Lea Bridge Industries of Essex, England, and a Nolaro tether. The Nolaro tether was 0.52 inches in diameter and weighed 90 pounds per 1000 feet. The winch used is permanently installed at Fair Site in the northwestern portion of the White Sands Missile Range.

The general arrangement of the 70,000 cubic foot aerodynamically shaped balloon is presented in Figure 4. The major elements of the balloon are the envelope, the tails and the suspension system. The envelope is divided into three separate chambers - the gas chamber, ballonet, and tail cone. The two near horizontal surfaces and the vertical rudder make up the tails (Table I lists the dimensions for the balloon).

TABLE I

DIMENSIONS FOR THE 70,000 FT<sup>3</sup> KITE BALLOON

#### PRINCIPAL PARTICULARS

Maximum Capacity of Envelope
Maximum Volume of Air Filled Tail (lower only). 6,000 Ft <sup>3</sup>
Maximum Volume of Horizontal Tails (each) 3,070 Ft <sup>3</sup>
Maximum Diameter of Envelope
Length of Envelope
Overall Width with Fins Inflated 43 Ft
Overall Height from Bottom of Rudder 48 Ft 6 In
Height of Balloon from Rigging Confluence Point 66 Ft
Ballonet Capacity
Bridle Confluence Point
45 Ft below Centerline of Hull



#### B. TEST BALLOON GEOMETRY

The geometry of the 70,000 cubic foot balloon was established with the aid of data from the balloon handbook (Reference 4) and the data on the BJ balloon (Reference 5). The overall length and diameter of the hull and location of the confluence point of the suspension lines are listed in Table I. The geometry of tails was established on the basis of data in References 4 and 5.

The pertinent tail dimensions for the tail surfaces are the chord (A), the span (B) and the radius of the tip (R) as defined on Figure 4. From Reference 5 for a BJ balloon, the proportions for the rudder (vertical tail surface) relative to the total envelope length (L) are

> A = 0.41 L B = 0.23 LR = 0.135 L

All horizontal fin surface dimensions are 80% of rudder dimensions. It is understood that the tail surfaces are as used on the BJ balloon. The test balloon has a hull known as the A shape and this hull has a fineness ratio of 2.7 as compared to 2.5 for the BJ balloon. Consequently, for equal hull volume the test balloon hull is longer than the BJ balloon hull. Tail dimensions for the 70,000 cubic foot barrage balloon were calculated by proportioning the length of an equivalent volume BJ balloon. The rudder dimensions computed for the test balloon are:

> A = 40 feet B = 22.4 feet R = 13.15 feet

C. BALLOON MASS CHARACTERISTICS

1. General

The balloon's physical and apparent mass characteristics are presented in this section and tabulated in Table II. The mass characteristics include the physical mass, additional masses in longitudinal, lateral and vertical translation, the apparent masses in roll, pitch and yaw; physical mass moments of inertia and apparent mass moments of inertia in roll, pitch, and yaw. Calculations include center of gravity, centers of additional mass and dynamic centers in pitch and yaw.

#### TABLE II

#### BALLOON MASS CHARACTERISTICS

118.10 slugs Balloon Physical Mass - with payload 54.44 feet Center of Gravity - with payload - Horizontal 6.57 feet - Vertical 30207 slug feet<sup>2</sup> Mass Moment of Inertia, with payload - Roll 149022 slug feet<sup>2</sup> - Pitch 134027 slug feet<sup>2</sup> - Yaw 10391 slug feet<sup>2</sup> Product of Inertia - with payload 114.04 slugs Balloon Physical Mass - without payload 55.24 feet Center of Gravity - without payload - Horizontal 5.30 feet - Vertical 24913 slug feet<sup>2</sup> Mass Moment of Inertia - without payload - Roll 141614 slug feet<sup>2</sup> - Pitch 131895 slug feet<sup>2</sup> - Yaw 7130 slug feet<sup>2</sup> Product of Inertia - without payload 22.00 slugs Additional Mass - Longitudinal 166.63 slugs - Lateral 151.58 slugs - Vertical 56.18 feet Center of Additional Mass, in pitch - horizontal 0.00 feet - vertical 58.39 feet Center of Additional Mass, in yaw - horizontal 1.66 feet - vertical 31422 slug feet<sup>2</sup> Additional Mass Moment of Inertia - roll 123811 slug feet<sup>2</sup> - pitch 132268 slug feet<sup>2</sup> - yaw -8729 slug feet<sup>2</sup> Additional Product of Inertia - in yaw 182.97 slugs Apparent Mass, Without Payload - roll 265.62 slugs - pitch 280.66 slugs - yaw 55.78 feet Dynamic Center, Without Payload, in pitch - horizontal 2.28 feet - vertical

#### TABLE II (cont.)

#### BALLOON MASS CHARACTERISTICS

```
Dynamic Center, Without Payload, in yaw - horizontal
                                                              57.11 feet
                                           - vertical
                                                               3.14 feet
Apparent Mass Moment of Inertia, without payload
                                                              54404 slug ft^2
                                           - roll
                                                             267256 slug ft^2
                                           - pitch
                                                            264854 slug ft^2
                                           - yaw
                                                               7525 slug ft<sup>2</sup>
Apparent Product of Inertia, without payload - in pitch
                                                               -805 slug ft^2
                                                 - in yaw
Apparent Mass, with payload - pitch
                                                             269.69 slugs
                                                             284.73 slugs
                               - yaw
                                                              55.42 feet
Dynamic Center, with Payload, in Pitch - horizontal
                                                               2.88 feet
                                           - vertical
Dynamic Center, with Payload, in yaw - horizontal
                                                              56.75 feet
                                                               3.69 feet
                                         - vertical
                                                             275832 slug ft^2
Apparent Mass Moment of Inertia, with Payload - pitch
                                                             267400 slug ft^2
                                                  - yaw
                                                              11193 slug ft<sup>2</sup>
Apparent Product of Inertia, with Payload - in pitch
                                                               2896 slug ft<sup>2</sup>
                                              - in yaw
```

Notes: 1. Mass is in slugs

- Horizontal distance is feet aft of theoretical bow
- 3. Vertical distance is feet below hull C
- 4. Inertia is in slug feet<sup>2</sup>
- 5. Balloon physical mass includes internal gas and air

Based on data received from Air Force Cambridge Research Laboratories, the estimated weight breakdown for the balloon system is given in Table III. This breakdown is considered to be representative of the test balloon flown.

