A STUDENT'S INTRODUCTION TO THE

WRIGHT BROTHERS WIND TUNNEL

AT MIT

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INTRODUCTION

A wind tunnel is an instrument whose purpose is to measure some aerodynamic property(ies) of the body installed in the test section. In some, but not all cases, the body is a sub-scale model represepting an actual structure like an airplane, a building, a racing automobile or sailboat, etc. In other cases, the body may be a full scale item like a bicycle or a set of oarlocks, an instrument to be calibrated or configured supporting a research program.

The Wright Brothers Wind Tunnel (WBWT) is a closed return, closed test section wind tunnel. The test section is basically a 7x10 foot (2.133x 33.281 m) ellipse and is 15 feet (4.877 m) long (Fig 1). While the tunnel can be pressurized from 0.25 atmospheres to 2.0 atmospheres, the test section is not isolated by an airlock and so testing times at test conditions other than atmospheric pressure are quite long. So tests at pressurized conditions are rarely conducted, unless when the testing environment demands such tests.

The tunnel is 'adiabatic' in the sense that there is no active cooling. At temperatures above 90 F, some mechanical elements may bind. Thus testing in the summer is stopped when the tunnel static temperature exceeds 90 F (32 C). The auxiliary air supply can be used to cool the tunnel when outside air temperatures are low enough to provide cooling air.

A 2,000 HP alternating current motor powers the WBWT. This motor runs at one of two constant speeds. The airflow speed is controlled by the pitch setting of the 6 bladed 13 foot 6 inch diameter fan. Because of a self-imposed noise constraint, the tunnel is usually run at first speed (up to about 90 mph), and only occasionally in second speed. Thus the upper limit of speed is about 150 mph (240 kmph). The lowest speed is about 15 mph (24 kmph). Under these limits the demand power is less than 350 HP.

As implied above, a wind tunnel is an instrument whose purpose is to measure forces and moments, or the pressure distribution, on models designed for that purpose. The tunnel is shaped to provide a steady uniform airflow. As an instrument, a wind tunnel consists of several elements; the wind tunnel shell, the propulsion system including a speed control unit, and a system of sensors and their associated electronics that record the model orientation with respect to the air stream, and the forces and moments acting on the model. Additional recorded data includes both the tunnel total and static pressure and total or static temperature. These data is used to compute the dynamic pressure, the Mach number, speed of sound, the tunnel velocity, and the Reynolds number.

MODEL CHARACTERISTICS

MODEL SIZE

The maximum model size is dependent upon the type of testing. In the case of aerodynamic vehicles the model should have a maximum cross section area of about three to five per cent of the tunnel cross section area, or from about 1.65 square feet to 2.95 square feet. The latter area should also include the frontal area of the aircraft at the maximum angle of attack. To reduce the wind tunnel wall upwash at the tip to a negligibly small level, the model's wing span should be five feet or less. In any case the wing span should not exceed six and a half to seven feet.

Other types of testing, such as aerodynamic loads on buildings, estimation of pedestrian level winds, and the like, the models can be up to ten per cent blockage, as are many automotive tests. The test designer for other tests such as those related to athletic performances may choose larger blockage areas, recognizing the a loss of accuracy might be encountered.

MODEL RIGGING

It is important to design the model such that the horizontal axis can be measured when the model is mounted in the wind tunnel. In addition, it is often desirable to make a pitch run with the model inverted. (The intersection of a plot of the lift coefficient upright versus angle of attack, and the inverted model versus the negative angle of attack provides a measure of the wind tunnel flow angle.) If an inverted run is anticipated, leveling sites will be needed on the bottom of the model, too.

If angle of roll or angle of yaw are important parameters in your test matrix, be sure your model design includes a reference points to allow these important angles to be set or measured accurately.

MODEL DESIGN

As mentioned above the maximum model blocking frontal area should be less that 2.95 square feet. As noted above, while the a better choice of wing span is five feet or less, the maximum wing span should exceed not six and a half or so.

In most cases the model should be designed for at least two times the expected maximum static load. A design load of three times the maximum expected load is better than two. In most cases the maximum pitching or yawing moment is not a critical design parameter;

BUT CHECK IT OUT NUMERICALLY; DON'T JUST ASSUME THIS PART OF THE LOAD CAN BE NEGLECTED!

To estimate the maximum load, guess at maximum the dynamic pressure, q. To do this recall that q is about 25.4 psf at 100 miles per hour, and that q changes as the square of ratio of your velocity to 100 mph.

After the model is constructed it should be loaded to 95% of the maximum design load to insure the model was constructed as designed.

Finally, if you have several model configurations to test, practice assembling and disassembling your model prior to you wind tunnel entry.

Nothing will have a greater adverse impact on you schedule than a model failure during test.

PRESSURE MODELS

The primary difference between a pressure model and a force and moment model is the pressure taps and the channels in the model for pressure lines or wires from imbedded transducers. If you are planning to conduct a pressure test discuss the location of the static pressure taps with your advisor. The pressure taps should be flush with the surface, deburred without rounding the edge of the hole. The pressure tap diameter is usually between 1/16 inch and at most 1/8 inch for large models. Pressure models are more complicated to build because of the need to provide a passage for the tubes connecting the pressure taps to the pressure transducers. Unless the model is very simple, pressure tests require models that are too complex to be satisfactory student projects.

