The F-14 Wind Tunnel Experiment

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Introduction

The purpose of testing an aircraft model in the wind tunnel is to help the engineer to predict what some of the aerodynamic characteristics of the full scale aircraft will be in flight. The type of aerodynamic characteristics that can be predicted are those concerned with steady-state or static flight conditions. These include force and moment changes with angle-of-attack and sideslip angle, and control deflections. Hence we can get information such as lift-curve slope, static stability parameters, and control effectiveness from the data.

Obtaining the required data is a non-trivial task requiring care and precision. Generally there are three ingredients which must be considered: the wind tunnel, the force and moment balance, and the model. The wind tunnel must be calibrated to that the flow angularity as well as the velocity distribution throughout the test section is known. Furthermore the test section pressure, temperature and speed must be recorded accurately for the test results to be meaningful. The balance must be calibrated and checked for accuracy before each test. In addition, the balance must be mounted in the model so that no interference occurs causing erroneous readings. The model itself must be scaled appropriately from the full scale aircraft and preferably have moveable controls and removable appendages. The latter are required to perform so-called build-up tests where the effects of different appendages on the overall aircraft stability can be assessed. For example in the F-5 aircraft it was found that at high angle-of-attack, the nose section was the prime contributor to lateral stability of the aircraft and that removing the vertical tail had little effect. Such insight could not be obtained by testing only the complete aircraft.

Preliminary

Before starting the tests, several preliminary investigations must be done. Most of these investigations will have been completed by the time your group does the experiment, but some must be repeated each time. In any case you should be familiar with what is required, regardless if you or someone else had to complete the work.

Calibrating the Tunnel

The test section should be calibrated, any velocity irregularities identified and any flow angularities noted. This particular wind tunnel has a very low turbulence level of approximately 0.1% and a variation of dynamic pressure of approximately 0.05% across the test section. Vertical flow angularity has been measured to be approximately ± 1 degree through the vertical sweep of the test section. At the middle, it is less than 0.25 degrees and will be ignored in this experiment.

Measuring the speed of the wind tunnel can be done in several ways, a pitot-static tube mounted in the test section, or by measuring the pressure drop across the contraction nozzle at the entrance to the test section. It is left for an exercise for the student to show that the pressure drop across the contraction section is proportional to the pressure drop across the pitot-static tube mounted in the test section which in turn is related to the airspeed in the wind tunnel. In this experiment we will use the pitot-static tube mounted in the test section.

The balance calibration and sign check must be examined prior to the first experimental runs. With the balance mounted in the wind tunnel, and the model mounted on the balance, and all data acquisition equipment ready to go, preliminary checks must be made on the balance to insure that the right excitation voltage is being used with the correct polarity. In addition the calibration constants used in the data acquisition and reduction program must be verified to be correct, and further, the data acquisition system must be checked for proper behavior and to ensure no balance-model interference is occurring.

Sign and Calibration Check

The balance should be installed and the polarity of the power supply checked such that a force aft is positive (axial), a force up is positive (normal), and a force toward the right wing is positive (side force). These three forces should be applied gently by hand to the model one at-a-time and the sign of the output checked to see if it is positive (reading loaded - reading unloaded > 0). If you could supply a dummy signal to the velocity or dynamic pressure data channel, the data acquisition system could be cycled to compute the appropriate “force coefficients,” which should all be positive. Once completed, a 10 lb. Weight should be positioned to excite each force individually by setting it on top of the aircraft, arrange it with a pulley so that it pulls on the front (or rear), and arrange it with a pulley to pull out the right wing. Cycle the data acquisition system each time and determine if the force measured is in the neighborhood of 10 lbs. Note that here again a dummy signal must be sent to the dynamic pressure sensor so that division by zero does not occur in the usual data conversion procedures.

A sign check for moments must also be made. Here two hands are required to provide an approximately pure moment. The balance sign convention is such that positive roll, pitch, and yaw moments are: right wing down, nose up, and nose right respectively. These can be checked in a similar manner as described for the forces previously. Actually providing a moment for a calibration check is more difficult and is usually not done. It is assumed that if the forces check out properly, the power supply etc. are correct for the moments.