The payload includes batteries, instrument package, instrument frame, cable cutter and load cell.

The density of the air and helium for the balloon mass characteristics analysis was based on a temperature of 50°F. Based on this temperature and the reported cable tension (free lift) it was estimated that the balloon was approximately 88% full of helium with approximately 12% air in the ballonets.

#### 2. Additional Mass

The acceleration of the balloon in any of the six degrees of freedom causes aerodynamic forces in addition to the velocity and attitude changes. It has been shown by Lamb (Reference 6) that the derivatives of these acceleration forces have the dimension of mass. For all practical purposes, this additional mass term may be added to the actual mass of the balloon for purposes of calculating forces and responses of the system. References 7 and 8 were also useful in the development of this section.

The additional mass and additional moments of inertia for acceleration in a fluid have been worked out theoretically for a number of ellipsoids of revolution. Figures 5 and 6 show these coefficients plotted against fineness ratio. The added mass is obtained by multiplying these coefficients by the mass of the displaced air. It has been proposed and has become the custom to use (for airships and balloons) values based on the ellipsoid having the same volume and the same length as the hull. In addition, the theoretical longitudinal coefficient of additional mass shown on the curves are increased 50% to allow for the boundary layer which is dragged along with the balloon.

The fineness ratio of the equivalent ellipsoid to the hull must be computed based on equal volumes and equal lengths.

$$\Psi = \frac{\pi}{6} d^2 L$$

$$d = \sqrt{\frac{6}{\pi} \frac{\Psi}{L}}$$
Fineness ratio 
$$= \frac{L}{\sqrt{\frac{6}{\pi} \frac{\Psi}{L}}} = \sqrt{\frac{\pi L^3}{6\Psi}}$$

## TABLE III

### ESTIMATED BALLOON WEIGHT BREAKDOWN

ITEM	WEIGHT-POUNDS
Hull	875
Horizontal Tail	116
Vertical Tail	91
Ballonet	248
Handling Lines	25
Rip Panel	8
Suspension Cables and Fittings	132
Gas Valves	18
Ballonet Blower	12
Pressure Tubing	6
Electric Cables	7
Miscellaneous Hardware	5
Total Balloon Weight	1543
Payload	131
Total Flight Weight (less tether)	1674



Figure 5. Variation of the Coefficient of Additional Moment of Inertia with Fineness Ratio of an Equivalent Ellipsoid



Figure 6. Variation of the Coefficient of Additional Mass with Fineness Ratio of an Equivalent Ellipsoid

The flat tail surfaces also exhibit an added mass effect when accelerated normal to their chords. For large aspect ratios, the added mass is equivalent to the mass of air contained in a cylinder whose diameter is equal to the chord of the tail. Tests have provided corrections for smaller aspect ratios and for taper. The tail added mass terms can be obtained from Figure 7 and added to the hull added mass for the total added mass and moment of inertia effects, and for determining the dynamic center.

The added mass of the tail is obtained by multiplying these coefficients of the mass of air contained in a cylinder having the length equal to the span and a diameter equivalent to the chord of a rectangular tail having the same area.

#### 3. Dynamic Center Location

Under dynamic loads the balloon will have a mass and moment of inertia which includes the additional mass and additional moment of inertia of the affected surrounding air.

Because of symmetry in the XZ plane the only product of inertia considered is  $P_{XZ}$ . Since the product of inertia about any axis of symmetry is zero,  $P_{XY}$  and  $P_{YZ}$  are therefore zero.

The additional mass along each major axis is added directly to the mass of the balloon. The center of the additional mass, however, does not coincide with the center of gravity. The combination of these two masses will determine the dynamic center about which the complete balloon will act in air. Since the value and location of the additional mass is different for accelerations along each axis, the dynamic center will be located at different places for the lateral and vertical accelerations.

Figure 8 shows how the dynamic center is located and the combined moment of inertia is calculated.

#### D. AERODYNAMIC CHARACTERISTICS

The static aerodynamic characteristics for the test balloon were developed from wind tunnel data obtained at the University of Washington as reported in References 9, 10 and 11. The aerodynamic coefficients as taken from these references are plotted in Figures 9 and 10. Note that the force coefficients are based upon a reference area of hull volume to the two thirds power which is compatible with the equations of motion which have been developed. However, the moment coefficients in Figures 9 and 10 are based upon a reference length of hull length and are about a reference center near the bridle confluence point of the bridle as noted in Figure 10.



FIGURE 7. VARIATION OF THE COEFFICIENTS OF ADDITIONAL MASS AND MOMENT OF INERTIA WITH ASPECT RATIO OF RECTANGULAR PLATES



FIGURE 8. LOCATION OF DYNAMIC CENTER (DC) FROM MASS CENTER (MC) AND CENTER OF ADDITIONAL MASS (CA)



FIGURE 9. LONGITUDINAL STATIC AERODYNAMIC CHARACTERISTICS OF BARRAGE BALLOON



Figure 10. Lateral Static Aerodynamic Characteristics 22

The static moment coefficients for the test balloon have been adjusted to change the reference length from hull length to  $\forall^{1/3}$  and the moments have been transferred from a reference center near the bridle confluence point to the center of volume of the hull. The static aerodynamic coefficients adjusted for reference length and reference center are listed in Tables IV and V.

The dynamic aerodynamic characteristics of the BJ balloon were developed analytically as reported in References 1 and 2. These coefficients were modified for the test balloon by accounting for the longer tail surface moment arms of this configuration. The dynamic coefficients are also listed in Tables IV and V.