BALANCE CALIBRATION

In many test programs, the fundamental goal is to determine the forces and moments acting on a model. These are measured using either a wind tunnel balance installed in the wind tunnel, or external strain gauge balances, or a special purpose balance made for your test. The balance is an instrument that resolves the force and moment vectors acting on the model into forces and moments in a rectangular wind axis coordinate system. In the Wright Brothers Wind Tunnel lift is usually positive upwards, normal to the wind tunnel longitudinal axis, (more or less normal to the wind direction), drag is positive aft along the wind tunnel axis (more or less along the wind direction), and side force is normal to the plane defined by lift and drag and completes a right handed coordinate system. (On occasion floor mounted half-span wing models are tested. In this case lift is in the direction of side force). Note the model weight is negative along the lift axis for non half-span models in the Wright Brothers Wind Tunnel. The balance system also converts these force and moment components into voltages. (The wind tunnel data system converts these voltage back into forces and moments.)

The process that relates these vector components to output voltages is called calibration. In this process a special apparatus, called the calibration apparatus, is mounted to the balance at the point where the force and moment vectors are resolved into components. This point is called the balance resolving center.

The calibration apparatus enables force and moment components to be applied to the balance and as such allows the calibrator to define a mathematical model that will convert the voltages back into forces and moments.

CALIBRATION PROCESS

Usually the calibration process falls in the category of a 'Factorial Design of Experiments'. For each test block, one variable is changed over its entire range, which the others are fixed. For the next block the initial variable is fixed, and another variable is changed over its range, and so forth. This leads to a large number of test blocks (actual 6 factorial or 720 blocks). Thus the process exceedingly tedious and time consuming process. Usually several shortcuts or truncations are made in the process. These truncations are based upon the assumption the balance is reasonably well designed and built so many of the interactions can approximated with far fewer blocks.

A detailed example for one degree of freedom is given below. The example will be a lift calibration. Suppose the lift loads vary from -50 pounds to plus 150 pounds. For ease of operation select 20-pound intervals but **include zero**, too. Be sure to record not only the lift output voltage, but also the other five components; drag, side force pitching, rolling and yawing moments. Be sure to note the excitation voltage setting.

The non-lift components are important for precise measurements. They are a measure of the imperfections in the actual construction and assembly process of the balance. Rarely are these extra data negligible.

NOTICE

BEFORE APPLYING A LOAD TO THE CALIBRATION APPARATUS; INSURE THE LOAD CELLS CURRENTLY INSTALLED IN THE BALANCE HAVE A LOAD RANGE THAT EXCEEDS YOUR CALIBRATION LOAD RANGE

EXAMPLE

Lift Calibration consisting of five loading blocks, -50 to 150 pounds range, with a 20 pound increment.

Block I Lift load only

Step 1. Record the output for zero applied loads. Record data after the data on the computer screen is steady, with the exception of a dither in the last place.
Step 2. Carefully locate -50 pounds of lift load on the calibration apparatus. Damp out any swinging motion by lightly touching the load perpendicular to the load direction. Record the data after the data on the computer screen becomes steady, except for a dither in the last significant place. Carefully remove the -50 pounds.
Step 3. Carefully place -30 pounds of weights on the apparatus and then repeat Step 2.
Step 4. Repeat Step 3, using -10 pounds of weights.
Step 5. Repeat Step 3, with zero load.
Step 6. Repeat Step 3 using +10 pounds of weights Steps 7 to 13. Repeat Step 3. using 30, 50, 70, 90, 110, 130 and 150 pounds of weight, respectively
Steps 14 to 26. Repeat Steps 13 through 1 by removing weights.
Step 27. Repeat Step 1.
Steps 28 to 54 Repeat Steps 1 through 27.

Block II Lift load plus a mean drag load on the drag loading apparatus.
Repeat Steps 1 through 54 above.

Block III Lift load plus mean drag and mean pitching moment loads.
Repeat Steps 1 through 54 above

Block IV Lift load plus mean pitching moment load.
Repeat Steps 1 through 54 above.

Block V Lift load only Repeat Block I.

Note that this loading plan does not call for a complete set of loads to determine the cross coupling terms in comparison with a strict Factorial Loading Pattern which requires all combinations of drag and pitching moment loads. The reduction is practical because the balance is designed to minimize the cross coupling effects.

Note the calibration of the force and moment balance is the one operation in which you, the user, control the accuracy of your data. You should strive to keep the standard deviation of your calibration to less than one part in one thousand. This is essential if you are aiming at an over all standard deviation of you data between five parts in one thousand and ten parts in one thousand. Reaching this goal requires care in handling and hanging the weights.

DATA REDUCTION

Average each load point in Blocks I - V; there will be 12 average load points of 4 readings each. Call out the overall maximum and minimum, or extreme deviation from all the means of each block. Compare this maximum deviation with the initial and final zero values for each Block. The difference between these two readings should not exceed the over all extremes.

