STATIC AND DYNAMIC FORCE/MOMENT MEASUREMENTS IN THE EIDETICS WATER TUNNEL

by

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Water tunnels have been utilized in one form or another to explore fluid mechanics and aerodynamics phenomena since the days of Leonardo da Vinci. Water tunnel testing is attractive because of the relatively low cost and quick turn-around time to perform flow visualization experiments and evaluate the results. The principal limitation of a water tunnel is that the low flow speed, which provides for detailed visualization, also results in very small hydrodynamic (aerodynamic) forces on the model, which, in the past, have proven to be difficult to measure accurately. However, the advent of semi-conductor strain gage technology and devices associated with data acquisition such as low-noise amplifiers, electronic filters, and digital recording have made accurate measurements of very low strain levels feasible.

The principal objective of this research effort was to develop a multi-component strain gage balance to measure forces and moments on models tested in flow visualization water tunnels. A balance was designed that allows measuring normal and side forces, and pitching, yawing and rolling moments (no axial force). The balance mounts internally in the model and is used in a manner typical of wind tunnel balances. The key differences between a water tunnel balance and a wind tunnel balance are the requirement for very high sensitivity since the loads are very low (typical normal force is 0.2 lbs), the need for water proofing the gage elements, and the small size required to fit into typical water tunnel models.

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This paper summarizes results of force/moment (F/M) measurements conducted in a water tunnel with a 5-component internal balance. The importance of having a balance that allows performing static and dynamic experiments in a water tunnel will be reviewed first. The requirements identified during these initial considerations dictate the specific technical objectives of the research program, which will be listed in detail. The most important features of the water tunnel balance will be described and the calibration procedures and results will be briefly discussed.

The following sections contain descriptions of the experimental setup (facility and models) and of the methodologies used in both static and dynamic tests. Of special interest are the results of unique water tunnel dynamic experiments, such as the rotary balance tests. The balance was extensively tested during a wide variety of conditions, and examples of results from selected experiments will be presented to show the performance of the balance. The key findings of this project will be highlighted in the concluding remarks.

OUTLINE

- INTRODUCTION

- TECHNICAL OBJECTIVES

- BALANCE DESCRIPTION AND CALIBRATION

- EXPERIMENTAL SETUP AND METHODOLOGY

- FORCE/MOMENT MEASUREMENT RESULTS

    - STATIC TESTS

    - DYNAMIC TESTS IN PITCH

    - DYNAMIC TESTS IN YAW

    - DYNAMIC TESTS IN ROLL

    - ROTARY BALANCE TESTS

- CONCLUDING REMARKS

The development of a system to measure the small forces and moments generated in a water tunnel would increase the usefulness of this type of research facility significantly. If the water tunnel could determine forces and moments to some level of accuracy simultaneously with the flow visualization, the interpretation of results would be greatly simplified. Also, it would be possible to quantify the changes produced by configuration modifications, conventional and unconventional control techniques, etc. Knowledge of the cause and effect of the complex flows and resulting non-linear aerodynamics at high angles of attack requires the capability to correlate what we see with what we measure in terms of airframe loads.

In addition to static force and moment measurements, the water tunnel force/moment balance may also provide a capability for dynamic experiments. The high flow speed typical of wind tunnel tests requires rapid movement of the model in order to simulate a properly scaled dynamic maneuver and the motions are mechanically difficult to implement. The fast model movement also places demanding requirements on the response of the data acquisition system to acquire data at high sample rates. In contrast, the flow speed of water tunnel tests is typically much lower (2 orders of magnitude or more), and consequently, the model motion required to simulate a dynamic maneuver is also very slow. Thus, the response rates for data acquisition required for force and moment measurements during transient and dynamic situations are less demanding than in a wind tunnel.

INTRODUCTION

IMPORTANCE OF WATER TUNNEL BALANCE

- QUANTITATIVE DATA MAKES WATER TUNNEL TESTING MORE ATTRACTIVE

- FLOW VISUALIZATION AND FORCE MEASUREMENTS CAN BE CONDUCTED SIMULTANEOUSLY

- QUANTITATIVE DYNAMIC TESTS CAN BE PERFORMED, WITH THE ADVANTAGE THAT MODEL MOVEMENT RATES AND DATA ACQUISITION RESPONSE RATES ARE LESS DEMANDING THAN FOR WIND TUNNEL TESTS

The long-term goal of this project was to create and demonstrate a comprehensive test capability in the Eidetics water tunnel for static and dynamic tests including a complete and stand-alone force/moment data acquisition system. To accomplish this, the specific technical objectives were the following:

1. Design and build a 5-component force/moment balance compatible with Eidetics' water tunnel or similar.

2. Design and build a suitable calibration rig and related hardware and software to perform an accurate balance calibration, determining sensitivities and interactions.

3. Increase the test capability of the Eidetics' water tunnel model support system from two axes of motion (pitch and yaw) to three axes (including roll) and modify the model support drive control system to produce high-resolution motions in all three axes to acquire "dynamic" force and moment time-history data. Develop an apparatus for producing a "coning" motion, or a roll motion about the velocity vector with fixed angle of attack and sideslip, commonly performed in wind tunnel tests on a rotary-balance apparatus.

4. Develop the techniques and methodologies for conducting dynamic tests.

5. Perform static and dynamic force and moment measurements on "generic" configurations (delta wing) and on "full" configurations (F/A-18 models) to evaluate the performance of the balance.

6. Compare results to existing wind tunnel data, assessing similarities and/or differences between data.

TECHNICAL OBJECTIVES

1) DESIGN AND FABRICATE A FIVE-COMPONENT WATER TUNNEL BALANCE (NO AXIAL FORCE) .

2) CALIBRATE THE BALANCE, DETERMINING SENSITIVITIES AND INTERACTIONS

3) IMPROVE THE WATER TUNNEL MODEL SUPPORT TO ALLOW FOR PRECISE AND SMOOTH COMPUTERIZED MOTIONS

4) DEVELOP THE METHODOLOGY FOR PERFORMING DYNAMIC TESTS IN THE WATER TUNNEL, INCLUDING ROTARY BALANCE TESTS

5) CONDUCT STATIC AND DYNAMIC TESTS ON GENERIC CONFIGURATIONS (DELTA WINGS) AND ON FULL CONFIGURATIONS (F/A-18) TO EVALUATE THE PERFORMANCE OF THE BALANCE

6) COMPARE THE RESULTS OBTAINED WITH WIND TUNNEL DATA ON SIMILAR CONFIGURATIONS, ASSESSING SIMILARITIES AND/OR DIFFERENCES BETWEEN WATER AND WIND TUNNEL DATA

Basically, the balance is similar to the sting balances used in wind tunnel tests and is located inside the model. It consists of a rolling moment section, two pitching moment sections and two yawing moment sections, all 0.75 inches in diameter. Five components will provide for the simultaneous measurement of pitching, yawing and rolling moments and normal and side forces. The moment of inertia of each section was carefully calculated in order to obtain the required stress levels that produce the desired sensitivity and resolution when the balance is loaded in the plane of interest and maximum stiffness in the other planes.

Semi-conductor strain gages are used to get the desired output, since they have a gage factor (change of resistance with strain) that is 50 to 100 times larger than that of wire or foil strain gages. Each section is composed of four gages, connected using a full Wheatstone bridge, and of some standard resistors added externally. These resistors are used to compensate for differences in the strain gage resistance and to compensate for temperature changes. Temperature compensation for this application is not very critical since the temperature changes during a typical water tunnel test are almost negligible.

The fact that the balance has to operate under water complicates the problem significantly. After the gages, terminals and wires were in place, a thin layer of microcrystalline wax was applied over the gages and terminals. The wax is an excellent water barrier, but since it is quite fragile, is not very good for mechanical protection. In order to protect the strain gages and to seal all of the wire/terminal connections, layers of RTV (silicon rubber) were applied over the wax, covering the entire area where the gages and terminals are located. A rubber sleeve was utilized as a secondary protection.

BALANCE DESCRIPTION

- BALANCE CONSISTS OF SEPARATE COMPONENTS TO ENSURE FLEXIBILITY AND SIMPLICITY

    - 1 ROLLING MOMENT SECTION

    - 2 PITCHING MOMENT SECTIONS

    - 2 YAWING MOMENT SECTIONS

    - DIMENSIONS: 3/4" DIAMETER
                       5" LONG

- SEMI-CONDUCTOR STRAIN GAUGES ARE USED TO ENSURE MAXIMUM SENSITIVITY

    GAUGE FACTOR = 145 (50-100 TIMES LARGER THAN FOIL GAGES)

- GAUGES AND TERMINALS ARE WATER-PROOFED AND A RUBBER SLEEVE IS USED AS A SECONDARY PROTECTION

A key to accurately acquiring data from a force/moment balance is a precise and repeatable calibration. For a multi-component balance, it is important to determine the response of each section to a load in its primary plane of action (sensitivity) and also to loads in other planes (interactions). A simple calibration apparatus, shown in the photograph, was designed and built to calibrate the 5-component balance.

A full calibration was performed using the calibration rig and standard procedures typical of wind tunnel sting balances. The balance was loaded at five load points with positive and negative normal and side forces, and at the balance reference center (LP3) with positive and negative rolling moments. After all the loading cases were completed, the slopes of the output of each channel at the different load points were plotted versus the distance to said load points. The first plot shows the response of the pitching moment gages to an applied pitching moment. The slopes of the lines are the sensitivity to pitching moment, while the y-intercepts are the sensitivity of these channels to a normal force. Similarly, the sensitivity of the yawing moment gages to an applied yawing moment was obtained.

The rolling moment calibration is presented in the other plot. The output at the gages in Volts is plotted versus moment for the five channels. The response of the rolling moment component (CH 2) is linear, both for the positive and negative cases. The slope of this line represents the sensitivity of the section to rolling moment, and the interactions with the other gauges are negligible. In general, all the interactions were found to be very small.