#### TABLE IV

EARRAGE BALLOON LONGITUDINAL AERODYNAMICS (Moments About Center of Hall Volume) (Reference Area  $\Psi_{Hull}^{2/3}$  - Reference Length  $\Psi^{1/3}$ )

Angle of Attack ( $\alpha$ )-10	-5	0	5	10	15	20	25
Lift Coefficient(C <sub>L</sub> )21	115	02	+.07	+.16	+.255	+.345	+.47
Drag Coefficient(C <sub>D</sub> ).09	.065	.05	.05	.07	.11	.16	.25
Pitching Moment(C_)280	1397	0352	+.0595	+.5194	069	2765	713

Lift Force due to Pitch Velocity  $C_{L_{\theta_B}} = 2.11/rad$ 

Pitching Moment Due to Pitch Velocity  $C_{m, e} = -3.21/rad$ 

Drag Force due to Pitch Velocity

$$C_{D_{\dot{\theta}_{B}}} = 0.9 C_{L}C_{L_{\dot{\theta}_{B}}}$$

## TABLE V

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BARRAGE BALLOON LATERAL A	ERODYNAMI	CS				
(Moments About Center of Hull Volume) (Reference Area ¥ 2/3 - Reference Length ¥ <sup>1/3</sup> )						
Static Aerodynamic Coefficients						
Sideslip Angle (β)	-20	0	+20			
Side Force Coefficient (C <sub>v</sub> )	+.450	0.0	450			
Yaw Moment Coefficient (Cn)	+.0787	0.0	0787			
Roll Moment Coefficient (C <sub>l</sub> )	008	0.0	+.008			

## Dynamic Aerodynamic Coefficients

Side Force Due to Yaw Velocity	(C) y	+2.19/Rad
Yaw Moment Due to Yaw Velocity	(C <sup>B</sup> )	-3.49/Rad
Roll Moment Due to Yaw Velocity	(C <sub><b>/</b></sub> , <sup>•</sup> B)	442/Rad
Side Force Due to Roll Velocity	$(\dot{C_{y}}_{\phi_{B}}^{\phi_{B}})$	+ .142/Rad
Yaw Moment Due to Roll Velocity	$(C_{n\phi_{B}})$	170/Rad
Roll Moment Due to Roll Velocity	(C <sub>ℓ †</sub> )	327/Rad
	D	

## Static Aerodynamic Stability Derivatives

Side	Force I	Due to	Yaw Angle	(С)) У <sub>Ф-</sub>	+1.29/Rad
Side	Force I	Due to	Lateral Velocity	$(C_{y_{v_B}})$	-1.29/Rad
Yaw M	loment I	Due to	Yaw Angle	(C <sub>nw</sub> )	+ .226/Rad
Yaw M	loment I	Due to	Lateral Velocity	$(C_{n_{v_{B}}})$	226/Rad
Roll	Moment	Due to	Yaw Angle	(C <sub>¢</sub> )	0229/Rad
Roll	Moment	Due to	Lateral Velocity	$(C_{\ell_{v_B}})$	+ .0229/Rad

#### SECTION IV

#### FLIGHT TEST PROCEDURES

Flight tests were conducted to obtain experimental balloon motion data for comparison with analytical predictions. As stated previously, a 70,000 cubic foot barrage balloon and a 0.52 inch diameter Nolara tether were flown.

Instrumentation consisted of the following items:

- (a) Cinetheodolite coverage of balloon to obtain
   X, Y and Z coordinates of the balloon. Motion
   was measured at the confluence point of
   balloon suspension lines.
- (b) Motion picture coverage of balloon motion (camera looked up vertically from tether point to give balloon yawing motion).
- (c) A telemetry package located at the confluence point which provided
  - (1) Horizontal relative wind speed
  - (2) Vertical relative wind speed
  - (3) X, Y and Z acceleration
  - (4) Roll angle
  - (5) Pitch angle
  - (6) Ambient pressure
  - (7) Differential pressure (helium compartment)
- (d) Pilot balloon data which gives wind direction and magnitude.

Five flight test data runs were made. The balloon was displaced and then released to obtain motion of the tethered balloon system. The balloon was pulled to the side to excite lateral motions and was pulled aft to excite longitudinal motion. A light nylon line attached to the confluence point of the balloon suspension lines provided initial displacement of the balloon. The line was secured at the ground a known distance from the ground tether point. The tether cable was then payed out until tether tension was reduced to one half. A test was initiated by cutting the auxiliary line at the ground.

The above listed data items were recorded for the following test conditions.

- (a) Run #1 Lateral balloon displacement of 100 feet to right. Tether length 1079 feet.
- (b) Run #2 Longitudinal balloon displacement of 150 feet aft. Tether length - 1118 feet.
- (c) Run #3 Lateral balloon displacement of 150 feet to right. Tether length - 1086 feet.
- (d) Run #4 Lateral balloon displacement of 150 feet to right. Tether length - 663 feet.
- (e) Run #5 Longitudinal balloon displacement of 150 feet aft. Tether length - 684 feet.

Table VI presents the test log for the flight test program.

TABLE VI - TETHERED BALLOON FLIGHT TEST LOG, NOVEMBER 10, 1972

Test Item - 70,000 Cubic Foot Kite Balloon-Nolara Tether .52 Inch Diameter, 90 Pounds/ 1000 Feet Otis Winch Installed at Fairsite

Run #1 - Lateral Disturbance	Pilot Ba	alloon Data -	12:00
Tether Cable Length - 1079 Ft. Balloon Displacement- 100 ft to right of Equilibrium Position	Alt. (Ft.)	Wind Direction (True) (Degrees)	Wind Speed (Knots)
Balloon Release Time - 12:00 Tension at Winch - Initial before release - 5001bs Fluctuation after release - 1300-1500 lbs.	Ground 300 600 900 1200 1500	185 190 190 190 190 190	05 07 09 11 12 12

Run #2 - Longitudinal Disturbance	Pilot Balloon Data - 12:40			
Tether Cable Length - 1118 Ft. Balloon Displacement - 150 Ft. Back of Equilibrium Position	Alt. (Ft.)	Wind Direction (True) (Degrees)	Wind Speed (Knots)	
Tension at Winch Initial before Release - 6001bs Fluctuation after release - 1350-1450 1bs.	Ground 300 600 900 1200 1500 1800 2100	120 130 150 155 160 175 180 195	04 04 04 05 07 08 09	