If the difference between the first zero reading in Block I and the last zero reading in Block V exceeds the limit defined above, then plot all the values of the zero reading against time. Linearly curve fit to determine if a sensible drift occurs. If such a drift occurs the interpolate the average for each loading condition as a function of time and correct them accordingly.

Compare each load point average in Bocks I and V, including the five cross coupling terms, i.e. drag output for each lift loading, pitching moment output due to lift loading, side force due to lift loading, etc, with the extreme maximum and minimum described above. If the Block I and Block V cross couplings lie within the extremes, assume the average for them. These are the initial values for the cross coupling terms from these two blocks.

Next, fit the best mean square straight line to the average lift output from Blocks I V and compute the standard deviation. The standard deviation should be less than one Dart in ten to the fourth.

Then divide cross coupling data in Blocks II, III, and IV by the magnitude of the secondary load, and compared with the same cross coupling data in Blocks I and V.

If these data fall within the extremes cited above, fit a straight line to the average cross coupling between the two drag and pitching moment levels.

The first column in a six by six matrix has been defined by the calibration process. If this process is repeated for the other five components, a 6 by 6 calibration matrix is defined. If the proposed test is requires measuring six components, three additional blocks, VI, VII and VIII will be needed to include an applied rolling moment, side force and yawing moment. These additional loads slightly enlarge the data reduction process.

In use, the output voltage for each component (a column matrix), is premultipled by the inverse of the calibration matrix to provide the component force and moment data.

OPERATIONAL PLANNING AND EXECUTION

TEST MATRIX

A "Test Matrix" is really an outline of the steps you plan to take while your test is in process. Thus the first step in preparing the test matrix is writing your test objective. This is a statement your goal, or the hypothesis you wish to test, and a description of the data you will need to accomplish your task. After this statement has been written, the test matrix is prepared.

The test matrix is a table of the step changes for the primary and secondary independent variables. It is developed from a "Run Schedule". A truncated run schedule is listed below.

Run Schedule

Run Number	Velocity	Configuration	Angle of Attack	Comment
1	50 mph	Wing alone	-5	
2	"	"	0	
3	"	"	5	
4	"	"	10	
5	"	"	5	
6	"	"	0	
7-12	75 mph	"		{same angles of attack
13 -18	100 mph	"		as in runs 1-6}
19 - 37		Wing plus Flap		same as runs 1 - 18

The Test Matrix takes the form below

Sample TEST MATRIX

For each Configuration (Wing alone; Wing with Flap)

Velocity\Angle of Attack (degrees)

50mph	5	0	5	10	5	0
75mph	5	0	5	10	5	0
100mph	5	0	5	10	5	0

(As a wild guess, if all is going smoothly, this sample test would take about a half day. Usually the first day's accomplishments are substantially less than suggested above).

EXECUTING THE PLAN

During the actual testing process, keeping a test log is **ABSOLUTELY ESSENTIAL**. The test log resembles the Run Schedule but without truncation. The test log also includes additional data like the test room air temperature, the barometric pressure, the tunnel air temperature, the date and time, as well as configuration, run number and comments. Some of this information is included in the data stream from the computer, but most test conductors like to have this information in the log. The comments column is the place to note observations on unexpected events; like a change in tunnel sound, need for a rerun if the data looks unusual, etc. Keep in mind the Run Schedule is not a blue print cast in iron, but is a guide. The test log is an accurate summary of the events **as they occur** during the test. The test log is invaluable for resolving ambiguities that are noted when the final report is written.

Prior to executing the test, it extremely helpful to carry out some first order approximate calculations of the data to provide some comfort that the data is reasonable, as the test is being conducted.

Note that the weight of a model at angle of attack contributes only to the lift load in a wind axis system, but contributes to both the normal force and axial force in a body axis coordinate system.

Data Reduction and Presentation

Data is more useful and valuable if it can be expressed in dimensionless form. The choice of dimensionless variables, and in some cases, the scales on the abscissa and coordinate should be discussed with your advisor.

Usually the force and moment data are reduced to non-dimensional form by dividing the, force data by the dynamic pressure, 'q', and the characteristic area,'S'; the pitching moment data is divided by q, S and a characteristic length, c which is usually the airfoil chord for wings and for missiles and projectiles the reference length on the maximum body diameter.

If your test involves lift and drag coefficients, there are some recommended standard ~ graphical scales that help the interpretation of the data. For example, when plotting lift l~! coefficient as a function of angle of attack the length for a change of 8 degrees in angle of attack should be the same length for a 0.4 change in lift coefficient. Here the angle of attack is the abscissa and lift coefficient is the ordinate.

The length for a drag polar are 0.004 in drag coefficient is the same as 0.4 in lift coefficient. Similarly - 0.1 in pitching moment coefficient corresponds to 0.4 in lift coefficient. Both these curves can be plotted on the same graph, with lift coefficient as the abscissa and both the drag coefficient and the pitching moment coefficient on the ordinate. Some airplane companies interchange the abscissa and the ordinate.