BALANCE CALIBRATION
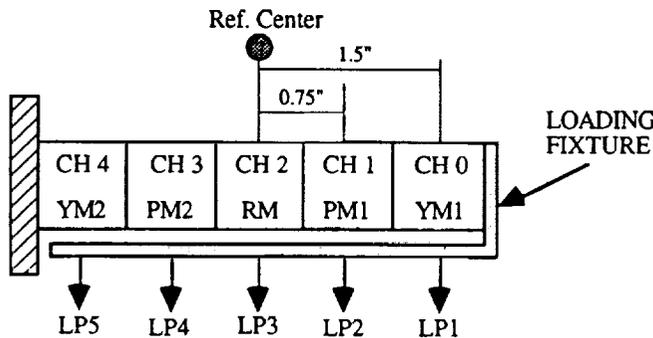
PITCHING MOMENT SENSITIVITY
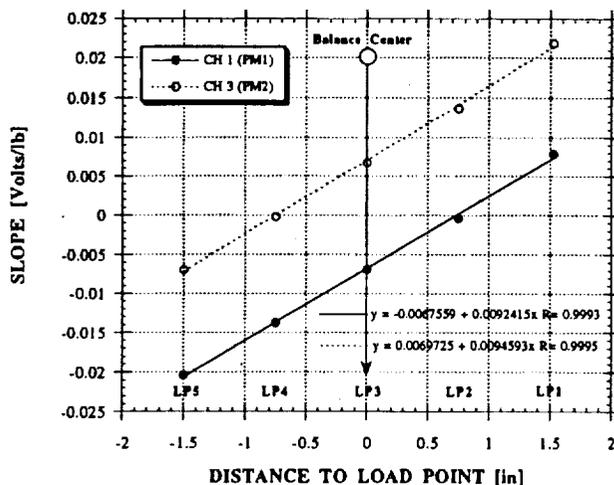
ROLLING MOMENT SENSITIVITY
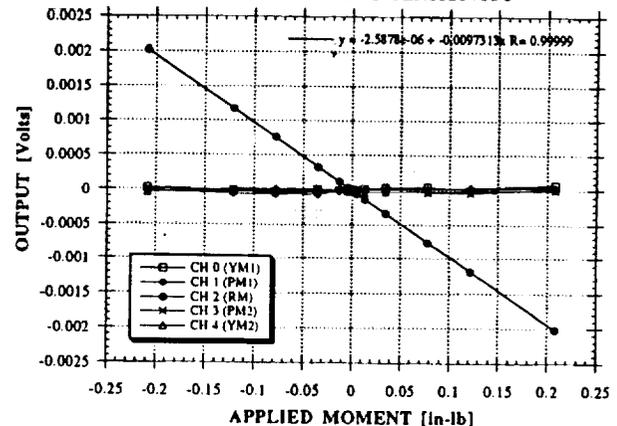
All experiments were conducted in the Eidetics Model 2436 Flow Visualization Water Tunnel. The facility is a continuous horizontal flow tunnel with a test section 3 ft high x 2 ft wide x 6 ft long.

A 70° flat plate delta wing was used for these experiments. The extensive wind tunnel test data base on delta wings provided enough material for comparison. The aluminum delta wing has a root chord of 15 inches and a double-beveled leading edge. The balance is located at the model centerline and two fiberglass fairings (top and bottom) covered the entire balance.

Additional static and dynamic experiments were performed on a 1/32nd-scale F/A-18 model. The reason for choosing the F/A-18 was also the availability of data from several wind tunnel tests on this configuration that could be used for direct comparison to evaluate the performance of the balance. The plastic model is equipped with dye ports for flow visualization and the balance is attached to an internal aluminum plate. Control surfaces were fixed at 0° throughout the entire test (leading edge flaps were fixed at 34°).

The rotary balance experiments were performed on a 1/48th-scale F/A-18 due to size constraints in the water tunnel. The width of the test section (24 inches) did not allow the use of the 1/32nd-scale F/A-18 model utilized for the other dynamic experiments. The smaller plastic model has a span of 10 inches and a total length of 14 inches. Moments are referenced to the 50% c̄ on the delta wing and to the 25% c̄ on the F/A-18 models, except when indicated.

EXPERIMENTAL SETUP

- EIDETICS 2' x 3' WATER TUNNEL

- MODELS

  - 70° DELTA WING (STATIC AND DYNAMIC TESTS)
  - 1/32nd-SCALE F/A-18 (STATIC AND DYNAMIC TESTS)
  - 1/48th-SCALE F/A-18 (ROTARY BALANCE TESTS)

70° DELTA WING   1/32nd-Scale F/A-18
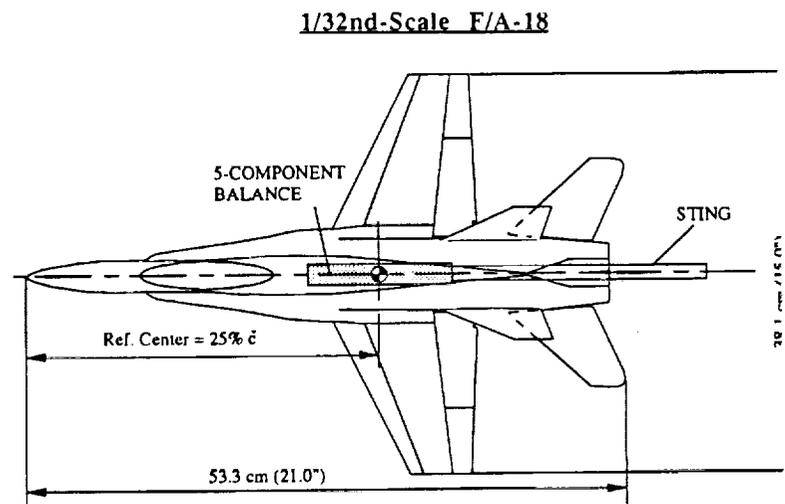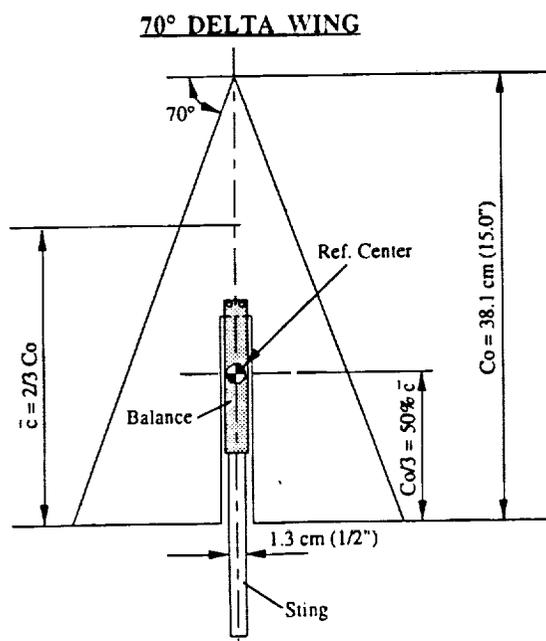
1/48th-Scale F/A-18
b = 10", L = 14"

The static tests were performed following standard "wind tunnel procedures". The gages were zeroed at the beginning of each run with the model at $\alpha = \beta = \phi = 0°$. A static tare (or weight tare) was performed before the actual run. This consists of an angle of attack sweep with the tunnel off ($q_\infty = 0$) to account for gravity effects. After that, the model is always returned to $\alpha = 0°$, a zero point is taken and the tunnel is started.

The water tunnel data were corrected only at high angles of attack. This correction is required as a result of a significant expansion of the wake when the wing stalls and it was developed by Cunningham (Ref. 1). It is a semi-empirical relationship based only on planform blockage and α.

The data acquisition/reduction software was developed specifically for this application using National Instrument's LabView, a graphical programming language. The basic methodology for the data reduction system, particularly the treatment of the balance equations, is based on the same approach used for typical wind tunnel data reduction schemes. The data acquisition/reduction software allows to perform a full balance calibration, as well as to acquire and reduce data during static and dynamic experiments. It allows the user to display "on-line" signals, acquire data at specified sampling rates and to reduce the data to coefficient form. Files with raw and coefficient data are created and saved to a disk for later plotting or reprocessing. Static data were acquired at 100 samples/sec for 25 seconds (500 samples/channel) and were not filtered. The large number of samples acquired permitted to obtain a mean value that closely represents the average gage reading at the particular loading condition. The force/moment measurements were conducted at velocities ranging of 0.42 to 0.58 ft/sec, that correspond to Reynolds numbers from 34,000 to 47,000 per foot.

METHODOLOGY (STATIC TESTS)

- TESTS PERFORMED USING STANDARD WIND TUNNEL PROCEDURES

- A STATIC TARE ("WEIGHT" TARE) IS PERFORMED BEFORE RUNNING A NEW CONFIGURATION

- WATER TUNNEL DATA WERE CORRECTED ONLY AT HIGH ANGLES OF ATTACK. THE CORRECTION (REQUIRED AS A RESULT OF A SIGNIFICANT EXPANSION OF THE WAKE WHEN THE WING STALLS) IS SEMI-EMPIRICAL AND IS BASED ON PLANFORM BLOCKAGE AND ANGLE OF ATTACK

- CUSTOM DATA ACQUISITION/REDUCTION SYSTEM (LabView/MACINTOSH BASED)

- TEST PARAMETERS:

  - α RANGE = 0 to 60°

  - β RANGE = -20° to 20°

  - V_∞ = 0.42-0.58 ft/sec

  - Re = 34,000-47,000 per foot

The longitudinal characteristics of the 70° delta wing during static conditions are presented and compared to wind tunnel data in the top two plots. The water tunnel data (obtained at $V_\infty = 0.58$ ft/sec) are compared to similar data obtained in another water tunnel (Ref. 1), and in the KU 3x4' wind tunnel (Ref. 2), the WSU 7x10' wind tunnel (Ref. 3) and the Langley 12' wind tunnel (Ref. 4). The normal force coefficient agrees very well with most of the data, except for the Langley data. The differences between these data and the other wind tunnel data are quite significant and are probably due to the type of corrections applied, mounting system, flow quality, etc. Since the software provided the moments referenced to the 50% $\bar{c}$, the appropriate transformations had to be applied to obtain C_m at other locations. The pitching moment at 30% $\bar{c}$ is compared to two sets of wind tunnel data and the agreement is satisfactory.