- TETHERED BALLOON FLIGHT TEST LOG, NOVEMBER 10, 1972 (cont.) TABLE VI

```
Initial Before Release - 6001bs
Immediate Peak After Cut - 13001bs
Fluctuation After Release - 1200-1700 1bs
            Tether Cable Length - 1086 Ft.
Balloon Displacement - 150 Ft. to right
Balloon Release time - 1:05 PM
Lateral Disturbance
                                                                                          Tension at Winch
       1
  Run #3
```

turbance e Length - 663 Ft.	Pilot B	alloon Data	- 1:38 pm
	Alt.	DULW	MING
	(Ft.)	Direction	Speed
		(True)	(Knots)
:40 pm		(Degrees)	,
	Ground	190	03
1	300	185	04
-	600	180	06
ut -	006	175	07
	1200	175	60
ISE I	1500	175	60
	1800	180	10
	2100	185	11

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TETHERED BALLOON FLIGHT TEST LOG, NOVEMBER 10, 1972 (cont.) 1 TABLE VI

2:10 pm Wind Speed (Knots) 01 02 04 05 05 05 05 05 05 07 07	3:08 pm Wind Speed (Knots) 03 04 05 05 05 05 07 07 08
<pre>1100n Data - Wind Wind (True) (True) (Degrees) 230 210 190 190 190 185</pre>	<pre>1100n Data - Wind Wind (True) (True) (Degrees) 130 130 130 135 135 135 150 150 155</pre>
Pilot Ba Alt. (Ft.) (Ft.) 300 600 900 1200 1500 1800 2100	Pilot Ba Alt. (Ft.) (Ft.) 300 600 1200 1200 1800 2100
<pre>Run #5 - Longitudinal Disturbance Tether Cable Length - 684 Ft. Balloon Displacement - 150 Ft. Back Balloon Release Time - 2:12 pm Tension at Winch Initial Before Release - 600 lbs. Immediate Peak After Cut - 1800 lbs. Fluctuation After Release - 1000-1100 lbs.</pre>	Conditions After Test Tether Cable Length - 0 Ft. Time - 3:07 pm Tether Tension -1250lbs Steady

#### SECTION V

### COMPARISON OF EXPERIMENTAL AND ANALYTICALLY PREDICTED DYNAMIC BEHAVIOR OF TETHERED BALLOONS

#### A. GENERAL

The geometric, mass and aerodynamic characteristics of the tethered balloon system which was flown have been described earlier in this report. The characteristic equations for longitudinal and lateral motion were solved to establish predicted natural frequencies, damped frequencies and damping ratios for this system. The dynamic response of the tethered balloon system to disturbances simulating test conditions was obtained by numerically integrating the longitudinal and the lateral equations of motion.

Initial conditions of displacement and tension were put into the dynamic simulation program as estimated from flight test data for a given test case. During tests, an auxiliary load was applied by the control line at the bridle confluence point to obtain initial balloon displacement aft or to the right. For computations, the balloon was displaced as in tests and the reduced tether tension as a result of the auxiliary load was simulated by an artificial payload which is removed at time one second of the calculations.

Computations were made with the stability and dynamic simulation computer programs to establish the predicted dynamic behavior of this balloon for two test conditions.

Longitudinal Test Run No. 5 was chosen for analysis because test data indicated relatively little lateral motion.

Test Run No. 3 was chosen for the lateral motion test since this test had the largest initial lateral displacement and data was available over the greatest length of time.

A comparison and correlation of analytically predicted and experimentally determined dynamic response for the tethered balloon system is discussed herein.

#### B. LONGITUDINAL MOTION

Calculated dynamic behavior of the barrage balloon for Longitudinal Test Run No. 5 is plotted in Figures 11a, 11b and 11c. An estimated wind speed of 17.4 feet per second was obtained from the onboard cup anemometer telemetry record (i.e., prior to release of the balloon).

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lla. Dynamic Response for Longitudinal Test Ru

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Dynamic Response for Longitudinal Test Run No. llb. Figure



Pilot balloon wind data was ratioed to this value to obtain the estimated wind on the tether. Balloon pitch angle and fore and aft motion as measured during the tests are superimposed on these plots for comparison purposes. Correlation of pitch angle ap-The frequency of motion is comparable and damping pears good. during the test is somewhat greater. Initial measured pitching motion may be attributable to instrumentation package motion rather than the balloon itself. Stability data is listed in The first computed mode of motion is for this case. Table VII a damped mode which has a damped frequency of .1132 rad/sec. Referring to the mode shapes of Table VII this represents a motion where the cable links move as a unit and balloon pitching motion is approximately 180 degrees out of phase. This phase relationship is also apparent in Figure lla where the three links comprising the tether move together and the balloon pitch angle is 180 degrees out of phase. The experimental results indicate a pitching frequency of 0.10 rad/sec which is in reasonable agreement.

Again referring to Figure 11b, the frequency of fore and aft motion (payload range) shows that reasonable agreement exists between experiment and predictions. Experimental motion is more highly damped. Although motion is primarily in the longitudinal plane, some yawing of the balloon did occur during the experiment, as shown in Figure 12. This would increase aerodynamic drag and some of the additional damping might be attributed to this. Also, all damping coefficients used in the theoretical predictions were calculated for zero angle-of-attack and zero side slip angle. It is apparent that the first mode of motion is the dominant one which has been excited.

#### C. LATERAL MOTION

Predicted dynamic behavior of the tethered balloon system for Lateral Test Run No. 3 is plotted in Figures 13a, 13b and 13c. Wind data used for the computer simulation was based on telemetry data from the cup anemometer before release of the balloon. The lateral displacement (payload cross range) comparison between prediction and experiment shows obvious discrepancies (Figure 13a). Initial lateral displacement is similar but as time progresses the balloon actually begins to converge to a different equilibrium position and some forcing function causes the balloon to oscillate with relatively high amplitude.

