HIGH WIND SPEED BEHAVIOR OF THE SKYBUDDY BALLOON SYSTEM IN A WIND TUNNEL

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Symbol	Definition
A,B,C,D,k	Constants
AA	Attack angle
BF	Buoyancy force
C_D	Drag coefficient
D	Average diameter of balloon, length scale, or drag
d	Diameter of string
E	Hot wire output voltage
F	Force
f	Frequency
g	Gravitational acceleration
H	Balloon height above the ground
L	Lift, balloon horizontal displacement, or length
m	Mass
NBF	Net buoyancy force
Re	Reynolds number
T	Period
TF	Tangential force
U	Free-stream velocity
V	Velocity
Vol	Volume
W	Gravitational force
γ	Specific weight
ρ	Density
μ	Dynamic viscosity

Symbol	Definition
ν	Kinematic viscosity
θ,α,β	Angles
rms	Root mean square

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1 INTRODUCTION

1.1 GENERAL INFORMATION

Any time you go camping, hunting, back packing, or skiing you could become lost and/or injured. Search and rescue teams take every possible means to locate you. As every minute goes by the chances for rescue become more slim.

"SKYBUDDY" is a device consisting of a small cylinder of helium, a balloon tied with several strings packed together and which weighs less than one pound. In case there is an emergency, the fully automatic mechanism can be activated to release a helium filled microfoil tethered by 126 feet of cord. The radio antenna with the balloon sends signals and the shiny international orange, microfoil balloon is easily visible to rescue teams on foot or in the air.

To make the balloon survive under strong wind conditions, two characteristics have been studied: The stability of the balloon and the tension on the string which allows the tethered balloon to be controlled from the ground.

The aerodynamics of the balloon under different wind conditions were modeled in the wind tunnel. The wind speed, the attack angle on the balloon and the variation of tether and fin locations were changed systematically while performing lift and drag measurements.

1.2 THE MODELS

Two different kinds of balloons were studied. They both have ellipsoidal shapes. The adult model is larger than the children's model, yet both have a diametric ratio of 1.62:1. The volume of the large balloon is 0.102 cubic meters (3.6 cubic feet), and the smaller volume is 0.045 cubic meters (1.6 cubic feet). Due to limited space inside the wind tunnel during testing, the larger balloon was attached to the force measurement device 1.31 meters (4.30 feet) below the center of the balloon and the smaller balloon 1.06 meters (3.48 feet). The attachment point to the force measurement device was 14 cm (5.5 in) above the tunnel floor, Figure 1.1.

The two microfoils of balloons (not inflated) weigh 0.478 Newton and 0.3 Newton, respectively. The inflated buoyancy forces (BF) are respectively:

For the large balloon:

$$Vol = 3.6\ ft^3 = 0.102\ m^3$$

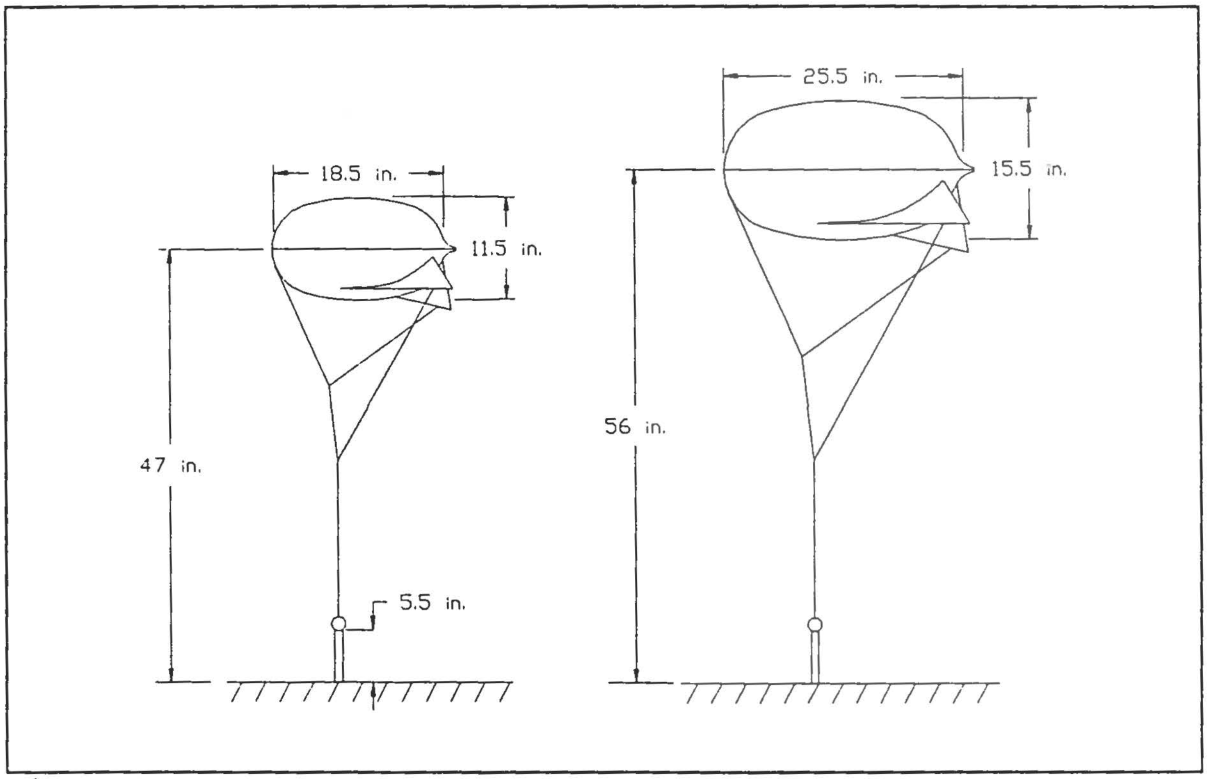

Figure 1.1 Small and Large Skybuddy Balloon Tether Arrangement for the Wind Tunnel Study

$$BF = (1 - \gamma)*\rho_{air}*g*Vol = (1 - 0.138)*1.06*9.802*0.102 = 0.913\ N$$

For the small balloon:

$$Vol = 1.6\ ft^3 = 0.0453\ m^3$$
$$BF = (1-0.138)*1.06*9.802*0.0453 = 0.406\ N$$

The net buoyancy forces (NBF) are

For the large balloon: NBF = 0.913-0.478 = 0.435 N

For the samll balloon: NBF = 0.406-0.300 = 0.106 N

As calculated here, the buoyancy forces are too small to effect the drag and lift forces under windy conditions. This implies that only the configuration of a balloon (the shape, the angle settings) is important for the balloon survival.

1.3 MODELING OF BALLOON FLIGHT IN THE WIND TUNNEL

Modeling the aerodynamic loading on the Skybuddy requires special consideration of the model flow conditions necessary to obtain similitude between model and prototype. The basic requirements are as follows:

1. The model and prototype must be geometrically similar.
2. The approach flow from the wind tunnel must be similar to the full-scale flow.
3. The Reynolds numbers (defined as $Re = \rho VD/\mu$, where D = length scale, V = velocity, ρ = density, μ = dynamic viscosity) for the model and prototype should be equal.
4. The Strouhal number (defined as $St = D*f/V$, where f = frequency, D,V similar to Re number) for the model and prototype should be equal.

Because full size balloons are to be studied, items 1 and 3 are satisfied automatically. The approach flow should be a roughly uniform, low turbulence flow representative of the wind field at balloon elevation.

To match item 4, Strouhal number equality requires that,

$$(D*f/V)_{model} = (D*f/V)_{prototype}$$

The balloon used in the field is tethered with 38.4 m (126 feet) of string. But, during the wind tunnel test, the tether distance is only 1.41 m (4.67 feet) from the center of the large balloon microfoil to the wind tunnel floor. This implies that the natural frequencies from the model test and the field test are quite different. For the balloon tether system Strouhal number equality is required in dynamic response, and this means that the dynamic loads of drag and lift (max, min and related rms values) in the laboratory experiment are equal to the field situation.

For a full understanding of the balloon behavior, two separate studies should be completed. First, a solid model of the same shape should be constructed. The model should be fixed on the force measuring device to measure the mean lift and drag forces in the absence of buoyancy and tether dynamics. The forces should be expressed as dimensionless numbers (see next paragraph) and plotted versus Reynolds number. By systematically varying the attack angle, a maximum lift and drag ratio can be determined at which the best flight angle occurs. Second, the balloon should be evaluated together with its tether dynamics.

The scaled magnitude of a lift or drag force is often represented by the force coefficient (a dimensionless number),

$$C_F = F / (\tfrac{1}{2}\rho U^2 A)$$

where ρ is air density, U is wind speed, A is reference area, and $\frac{1}{2}\rho U^2$ is the reference dynamic pressure.

A limited set of tests have been completed to determine the magnitude of the drag and lift forces and balloon behavior at different wind speeds and attack angles. Video tapes and slides were used to observe the stability of the balloon at different wind speeds and attack angles. The forces have been presented in the data files as real forces (lb.) instead of dimensionless coefficients. They are interchangable if reference wind speed and reference area are known (refer to the force coefficient definition). The tabulated wind speed is noted in units of mph.

The Reynolds numbers during the tunnel tests were in the range:

$$Re_{low} = V_{low}*D/\nu = 2*0.457/1.65*10^{-5} = 5.54*10^{4}$$

$$Re_{high} = V_{high}*D/\nu = 20*0.457/1.65*10^{-5} = 5.54*10^{5}$$

where D is roughly the average diameter of the large ellipsoidal balloon (D = 1.5 ft = 0.5*(1 ft + 2 ft) = 0.457 m). The velocity of the wind tunnel for this study ranged from 4.48 mph (2 m/s, V_{low}) to 44.8 mph (20 m/s, V_{high})), and the ν kinematic viscosity of air is equal to $1.65*10^{-5}$ m^2/s.

1.4 MATHEMATICAL ANALYSIS FOR BALLOON

The shape of the tether string tied to the balloon and the drag and lift forces at the end of that string can be calculated as long as the drag and lift on the balloon are known. The drag and lift on the balloon can be assumed equal to the drag and lift measured in the tunnel by the force balance iqnoring the drag caused by the wind on the shorter wind tunnel test tether string and the weight.

For a very small string segment at (x,z), the drag and gravitational forces are respectively,

$$dD = \tfrac{1}{2}\rho_{air}(U \sin\theta)^2 * C_D(Re) * d * (dz/\sin\theta)$$

$$dW = \tfrac{1}{4}\pi d^2 * \rho_s * (dz/\sin\theta)$$

where $C_D(Re)$ is the drag coefficient for a cylinder (a small segment of the string is a tiny cylinder), d is the diameter of the string, ρ_{air} is density of air, and ρ_s is density of the tether string.

A coordinate system is set up for the balloon in the field as shown in Figure 1.2. The x direction is the wind direction the height from the ground to the balloon).

The Reynolds number for the string would vary with the wind speed and the string bending angle θ, which is,

$$Re = (U \sin\theta)*d/\nu$$

For such a Reynolds number, a drag coefficient (C_D) can be retrieved from Figure 1.3.

For any location at (x,z), the tether tensions required to balance the string and balloon are,

$$F_D = F_{DO} + \int dF_x$$

$$F_L = F_{LO} + \int dF_z$$

$$tg\theta = F_L / F_D$$

where

$$dF_X = dD_X = dD \sin\theta$$

$$dF_Z = -dW - dD_Z = -dW - dD \cos\theta$$

If the velocity does not change significantly over the height, an average drag coefficient C_D and an average free-stream velocity U_∞ can be used. Assuming that H is the balloon height above the end of the string (control point on the ground), the result can be written;

$$tg\theta = \frac{F_{LO} - \int_o^z [\frac{1}{4}\pi^2 * \rho_s * (dz/\sin\theta) + \frac{1}{2}\rho_{air} * U^2 * C_D * d * \sin\theta * \cos\theta dz]}{F_{DO} + \int \frac{1}{2}\rho_{air} U^2 * C_D * d * \sin\theta^2 dz}$$

The angle of their ratio is the derivative of function z(x),

$$tg\theta = z',$$

$$z' = \frac{F_{LO} - \int_o^z [\frac{1}{4}\pi d^2 \rho_s * (dz/\sin\theta) + \frac{1}{2}\rho_{air} * U^2 * C_D * d * \sin\theta * \cos\theta dz]}{F_{DO} + \int \frac{1}{2}\rho_{air} U^2 * C_D * d * \sin\theta^2 dz}$$

This is the differential equation for the string shape.