Side force changes were observed during sideslip sweeps at constant angles of attack. These changes are due, in part, to the large fiberglass fairings that cover the balance and act like a body. Results compare very well to wind tunnel data from Ref. 5 at $\alpha = 10°$, where a delta wing with a similar fairing was tested. Changes in rolling moment with sideslip variations are as expected. The asymmetric vortices over the delta wing produce negative rolling moments with positive β and vice versa.

STATIC FORCE/MOMENT MEASUREMENTS
(70° DELTA WING MODEL)
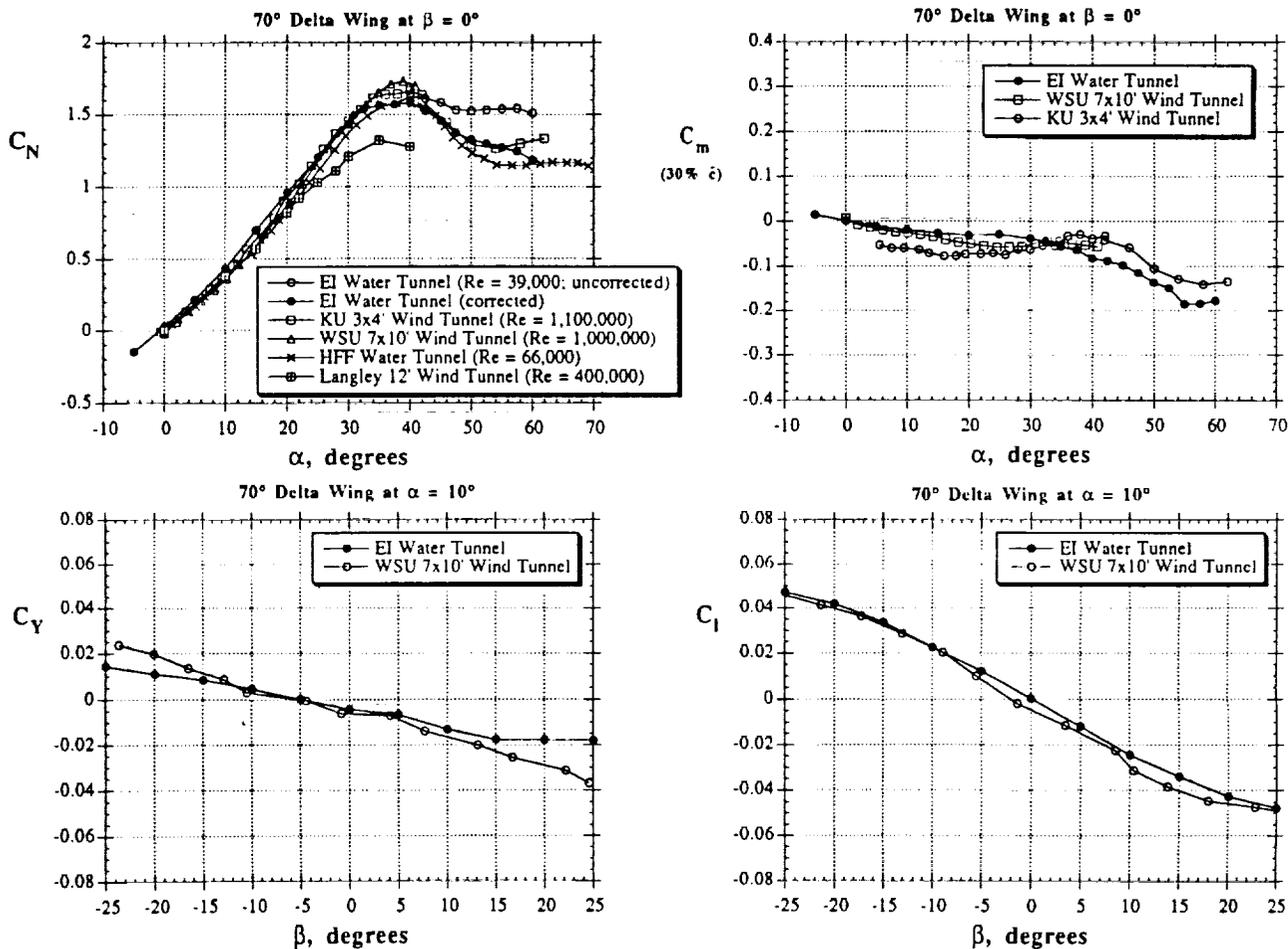
This figure shows a comparison between the water tunnel test and other wind tunnel tests for the baseline F/A-18. Angle of attack sweeps at $\beta = 0°$ were performed and the agreement in C_N is very good, both in slope and absolute magnitude. The data obtained in the water tunnel match not only other small-scale wind tunnel tests (Refs. 6-7 and 9), but the full-scale test at the NASA Ames 80x120' (Ref. 8) and the F/A-18 Aero Model used in simulation as well. Only one data set (Langley 12', Ref. 10) has much lower values than those obtained in this test. The pitching moment measurements also agree well with other data; small differences are seen between 45° and 55° angle of attack, but trends and slopes are very similar.

Lateral/directional characteristics were compared to data from Ref. 9, as seen in the bottom two plots, and similarities in the C_Y and C_l curves during β sweeps at $\alpha = 30°$ are evident. It should be noted that corrections due to wall proximity during sideslip sweeps were not introduced in the data reduction scheme, and therefore, small discrepancies can be expected. These comparisons show that the balance can be used effectively to measure five components of the forces and moments experienced by a "real" configuration (as opposed to "generic", as in the case of the delta wing) in this flow regime.

STATIC FORCE/MOMENT MEASUREMENTS
(F/A-18 MODEL)

F/A-18 at $\beta = 0°$

Legend:
- Water Tunnel (Re = 12,500; uncorrected)
- Water Tunnel (corrected)
- Ames 7x10' (Re = 650,000)
- DTRC 7x10' (Re = 1,200,000)
- Langley 12' (Re = 270,000)
- Ames 80x120' (Full Scale)
- F/A-18 Aero Model

F/A-18 at $\beta = 0°$

Legend:
- Water Tunnel (uncorrected)
- Water Tunnel (corrected)
- Ames 7x10' Wind Tunnel
- F/A-18 Aero Model

F/A-18 at $\alpha = 30°$

Legend:
- Water Tunnel ($\alpha = 30°$)
- DTRC 7x10' ($\alpha = 30°$)

F/A-18 at $\alpha = 30°$

Legend:
- Water Tunnel ($\alpha = 30°$)
- DTRC 7x10' ($\alpha = 30°$)

An example of the importance of having the capability of performing F/M measurements and flow visualization simultaneously is given by the particular flow field of the F/A-18 at high angles of attack. The yawing moment coefficient measured in the water tunnel agrees very well with wind tunnel data up to $\alpha = 50°$; at higher angles of attack, the water tunnel data show a much larger C_n, which could be due to a large forebody vortex asymmetry. The presence of the asymmetry is confirmed by the flow visualization. As the photographs show, the forebody vortex flow field is symmetric for angles of attack up to $\alpha = 50°$. At $\alpha = 55°$, however, the flow presents a strong left-vortex-high asymmetry that will produce a large positive or "nose-right" yawing moment. Sideslip variations (positive and negative β) at $\alpha = 55°$ indicated a significant hysteresis effect on the forebody asymmetry orientation and resulting yawing moments. The direction of the asymmetry at $\beta = 0°$ depends on the direction of the sideslip variation, thus providing a "bi-stable" behavior of the forebody vortices. This behavior was also observed in Ref. 11. At $\alpha = 60°$ the flow is still asymmetric, but the right forebody vortex has moved away from the body surface, therefore decreasing the asymmetry and the magnitude of the yawing moment.

The disagreement in the directional coefficients is not surprising considering that the forebody aerodynamics of this configuration is very sensitive to Reynolds number and to imperfections or perturbances (such as blowing ports) in the nose region.

STATIC F/M MEASUREMENTS AND FLOW VISUALIZATION
(F/A-18 MODEL)