After all calibration tests, the zero or unloaded reading should be checked to see if it is the same as when the tests were started. A shifting zero reading is an indication of some serious problems in your experimental setup (for example - loose bolts, balance interference, and others).

Model measurements

In order to reduce the data and make corrections for blockage and other effects, it is necessary to know certain dimensions of the model. (Note that when a test-section-mounted pitot

-static tube is used to measure the test section dynamic pressure, blockage corrections are usually not necessary). The required dimensions for reducing the data include the planform area of the wing (or some specified reference area), the wing span (or some specified lateral reference length), and the wing mean aerodynamic chord (or some longitudinal reference length). In addition to these dimensions, simplified blockage corrections can be made if the planform area, the frontal area, and the profile area of the complete model are known.

In addition to these physical measurements other definitions must be made. These definitions include the desired aerodynamic reference center about which the moments are defined and the reference line from which the angle-of-attack is measured. Both of these quantities are free for you to chose, but must be defined. Generally by the time you receive the model, someone else has defined these references.

The final measurement that must be determined is the location of the balance center with respect to the aerodynamic reference center. In general there may be an X and Z displacement, but not usually a Y displacement. Once these offsets are known, the data referenced to the balance center can be converted to data referenced to the aerodynamic reference center.

Longitudinal Tests

Longitudinal tests usually consist of determining the effects of angle-of-attack change on the various aerodynamic characteristics of the aircraft. Consequently these tests consist of measuring aerodynamic forces and moments at angles-of-attack from some negative values to values beyond stall in small increments of 2 or 5 degrees. Here we will use two degree increments. These “alpha sweeps” as they are called, may be done for several different configurations of the aircraft. The important data obtained will be the lift, drag, and pitch-moment values which when reduced, lead to the respective coefficients. Of interest then is determining the lift-curve slope, the drag polar, and the longitudinal stability parameter, the pitch-moment slope.

Once these calculations are made, if one assumes a parabolic drag polar, an additional calculation can be made to find the zero-lift drag coefficient and the induced drag coefficient which gives a least squares fit to the data for the control-fixed drag polar. The results of these calculations can be plotted over the actual drag polar and compared.

Lateral-Directional Tests

Lateral-directional tests may be easy, difficult or impossible to do, depending upon the wind tunnel set-up. At the present time, they are impossible. By this statement we mean that the sting mount does not have the capability to yaw, precluding doing sideslip angle sweeps. Furthermore, this particular mount does not have the capability to roll the model. If it did, by including the proper roll angles with selected pitch angles, it would be possible, although somewhat painful, to get the angles-of-attack and sideslip angle combinations that you need to calculate the sideforce slope and the lateral and directional stability derivatives. The desired relationships can be determined using simple coordinated transformations and for now is left as an exercise for the student.

In these measurements, the important forces and moments are the sideforce, the rolling and yawing moments. Of interest is how the corresponding coefficients change with the sideslip angle, β. The rolling moment change with β is the dihedral effect, while the yawing moment behavior with β is the weathercock stability parameter. Again, these sweeps should be done for all configurations.

General

The experiment we are going to do here does not fall in the realm of a standard wind tunnel test. Due to circumstances beyond our control, we have an asymmetric wind tunnel model. In particular, we have a wind tunnel model of an F-14 with its variable sweep wings fixed with one in the forward position and the other in the mid-sweep position. We are interested here in determining the aerodynamic characteristics of an aircraft whose wing-sweep mechanism had a malfunction in flight. As a result, the usual longitudinal tests, which for symmetric aircraft produce little out-of symmetric-plane forces and moments, will now have possibly significant non-symmetric forces and moment components.

Problem

The F14 aircraft is designed to operate with a swing-wing. The wing is swept to its forward position of low speed flight and landing, and is moved to its aft position for high speed flight. An intermediate position is available for maneuvering flight. The problem that may be encountered during flight is the possibility of a wing-sweep mechanism failure causing only one wing to sweep to the desired position while the other remains fixed in its original position. It is likely that the aircraft can fly in this mode provided the controls are powerful enough to balance the asymmetric forces and moments that are caused by such a configuration. The critical case is the approach-to-landing where the speeds are the lowest and the angle-of-attack the highest. Your job as an engineer is to determine the aerodynamic characteristics of this asymmetrically configured vehicle.