When the angle θ is large enough (close to 90°), then

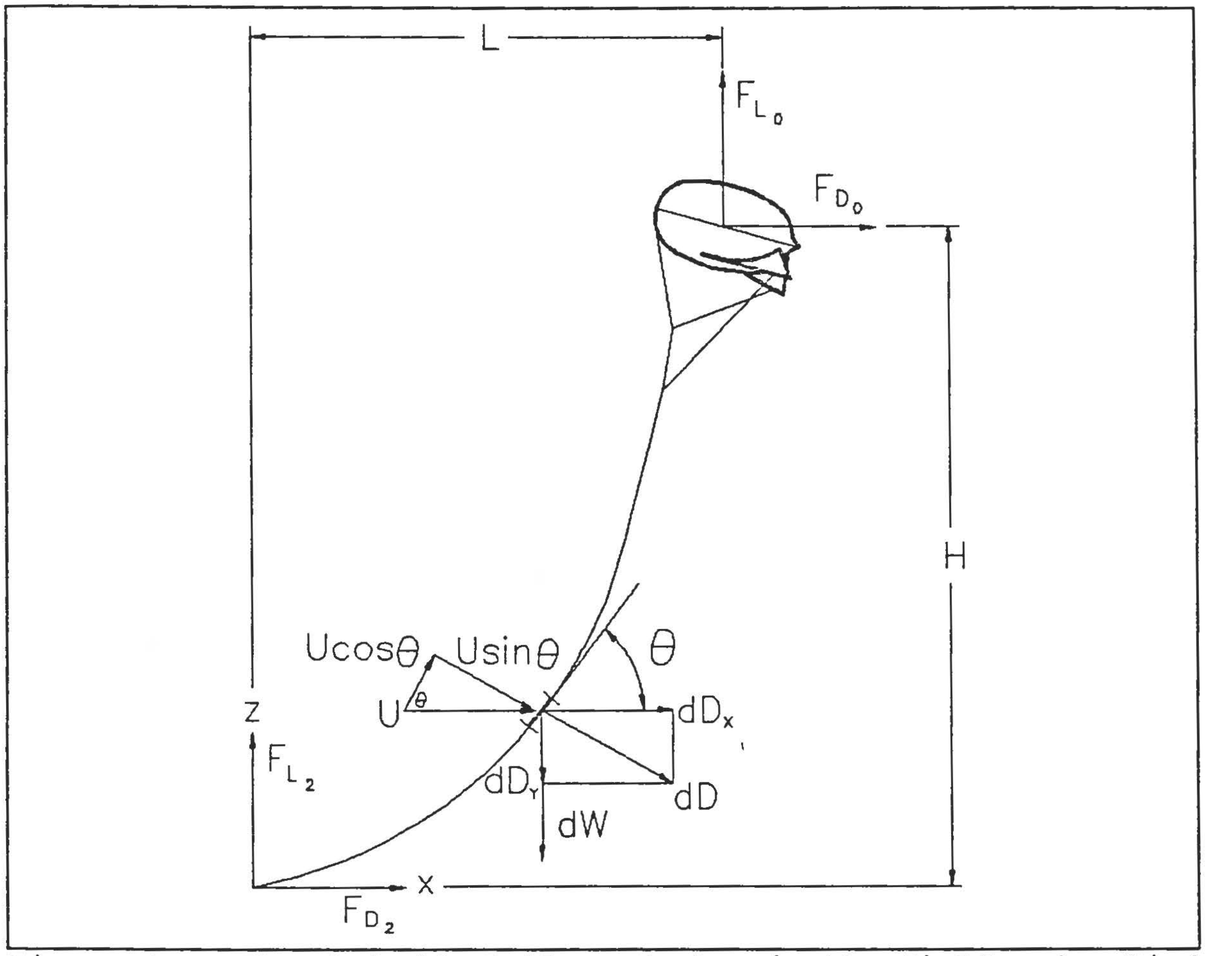

Figure 1.2 The Skybuddy Balloon System in the field under Wind Condition

$$\sin\theta \approx 1.0, \quad \cos\theta \approx 0.0,$$

$$z' \approx \frac{A + B*z}{C + D*z}$$

where

$$A = F_{LO}$$

$$B = -\frac{1}{4}\pi^2 \rho_s$$

$$C = F_{DO}$$

$$D = \frac{1}{2}\rho_{air} U^2 C_D d$$

Here is the approximate function for the string shape.

$$x = (D/B)z + (1/B)*(C-D*A/B)*[\ln(A+B*z)-\ln A]$$

Note that the result expresses coordinate x as a function of z instead of z as a function of x.

When the above approximation holds, the drag and lift forces at the end of the string (control point) can also be calculated. Assuming that the weight of the entire string weight is W,

$$F_L = F_{L0} - W$$

$$F_D = F_{D0} + \tfrac{1}{2}\rho_{air} * U^2 * (d*H) * C_D$$

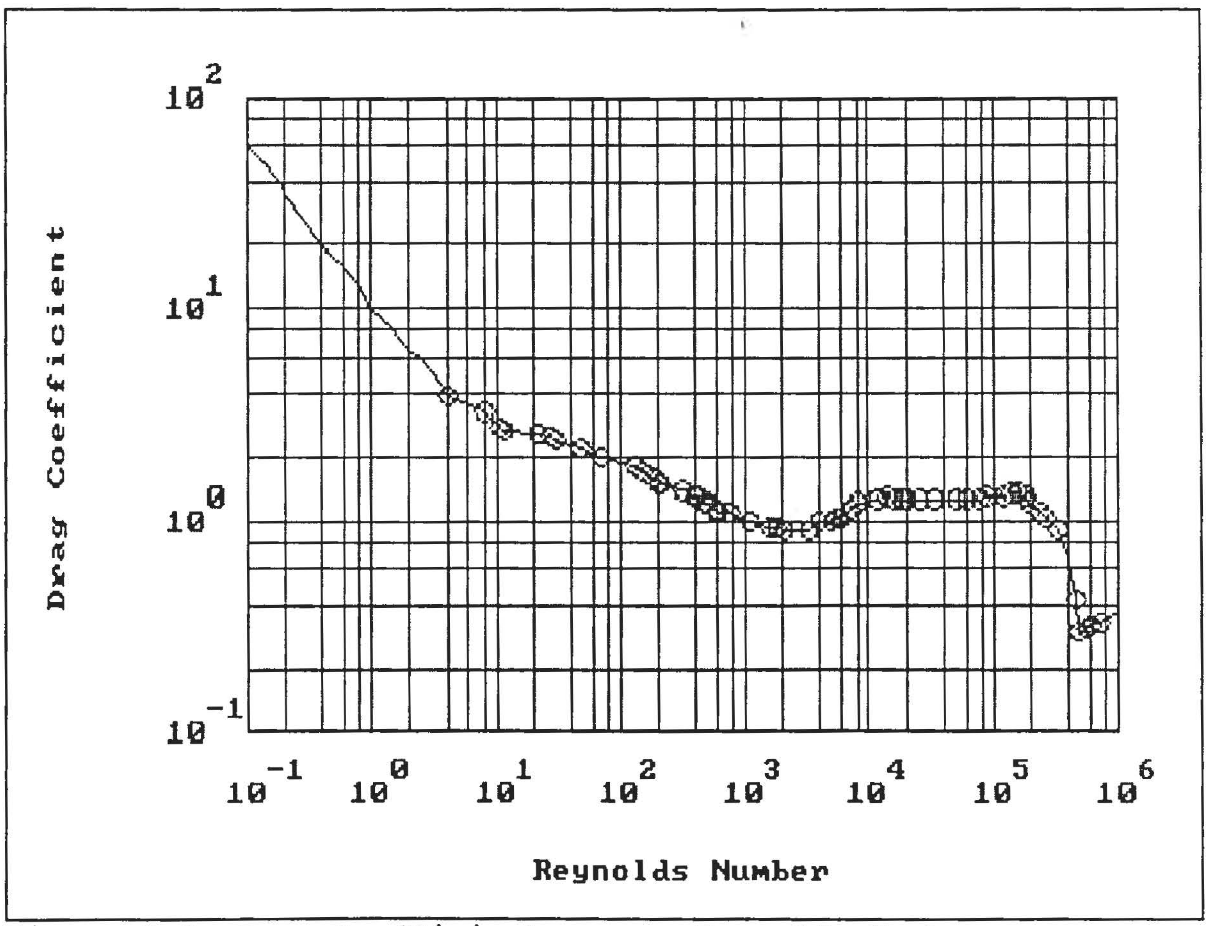

Figure 1.3 Drag Coefficient versus Reynolds Number

2 EXPERIMENTAL CONFIGURATION

In this chapter the experimental apparatus and methods are discussed, and also the model set-up and the format for the data presentation are presented.

2.1 EXPERIMENTAL APPARATUS

Measurements were performed at the Fluid Dynamics and Diffusion Laboratory of the Engineering Research Center at the Colorado State University. All the data was collected in the Industrial Wind Tunnel, Figure 2.1.

The closed circuit Industrial Wind Tunnel is powered by a 56 kw electric induction motor connected to a sixteen blade propeller. The useful mean flow velocity may be varied from 4.5 to 50 mph (2.0 to 22 m/s). A flexible roof permits a boundary layer flow to be developed but with a zero pressure gradient to better approximate atmospheric flows. Different combinations of roughness elements on the wind tunnel floor and spires at the entrance to the working section develop velocity profiles comparable to those found in real environments.

During the Skybuddy tests, no roughness elements and spires were used.

The force balance used is a strain sensing apparatus consisting of three main parts: a heavy steel, square reaction or inertia ring, a steel sprung plate supported by steel cross beams and a stem of aluminium tubing. The reaction ring is bolted to a wind-tunnel turntable. A right-handed coordinate system is used, orientated with the z axis coincident with the balance and model vertical axis. The x axis is along the wind direction. An upper and lower set of strain gages and associated bridge networks sense the total bending moment about the x and y axes at that level.

The lower level strain gages are attached to a necked down segment of the steel cross members which connect the sprung portion of the balance to the reaction ring. The upper gages are attached to the stem as shown in Figure 2.2. Temperature compensating resistors within each gage bridge network are installed within the base of the force balance.

The bridge system was calibrated before the force balance was used to measure the forces (Fx, Fz). For this balloon measurement, only the drag and lift forces were calibrated. Calibration is performed by using different known masses to provide the loads. The resulting voltage signals vary linearly with load. The slopes of these plots are the calibration coefficients.