F/A-18 at $\beta = 0°$

Legend:
- EI Water Tunnel
- Ames 7x10' Wind Tunnel

Y-axis: C_n, from -0.08 to 0.08
X-axis: α, degrees, from -10 to 70

Symmetric Vortices

$\alpha = 50°$

Left Vortex

Right Vortex

Asymmetric Vortices

$\alpha = 55°$
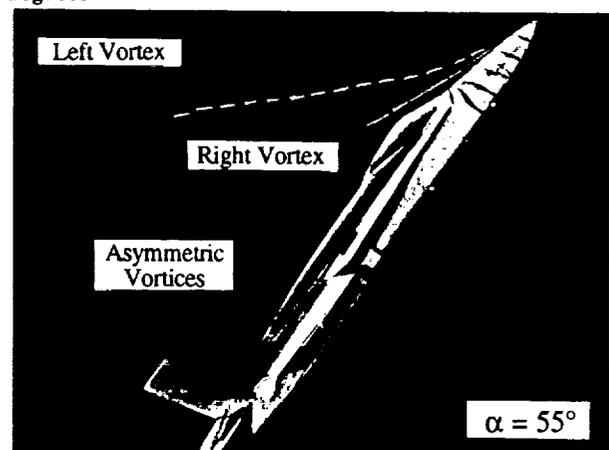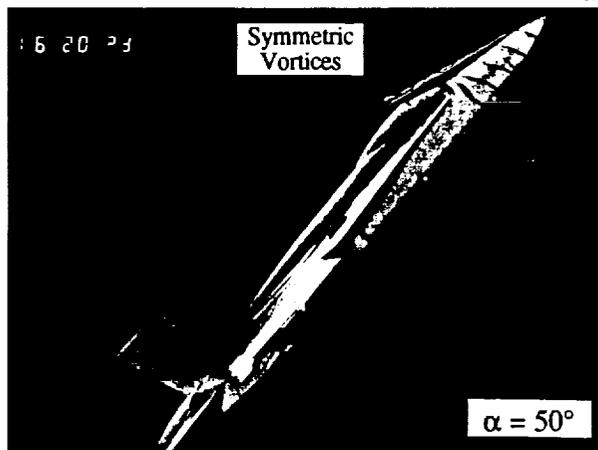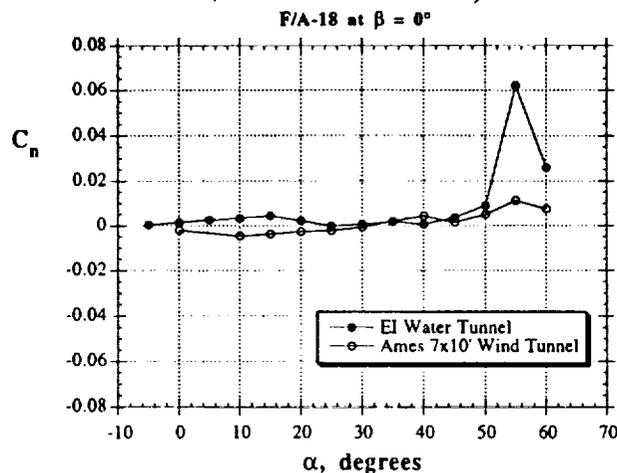
Some of the dynamic experiments conducted in this project, with the appropriate reduced rate parameter, are summarized in this table. The rates selected for experiments in the water tunnel should, of course, be scaled properly to represent the correct relationship between rotation rate, scale, and free stream velocity.

During the dynamic experiments, the data are corrected at high angles of attack with the same technique utilized during the static water tunnel experiments. The software handles the entire data acquisition and reduction processes, as well as the model motion. In order to correlate the F/M measurements with the model position, the software takes an encoder reading, then acquires the balance data, takes a second encoder reading and assigns the balance values to the average of the two encoder readings. The number of balance samples acquired between each encoder reading can be varied, and the final value for each channel is the arithmetic average of the samples taken. As expected, the larger the number of samples acquired, the better the quality of the data. It was found that by acquiring 800/1,000 per channel, the data obtained are very smooth and repeatable, requiring no post-processing or curve-fitting and clearly indicating the value of the force/moment at the particular model location. Since the A/D board used allows acquiring data very fast (10,000 samples per second), it was possible to take a large number of samples per channel and still obtain an adequate density of points (again, the low motion rates required in the water tunnel facilitate these experiments).

For the rotary balance tests, data were acquired and averaged over two revolutions to avoid excessive twisting of the cables (no slip-ring was used). A weight tare ($V_\infty = 0$), also averaged over exactly two revolutions, was performed at each angle of attack and subtracted from the "tunnel on" data.

METHODOLOGY (DYNAMIC TESTS)

- DYNAMIC TESTS INCLUDED:

Maneuver	Reduced Rate Parameter
PITCH-UP/PITCH-DOWN AND HOLD	$q_0 = \dfrac{q\,\bar{c}}{V_\infty}$
LARGE AMPLITUDE OSCILLATIONS IN PITCH, YAW AND ROLL	$k = \dfrac{\pi\,f\,\bar{c}}{V_\infty}$
ROTARY-BALANCE TESTS	$\Omega = \dfrac{\omega\,b}{2\,V_\infty}$

- DYNAMIC WATER TUNNEL DATA WERE CORRECTED USING THE SAME BOUNDARY CORRECTIONS AS IN THE STATIC TESTS

- A WEIGHT TARE IS PERFORMED BEFORE THE DYNAMIC MANEUVER

- FOR THE ROTARY BALANCE TESTS, DATA ARE AVERAGED OVER TWO REVOLUTIONS. A WEIGHT TARE ($V_\infty = 0$) IS PERFORMED AND DATA ARE ALSO AVERAGED OVER TWO REVOLUTIONS

- MOTION SOFTWARE IS ALSO LabView/MACINTOSH BASED

- DUE TO THE LOW ROTATION RATES, THE INERTIAL CONTRIBUTION TO FORCES AND MOMENTS WAS FOUND TO BE VERY SMALL, AS EXPECTED, AND DEPENDING ON THE ACCURACY OF THE DATA, THE INERTIAL TARES CAN BE NEGLECTED

One of the unknowns in dynamic water tunnel experiments was the model inertia effects on the data, i.e., the effect of the resistance to motion due to the model mass moment of inertia. Before actually performing the experiments, it was calculated that the inertia contribution to the aerodynamic values to be measured would be small, because of the low motion rates used in the water tunnel. The inertia effects are determined by measuring the time-variant moment recorded by the balance with the model in motion with the tunnel velocity at zero. This motion must be identical to the motion generated with the tunnel on ($V_\infty > 0$). The aerodynamic contribution is determined by subtracting the measured moment at $V_\infty = 0$ from the moment measured at $V_\infty > 0$.

Results indicate that the inertial contribution is, indeed, very small. The first plot in this figure shows the measured normal force on the 70° delta wing during a ramp-hold maneuver from 15° to 60° angle of attack. The value of the normal force N (lbs) measured during the pitch-up motion when the water tunnel is off ($V_\infty = 0$) is almost negligible, approximately 1% of the value measured with tunnel speed. Also included in this plot is the value of the normal force measured during the specified motion with no water in the tunnel. The value of N throughout the dynamic maneuver under the "no water" condition is very similar to the $V_\infty = 0$ case, indicating that there are no major "virtual mass effects" (resistance of the surrounding water to being displaced by the moving model). Similar results were obtained during pitch oscillations, both for the 70° delta wing and the F/A-18 models, and during the other dynamic experiments (yaw and roll oscillations, rotary balance tests). Therefore, depending on the quality of the data required, the inertia effects can be ignored, facilitating the testing and the data reduction process.

Fourth NASA High Alpha Conference

E I D E T I C S

EFFECT OF INERTIAL TARES ON DYNAMIC DATA

70° Delta Wing

PITCH UP AND HOLD
$\alpha = 15°$ to 60°
$q_0 = 0.0074$

RUN 234 ($V_\infty = 0.42$ ft/sec)
RUN 281 (NO WATER)
RUN 285 ($V_\infty = 0$ ft/sec)

70° Delta Wing

PITCH OSCILLATION
$k = 0.0376$
$\alpha_0 = 37°$
$\alpha = \alpha_0 \pm 18°$

RUN 251 ($V_\infty = 0.42$ ft/sec)
RUN 253 ($V_\infty = 0$ ft/sec)
RUN 263 (NO WATER)

F/A-18

PITCH OSCILLATION
$\alpha = 15°$ to 55°
$k = 0.04$

RUN 351 ($V_\infty = 0.42$ ft/sec)
RUN 380 ($V_\infty = 0$ ft/sec)
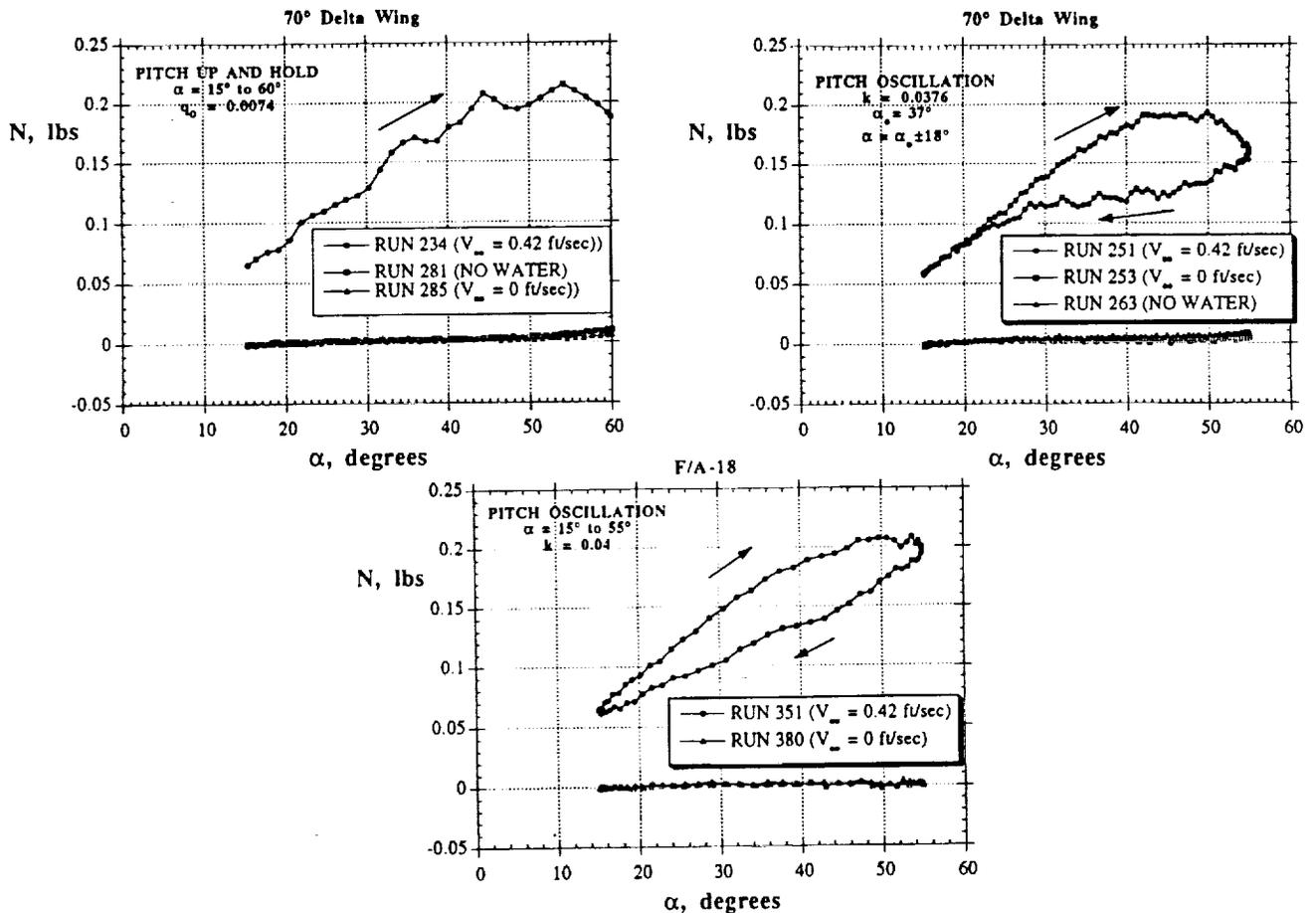
The first set of dynamic experiments consisted of large-amplitude pitch oscillations about a mean angle of attack α_0. The purpose of these tests was to directly compare the water tunnel data to results from wind tunnel tests conducted at NASA Langley by Brandon and Shaw, where a 70° wing was investigated for forces and moments produced by these large-amplitude pitch motions (Ref. 4). This figure presents changes in the normal force and pitching moment coefficients produced by oscillating the delta wing ±18° about different α_0's with a reduced frequency k = 0.0376. This k value corresponds to a maximum full-scale pitch rate of approximately 60 deg/sec for a typical fighter aircraft at altitude and at V_∞ = 200 ft/sec. The hysteresis loops are evident in the force measurements, with all the cases producing similar values of C_N overshoot. Results from the wind tunnel tests in Ref. 4 are shown in the plots at the right hand side and the similarities in the two data sets can be clearly identified. The level of C_N is slightly lower in the wind tunnel test, especially above 25°, but the shape of the dynamic loops and the relative increments are very similar in both tests. Even though the models in the two experiments rotated about a different reference point (50% $\bar{c}$ for the present investigation and 40% $\bar{c}$ for the wind tunnel test), the behavior of the pitching moment is very similar. As the angle of attack is increasing, the lag in the burst point of the vortex produces a destabilizing increment in C_m at high angles of attack. When the model reverses direction, a negative C_m increment is produced for the higher α_0 cases. This increment, produced by a lag in the flow reattachment, is very small for the α_0 = 22° and 27° cases; the dynamic C_m curves follow the static curve very closely. As in the normal force case, the size of the hysteresis loops in pitching moment increases as the mean angle α_0 increases.