The stability analysis for Lateral Test Run No. 3 is listed in Tables VIII and IX. Referring to Table VIII, the first mode of motion has the following characteristics:

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ALTITUDE WIND VELO	PRÖFILE CITY PRUF	ILE	0.0 6.0	4713.0 6.0	5013.0 8.0	5313.0 12.0	5613.0 16.0	5913.0 17.4	7000.0 20.0	0.0 0.0	
RJM RJA RJG	RKM RKA RKG RKB	CNPSB CLPSB CYPSB DC	CNPSOB CLPSOB CYPSDB CDC	СNРНОВ ССРНОВ С УРНОВ	CNVB CLVB CYV8	LS ₩B ₩TC	MPL SB DB	I Z B I Y B I Y Z B	ТЕТН MAS тнео	X10(1) X10(2) X10(3)	RANGE ALTITUDE DYPRB
<u>24</u> .7500 9.7000 23.2400	-42.8100 -46.5000 -41.2000 -45.6900	$ \begin{array}{c}     0.2260 \\     -0.0229 \\     1.2900 \\     0.0434 \end{array} $	-3.4900 -0.4420 2.1900 1.1000	-0.1700 -0.3270 0.1420	-0.2260 0.0229 -1.2900	5080 <u>.0</u> 3668.0 97.7	4.1 1700.0 41.2	_267400 <u>.0</u> 54404.0 2896.0	1079.0 166.6 -1.415	88.345 88.452 88.658	<u>-50.7</u> 1120.4 0.041
		ALPHA(I,J	)				BETA	I,J}		-	
0.42E 06 -0 -0.23E 06 0 -0.24E 07 0 -0.24E 07 0 -0.24E 07 0 -0.24E 07 0	.28E 06 .57E 06 .43E 07 .43E 07 .43E 07	-0.24E 07 0.43E 07 0.37E 08 0.37E 08 0.37E 08 0.37E 08	-0.24E 07 0.43E 07 0.37E 08 0.37E 08 J.37E 08	-0.24E 07 0.43E 07 0.37E 08 0.37E 08 0.37E 08		0.79E 05 0.11E 05 -0.50E 06 -0.50E 06 -0.50E 06	0.31E 04 0.54E 04 0.20E 06 0.20E 06 0.20E 06 0.20E 06	-0.72E -0.10E 0.20E 0.20E 0.20E	04 -0.72E 0 05 -0.10E 0 07 0.20E 0 07 0.20E 0 07 0.20E 0	04 -0.72E 05 -0.10E 07 0.20F 07 0.20F 07 0.20F	04 35 07 97 07
	GAMMA(I,	J)									
0.12E 03 0. 0.17E 03 0. -0.33E 05 0. -0.33E 05 0. -0.33E 05 0.	0 81E050 0000 0000 0000	.0 0. .0 0. .4 3E_06_0. .0 0.	0 0.0 0 0.0 0 0.0 0 0.0 44E 06 0.0 0 0.4	5E 06							
CUEF	FICIENTS	OF CHARACTE	RISTIC EQUA	TION IN AS	CENDING C	DRDER					
0.8490	24 0.555	0 27 0.679	0 28 0.126	0 30 0.51	00 30 0.	.2080 30 0.	5270 30 0	•587D 29	0.1150 30	0.2590 28	0.4430 28
RUOTS (	HAVE BEE DF <u>CHARAC</u> AL	N ACCORATEL TERISTICEQ IMAGINAR	Y DETERMINE UA <u>TION</u> Y	NATURAL FR	EQUENCY	STABILITY DAMPED F	PARAMETERS	DAMPIN	G RATIO	TIME TO Dougle	HALF_OR
-0.2	168D_00	0.2438D-1	9	0.21680	00	0.24	38D-19	0.10	00D_01	0.31	970 01
-0.1	9040-01 9040-01 0640-01	-0.69490-0 0.6949D-0 0.1130D 0	L L L	0.72060 0.72060 0.11330	0-01 0-01	0.694	+9 D-01 300 01	0.26	430 00 430 00 16D-01	0.36 ).36 ().85	40D 02 96D 01
-0.8 -0.1 -0.5	0640-01 5580-02 3560-0 <u>1</u>	0.1130D 0 -0.2777D-2 -0.2043D 0	L 3 1	0.11330 0.15580 0.20430	0 01 0-02 0 01	0.11 0.27 0.20	30D 01 77D-23 43D_01	0.71 0.10 0.26	169-01 00D 01 210 <b>-01</b>	0.85 0.44 0.12	950 01 480 03 940 02
						0.204		0.24	210-01	a. 12	940 03

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Table VIII (Cont)