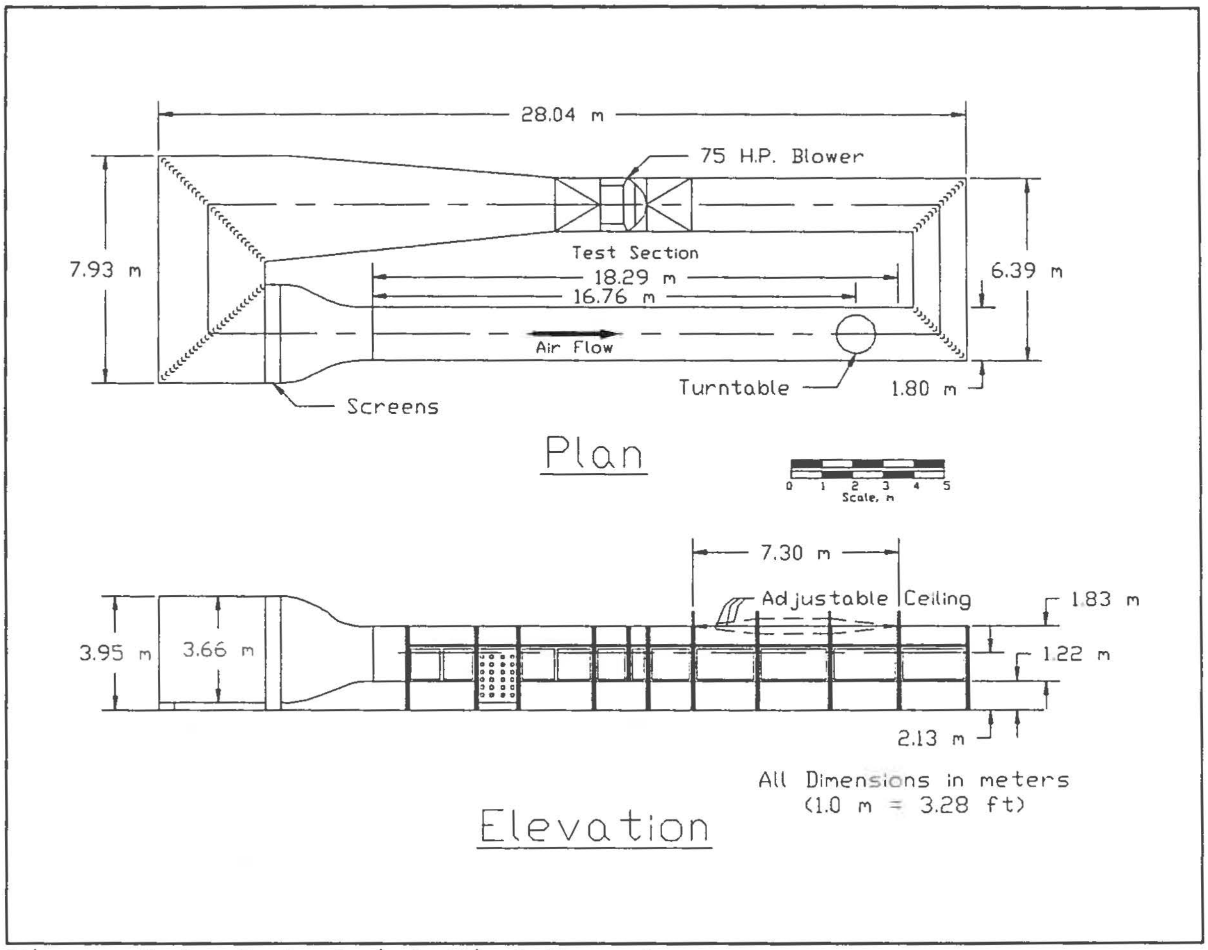

Figure 2.1 Industrial Wind Tunnel

A pitot-static tube was mounted upwind of the models to record the approach wind speed. The velocity was measured at the height of 80 cm from the wind-tunnel floor.

When model cross-section subtends a large portion of the wind tunnel cross-section, lift and drag forces must be corrected for wall interference. The maximum possible blockage of the balloon inside the tunnel is the area with the larger diameter,

$$A = \tfrac{1}{4}\pi D^2 = \tfrac{1}{4}\pi * (25.5/12)^2 = 3.55 \text{ ft}^2;$$

hence, the blockage factor (BF) for a 6 by 6 feet tunnel is

$$BF = 3.55 / (6*6) = 9.85\%$$

The blockage effect is generally considered minor when the blockage factor is larger than 10%. Thus for this experiment the blockage effect was iqnored.

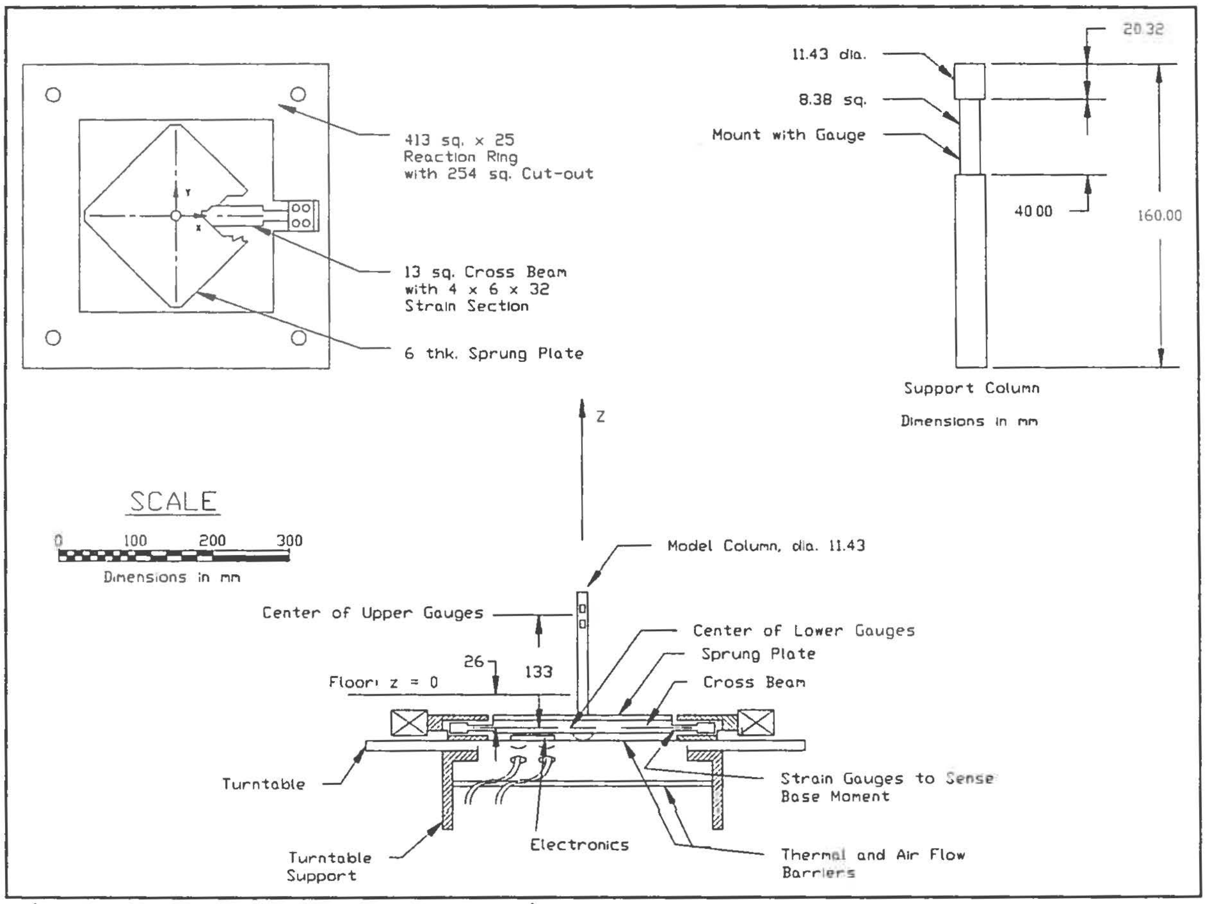

Figure 2.2 Force Balance Diagram

2.2 PROFILES

The wind tunnel approach flow velocity profile is shown in Figure 2.3. The profile maintained a uniform and low turbulence level for the entire experiment.

These profiles were obtained using a hot wire anemometer mounted on a traverse mechanism. The fast response time of the hot wire allowed fluctuations from the mean to be recorded as well as the mean values. The wire was calibrated against a test nozzle which gives the coresponding mean velocity. By the modified King's Law,

$$E^2 = A + B\ U^c$$

where E is the hot wire output voltage, U is the mean velocity and A, B and C are coefficients developed from a curve fitting procedure. The root mean square turbulent velocity was obtained from:

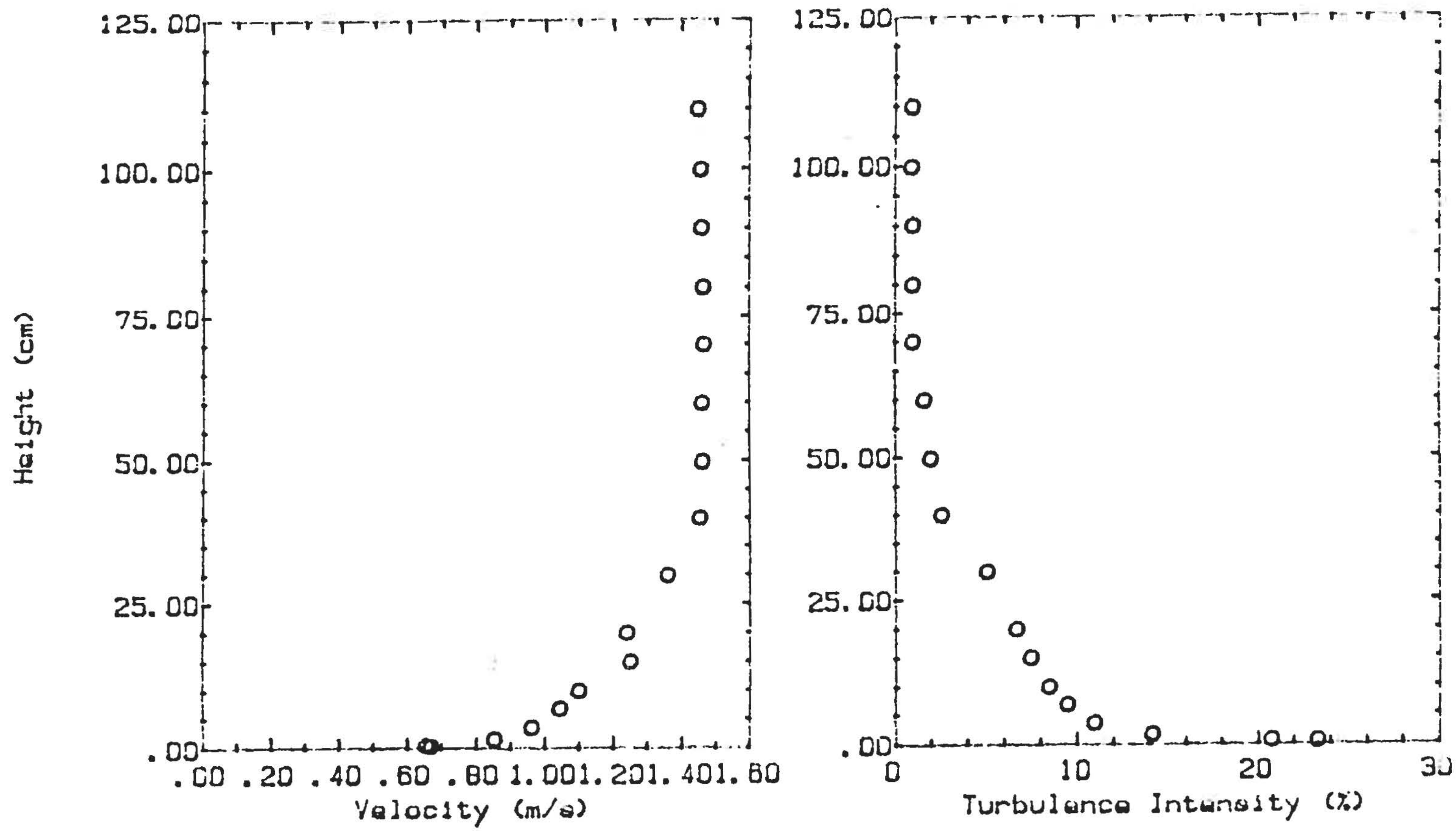

Fig. 2.3 Velocity and Local Turbulence Intensity Profiles

$$U_{rms} = \frac{2\ E\ Erms}{B\ C\ U^{c-1}}$$

Where Erms is the root mean square voltage output from the anemometer.

2.3 MODEL SET-UP AND DATA ACQUISITION

The balloon was first tested inside the wind tunnel without any lateral restraint. But since the balloon behaves as an upside down pendulum having a very short length, it had a very short period of oscillation compared to the balloon in the field tethered by a long string. The vibration caused by the wind on the model system was large, which made the balloon move sideways and hit the tunnel walls.

Screens were placed on either side of the balloon to limit its lateral movement. When the small balloon was tested, the screens were moved closer together, Figure 2.4.