DYNAMIC FORCE/MOMENT MEASUREMENTS
(PITCH OSCILLATIONS, 70° DELTA WING MODEL)
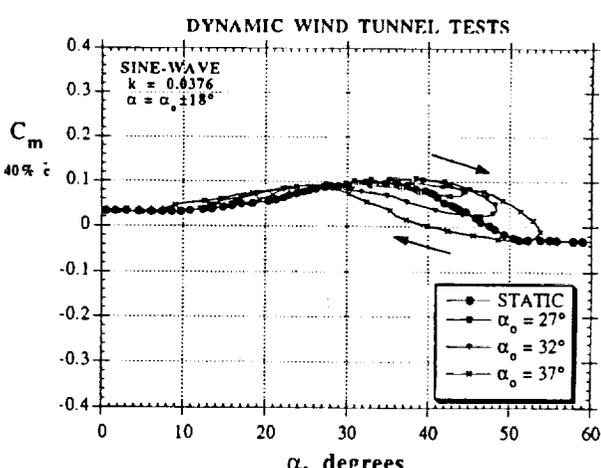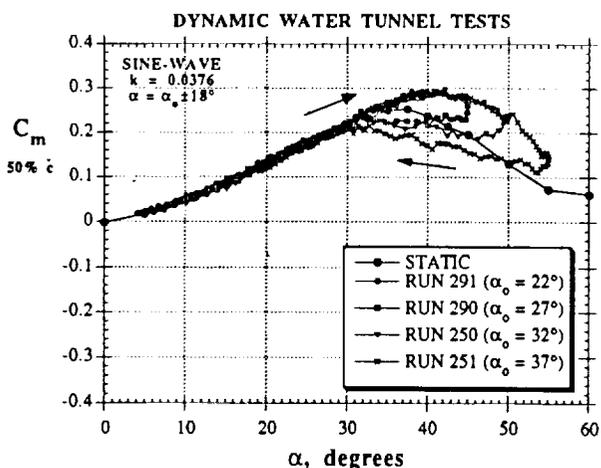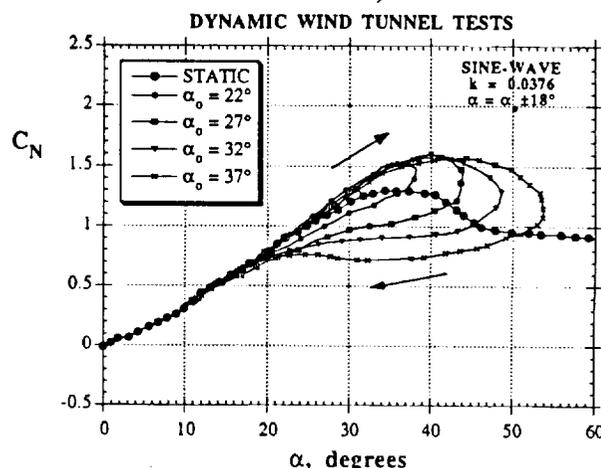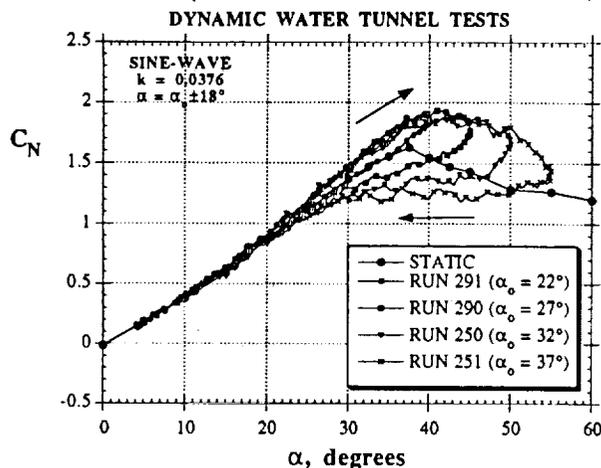
Experiments on the 1/32nd-scale F/A-18 model included pitch-up/down and hold maneuvers. The model rotates about the 25% $\bar{c}$, and the motions are basically constant rate ramps. The top plots present results for pitch-up and hold motions from 15° to 65° angle of attack for different non-dimensional pitch rates q_0. The normal force and pitching moment data show a dependency on pitch rate, as reported by Brandon and Shaw in Ref. 10. In general, there is an increase in C_N and a decrease in C_m over the entire range of motion. As discussed in Ref. 10, the induced angle of attack in the horizontal tails and the lag in the separation and vortex formation are mainly responsible for the negative C_m increment at angles of attack lower than 55°. At higher angles of attack, the lag in the breakdown of the LEX vortex becomes dominant, generating a positive C_m increment.

This set of experiments was completed with pitch-down and hold maneuvers at different rates. The maneuver consisted of pitching down the F/A-18 model from 65° to 15° angle of attack, and the responses of the normal force and the pitching moment are also revealed in this figure The data show an undershoot in C_N that is independent of rate at the beginning of the motion (from 65° to 50° angle of attack). Between 50° and 15° angle of attack, the high rate motion generates a larger undershoot in C_N and a larger overshoot in C_m.

DYNAMIC FORCE/MOMENT MEASUREMENTS
(PITCH UP/DOWN AND HOLD, F/A-18 MODEL)

PITCH UP/HOLD

α = 15° to 65°

- RUN 348 (STATIC)
- RUN 371 (q_0 = 0.0061)
- RUN 370 (q_0 = 0.0120)
- RUN 366 (q_0 = 0.0182)

PITCH UP/HOLD

α = 15° to 65°

- RUN 348 (STATIC)
- RUN 371 (q_0 = 0.0061)
- RUN 370 (q_0 = 0.0120)
- RUN 366 (q_0 = 0.0182)

PITCH DOWN/HOLD

α = 65° to 15°

- RUN 348 (STATIC)
- RUN 379 (q_0 = -0.0061)
- RUN 374 (q_0 = -0.0182)