The F-14 Wind Tunnel Experiment

This experiment consists of three parts: 1) taking data, 2) reducing data, and 3) interpreting the results.

Taking Data

General:

Here we will describe the general procedure for taking data, and subsequently we will describe the data to be taken and the overall procedure. Data is to be taken using the Labview software and is stored on disk. The data actually measured are just voltages associated with the various data channels. The code is capable of converting these voltages to values of the physical variables of interest (pressures, temperatures, forces and moments). This conversion is done through calibration factors , (voltage x calibration factor = value). It is expected that the data stored on the disk will be the physical values of tunnel speed, temperature, atmospheric pressure, forces, and moments. The final calculations will be done by the student to get the appropriate coefficients of interest.

For each angle-of-attack and configuration it is necessary to take both wind-off (tare) readings and wind-on readings. The most accurate way to do this is to take wind off readings at one angle of attack, and then take wind-on readings at the same angle of attack. When the tunnel is turned off the readings should return to the wind-off readings. If they don't there is a problem. Often times, to save time and wear and tear on the wind tunnel motors, the wind-off readings can be taken all at once. That is, set up the configuration of interest and take and wind-off reading at each angle-of-attack of interest. These are stored in the computer. Then the wind tunnel is turned on, and all the wind-on readings are taken at each corresponding angle of attack. Even in this case, after the tests are run, there should be some spot checks on the wind-off values to see that they haven't changed. These type of checks are essential to insure there are not problems with the model-balance interface, and with the data acquisition system in general. (To repeat: For more accuracy, wind-off and wind-on readings should be taken alternately at a given angle-of-attack before moving on to the next one. However, with care, a wind-off angle-of-attack sweep followed by a wind-on sweep as we do here can be accurate).

Experiment Information and Procedures:

The details of the experimental procedure are presented next. These include a description of the equipment, and its use in obtaining the required data. The information is given in a step by step sequence. Some of these steps may already be done prior to your group doing the experiment. In any case these are the sequence of events that must be completed by somebody even if it isn't your group.

Set-up

1. Mount the F14 aircraft model on the Stability Wind Tunnel sting mount using the STO1, six component, internal strain gage balance.

2. By setting the data acquisition system to record one channel at a time, check the sign convention of the balance by manually applying a force or moment to the model along or about the axis of interest. Verify that positive loads cause positive readings (reading with load - reading without load > 0). Also verify that the unloaded reading is the same after the load has been applied and released to the unloaded reading before the load had been applied. If a difference occurs, then the test cannot proceed since something is wrong!

3. Select a vehicle configuration to test, and remove or add parts to put the plane in this configuration. At least two configurations must be examined:

    1) Full configuration
    2) Full configuration with the horizontal tail removed

Other configurations that can be examined if you have time are:

    3) Full configuration with horizontal and vertical tail removed
    4) Full configuration with one wing removed (H and V tail attached)
    5) Fuselage only
    6) Other

4. Obtain data for each configuration selected (a minimum of two). The data is obtained using a high speed PC with a high speed data acquisition card and software. Custom software has been written for this experiment that gives the user more control and understanding of the data acquisition process. The following is a list of equipment used to perform the data acquisition operation:

- Data acquisition card: National Instruments AT-MIO 16-X
  16 different channels without multiplexing, Max sample rate at 25,000 hz
- Multiplexer: National Instruments AMUX-64, 32 differential channels, 64 single
- Data acquisition software: National Instruments Labview 4.0

The procedure for running the software is as follows: (Note that the two data acquisition “virtual instruments” or Vis as they ae called in Labview should already be loaded and running before the lab begins. If not, the two Vis to load are “uglab.vi” and ugplot.vi”

a. Enter file paths and NAMES for the storage of the Tare (wind-off) and Wind-on voltage readings in the boxes at the bottom of the “uglab” vi. The default values are okay, but MUST BE CHANGED when the next configuration (e.g. no horizontal tail) is tested, otherwise the data will be overwritten.

b. Set the “Number of Channels” to 9, the “Sample Rate” to 100, and the “Samples” to 1000.

c. Set the “Tunnel Status” switch to read “WIND OFF.”

d. Set the angle-of-attack to the desired value (-6.00 deg for first reading).