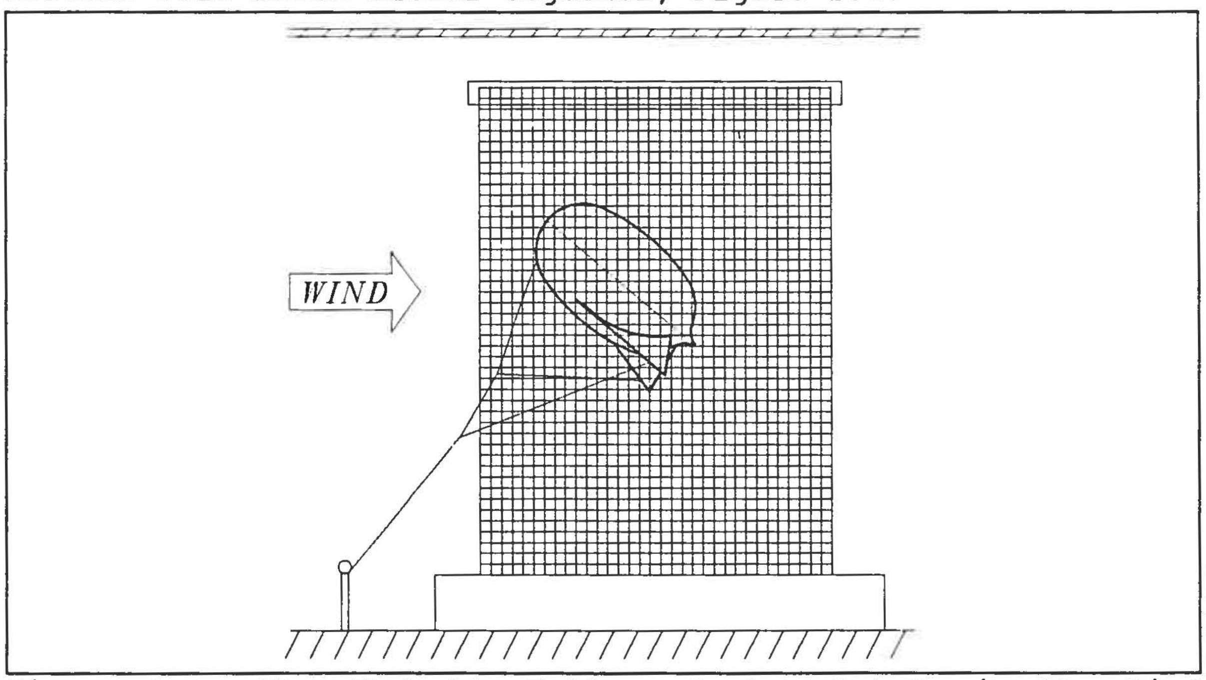

Figure 2.4 The Skybuddy Balloon System Set-Up in the Wind Tunnel

For the model coordinate system, two directions are defined for this study: the x-axis is the drag force direction and the z-axis is the lift force direction. There are also two control angles which are important for this study: alpha and beta. Beta is a pre-set angle which can be either positive or negative, and alpha is the average of the angle from each lift and drag ratio (arctan (F_z/F_x)) through the data taking period. The sample time for this study was 20 seconds, and the sample rate was 128 Hz.

The total samples for each run are the product of sample time and sample rate, or 2560 samples.

A balloon attack angle can be defined as:

$$AA = 90 - (\alpha+\beta)$$

All the angle definitions refer to Figure 2.5.

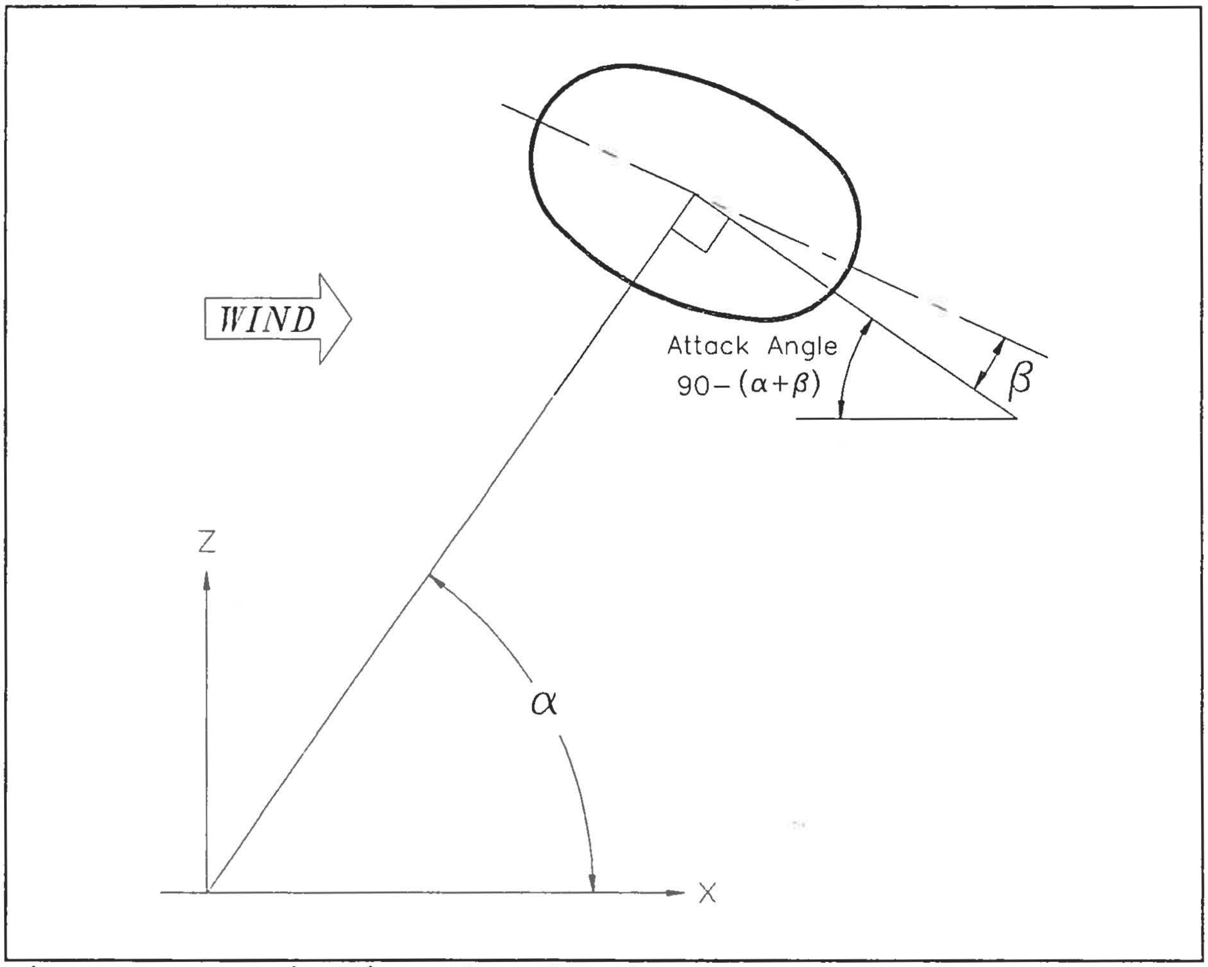

Figure 2.5 Defination of Angles for the Skybuddy Balloon System

The abbreviations used in the enclosed data tables are defined below:

Mean	=	Time average,
Rms	=	Root-mean-square of the fluctuating values about the mean,
Max	=	Largest values recorded during each 20 second run,

Min	=	Smallest values recorded during each 20 second run,
Gfac	=	Gust factor, which is peak divided by the mean,
Pfac	=	Peak factor, (Peak-Mean)/Rms.

3 RESULTS AND DISCUSSION

The test results are discussed in this chapter together with the predicted balloon behavior.

3.1 GENERAL BALLOON BEHAVIOR

Two different balloon sizes were studied in the wind tunnel (see Table I and II).

The first table column is the run number shown on the data file SBF1 and SBF2. The second column indicates the television VCR tape index for visualization of the balloon behavior during each test. The third column is the beta pre-set angle (degrees, refer to Figure 2.5). The fourth column is the lift force (pounds), while the fifth is the drag force (pounds). The sixth column is the alpha angle (degrees), which is the arithmetic average of the angle infered from each lift and drag ratio ($\arctan(F_z/F_x)$). The attack angle (degrees) is provided in the seventh column. The last column is the wind speed (mph).

For the large balloon, there are three settings for the beta angle, 8°, 0° and -4° (for beta definition, check Section 2.3). The beta angle at 8 degrees gave a more survivable position for strong winds in the wind tunnel. Over the beta range from -4° to 8°, the balloon would always become unstable at low wind speeds.

During the test, the wind speed ranged from 10 mph to nearly 50 mph. At 10 mph the alpha angle output in the data file is not accurate, since the force ratio resulting from the division of two small numbers is not accurate. The attack angle varys with wind speed. For a larger angle of beta, the attack angle becomes smaller. The variation of the attack angle implies that for a beta angle from -4° to 0°, the balloon is more stable and changes less with wind speed. The balloon could not survive for the high speed winds at a beta equal to 8°. Table 1 also suggests that the alpha angle stays near 40° no matter what beta angle is selected, which means that the drag and lift ratio remains the same regardless of the pre-set angle of beta. Over the entire range of the alpha angle, the beta range from 0° to -4° is more stable than a beta angle equal to 8°.

Figure 3.1 indicates that the feasible range of tether angles for a large balloon includes a combination of survival position and survival wind speed.

For the small balloon, the tests were not as successful. The pre-set angle of beta had to be at least 5 degrees to start the test, because, for a smaller beta angle, the balloon would

Table I Test Matrix for the Large Skybuddy Balloon

File: SBF1 Large Balloon

Run #	Tape #	Beta	lift (lb)	Drag (lb)	Alpha	Ak Agl	Speed (mph)
5	173	0	0.49	0.44	44	46	10
6	261	0	1.07	1.03	45	45	15
7	345	0	1.92	1.85	46	44	20
8	434	0	2.89	2.92	45	45	25
9	525	8	3.3	4.99	34	48	30
10	615	-4	6	7.4	39	55	35
11	710	8	7.83	8.48	43	39	40
12	814	8	10.5	11.3	43	39	45
13	915	8	11.99	12.9	43	39	49
14	983	8	0.47	0.42	44	38	10
15	1055	8	0.95	1.01	42	40	15
16	1122	8	1.56	1.99	38	44	20
17	1198	8	2.95	2.95	45	37	25
18	1253	-4	0.48	0.5	41	53	10
19	1315	-4	0.93	1.17	38	56	15
20	1371	-4	1.64	2.16	37	57	20
21	1433	-4	2.53	3.45	36	58	25
22	1495	-4	3.44	5.2	34	60	30
23	1545	0	4.26	4.67	42	48	30
24	1596	0	5.77	6.54	41	49	35
25	1653	0	7.5	8.86	40	50	40

Attack angle variation under different wind speeds

Beta	Atk Angl	Var.	Alpha	Var.
8	37-48	11	34-45	11
0	53-60	7	34-41	7
-4	44-50	6	40-46	6

not survive lateral and vertical instabilities for winds of 20 - 25 mph. At a 5° beta angle the balloon survived to wind speeds of 35 mph. A beta angle of 10° was also tested, but the balloon would not survive the tunnel test at a low wind speed.

3.2 DRAG AND LIFT FORCE MEASUREMENTS

The mean and peak drag and lift forces (lbs) were plotted against wind speed (mph). Because a dynamic simulation of balloon flight was not performed, the peak drag and lift are not necessarily quantitatively meaningful. They are included only for reference to compare to the mean values. Each plot corresponds to one pre-set angle of beta. The circle symbol is for mean drag Fx, and the triangle is for mean lift Fz. The square symbol is for maximum drag and the upside-down-triangle is for maximum lift, Figure 3.2, 3.3, 3.4, 3.5.

Figure 3.2, 3.3 and 3.4 display the forces for the large balloon with beta = -4°, 0°, 8° in that order. For the large balloon, the drag and lift forces increased with the wind speed as expected. The magnitude of both mean values were close and no more than 15 lbs for a wind speed of 50 mph. There is a tendency for the forces to increase with an increase of angle beta, which implies that the drag and lift decrease with the increase of the attack angle.

The forces acting on the small balloon were relatively smaller. The mean drag and lift forces were no more than 4 lbs for a wind speed of 35 mph. The variation of the forces on the small balloon was similar to those on the large balloon, Figure 3.5.