PITCH DOWN/HOLD

α = 65° to 15°

- RUN 348 (STATIC)
- RUN 379 (q_0 = -0.0061)
- RUN 374 (q_0 = -0.0182)
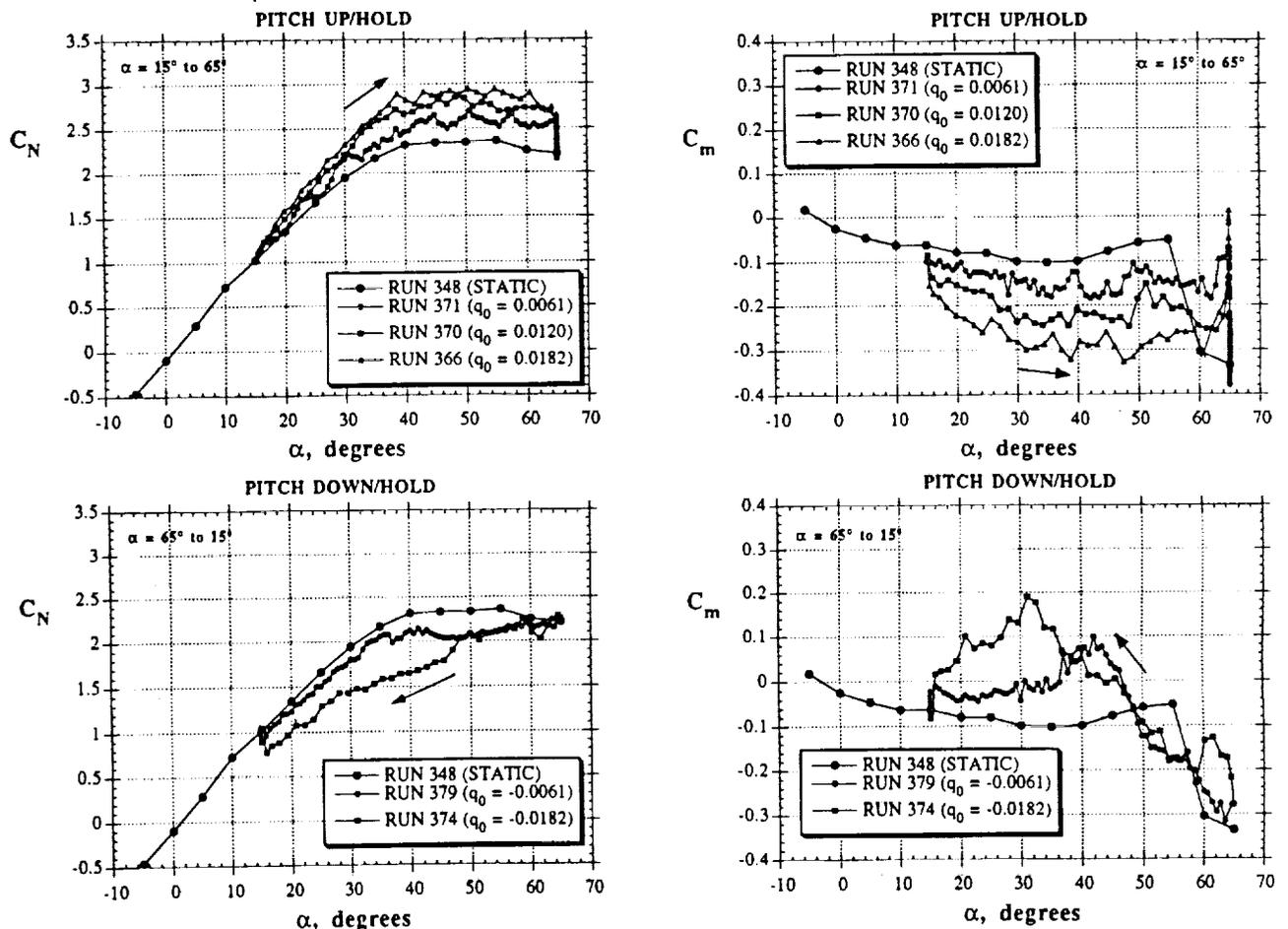
The motion profiles for the maneuvers described in the previous page, along with the variation of the normal force coefficient with time, are illustrated in this figure. The "persistence" in normal force, defined as the time it takes the force to reach its steady or static value from the moment the motion stopped, is clearly observed in the first plot. The plot in the right hand side shows the motion profiles and the change in the normal force coefficient versus time for the pitch-down and hold maneuver. It is very interesting to notice that, contrary to the behavior observed during the pitch-up maneuvers in terms of persistence, by the time the model stops after the pitch-down, the value of the normal force is almost the same as the static value, denoting a very small or almost zero persistence. The persistence in C_N, in terms of convective time units, is compared to data from the wind tunnel experiments (Ref. 10) in the bar chart. A convective time unit is the time it takes one particle in the free stream to travel a distance equal to the mean aerodynamic chord on the model. The similarities between the results from the two experiments are quite evident, indicating similar flows and dynamic force/moment responses. The small discrepancies in the value of persistence observed in each test can be attributed to the difference in motions. While the pitch-up and pitch-down angles from the present test were between 15° and 65° angle of attack, those performed in Ref. 10 were between 0° and 75°. Results from the same investigation indicated that the persistence is a strong function of not only the non-dimensional pitch rate, as the water tunnel test indicates, but of the ending angle of attack as well. Limitations in the water tunnel model support did not allow for reproducing the same motion.

DYNAMIC FORCE/MOMENT MEASUREMENTS
(PITCH UP/DOWN AND HOLD, F/A-18 MODEL)

PITCH UP/HOLD

ALPHA (RUN 371, q_0 = 0.0061)
ALPHA (RUN 366, q_0 = 0.0182)
CN (RUN 371, q_0 = 0.0061)
CN (RUN 366, q_0 = 0.0182)

α = 15° to 65°

PITCH DOWN/HOLD

α = 65° to 15°

ALPHA (RUN 379, q_0 = -0.0061)
ALPHA (RUN 374, q_0 = -0.0182)
CN (RUN 379, q_0 = -0.0061)
CN (RUN 374, q_0 = -0.0182)

NORMAL FORCE PERSISTENCE

PITCH UP q_0 = 0.0182
PITCH UP q_0 = 0.0061
PITCH DOWN q_0 = 0.0061
PITCH DOWN q_0 = 0.0182

Eidetics Water Tunnel
Wind Tunnel (Brandon and Shah)
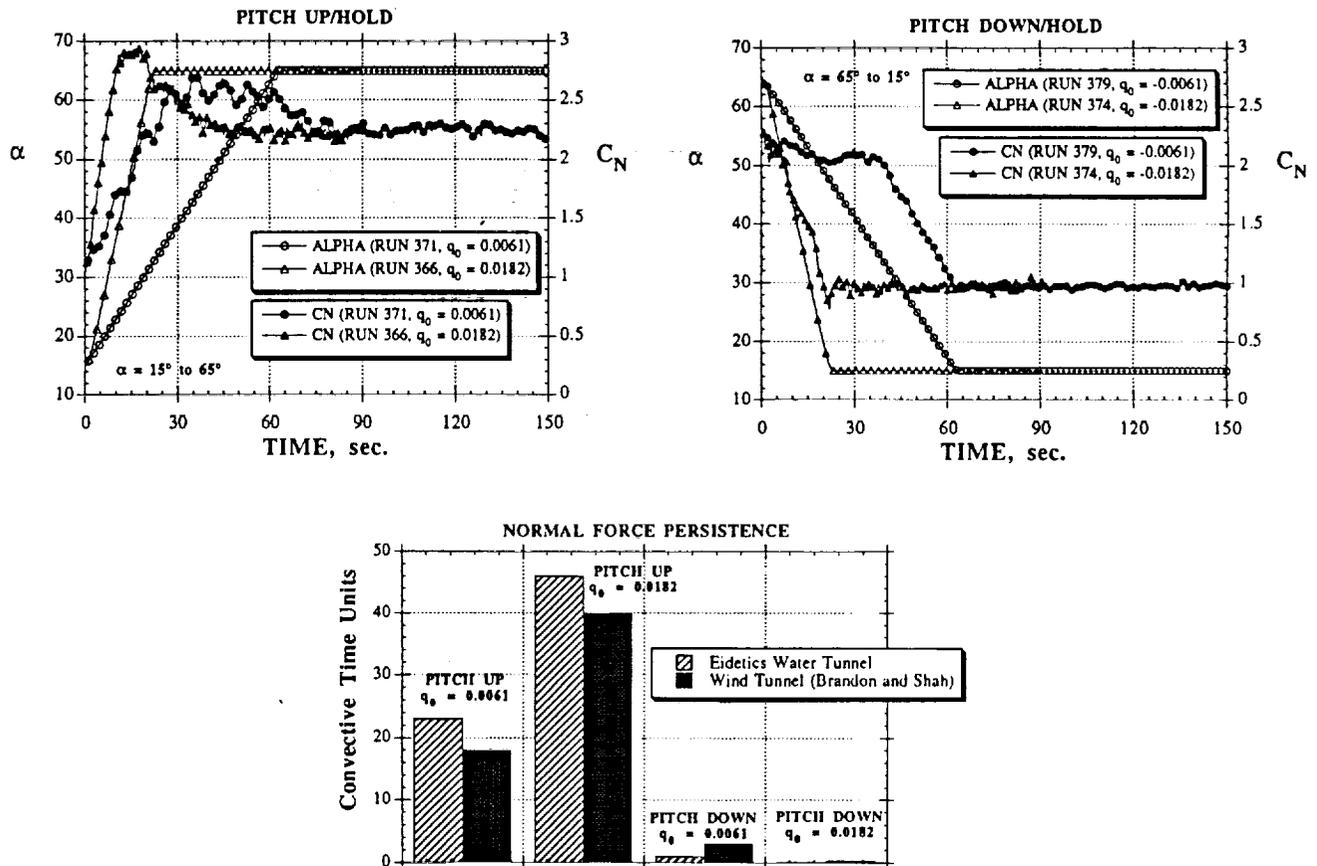
The methodology and procedures for conducting the dynamic experiments in yaw are very similar to those utilized for the pitch experiments. Since the tests were performed in a horizontal tunnel, the weight component does not change with sideslip angle, and therefore, a weight tare is not needed.

The dynamic tests in the yaw axis were limited to oscillations between 0° and 20° sideslip angle, at $\alpha = 30°$, and at two reduced frequencies k. The motion profiles and the response of the rolling moment coefficient with time are presented in the first plot in this figure. Results indicate that the hysteresis in the longitudinal characteristics is minimum; the values follow the static case very closely. The major changes are observed, as expected, in the lateral-directional characteristics. The yawing moment and rolling moment data present hysteresis loops with opposite directions. The loops for C_n are clockwise, while the loops for C_l are much larger and counter-clockwise. While the principal mechanism for the loops in yawing moment is probably the yaw damping produced by the vertical tails, the primary mechanism responsible for the loops in C_l is the lag in the LEX vortex burst and reformation.

DYNAMIC FORCE/MOMENT MEASUREMENTS
(YAW OSCILLATIONS, F/A-18 MODEL)

F/A-18 at $\alpha = 30°$

Legend:
- Cl (RUN 386, k = 0.04)
- Cl (RUN 385, k = 0.06)
- beta (RUN 386, k = 0.04)
- beta (RUN 385, k = 0.06)

$\beta = 0°$ to 20°
$\alpha = 30°$

TIME, sec.