GENERAL REMARKS ON AIRFLOW

Flow Properties

The flow uniformity is determined by measurement of dynamic pressure and flow angle over several planes normal to the tunnel centerline. Figure 2 (Ref 1) shows the distribution of the ratio of the local dynamic pressure to the set pressure in the plane of the balance. The iso-q ratio lines are shown, together a few recent measurements.   This data suggests the velocity distribution a comparable to newer tunnels Figure 3,(Ref 2) Figure 4, (Ref 3) shows the flow angle is acceptably small, but that there is a slight swirl that will appear as an off set on rolling moment data.

The fundamental aerodynamic property that characterizes any wind tunnel test is the dynamic pressure. It is one of the key variables in non-dimensionalizing the data and is ǀa defined quantity.

The dynamic pressure q, is defined as

$$q = \frac{1}{2}\rho_\infty V_\infty^2 \tag{1}$$

which is identical with

$$q = \frac{\gamma}{2}p_\infty M_\infty^2$$

Where

$$M_\infty^2 = \frac{2}{\gamma - 1}\left\{\left(1 + \frac{p_T - p_\infty}{p_\infty}\right)^{\frac{\gamma-1}{\gamma}} - 1\right\} \tag{2}$$

Equation 2 is preferred because it automatically includes the effect of compressibility on q.

Since no instrument is ideal, the data is distributed about a mean. Figure 5 shows the one standard deviation of q as a function of tunnel speed. Note this is the absolute value of standard deviation, not a percentage. The standard deviation of q is about three times the standard deviation of the instrumentation used to determine q and as such is quite reliable. The peak value of the standard deviation that occurs around 80 mph, about 0.06 psf, is due to unknown tunnel phenomena.

A hot wire anemometer is used to characterize the unsteady or fluctuating velocity level in the WBWT. When the fluctuations are more or less random, the unsteadiness is called turbulence. The turbulence level is defined by the root-mean-square velocity fluctuation level divided by the mean tunnel velocity. In the WBWT the turbulence level is about 0.5 percent, independent the tunnel speed setting (Ref 4 and 5). This level has a negligible effect on the data for most tests.

Figures 6, 7, and 8 show the ratio of the turbulent energy to the root mean velocity squared as a function of the log of frequency for three cases.

The first is with the power on and the fan running at 440 rpm but at zero pitch, so the wind tunnel velocity is zero. The second is for the tunnel running at about 50 mph at the same fan speed, while the third is at a wind tunnel speed of about 70 mph and a fan speed of 558 rpm.

The 440 rpm peak occurs at log n of 0.865 or at a frequency of 7.33 Hz. The peak at 7.1 Hz is indistinguishable from the 440 rpm peak, within the accuracy of the data. This frequency seems match a wave traveling around the circuit at the local speed of sound. It is surprising that the fundamental longitudinal mode does not compare with the rotational speed since the fan is six bladed. (The six bladed fan frequency should lead to 44 Hz).The 63 Hz frequency seems to correspond to the fundamental radial acoustic mode based on the geometric mean diameter between the fan and the stilling section screen. However, we lack data to positively identify this mode.

Tunnel Wall Effects

The flow around a model in a wind tunnel differs from that in free air due effects can be described in three categories; horizontal buoyancy, flow blocking, and trailing vortex constraints. The effects of the first two categories are estimated when the model is at zero degree angle of attack.

Horizontal buoyancy results from a pressure gradient along the flow direction due to tunnel geometry and boundary layer growth, or are self induced. These effects are negligible in the Wright Brothers Wind Tunnel as long as the desired accuracy for an aerodynamic coefficient is roughly one-half percent or larger.

Flow blockage causes in change in the effective tunnel speed. Solid blockage is a consequence of the volume displacement of the model, and its distribution. Wake blockage is a consequence of the displacement of fluid by the non -uniform flow in the wake. The static pressure reference used to determine tunnel speed is located approximately at the plane of maximum model area cross section, rather than upstream as is common. Thus the tunnel speed setting includes the blockage corrections to a good approximation.

The trailing vorticity from a lifting model is constrained from following it's desired trajectory by the image downwash caused by tunnel floor and walls. The correction for this effect is based upon a calculation of the downwash from image vorticity under the assumption the lift is correct, but the angle of attack is slightly small. The side wash is assumed to be negligible

Thus,
$$\Delta \alpha = \delta (\frac{S}{C})(c_L)(57.3)$$
and

$$\Delta c_D = \delta (\frac{S}{C})C_L^2$$
where C = 55.00 square feet
        S = model wing area

The value of delta can be estimated from Figure 10.3, p385 of Reference 2; with lambda = 0.7 and k = model span/10 feet.

For more details see Barlow, Ref 2, Chapter 10 sections 7 and 8.

References

1. Genn, S; Flow Behavior in the Wright Brothers Facility; Report WBWT – TR=1187 MIT Sept 1983.

2. Barlow, Jewel, Rae, William H. jr., and Pope, Alan; Low Speed Wind Tunnel Testing, John Wiley, New York, 1999

3. D'Angelo, Michael and Durgin, Frank H,; The Measurement of Static and Dynamic Flow Angles; with and without an upstream wing; Report WBWT - TR- 1243; Dec 1987

4. Lazar, Drahumir, Response of Pressure Probes to Longitudinal and Lateral Turbulent Fluctuations in Isotropic Turbulence; MIT SM Thesis submitted to the Department of Aeronautics and Astronautics, June 1979.