	MUDAL AN	ALYSIS	
FIGEN	FC TOR		
<u></u>	IMAGINARY	MAGNITUDE	DIRECTION ANGLE
0.1214E 00	-0.1663E-19	0.1214E 00	0.3600E 03
0.3928E-02	-0.3291E-21	0.3928E-02	0.3600E 03 ( U(C.U.mor))
0.33495-02	-0.3313E-21	0.3849E-02	0.3600E 03   Mode
0.37976-02	-0.3440E-21	0.3197E-02	
0.65976-01	0-11358 00	0-1312E 00 0	0-59828 02
0.1891E-01	0.1460E 00	0.1478F 00 G	0.8265E 02
0.1861E-01	0.1424F 00	0.1436F 00 0	0.8255E 02
0.13526-01	0.1381E 00	0.1393E 00 0.	0.8236E 02
			FIRST MODE
0.6597E-01	-0.1135E 00	0.1312E 00	0.3002E 03
0.1391F-01	-0.1466E 00	0.1478E 00	0.2774E U3
0.1861E-01	-0.1424E 00	0.1436E 00	0.2774E 03
0.1352E-01	-0.1381E OJ	0.1393E 00	0.2776E 03)
0 11055 02	0 14305 03	0 14425 07	
	0.10116.02		
	-0.627/5.01		
0.2599E 00	-0.4490E 00	0.51885 00	
	0	0.91000 00	
J.1195E 02	-0.1439F 03	0.1443E 03	0.2747E U3
-0.1133E 01	0.1011E 02	0.1018E 02	0.9639E 02
ω -0.5647E 00	0.6274E 01	0.6299E 01	0.9514E 02
0.2599E 00	0.4490E JU	0.5188E 00	0.5994E 02
-0.1967L-02	0.21626-24	0.1967E-02	0.1800E 03
J. 7548E-01	-0.54926-24	0.7545E-J1	
	0.5408E-24 _	0.7348E-01	
0.11376-01	-0.34046-24	0.11576-01	U-3800E U3
-J.1144E 02	-0.1697E JU	0.1144E 02	0.1808E 03
-0.3237E 02	-0.7342E 00 -	0.3237E 02	0.1813E 03
0.1486E 01	0.3039E-01	0.1486E 01	0.1172E 01
0.3240E 02	0.7303E_00_	0.3241E_02	0.1291E 01
-0.1144E 02	0 1697E 00	0 1144E 02	0 17025 03
-0.32376 02	0 73625 00	0 3237E 02	
	0.73426_00		0.35888 03
J. 3240F 02	-0.7303E 00	0.3241E 02	0.3587E 03
-J.8399E 01	-0.1338E 00	0.8400E 01	0.1809E 03
0.9251E 02	0.1443E 01	0.9253E 02	0.8933E 00
	0.2918E01	0.1868E_03	0.1809E 03
0.9546[ 02	0.1495E 01	0.9547E 02	0.8972E 00
- J- 8399F 01	0,13395 0.1	0.8400F 01	0.17915 03
0.9251E 02	-0,1443F 01	0_9253F02	0.3591F 03
-0.1368F 03	0.2918F 01	0.1868E 03	0.1791E 03
0 9544E 0)			

									DJ DALLUUM		•
	ALTITUDE PROFILE WIND VELOCITY PROFILE	0.0 6.0	4713.0 6.0	5013.0 8.0	5313.0 12.0	5613.0 16.0	5913.0 17.4	7000.0	0.0		
· -	ANGLE-OF-ATTACK (DEG)	-10.0000	-5.0000	0.0	5.0000	10.0000	15.0000	20.0000	25.0000		
``	MOMENT COEFFICIENT	-0.2800	-0.1397 -	-0.0352	0.0595	0-5194	-0.0690	-0.2765	-0.7130		
_	DRAG COEFFICIENT	0.0900	0.0650	<u>-0.0200</u> 0.0500	0.0 <u>700</u> 0.0500	0.1600	_0.2550_ 0.1100	0.3450	0.4700		
_	THE TA XLOS	1) <u> </u>	X10(3)	)							•
r	1.00000 86.99	995 87.9999	5 88.9999	94							•
	-1.36832 83.34	852 88.4655	588.6614	<u> </u>							
	-1.41481 88.34 -1.41489 88.34	447 80-4616 447 83-4616	1 85.6590 1 88.6580	00						•	
-		44788.4616	1 83.6580	00							
``	-1.41499 88.34	447 88.4616	1 88.6580	00					,		
	-1.41495 88.34 -1.41495 88.34	447 88.4616 441 88.4616	L 83.6580								
、 —	FINAL SOLUTION			···							
·	-1.41496 89.34	447 88.4616	1 88.6580	00							
	RJM RKM C	MB CMAB	CHTOB	LS	MPL	тетн	1 X8				
	RJA RKA CI	LB CLAB	CLTDB	WB	58	DC	HAL				
	<u> </u>	DBCDAB ANGE ALTIT	CUTUB UDF DYPRA	WT <u>C</u>	03	CDC	<u> </u>				
- )											
-	- 23.4230 -43.6200 -0	.0648 1.197	53.2100	5080.	4.09	1379	357404.				
2	23.2400 -41.2000 0	.0542 -0.171	9 -0:0890	97.7	41.200	1.100	151.600				
	17.203 -45.690 -	50.7 5833.4	0,290E 00	)							
, i	ALPHA(I,J)			BETA	([,])				GAMMA(I,J)		
	9.76E 96 -2.23E 07 -0.22E 0	7 -0.22F 07	0,18F 0b	-0.55F 04	-0.55E 04	-0.55E 06		4E 05 0-0	<u> </u>		
	-0.23E 07 0.18E 08 0.18E 0	B 0.13E 08	-0.11E 06	0.55E 06	0.52E 00	5 0.45E 06	-0.3	6E 05 0.4	42E 06 0.43	E 02 0.66E 0	2
	<u>-0.22E 07 0.18E 09 0.18E 0</u>	<u>8_0.18E_08</u>	<u>-0.11E_06</u>	_0.528_06	0.50E_00	<u>0.45E_06</u>	3	6E_050.0	0.43	E_06_0.69E_0	Z
		5 0.182 08	-J.IIE 06	U.45t J6	0 0.45E 00	5 0.432 06	-0-3	SE 05 0.0	0.0	0.45E 0	6
 •,	COEFFICIENTS OF CHAN	RACTERISTIC	JATION IN AS	CENDING O	RDER						
-	0.5290 22 0.3320 23	<u></u>	0.2060 25	_0.5460_2	50-1100	250+15	5D 25 0	.6030 23	0.6360 23		
~	•										
	ALL_ROOTS HAVE BEEN ACCU	PATELY_DETERMU	NEO	····		<del>.</del>	•		······································		
•	ROOTS OF CHARACTERIST	IC EQUATION			STABILITY	PARAMETER	S		TIME T	O HALF OR	
		<u>SINARY</u>	<u>NATURAL_FR</u>	EQUENCY	DAMPFO	FREQUENCY	<u> </u>	NG_RAJ <u>IO</u>		AMPLI TUQE	
1	-0.18220 00 0.30	740 00	0.35730	00	0.30	074D 00	0.5	098D 00	0.3	805D 01	
	0.13220_000.30	74D OJ	0.35730	00	J. 3 (	074D 00	0.5	098D 00		8050 01	
•		600-01 600-01	0.90630		0.89	9600-01	0.1	504D 00	0.5	085D 02	
•		880_01	0.1996D		0.19	988D_01	0.1	3040 00 803D-01	0.9	9450 02	
	-0.17570 00 -0.19	88D 01	0.19960	01	0.19	10 D846	0.8	8030-01	0.3	9450 01	
	-0.13300 00 -0.44	630 01	0.44649	01	0.44	630 01	0.2	3070-01	0-6	7310 01	