$\beta = 0°$ to 20°

- RUN 384 (STATIC)
- RUN 385 (k = 0.06)
- RUN 386 (k = 0.04)

β, degrees

$\beta = 0°$ to 20°

- RUN 384 (STATIC)
- RUN 385 (k = 0.06)
- RUN 386 (k = 0.04)

β, degrees
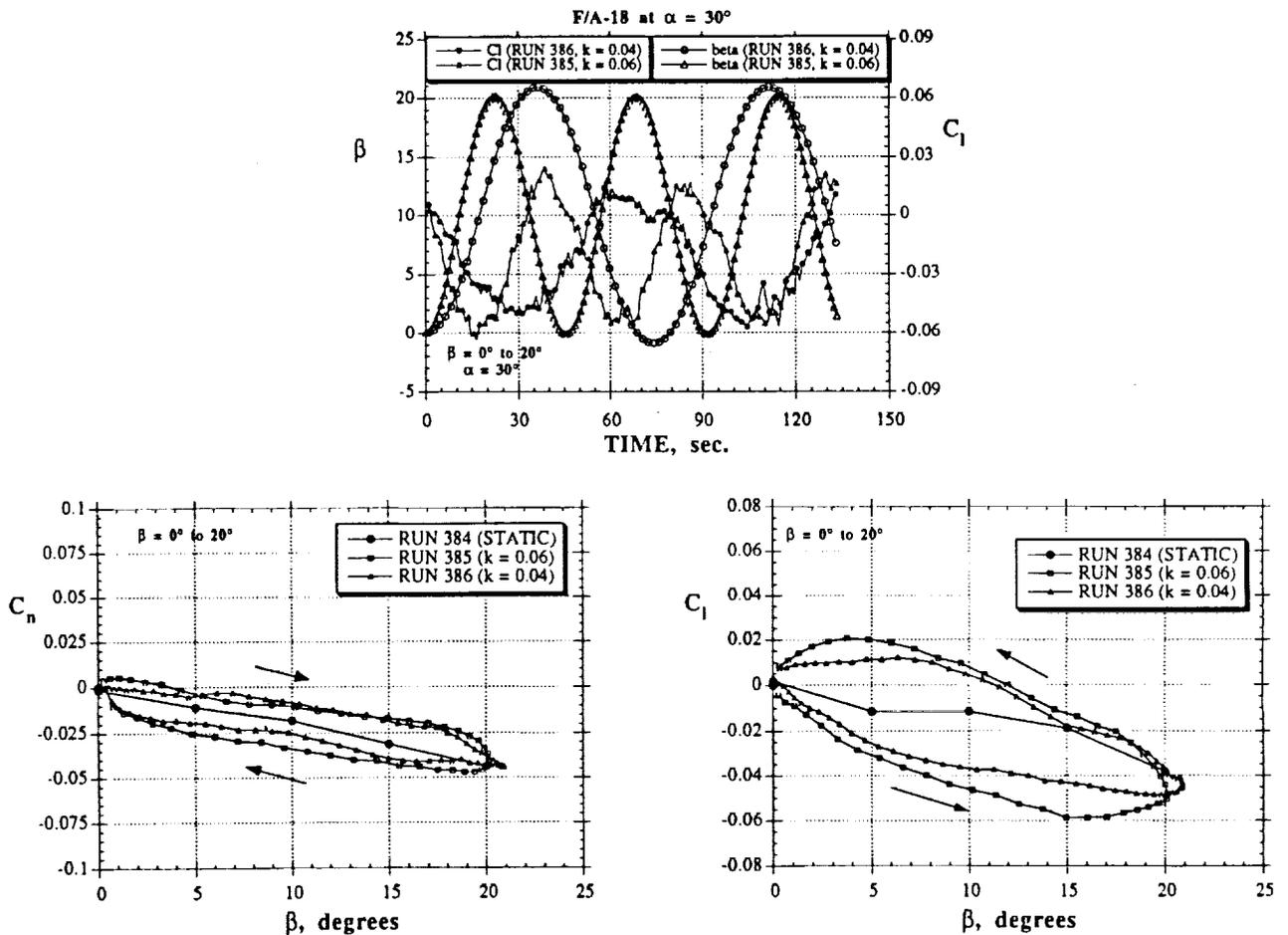
Roll oscillations were also conducted using the 1/32nd-scale F/A-18 model. For these particular dynamic experiments, the model is positioned at the desired angle of attack and a weight tare ($V_\infty = 0$) is performed throughout the entire roll angle range.

The approach for the set of experiments presented here was to match the free-to-roll motion obtained in the wind tunnel test performed in Ref. 12. In that investigation, a 2.5%-scale model of the F-18 presented a limit cycle oscillation or "wing rock motion" for angles of attack between 30° and 50°, with peak-to-peak amplitudes that could exceed 40° roll angle. At Re = 20,000 and $\alpha = 40°$, the F-18 oscillated between -13° and 13° in the wind tunnel. This condition was explored in detail in the present water tunnel test. It should be noted that the motion utilized is a sine wave approximation, and therefore, small differences in some motion parameters, especially acceleration, and in the response of the forces and moments, can be expected.

Four components of the forces and moments measured with the balance during a body-axis roll (between -13° and 13°) at k = 0.025 (which matches exactly the wind tunnel reduced frequency) are presented in this figure. Variations in normal force are small, but the changes in C_m produced by the rolling motion are more noticeable. Changes in directional characteristics are significant and, in general, a positive roll angle ϕ is associated with positive side force and yawing moment coefficients and vice versa.

DYNAMIC FORCE/MOMENT MEASUREMENTS
(ROLL OSCILLATIONS, F/A-18 MODEL)

F/A-18 at $\alpha = 40°$

F/A-18 at $\alpha = 40°$

F/A-18 at $\alpha = 40°$

F/A-18 at $\alpha = 40°$
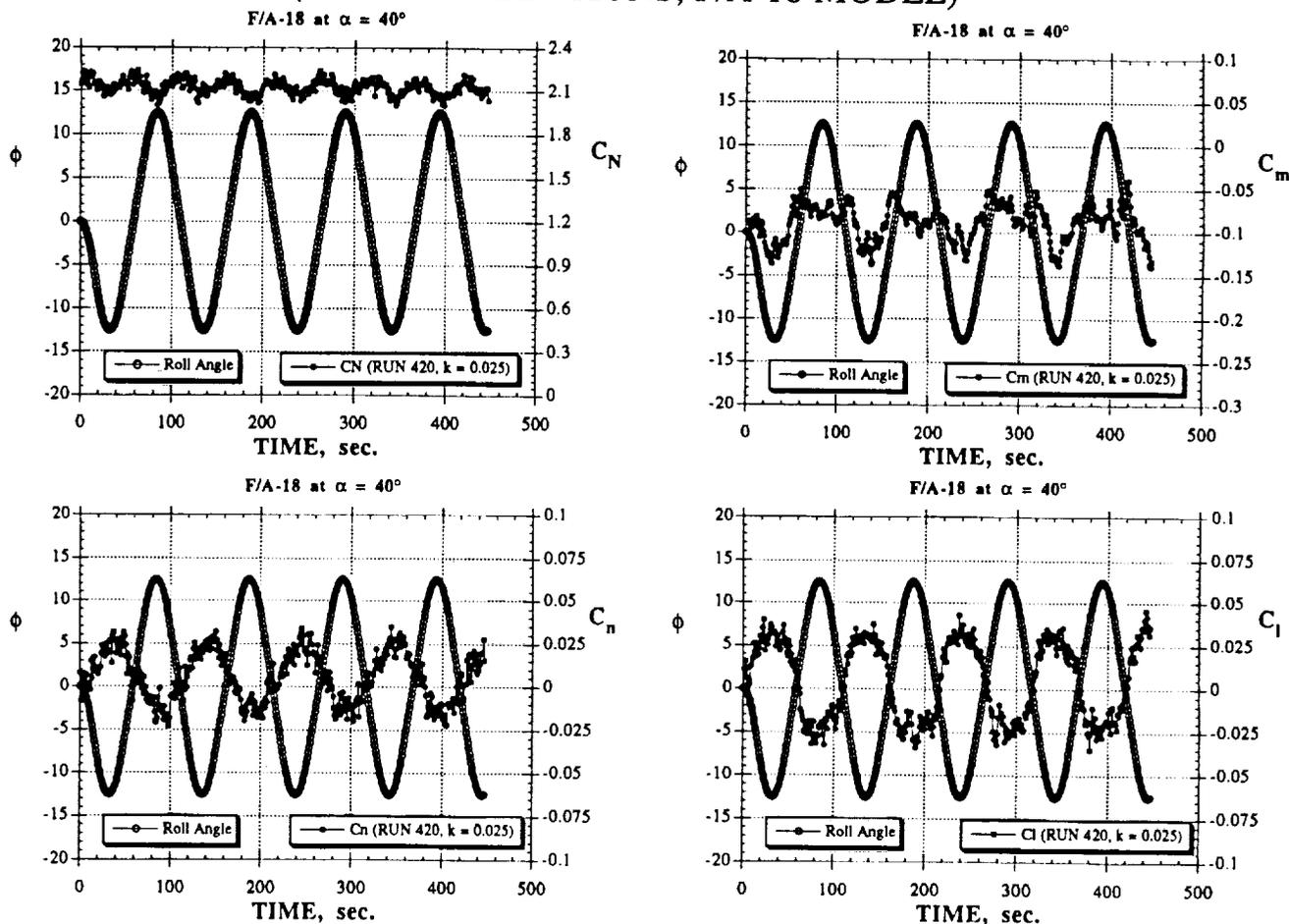
The rolling moment behaves as expected, with negative rolling moments occurring during positive roll angles and vice versa . In order to observe the hysteresis in rolling moment, C_l can be plotted versus roll angle. Typical "wing rock" or hysteresis phase plots are obtained by plotting $\ddot{\phi}$ versus ϕ. Since the acceleration $\ddot{\phi}$ is proportional to the total aerodynamic rolling moment coefficient, $(C_l = \dfrac{\ddot{\phi}\, I_{xx}}{q_\infty S b})$ then the shape of the C_l vs. ϕ plot should show similar characteristics. In a phase plot, a clockwise loop denotes an area where energy is being added to the system, i.e., the oscillations are being driven (destabilizing). The counter-clockwise loops near the maximum roll angle represent areas where the system is consuming energy, and therefore the motion is being damped (stabilizing). The areas contained within the destabilizing and stabilizing loops are about equal, indicating an energy balance which is required to sustain the limit-cycle wing rock. The hysteresis plot seen in the top right corner of this figure (k = 0.025), shows a large central clockwise loop, but near the roll angles extremes, the typical counter-clockwise loops are not well organized. This could be due to the differences in accelerations between the real free-to-roll motion and the oscillation performed in the water tunnel.