3.3 CALCULATION OF OSCILLATION FREQUENCY UNDER WIND CONDITIONS

During the balloon tests in the wind tunnel, the balloon was tied to a force measurement device like a short upside-down simple pendulum, Figure 3.6. From a simple pendulum, the period can be calculated as

$$T = 2\pi(m/k)^{1/2} = 2\pi(L/g)^{1/2} .$$

For a upside-down pendulum (refer to the large balloon) with buoyancy force upward, the effective g should be

$$g = NBF/m = 0.435/0.0488 = 8.914 \text{ m/s}^2$$

Thus the periods (T_L and T_S) of oscillation for a no wind condition are for each balloon:

$$T_L = 2\pi(1.31/8.914)^{1/2} = 2.4 \text{ (s), and}$$

$$T_S = 2\pi(1.06/8.914)^{1/2} = 2.2 \text{ (s).}$$

For the big balloon L = 4.30 ft = 1.31 m, while for the small balloon L = 3.48 ft = 1.06 m.

Under windy conditions, the additional forces caused by the wind would cause the oscillation frequency to change. The following derivation gives a way to calculate the period of the balloon.

Table II Test Matrix for the Small Skybuddy Balloon

File: SBF2 Small Balloon

Run #	Tape #	Beta	Lift (lb)	Drag (lb)	Alpha	Ak Agl	Speed (mph)
1	128	5	0.26	0.23	37	---	10
2	222	5	0.58	0.55	44	41	15
3	311	5	0.98	0.99	44	41	20
4	403	5	1.36	1.67	39	46	25
5	492	5	1.76	2.57	34	51	30
6	577	5	2.43	3.61	34	51	35
7	666	10	0.22	0.22	32	---	10
8	757	10	0.38	0.67	27	53	15

Attack angle varies 12 degrees for Beta = 5 degrees under wind condition from 10 mph to 35 mph

If the buoyancy force is iqnored (only 0.1 lb), the tangential force (TF) is the difference between drag and lift projections in that direction (Figure 3.6), which is

$$TF = F_Z \cos(\alpha-\theta) - F_X \sin(\alpha-\theta)$$
$$= F_Z \cos\alpha \cos\theta + F_Z \sin\alpha \sin\theta - F_X \sin\alpha \cos\theta + F_X \cos\alpha \sin\theta.$$

But at balance position α,

$$F_Z \cos\alpha - F_X \sin\alpha = 0$$

But the angle θ is small enough to make $\sin\theta$ nearly equal to θ, which is itself equal to x/L. L is the length of the string tied to the balloon, and x is the displacement from the equilibrium position. Therefore the force is

$$TF = (F_Z \sin\alpha + F_X \cos\alpha)*\sin\theta$$
$$= (F_Z \sin\alpha + F_X \cos\alpha)*(x/L) = kx,$$

where k is a proportionality constant called the force constant, which is equal to