FIGURE 1
WRIGHT BROTHERS
WIND TUNNEL

OWNER	FACILITY NAME	DATE BUILT	COUNTRY	TEST SECTION		WALLS Open, perforated, slotted, acoustic, adaptive	SPEED, MACH
				Nb	Dimensions X,Y,Z,ø O		
M.I.T.	Wright Brothers Memorial Tunnel	1938	USA		7'x10' ellipse 15' long	closed	see chart

STAGNATION		REYNOLDS Nb $0,1 \sqrt{\ } s$	RUN DURATION	CIRCUIT Return single	POWER SUPPLY	
Pressure	Temperature				POWER	Type (fan, compressor, HP)
$\frac{1}{4}$ to 2 atmos	~100° F or less	~2.5 x 10^6	unlimited	single return	1000HP	fan

EQUIPMENT		TYPE OF TEST			SCHEME OF THE CIRCUIT, PERFORMANCE DIAGRAM
Hp air supply pressure 4.8,1.8,0.5,.07 #/sec		Aero	X		
Hp air supply mass flow 3,60,100,2000 psi 800 cfs to 4psi vacuum		Ground transportation	X		
Sting holder	X	Building	X		
Wall balance and turret	X	Lateral & longitudinal gust gen.	X		
Ground effect type	--				
(belt, suction, blowing)	--				
acoustic treatment	--				
DATA ACQUISITION Automatic - 48 channels		COMPUTER Ultra			
PLANNED IMPROVEMENTS					

10/18/94

FIGURE 2
FLOW DISTRIBUTION AT
TRUNION PLANE

Contours of Constant Pressure Coefficient Cp_n''
TUNCAL Phase of Test, Facing Upstream
Wind speed   50 mph

$\dfrac{q_{LOCAL}}{q_{SET}}$

LINES – GENN'S DATA
POINTS   9/0.0   DATA
FULL SCREEN

□ A
O B
△ C

| Less than 0.5% from mean. | 1.0 to 1.5% from mean. |
| 0.5 to 1.0% from mean. | 1.5 to 2.0% from mean. |

FIGURE 4

Downstream Flow Angularity with Clean Tunnel

Inches from tunnel centerline - looking downstream

FIGURE 5A

Downstream Flow Angularity with Clean Tunnel

FIGURE 5B

FIGURE 6
REPEATABILITY OF
DYNAMIC PRESSURE

ENVELOPE

0.2% LINE

I.S.

σ — STANDARD DEVIATION OF "q" psf

VELOCITY mph
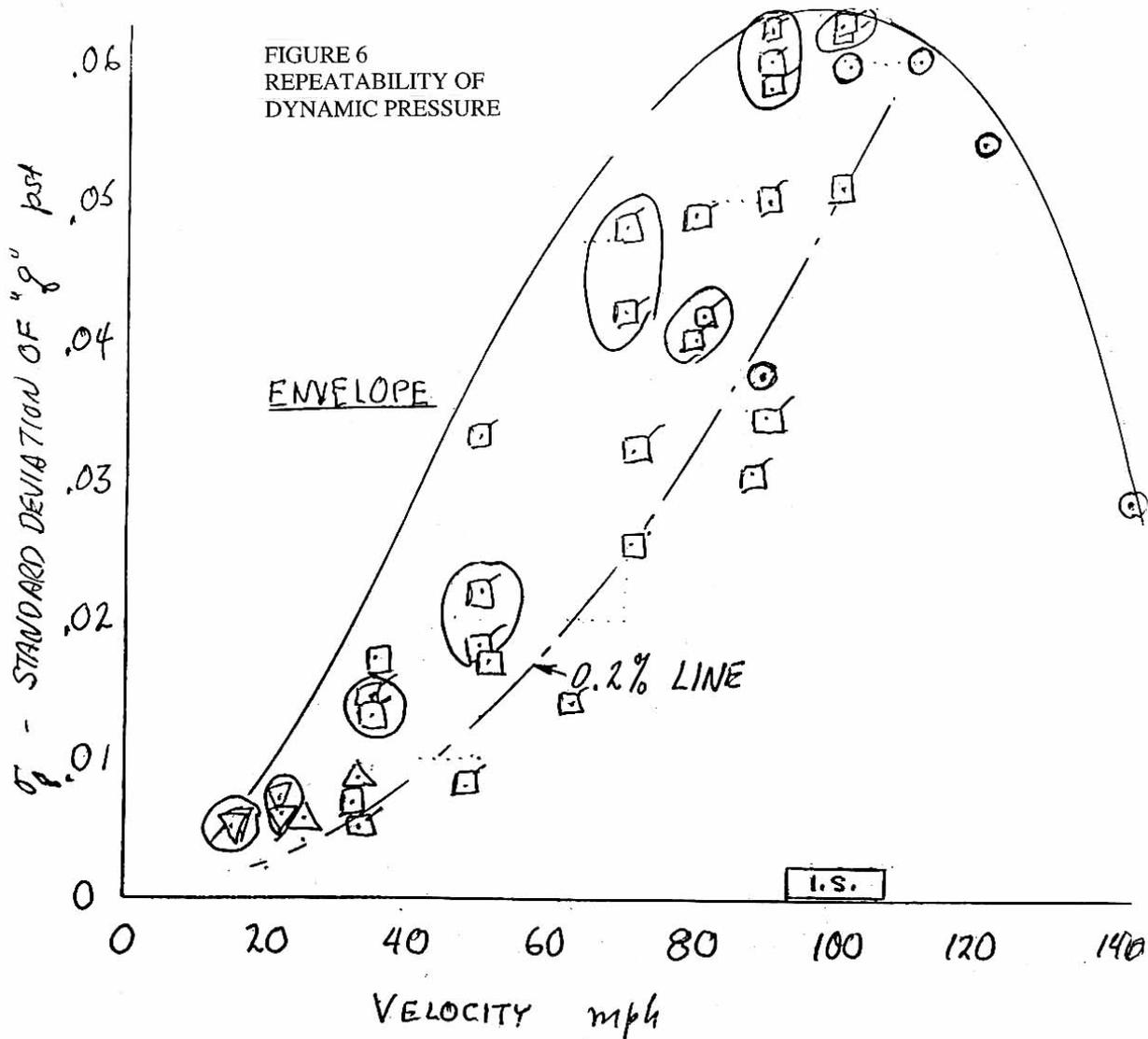
CIRCLED POINTS
ARE REPEAT POINTS