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		<u>M</u> OD <u>E_SHA</u>	P <u>F</u> S		
	EIGENV REAL	ECTORS	MAGNITUDE	DIRECTION ANGLE	
	0.40876-01	-0.2848E-04	0.4087E-01	0.3600E 03	
	0.38716-01	-0.3282E-03	0.3871E-01	0.3595E 03	
	0.34946-01	0.2387E-03	0.3494E-01	0.3915E UO	
<u></u>	0.4087E-J1	0.2848E-04	0.4087E-01	0.3993E-01	
	0.3871E-01	0.3282E-03	0.3871E-01	U.4857E 00	
	J. 3494E-01	-0.2387E-03	0.3494E-31	0,35965_03	
	-0.1082E 01	0.3608E-01	0.1082E 01	0.1781E 03	
	-0.1049E 01	0,2489E-01	0.1050E_01	0.1786E 03	
	-0.1315E 01	-0.3572E-02	0.1015E 01	0.1802E 03	
	<u>-0.1382E 01</u>	-0.3608E-01	0.1082E 01	0.18195_03	
	-0.1049E 01	-0.2489E-01	0.1050E 01	0.1914E 03	
	-0.1015E 01	0.3572E-02	0.1015E 01	0.1793E 03	
	-0.7087E 02	-0.3310E 32	0.7822E U2	0.2050E 03	
	J.9428E 00	0.2286E 01	0.2473E 01	0.6759E 02	
	0.7062E 02	0.3094E 02	0. <u>7</u> 710€_ <u>0</u> 2	0.23 <u>66</u> E_02	
	-0.7087E 02	0.3310E 02	0.7822E J2	0.1550E 03	
	0. 742 8E_00	<u>0.2286E_01 _</u>	0.2473E 01	0.2924E 03	
	0.7062E 02	-0.3094E 02	0.7710E 02	0.3363E 03	
<u> </u>	0.1765E 03	_0_2825E_02_	<u>0.1788E_03</u>	0.3509E_03	
	-0.3537E 03	0.6224E 02	0.3592E 03	0.170UE 03	
	0.1778E 03	-0.34J3E 02	0.1810E 03	0.3492E 03	
	0.1765E 03	0.2825E 02	0.1788E 03	0.9093E 01	
	-0.3537E 03	-0.6224E 02	0.3592E 03	0.1900E 03	
	0.1778E 03	0.3403E 02	0.1810E 03	0.1083E 02	

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Natural frequency	=	.072 rad/sec
Damped frequency	=	.069 rad/sec
Damping ratio	=	.264

The modal analysis (Table VIII) indicates that this is a coupled yaw lateral displacement mode (i.e., the tether link angles  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_3$  are approximately equal). Lateral displacement leads the balloon yaw motion by approximately 80 degrees. Table IX presents the longitudinal stability characteristics as added information. The experimental lateral response for Test Run No. 3 is again plotted in Figure 14 with additional data. The frequency of this motion is approximately 0.074 rad/sec as noted. The ratio of successive amplitudes of motion is

$$\frac{x_1}{x_2} = \frac{137}{62} = 2.21$$

The frequency of motion is in relatively good agreement with the small perturbation stability theory of .069 rad/sec damping ratio ( $\xi$ ) which was predicted for the first lateral mode is .264 which corresponds to successive amplitude ratio as follows:

$$\delta = \frac{2\pi \xi}{\sqrt{1-\xi^2}} = \ln \frac{x_1}{x_2}$$

$$\delta = \frac{2 \times .264}{\sqrt{1 - (.264)}} = 1.72$$

$$\frac{x_1}{x_2} = 5.59$$

The analytically predicted values of amplitude ratio are substantially higher than observed in the experimental data of Figure 14. However, a direct comparison can not be made inasmuch as forcing functions due to wind gusts effect the motion. In the stability theory, a free vibration condition is assumed.

A further attempt was made to deduce the probable wind fluctuations with time from the available flight test data. The relative wind which the balloon sees is a vectoral summation of the actual wind and the relative wind due to balloon



Figure 14. Time History of Lateral Displacement for Test Run No. 3

motion through the air mass. Balloon motion at the suspension line confluence point was observed by cinetheodolite. The magnitude of the relative wind at the confluence point was measured by means of a cup anemometer but direction of this relative wind is unknown. Assuming a constant value of the fore and aft wind relative to the tether point and the available data an attempt was made to calculate a possible lateral or side gust time history which might have existed during the test. A calculated balloon lateral response for this side gust time history did not correlate with the experimentally determined displacement.

In view of the inability to obtain a direct correlation between analytical predictions and experimental data, a more fundamental study was undertaken. This study consisted of an examination of the predicted response of the tethered balloon system to simple wind disturbances and an examination of the effects of aerodynamic damping on balloon motion.

The dynamic response of the balloon with a constant wind gust of 3 feet per second directed to the right after release of the balloon is plotted in Figures 15a, 15b and 15c. It is apparent in Figure 15a that the balloon's lateral displacement is retarded and more closely conforms to the actual motion observed during the first 60 seconds of the test. With the side gust maintained the balloon converges to a new yaw angle and the sideslip angle approaches zero (Figure 15b) as would be expected.

The nature of the experimental lateral displacement time history for Lateral Run No. 3 changes at 60 to 90 seconds as observed in Figure 14. It is considered that a change in wind direction or magnitude could excite the lateral motions of the tethered balloon system. A 3 fps side gust superimposed on a steady state 17 fps aft wind is approximately equivalent to a wind of constant magnitude but shifted in azimuth by 10 degrees. This wind change could be consistent with the light and variable winds existing during the time of the test. Consequently, it was chosen to further investigate the dynamic behavior of the test balloon system.