$$k = (F_Z \sin\alpha + F_X \cos\alpha)/L.$$

Therefore, the period of an upside down pendulum displaced by the wind is

$$T = 2\pi(mL / (F_Z \sin\alpha + F_X \cos\alpha)^{\frac{1}{2}}$$

This formula can be applied to calculate the oscillation

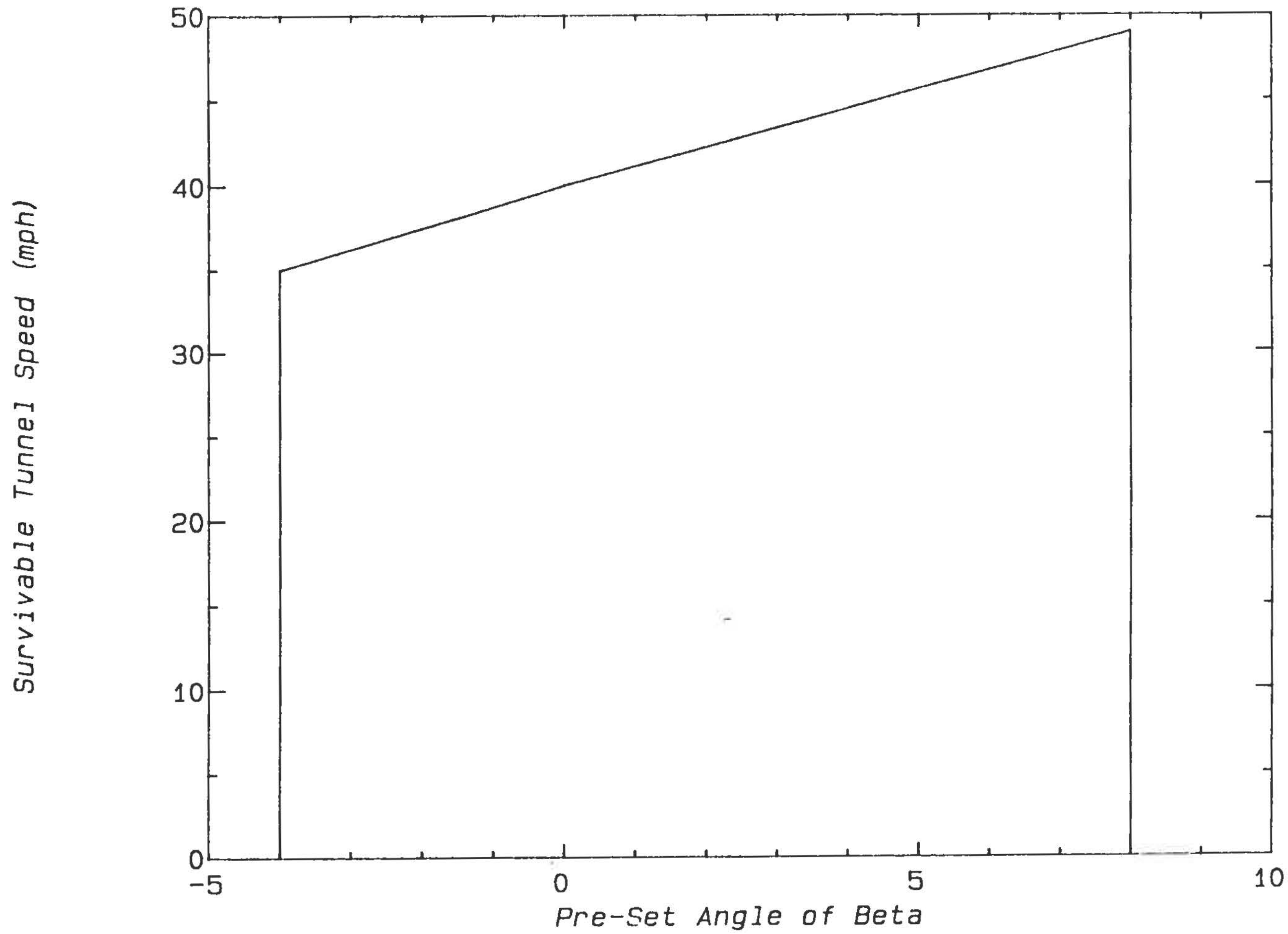

Figure 3.1 Survivable Tunnel Speed vs. Beta Angle

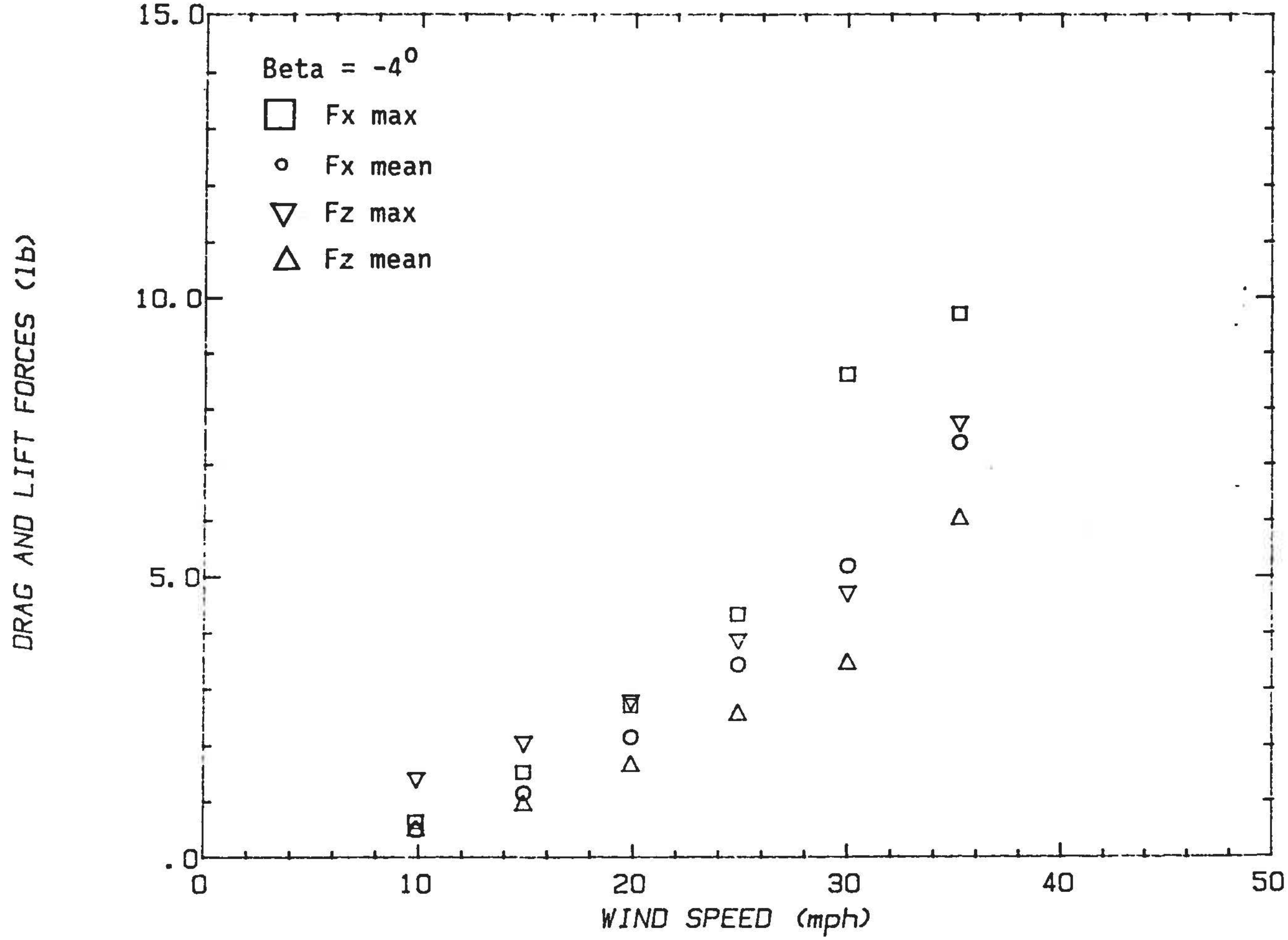

Fig. 3.2 Drag and Lift Forces at Beta = -4^{0} for large balloon

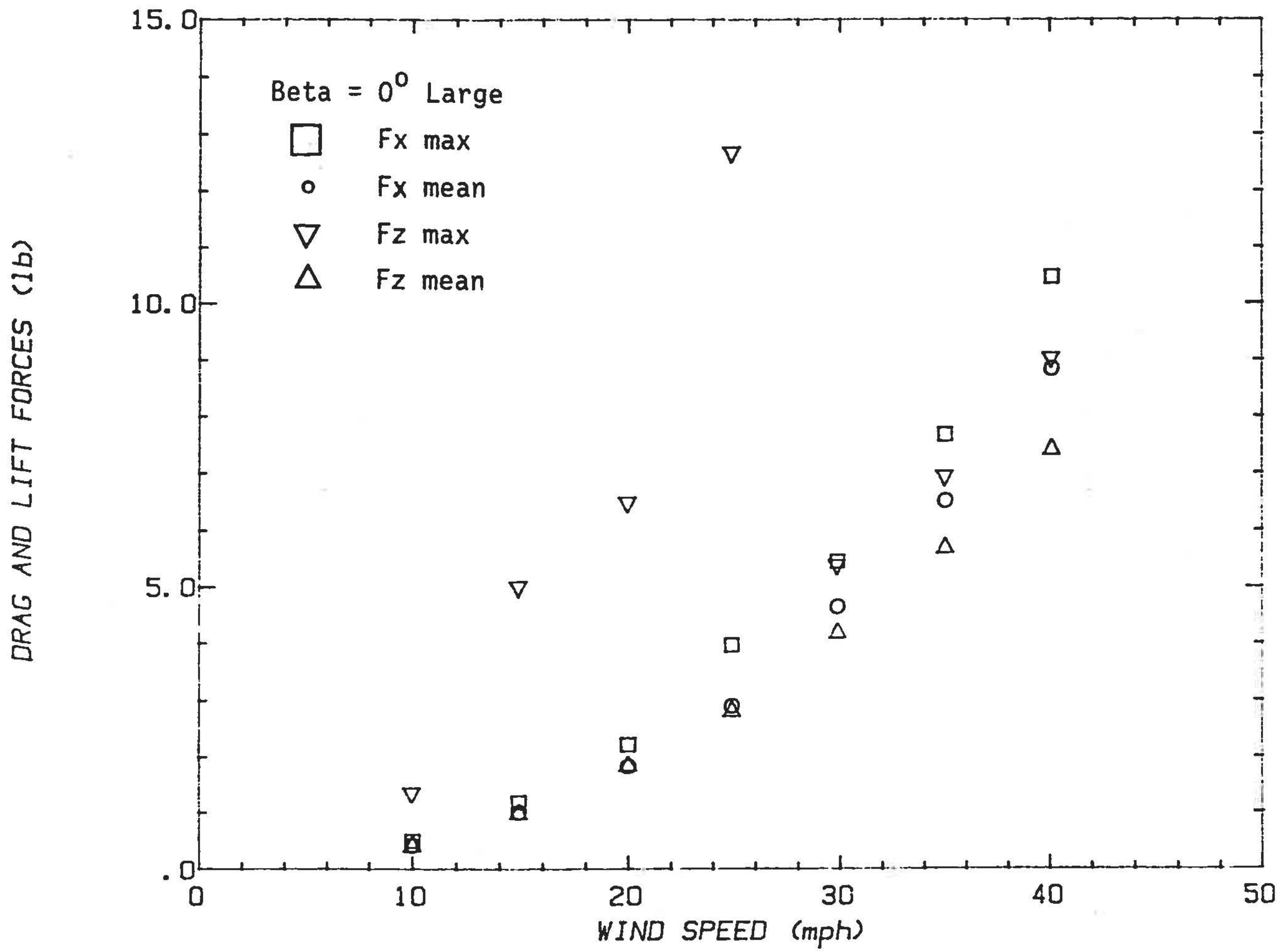

Fig. 3.3 Drag and Lift Forces at Beta = 0^o for large balloon

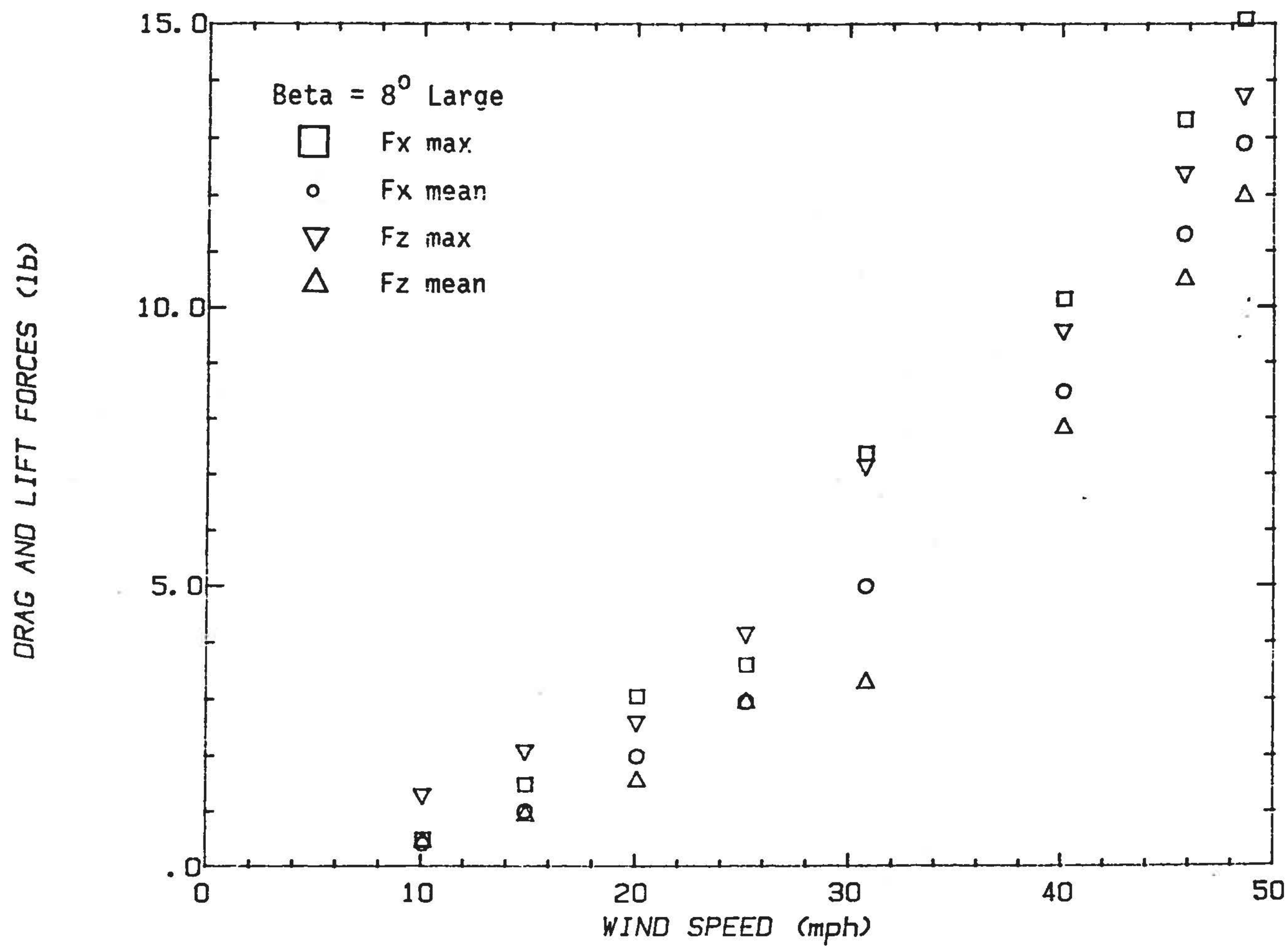

Fig. 3.4 Drag and Lift Forces at Beta = 8^0 for large balloon

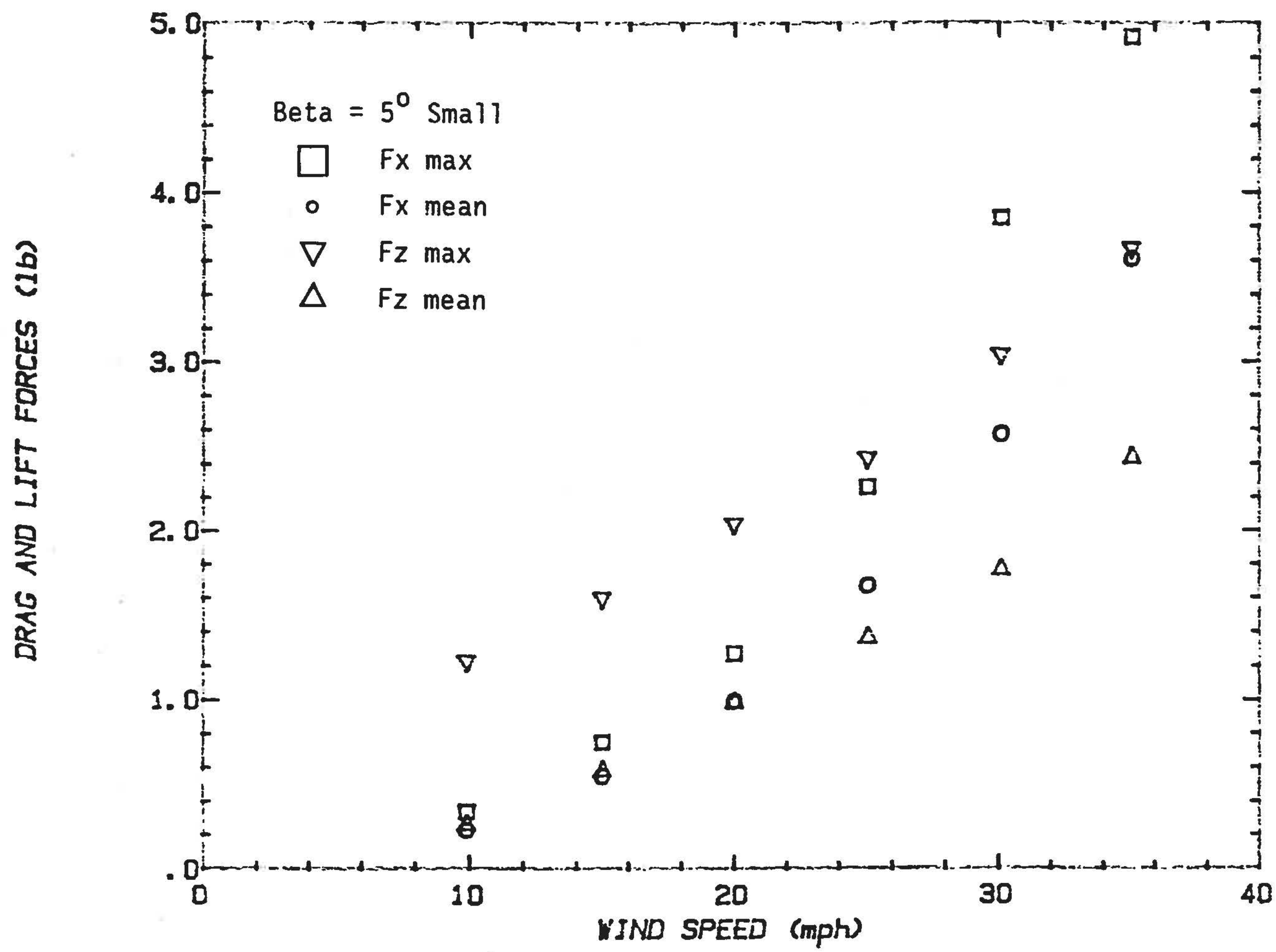

Fig. 3.5 Drag and Lift Forces at Beta = 5° for small balloon

frequency for the wind tunnel study.

For example, at a wind speed of 20 mph and a pre-set angle 0° for the large balloon,

$$F_X = 1.85 \text{ lb}, \quad F_Z = 1.92 \text{ lb}, \quad \alpha = 45.6°,$$

$$F_Z \sin\alpha + F_X \cos\alpha = 2.666 \text{ lb} = 11.86 \text{ N},$$

$$L = 4.30 \text{ ft} = 1.31 \text{ m}, \quad m = 0.0488 \text{ kg, and}$$

$$T = 2\pi(0.0488*1.33/11.86)^{1/2} = 0.46 \text{ s}.$$

Thus, under windy situations the oscillation frequency is higher than without wind as expected.