e. Once the model is set at the corresponding angle-of-attack, click the “Run” (looks like an arrow) button in the upper left corner of the vi.

f. The vi will take voltage readings for 10 seconds, average the results, and write them to the “Tare” file specified previously.

g. Increment the “Angle of Attack” Up 2 deg and repeat until an angle of 20 deg. is reached.

h. Now, AFTER ALL OF THE TARE RUNS ARE COMPLETED, switch the “Tunnel Status” switch to “WIND ON”, and RESET THE ANGLE-OF-ATTACK” to - 6.00 Deg!

i. Now, in the vi that is open to the RIGHT of “uglab,” is the vi named “ugplot.” Enter the SAME file paths and names into the “Tare” and “Wind ON” Data file name entry boxes as in “uglab.” Also enter file names and path for the final “Reduced Data” (the force and moment coefficients), and the final “Force Data” (the actual forces and moments).

j. Reset the F-14 model to -6.00 deg. And run “uglab” as before. MAKE SURE that you enter the same values for the “Angle-of-Attack” as during the tare runs.

k. Now, IN BETWEEN each angle increment, you MAY “Run” the VI “ugplot” which will plot the resultant coefficients on the graph. DO NOT try to run “ugplot” while “uglab” is acquiring data!

l. ONCE 20 deg. “Angle-of-Attack” has been reached and the data stored, turn ON the switch in”ugplot” labeled “WRITE DATA.” This action will write the final output data to the files specified.

m. You should now see a completed plot of the data acquired, and it should have been written to the specified files. Now, from the “Rile” menu of “ugplot,” select “Print Window.” This action will print the entire front display of “ugplot,” including the graph and the calibration constants.

n. Now, to do the next configuration, repeat the same steps as above, BUT, enter DIFFERENT FILE NAMES, or the program will try to OVERWRITE the previous data!

o. Copy all the acquired data onto your floppy disk, because it WILL be erased after the lab. Also, copy the file “column.txt” located in the c:\uglab\data directory. This file contains the specifications for what quantities are in which column of each data file.

p. THE END.

Note: Remember, the file name entry boxes in “uglab” and “ugplot” MUST have the same entries for the Tare and Wind On dat file names!!!

5. Recheck the wind-off reading at the lowest angle of attack (-6.00 deg) and at the highest angle-of-attack (20.0 deg) to verify that the zero readings repeat. If they don’t (within some small tolerance), repeat the entire experiment. This returning to the zero reading requirement is very important, otherwise you have nothing!

6. Set up new configuration and repeat step 4 again until all configurations desired are tested.

Reducing Data

The data taken must be converted to physical variables (if not already converted in the program), corrected for known errors, and put in a form useful for presentation. Here the data is taken in balance-fixed axes. That is, the forces are measured in the axial direction (positive along the negative x axis), normal direction (positive along the negative z axis, and side-force (positive along the positive y axis). The moments are positive around the x, y, and z axes, (right wing down, nose up, and nose right). Consequently we must convert these forces and moments to the aerodynamic reference center of the aircraft and to the usual lift drag and side-force.

Balance to Wind Forces

We can convert from balance axes to wind axes forces by using a coordinate transformation. It is essentially the same as the transformation from body-fixed axes to wind axes. The transformation consists of two rotations, the first about the y^b axis an amount $-\alpha$, to an intermediate axes set, say the “1" set, then about the z^1 axis an amount β, to the wind axes. Since in this case we have no sideslip angle, we simply have the angle-of-attack transformation. This can be written as:

$$\begin{Bmatrix} -\mathrm{D} \\ Y_A \\ -\mathrm{L} \end{Bmatrix}^{w} = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{Bmatrix} -Axial \\ Y_A \\ -Normal \end{Bmatrix}^{bal}$$

or

$$\begin{aligned} \text{Lift} &= Normal \cdot \cos\alpha - Axial \cdot \sin\alpha \\ \text{Drag} &= Normal \cdot \sin\alpha + Axial \cdot \cos\alpha \\ \text{Side} &= Side \end{aligned}$$