The experimental yaw angle of the balloon during the test (Figure 16) can be used to obtain initial conditions for digital computer simulation of the mathematical model. From Figure 16 at time 63 seconds yaw angle ( $\psi$ ) is zero and the yawing velocity ( $\dot{\psi}$ ) is -2.7 degrees per second. (i.e., nose rotating to left when looking down on the balloon). From cinetheodolite data the suspension line confluence point is moving to the right at +3.0 fps. A dynamic simulation of the balloon motion was obtained with these initial conditions and a forcing function consisting of a side gust of 3 fps to the



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The lateral response of the tethered balloon system to this disturbance is duplicated in Figures 17a, 17b and 17c. Α comparison of simulated and experimental lateral balloon motion shows some similarities and some differences. Consider one cycle of motion from 110 seconds on after the forcing function has The simulated motion has a period of 98 seconds been removed. or a frequency of 0.064 rad/sec and the experimental motion has a period of 90 seconds or a frequency of 0.070 rad/sec. These results are in close agreement. The stability and modal analysis for this balloon system (Table IX) also identifies this motion as the first mode with a frequency of .069 rad/sec. The mode is a coupled yaw-lateral displacement with the lateral displacement lagging the yawing motion.

It is also apparent in comparing experimental data and the dynamic simulation that the simulated motion at this frequency is more highly damped. An additional mode of motion is apparent in the simulation after the first mode has damped out. This mode is a slow convergence of balloon yaw and lateral displacement to the initial equilibrium position. Again, examination of the model, analysis of Table IX reveals an overcritically damped mode with balloon yaw motion and lateral displacement in phase.

The highly damped first mode indicated by the dynamic simulation is not in accordance with the observed response. This might be attributed to the accuracy with which aerodynamic damping characteristics can be determined by calculations or the inability to input the proper forcing functions. Considering the former further calculations were made with the dynamics computer simulation program to determine the effects of aerodynamic damping on system motion. The effect of reducing aerodynamic damping coefficients on lateral motion is shown in The lateral displacement has been obtained with a 3 Figure 18. fps side gust as before and the six lateral aerodynamic damping coefficients have been reduced to percentages of 100% damping presented in Section III. Although static lateral aerodynamic data were not available for angles of sideslip greater than 20 degrees a projection of possible aerodynamic characteristics (Figure 19) was made to permit dynamic simulation at larger angles. It is apparent that lateral balloon motion is quite sensitive to aerodynamic damping.

In Figure 18 a reduction in aerodynamic damping was shown to have a very significant effect on the lateral dynamics of the tethered balloon. In fact, at a point between 81% and 85% of the estimated damping the lateral motion becomes unstable. Lateral stability computer runs were made with damping coefficients reduced by as much as 20%; and although the roots of the

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Figure 17c. Lateral Dynamic Response of Test Balloon to a 3 fps Side Gust of 40 Seconds Duration

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Figure 19. Estimate of Static Lateral Aerodynamic Coefficients at Large Sideslip Angles

characteristic equation become less stable, they give no indication of the unstable motion encountered in the dynamic simulation. This points out an inadequacy of the stability program. Although a balloon can be designed to be stable near its equilibrium position, it may develop motions far away from equilibrium which are unstable. It should be pointed out that the damping coefficients are considered to be invariant from this equilibrium condition. In reality they would vary, possibly enough to prevent the unstable motion shown in the simulation.

#### SECTION VI

#### CONCLUSIONS AND RECOMMENDATIONS

Digital computer programs were developed previously to describe tethered balloon stability qualities and to simulate dynamic motions of tethered balloon systems. Experimental test conditions and test tethered balloon characteristics were input in the computer programs and balloon dynamic behavior was predicted. A comparison of experimental and predicted results permits establishing the validity of these mathematical tools. The following conclusions are drawn from this program.

1. Experimental and predicted longitudinal dynamic behavior are in reasonable agreement. The experiment clearly excites the first mode of motion with a frequency as predicted by stability theory. This mode is a coupled motion of balloon pitch and fore and aft motion of the tether as a whole (180 degrees out of phase). Damping of the fore and aft motion is greater in the real world and may be attributed in part to the fact that yawing motions existed and would contribute to greater aerodynamic drag forces.

2. The experiments, even though carefully controlled to excite longitudinal and lateral motions independently, result in coupled tethered balloon system motions. This may be attributed in part to the light and variable winds. It is apparent that the lateral motion of the test balloon in particular is sensitive to wind changes.

3. It is more difficult to establish correlation of experimental and predicted lateral motions than longitudinal motions.

4. The stability analysis and dynamic simulation identify two lateral modes of motion which are excited. The first lateral mode is a coupled yaw-lateral displacement with the lateral displacement lagging the yawing motion. The frequency of this mode is in good agreement with experimental measurements. The second mode is a highly damped mode with balloon yaw motion and lateral displacement in phase.

5. Discrepancies between experimental and predicted lateral motions may be attributed to undefined wind forcing functions and the accuracy with which aerodynamic damping coefficients can be calculated. Analysis indicates that lateral motions can be relatively sensitive to aerodynamic damping.

6. The comparison of experimental and predicted dynamic characteristics of the tethered balloon shows a reasonable match although some discrepancies do exist. In spite of these,

stability and dynamic simulation computer programs are a powerful tool for design and analysis of tethered balloon systems.

As a result of this program the following recommendations are made:

1. For future analysis, obtain additional and more accurate data for tethered balloon systems of interest. Additional aerodynamic data, particularly aerodynamic damping data, may be obtained with dynamic wind tunnel models. Additional field testing with accurately determined time histories of wind magnitude and direction might also permit deduction of aerodynamic damping characteristics.

2. It is recognized that some limitations exist in the present dynamic simulation techniques as a result of treating the longitudinal and lateral motions as uncoupled. It is recommended that the mathematical model be extended to be completely three dimensional and that provisions for a wind vector changing in direction and magnitude as a function of time be incorporated.

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