3.4 CONCLUSIONS AND RECOMMENDATIONS

Based on the experiments completed the following conclusions are appropriate:

1. For the large balloon to survive under strong wind conditions, a pre-set angle of beta should be used in the

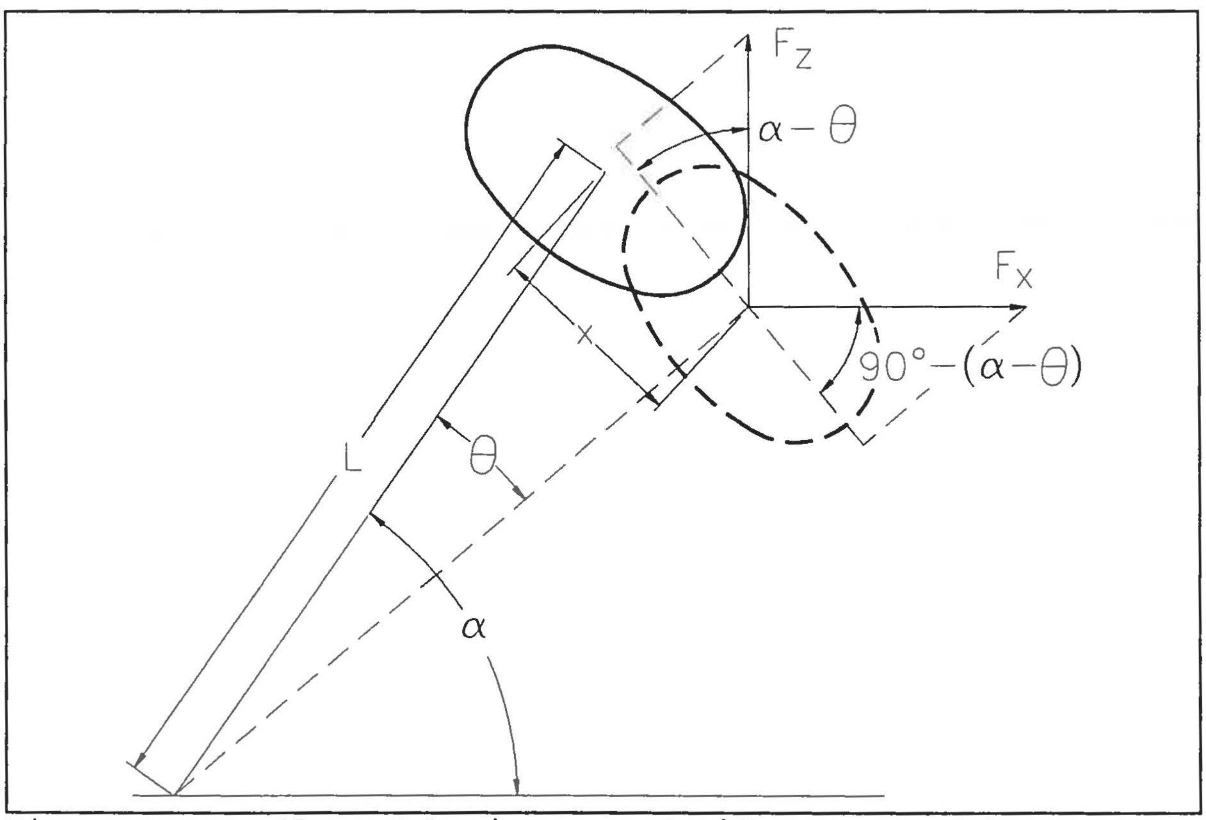

Figure 3.6 Balloon Behavior as a Upside-Down Pendulum

range from 8 to -4 degrees(refer to Figure 2.7 for the beta angle definition).

2. In order for the balloon to remain stable under different wind conditions, a pre-set angle in the range from 0 to -4 degrees is recommended.

3. The magnitudes of both mean lift and drag are close, and they do not exceed 15 lbs even for a 50 mph wind speed.

4. The small balloon does not survive as well as the large balloon.

5. For the small balloon, a pre-set angle of 5 degrees is recommended. The mean lift and drag forces do not exceed 4 lbs under 35 mph wind.

Experience obtained on the behavior of the Skybuddy balloon system during this study suggests additional measurements would be profitable.

1. For a future study, a styrofoam model with similar shape to the Skybuddy balloon should be constructed and fixed to a force balance to determine a complete set of force coefficients versus different attack angles and wind speed.

2. For a future dynamic study, the model should be studied over a range of different Reynolds numbers and different Strouhal numbers to obtain a full understanding of balloon dynamic response.

APPENDIX A: THE SKYBUDDY BALLOON SYSTEM, NEW DESIGN

After the measurements about the Skybuddy balloon systems discussed in the main report were completed, the sponsor produced a new Skybuddy balloon design. The new design uses the same sizes of microfoils as on the old balloons, but the wings and fin configuration have been changed. Figure A.1 shows the old design and Figure A.2 is the new design.

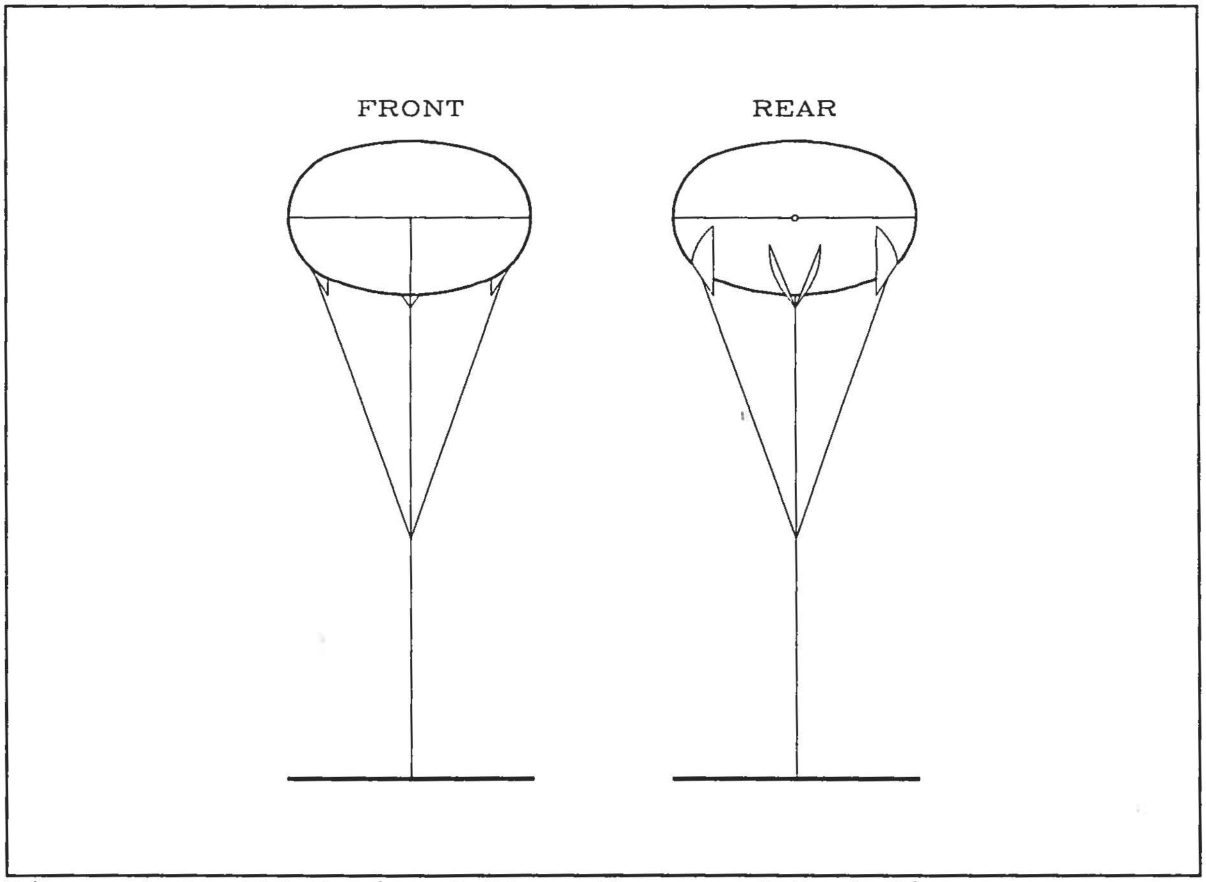

Figure A.1 Old Design Balloon Front and Back View

The new Skybuddy balloons behaved very well under the high wind speeds. Table A.1 presents the supplemental visualization test matrix which shows that the new design balloon survives to 75 mph. Two sizes of balloons were studied. The small balloon survived until 50 mph, and the large balloon survived at 75 mph over the entire test period. The tapes resulting from this visualization are Tape #3 and Tape #4. Each wind test run is noted by tape index. The beta angle has the same definition as used for the earlier design (refer to Figure 2.5).

The new Skybuddy balloon system is much more stable than the

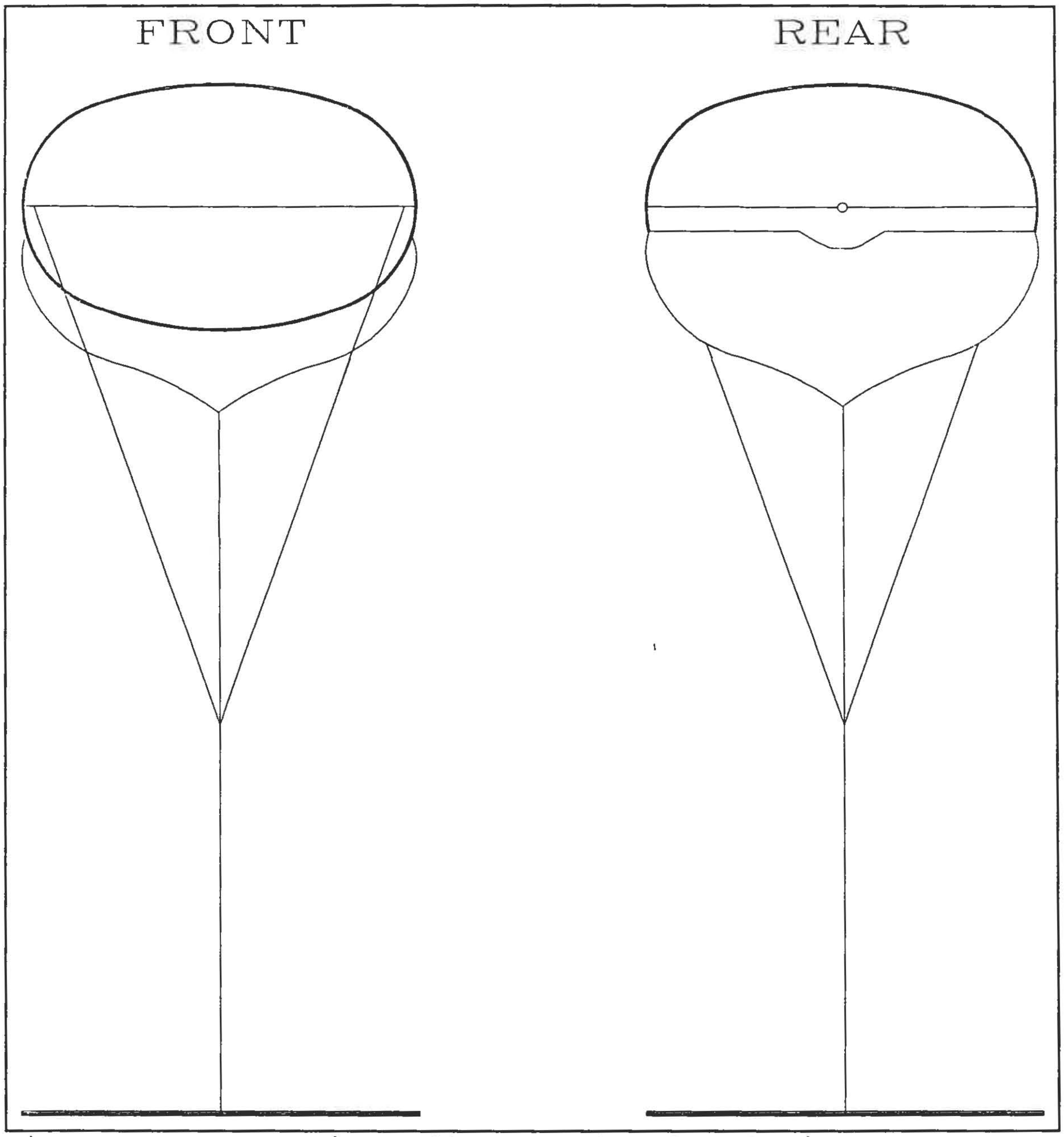

Figure A.2 New Design Balloon Front and Back View

old design. During visualization test, it was not necessary to place screens on either side of the balloon to limit its lateral movement. By carefully adjusting the strings tethered with the balloon (refer to section 2.3), an arrangement could be found where the balloons did not move sideways even at strong wind conditions. A very stable situation can be expected in the field for this new design balloon system according to these wind tunnel test results. For details refer to Tape #3 and Tape #4.