Moment Reference Point Corrections

The balance reference is the point on the balance to which all moments are referenced. Ideally the balance should be mounted in the model so that its reference point will correspond to the reference point of the aircraft (usually the cg of the actual aircraft, not the cg of the model). Since we generally don't know where the cg. will be in the aircraft, we designate the reference point the aircraft aerodynamic reference location. However due to size restrictions, it was impossible to mount the balance so that the two reference points coincided. Hence it is necessary to transfer the moments measured with respect to the balance reference point to the reference point of the aircraft. In this case, the balance reference point is four inches behind the aircraft (model) aerodynamic reference location so that we must correct the moments measured for the balance "offset." Here we will define the balance offset in the x direction with the following convention: x_{cg} is positive if the cg. or aerodynamic reference center is in front of the balance. This correction is as follows: (L = roll-moment, M = pitch-moment, and N = yaw-moment):

$$\begin{aligned} L_{\text{aero ref}} &= L_{bal} \\ M_{\text{aero ref}} &= M_{bal} - x_{cg} \cdot Normal \\ &= M_{bal} - x_{cg} \cdot \left[\text{Lift} \cdot \cos\alpha + \text{Drag} \cdot \sin\alpha \right] \\ N_{\text{aero ref}} &= N_{bal} - x_{cg} \cdot \text{Side} \end{aligned}$$

All these forces and moments must be converted to aerodynamic coefficient form. The forces and moments are converted using:

$$C_F = \frac{F}{\frac{1}{2}\rho V^2 S} \qquad C_m = \frac{M}{\frac{1}{2} rhp\, V^2 S \bar{c}} \qquad C_{l,n} = \frac{L,N}{\frac{1}{2}\rho V^2 S b}$$

where the geometry of the model required is:

Area S - 1.167 ft.^{2}
Mean Aerodynamic Chord $\bar{c}$ = 0.4450 ft.
Wing Span, b = 2.830 ft.
x_{cg} = 0.3333 ft.

Data Presentation and Analysis

Presentation

Generally the most convenient way to present wind-tunnel data is by graphs. Consequently, ***for each configuration tested***, graphs should be made of the following variables.

Plot all six aerodynamic coefficient values vs angle-of attack. Normally, for sideslip equal to zero, only the longitudinal variables would be of interest (lift, drag, and pitch moment). Here, however, since we have asymmetric sweep, the lateral directional variables will necessarily be zero (side force, roll- and yaw-moment). Generally graphs of the same variable for all configurations are plotted in the same figure. For example, the lift coefficient vs angle-of-attack for all the configurations would be on the same graph.

Analysis

Your job, as an engineer is to see if the curves make sense, and to explain the differences for the different configurations. There are two main points of interest here: 1) the effect of angle-of-attack changes for any given configuration, and the effect of changing configurations, such as removing the horizontal tail on all of the longitudinal properties, and 2) the effect of asymmetric wing sweep on the lateral directional variables in general and for the different configurations. The following are the minimum features that should be discussed:

1) Longitudinal variables

a. The shape of the lift-curve as the angle-of-attack is increased
    Determine the stall angle-of-attack (if it occurs)
b. The lift curve slope for each configuration
    Estimate the lift-curve slope based on the wing shape using DATCOM methods, and discuss how it compares with the wind-tunnel test. Speculate on why they might be different (if they are).
c. The change in the lift-curve slope for different configurations
    Explain why the slopes are different
c-f. Repeat a, b, and c in an analogous way for pitch-moment, and drag.

g. For the full configuration, estimate (from the data) the static margin and the neutral point. (Note, the static margin is approximately ($d\,C_m/ d\,C_L$)). Assume the aircraft aerodynamic reference point is the mean aerodynamic quarter chord point

2) Lateral-Directional variables

a. The shape of the roll-moment curve as the angle-of-attack is increased
    You should be able to justify from your knowledge, the shapes observed, or at

least if they do not follow your expectations, provide some discussion.

b-c. The shape of the yaw moment and side-force curve as angle-of-attack is increased One would expect the side-force to be small. Verify this. Justify the shape of the yaw-moment curve

d. Determine if the horizontal tail is a significant contributor to these asymmetric forces and moments. For this to be true, the asymmetric wing deflections would have to cause significantly different flow over the tail. Select a particular set of data that you could use to answer this question, then answer it.

Feel free to use your analytic powers and curiosity to extend your discussion to other items that you may have observed.