		LIMIT
O	2nd SPEED,	EXCITATION 1.0 VOLT
⬠	2nd SPEED,	EXCITATION 0.1 VOLT
□	1st SPEED	" "
△	1st SPEED	EXCITATION 0.01 VOLT
▽	2nd SPEED	" "

FIGURE 7

RUN 12A

NOISE SPECTRA

IIIC, NO GRID, FORWARD TUNNEL POSITION

U = 0 mph

PROPELLER RPM = 440

LOG
Q (Hz)$^{-1}$

O Q_P^M

+ Q_P^M

— Q_P^M / Q_P^M

LOG n (Hz)
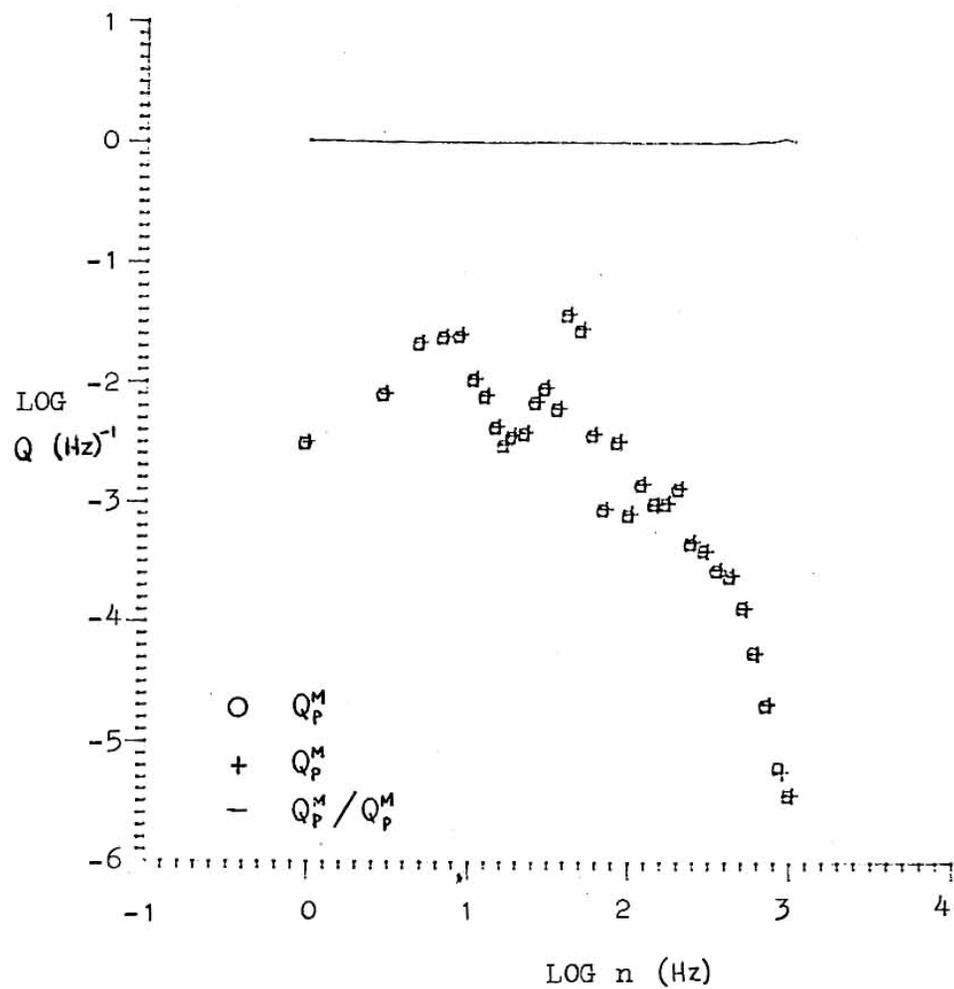
FIGURE 8

RUN 12B

NOISE SPECTRA

IIIC, NO GRID, FORWARD TUNNEL POSITION

U = 55.08 mph

log 440 = 2.64
ln 43 = 1.8   9 log .85 7.07 = .85
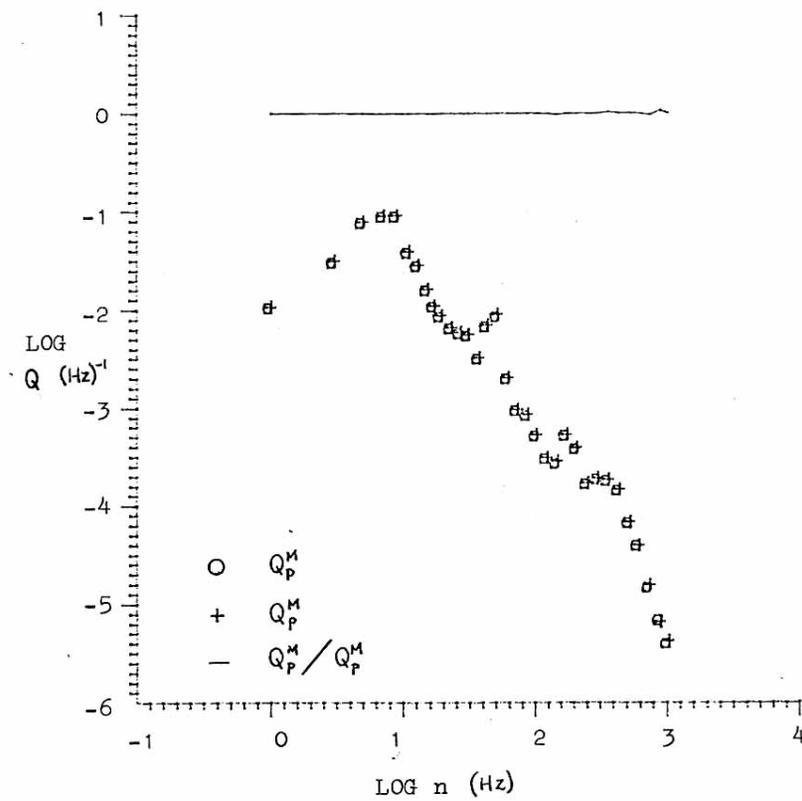
FIGURE 9