Table A.1 Visualization Test Matrix for New Design Balloon

Tape #3

Beta	Wind Vel. (mph)	Tape Indx
	Small Skybuddy Balloon (New Design)	
10	10	111
10	15	231
10	20	338
10	25	432
10	30	517
10	35	598
10	40	676
10	45	743
	Large Skybuddy Balloon (New Design)	
10	10	885
10	15	925
10	20	960
10	25	995
10	30	1036
10	35	1072
10	40	1104
10	45	1140
10	50	1177
10	55	1212

Tape #4

Beta	Wind Vel. (mph)	Tape Indx
	Large Skybuddy Balloon (New Design)	
10	65	106
10	70	153
10	75	226

Lift and drag measurements were not performed on the new design. But, because the same shape balloons were used and the manner of tethering the balloons was similar, the same lift and drag forces are expected for the new Skybuddy balloon system. Since the old balloon design did not survive above 50 mph, the lift and drag force data are not available above that wind speed. But if the wind speed is doubled, the forces will be roughly four times greater. This result assumes that the drag and lift force coefficients do not change dramatically over the wind speed range from 10 mph to 50 mph.

APPENDIX B: DATA FILE OUTPUT

Data for File : SBF1
Data taken on : 09-05-88

Run	Vel
5	10.0

Com :	Fx	Fz	Alpha
Mean :	.44	.49	43.98
RMS :	.03	.25	16.54
Max :	.55	1.49	73.09
Min :	.33	-.20	-27.46
Gfac :	1.24	3.03	1.66
Pfac :	3.06	3.99	1.76

Data for File : SBF1
Data taken on : 09-05-88

Run	Vel
6	14.9

Com :	Fx	Fz	Alpha
Mean :	1.03	1.07	45.35
RMS :	.06	.30	7.80
Max :	1.24	5.14	79.79
Min :	.76	-1.89	-62.47
Gfac :	1.20	4.79	1.76
Pfac :	3.28	13.61	4.42

Data for File : SBF1
Data taken on : 09-05-88

Run	Vel
7	20.0

Com :	Fx	Fz	Alpha
Mean :	1.85	1.92	45.63
RMS :	.13	.33	5.14
Max :	2.27	6.63	74.14
Min :	1.46	-3.18	-63.45
Gfac :	1.23	3.46	1.62
Pfac :	3.33	14.30	5.55

Data for File : SBF1
Data taken on : 09-05-88

Run		Vel	
8		24.9	

Com :	Fx	Fz	Alpha
Mean :	2.92	2.89	44.48
RMS :	.23	.45	3.95
Max :	4.02	12.81	76.08
Min :	2.00	-1.74	-32.52
Gfac :	1.38	4.44	1.71
Pfac :	4.72	22.26	8.00

Data for File : SBF1
Data taken on : 09-05-88

Run		Vel	
9		30.8	

Com :	Fx	Fz	Alpha
Mean :	4.99	3.30	33.55
RMS :	.53	.56	5.41
Max :	7.38	7.18	52.18
Min :	3.31	-7.87	-60.59
Gfac :	1.48	2.17	1.56
Pfac :	4.55	6.94	3.44

Data for File : SBF1
Data taken on : 09-09-88

Run		Vel	
10		35.2	

Com :	Fx	Fz	Alpha
Mean :	7.40	6.00	38.99
RMS :	.53	.63	2.58
Max :	9.71	7.75	45.88
Min :	5.43	4.07	29.47
Gfac :	1.31	1.29	1.18
Pfac :	4.35	2.80	2.67

Data for File : SBF1
Data taken on : 09-09-88

Run	Vel
11	40.1

Com :	Fx	Fz	Alpha
Mean :	8.48	7.83	42.70
RMS :	.43	.41	1.31
Max :	10.16	9.61	47.81
Min :	7.18	6.36	37.99
Gfac :	1.20	1.23	1.12
Pfac :	3.94	4.35	3.90

Data for File : SBF1
Data taken on : 09-09-88

Run	Vel
12	45.8

Com :	Fx	Fz	Alpha
Mean :	11.30	10.50	42.90
RMS :	.58	.52	1.16
Max :	13.33	12.41	46.64
Min :	9.35	8.57	38.39
Gfac :	1.18	1.18	1.09
Pfac :	3.49	3.65	3.21

Data for File : SBF1
Data taken on : 09-09-88

Run	Vel
13	48.6

Com :	Fx	Fz	Alpha
Mean :	12.90	11.99	42.91
RMS :	.67	.60	1.18
Max :	15.09	13.77	46.52
Min :	10.61	9.49	37.39
Gfac :	1.17	1.15	1.08
Pfac :	3.29	2.97	3.05

Data for File : SBF1
Data taken on : 09-09-88

Run		Vel	
14		10.1	

Com :	Fx	Fz	Alpha
Mean :	.42	.47	44.08
RMS :	.03	.24	17.12
Max :	.52	1.34	74.27
Min :	.28	-.25	-35.03
Gfac :	1.25	2.88	1.68
Pfac :	3.05	3.61	1.76

Data for File : SBF1
Data taken on : 09-09-88

Run		Vel	
15		14.9	

Com :	Fx	Fz	Alpha
Mean :	1.01	.95	42.37
RMS :	.12	.27	8.81
Max :	1.50	2.12	68.15
Min :	.59	.07	3.82
Gfac :	1.49	2.24	1.61
Pfac :	4.11	4.34	2.93

Data for File : SBF1
Data taken on : 09-09-88

Run		Vel	
16		20.1	

Com :	Fx	Fz	Alpha
Mean :	1.99	1.56	37.82
RMS :	.23	.32	6.41
Max :	3.06	2.63	58.84
Min :	1.34	.56	14.26
Gfac :	1.54	1.69	1.56
Pfac :	4.64	3.36	3.28

Data for File : SBF1
Data taken on : 09-09-88

Run	Vel
17	25.2

Com :	Fx	Fz	Alpha
Mean :	2.95	2.95	44.99
RMS :	.19	.29	2.76
Max :	3.62	4.19	55.30
Min :	2.42	1.99	36.33
Gfac :	1.23	1.42	1.23
Pfac :	3.52	4.19	3.73

Data for File : SBF1
Data taken on : 09-09-88

Run	Vel
18	9.9

Com :	Fx	Fz	Alpha
Mean :	.50	.48	40.93
RMS :	.05	.24	15.42
Max :	.65	1.43	73.40
Min :	.34	-.20	-25.66
Gfac :	1.30	2.97	1.79
Pfac :	2.98	3.96	2.11

Data for File : SBF1
Data taken on : 09-09-88

Run	Vel
19	14.9

Com :	Fx	Fz	Alpha
Mean :	1.17	.93	37.95
RMS :	.10	.25	7.68
Max :	1.54	2.06	62.10
Min :	.89	.22	10.10
Gfac :	1.32	2.21	1.64
Pfac :	3.56	4.48	3.15

Data for File : SBF1
Data taken on : 09-09-88

Run	Vel
20	19.9

Com :	Fx	Fz	Alpha
Mean :	2.16	1.64	36.92
RMS :	.16	.27	4.53
Max :	2.71	2.79	52.32
Min :	1.63	.79	19.82
Gfac :	1.25	1.70	1.42
Pfac :	3.44	4.24	3.40

Data for File : SBF1
Data taken on : 09-09-88

Run	Vel
21	24.9

Com :	Fx	Fz	Alpha
Mean :	3.45	2.53	36.20
RMS :	.24	.30	3.29
Max :	4.34	3.88	47.81
Min :	2.77	1.50	23.77
Gfac :	1.26	1.54	1.32
Pfac :	3.72	4.45	3.52

Data for File : SBF1
Data taken on : 09-09-88

Run	Vel
22	30.0

Com :	Fx	Fz	Alpha
Mean :	5.20	3.44	33.55
RMS :	.54	.52	4.81
Max :	8.62	4.72	44.03
Min :	3.85	1.25	10.44
Gfac :	1.66	1.37	1.31
Pfac :	6.39	2.45	2.18

Data for File : SBF1
Data taken on : 09-09-88

Run		Vel	
23		29.9	

Com :	Fx	Fz	Alpha
Mean :	4.67	4.26	42.29
RMS :	.24	.32	1.92
Max :	5.50	5.52	49.41
Min :	3.96	3.28	35.62
Gfac :	1.18	1.30	1.17
Pfac :	3.40	4.02	3.71

Data for File : SBF1
Data taken on : 09-09-88

Run		Vel	
24		35.0	

Com :	Fx	Fz	Alpha
Mean :	6.54	5.77	41.41
RMS :	.33	.36	1.59
Max :	7.73	7.09	47.04
Min :	5.43	4.27	36.32
Gfac :	1.18	1.23	1.14
Pfac :	3.59	3.64	3.53

Data for File : SBF1
Data taken on : 09-09-88

Run		Vel	
25		40.1	

Com :	Fx	Fz	Alpha
Mean :	8.86	7.50	40.24
RMS :	.45	.45	1.47
Max :	10.52	9.18	44.96
Min :	7.31	5.67	34.39
Gfac :	1.19	1.22	1.12
Pfac :	3.65	3.77	3.21

Data for File : SBF2
Data taken on : 09-16-88

Run		Vel	
1		9.9	

Com :	Fx	Fz	Alpha
Mean :	.23	.26	36.96
RMS :	.03	.24	31.25
Max :	.34	1.23	79.29
Min :	.12	-.40	-64.31
Gfac :	1.44	4.71	2.15
Pfac :	3.12	4.00	1.35

Data for File : SBF2
Data taken on : 09-16-88

Run		Vel	
2		15.0	

Com :	Fx	Fz	Alpha
Mean :	.55	.58	44.35
RMS :	.04	.24	12.79
Max :	.75	1.60	71.08
Min :	.42	-.04	-3.70
Gfac :	1.37	2.73	1.60
Pfac :	4.71	4.17	2.09

Data for File : SBF2
Data taken on : 09-16-88

Run		Vel	
3		20.0	

Com :	Fx	Fz	Alpha
Mean :	.99	.98	43.79
RMS :	.06	.25	7.50
Max :	1.27	2.04	62.87
Min :	.77	.24	14.55
Gfac :	1.28	2.09	1.44
Pfac :	4.42	4.25	2.55

Data for File : SBF2
Data taken on : 09-16-88

Run		Vel	
4		25.1	

Com :	Fx	Fz	Alpha
Mean :	1.67	1.36	38.97
RMS :	.14	.29	6.55
Max :	2.26	2.43	55.87
Min :	1.25	.47	12.83
Gfac :	1.36	1.78	1.43
Pfac :	4.16	3.70	2.58

Data for File : SBF2
Data taken on : 09-16-88

Run		Vel	
5		30.1	

Com :	Fx	Fz	Alpha
Mean :	2.57	1.76	34.35
RMS :	.30	.35	6.64
Max :	3.85	3.04	53.71
Min :	1.78	.66	12.34
Gfac :	1.50	1.73	1.56
Pfac :	4.25	3.69	2.91

Data for File : SBF2
Data taken on : 09-16-88

Run		Vel	
6		35.1	

Com :	Fx	Fz	Alpha
Mean :	3.61	2.43	33.97
RMS :	.35	.35	4.57
Max :	4.92	3.67	50.30
Min :	2.52	1.25	17.78
Gfac :	1.36	1.51	1.48
Pfac :	3.73	3.53	3.57

Data for File : SBF2
Data taken on : 09-16-88

Run		Vel	
7		9.5	

Com :	Fx	Fz	Alpha
Mean :	.22	.22	32.08
RMS :	.03	.25	35.84
Max :	.32	1.18	80.66
Min :	.14	-.51	-69.41
Gfac :	1.47	5.43	2.51
Pfac :	3.88	3.89	1.36

Data for File : SBF2
Data taken on : 09-16-88

Run		Vel	
8		14.8	

Com :	Fx	Fz	Alpha
Mean :	.67	.38	27.20
RMS :	.06	.24	15.90
Max :	.89	1.28	64.05
Min :	.50	-.33	-28.26
Gfac :	1.33	3.41	2.36
Pfac :	3.83	3.70	2.32