RUN 12C

NOISE SPECTRA

IIIC, NO GRID, FORWARD TUNNEL POSITION

U = 70.10 mph

LOG Q $(Hz)^{-1}$

O Q_P^M

+ Q_P^M

— Q_P^M / Q_P^M

LOG n (Hz)
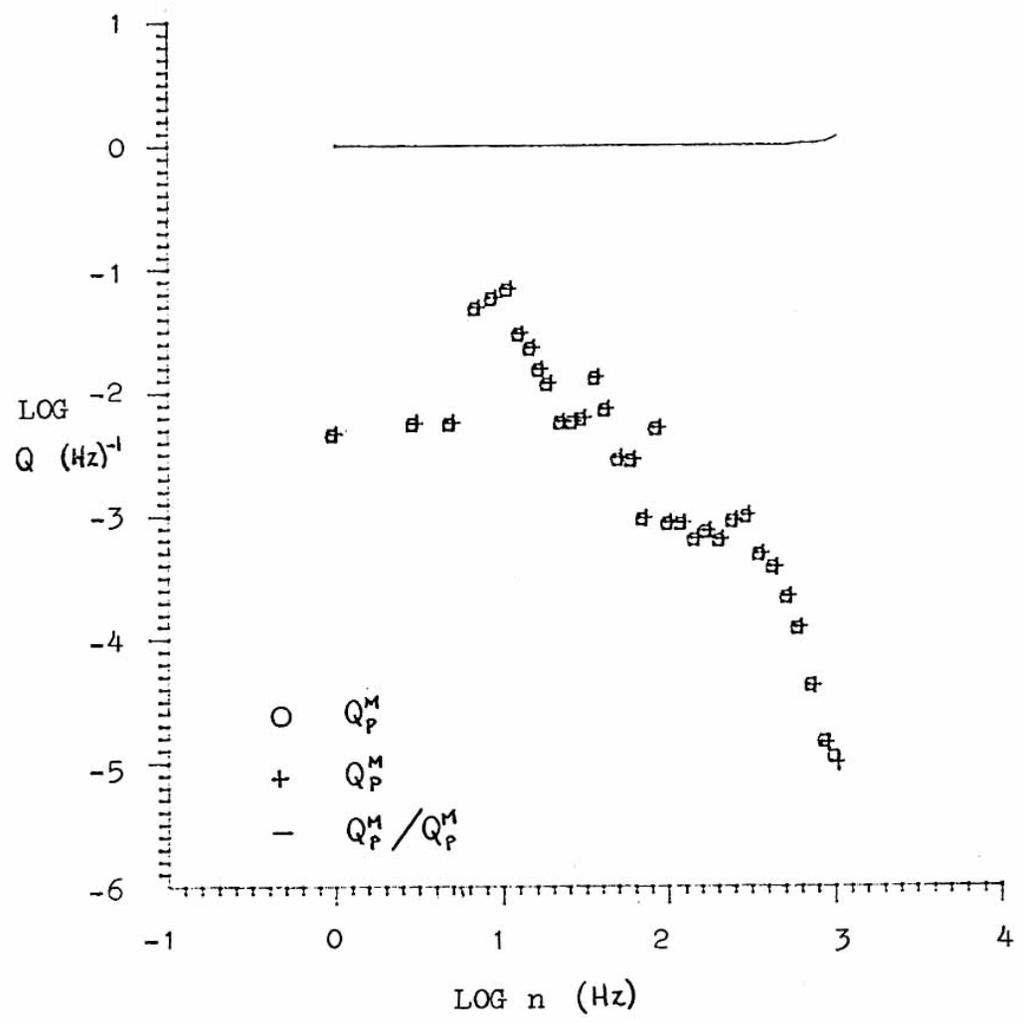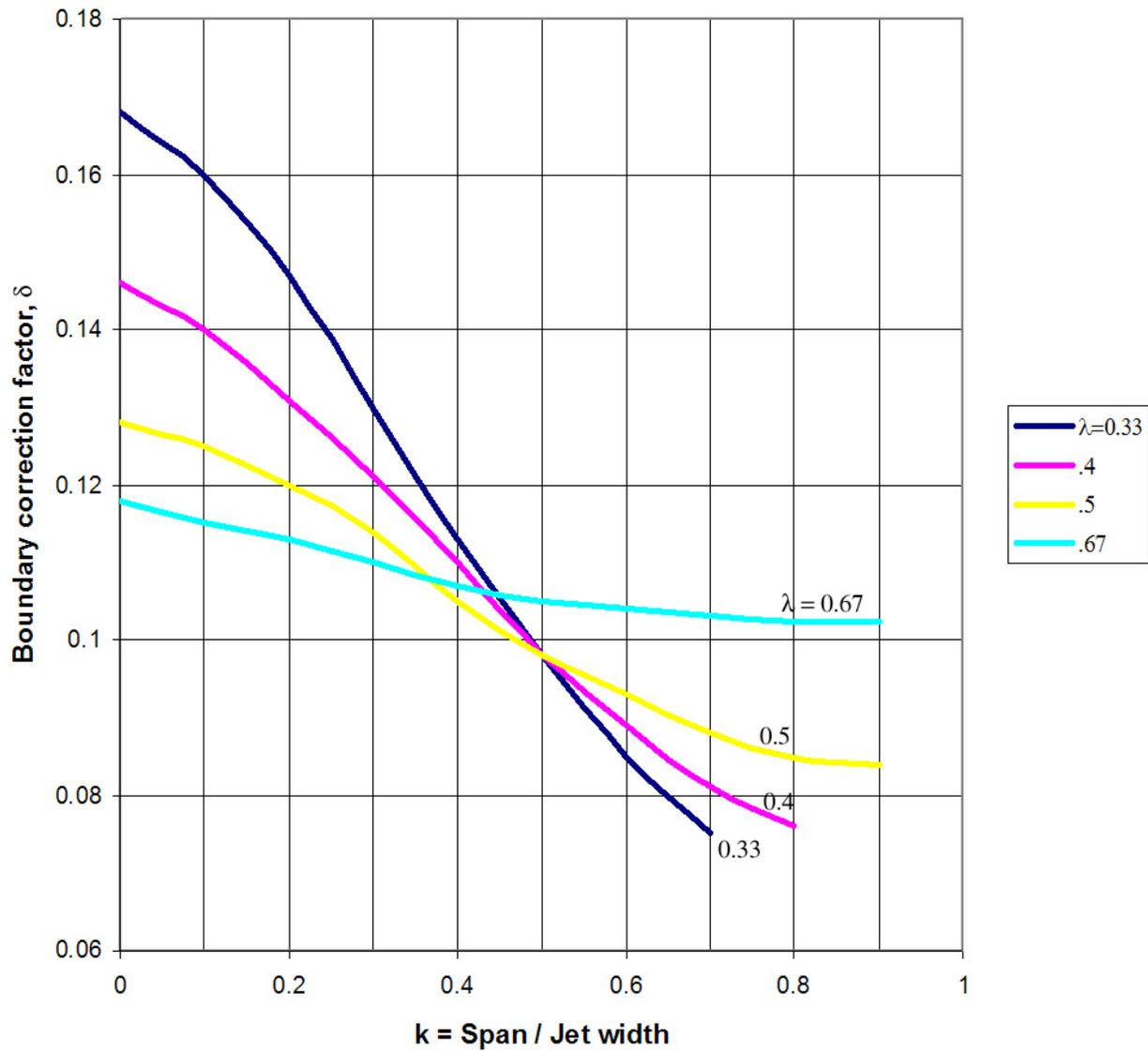
Values of δ for a wing with elliptical loading in a closed elliptic jet