This investigation also reveals that the shape of the hysteresis plots is strongly dependent on the frequency. The same "forced-to-roll" motion was performed at reduced frequencies of k = 0.050 and 0.10, and it appears that by increasing the frequency, the central clockwise loop (destabilizing) starts decreasing, while the two counter-clockwise loops near the extremes become larger. The central loop disappears completely for the high frequency oscillation (k= 0.10); only a single counter-clockwise loops is observed in this particular case.

DYNAMIC FORCE/MOMENT MEASUREMENTS
(ROLL OSCILLATIONS, F/A-18 MODEL)

Typical Wing Rock Phase Plot

$\ddot{\phi}$

ϕ, degrees

F/A-18 at α = 40°

C_l

k = 0.025

— RUN 421 (STATIC)
— RUN 420 (k = 0.025)

ϕ, degrees

F/A-18 at α = 40°

C_l

k = 0.050

— RUN 421 (STATIC)
— RUN 419 (k = 0.05)

ϕ, degrees

F/A-18 at α = 40°

C_l

k = 0.10

— RUN 421 (STATIC)
— RUN 418 (k = 0.10)

ϕ, degrees
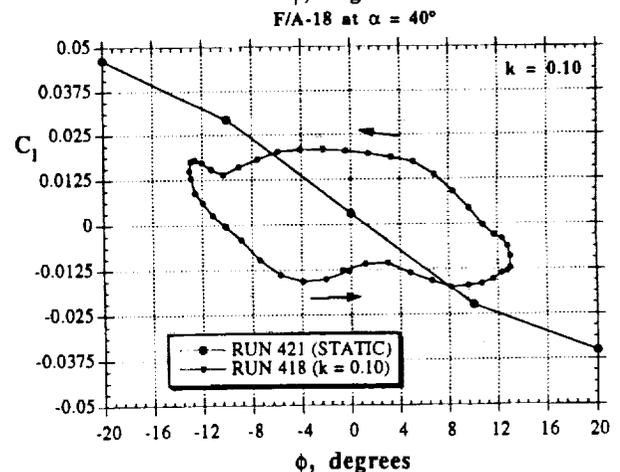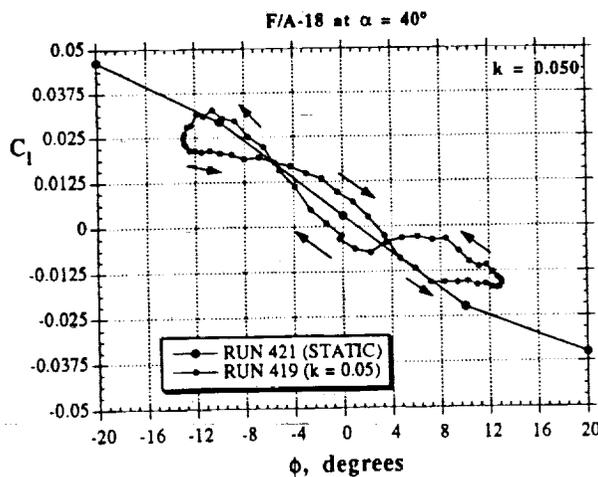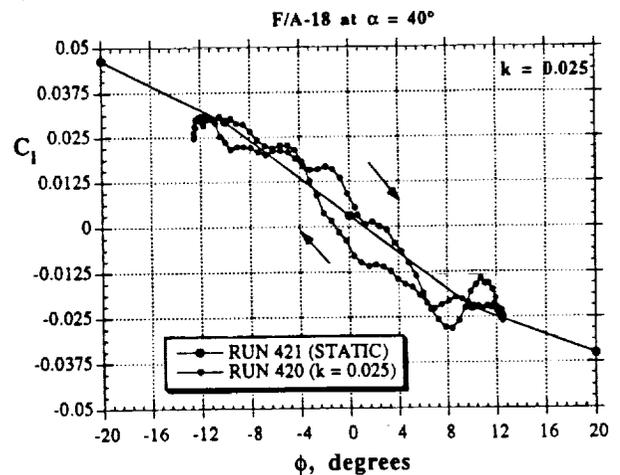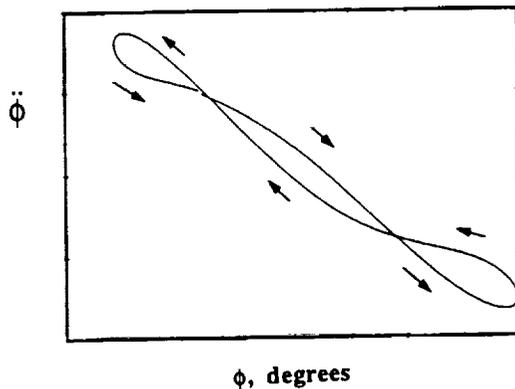
Another important maneuver for present and future aircraft is the "loaded roll" or rolling around the velocity vector at medium to high angles of attack. In the wind tunnel, rotary balances are used to acquire force and moment data from an internal balance with the model rotating around the velocity vector at varying rotation rates. With the balance, the water tunnel can provide a simplified version of the same type of test capability with the added benefit of being able to observe the behavior of the flow at the same time.

The rig consists of an aluminum C-strut that attaches to the roll mechanism and the water tunnel main C-strut. The angle of attack is changed manually by sliding the arm along the C-strut, allowing testing at angles of attack between 0° and 60°. Once the desired α is obtained, the arm is fixed in position. Sideslip can be varied by rotating the sting in the adapter located at the end of the arm.

This figure shows flow visualization performed on the $1/48^{th}$-scale F/A-18 model at $\alpha = 50°$ and at three conditions: static, and positive and negative rotations ($\Omega = \pm 0.15$). For the static case, the forebody vortex flow field is symmetric, as observed during the static tests performed with the $1/32^{nd}$-scale F/A-18 model. The positive rotation (clockwise, pilot's view), causes that the windward (right/red) gets lifted up from the body. A "right-vortex-high" asymmetry is created, with the associated negative side force and yawing moment. The opposite occurs when the model is rotated at $\Omega = -0.15$, i.e., a "left-vortex-high asymmetry is produced. The excellent flow visualization provides interesting information not only about the forebody vortex position, but also about the different vortex interactions.

FLOW VISUALIZATION
(ROTARY BALANCE TESTS, F/A-18 MODEL)

Symmetric Vortices
C-Strut
Roll Mechanism
Sting
Arm

Static
$\alpha = 50°$

Windward Vortex
Leeward Vortex
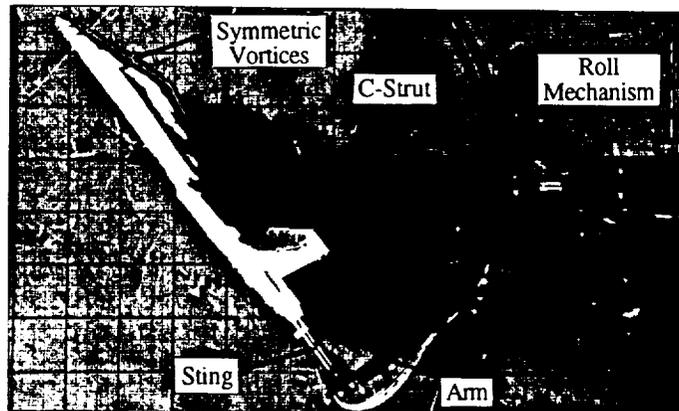
Positive Rotation, $\Omega = 0.15$

Windward Vortex

Negative Rotation, $\Omega = -0.15$

As mentioned before, and because of the complexity associated with a hydraulic slip-ring for the dye and with a electric (submersible) slip-ring for the balance, the number of revolutions are limited. Data were acquired and averaged over exactly 2 revolutions. Four components of the forces and moments at $\alpha = 50°$ are presented in this figure. Data from the water tunnel rotary balance tests correspond to runs at 0.42 ft/sec and 0.58 ft/sec. These data are compared to results from a rotary balance test performed by Eidetics on a 6%-scale F/A-18 in the NASA Ames 7' x 10' wind tunnel (Ref. 13).

The normal force coefficient presents the same trends in both tests, i.e., a slight increase with rotation rate. There is a difference in the static value ($\omega b/2V_\infty = 0$) that could be due to boundary corrections, geometry differences, etc.

The agreement in the lateral/directional coefficients is quite acceptable. Evidently, the forebody vortex flow fields in the water and wind tunnel experiments present opposite asymmetries, as indicated by the side force value at $\omega b/2V_\infty = 0$, but the anti-spin slope is similar in both tests. The yawing moment coefficient obtained in the water tunnel presents a smaller slope than that revealed by the wind tunnel results, especially for negative rotations, denoting a possible slight shift in the center of pressure. The anti-spin behavior, however, is still present. The rolling moment shows positive slopes in both tests, and it is the component that shows the larger Reynolds number effects in the water tunnel tests. Results from these experiments can be considered quite encouraging, especially in terms of having the capability of performing flow visualization and F/M measurements to assess spin characteristics during the preliminary design phase.

DYNAMIC FORCE/MOMENT MEASUREMENTS
(ROTARY BALANCE TESTS, F/A-18 MODEL)

F/A-18 at $\alpha = 50°$

EJ Water Tunnel (Run 490, Re = 8,100)
EJ Water Tunnel (Run 493, Re = 11,500)
Ames 7x10' Wind Tunnel (Re = 636,000)
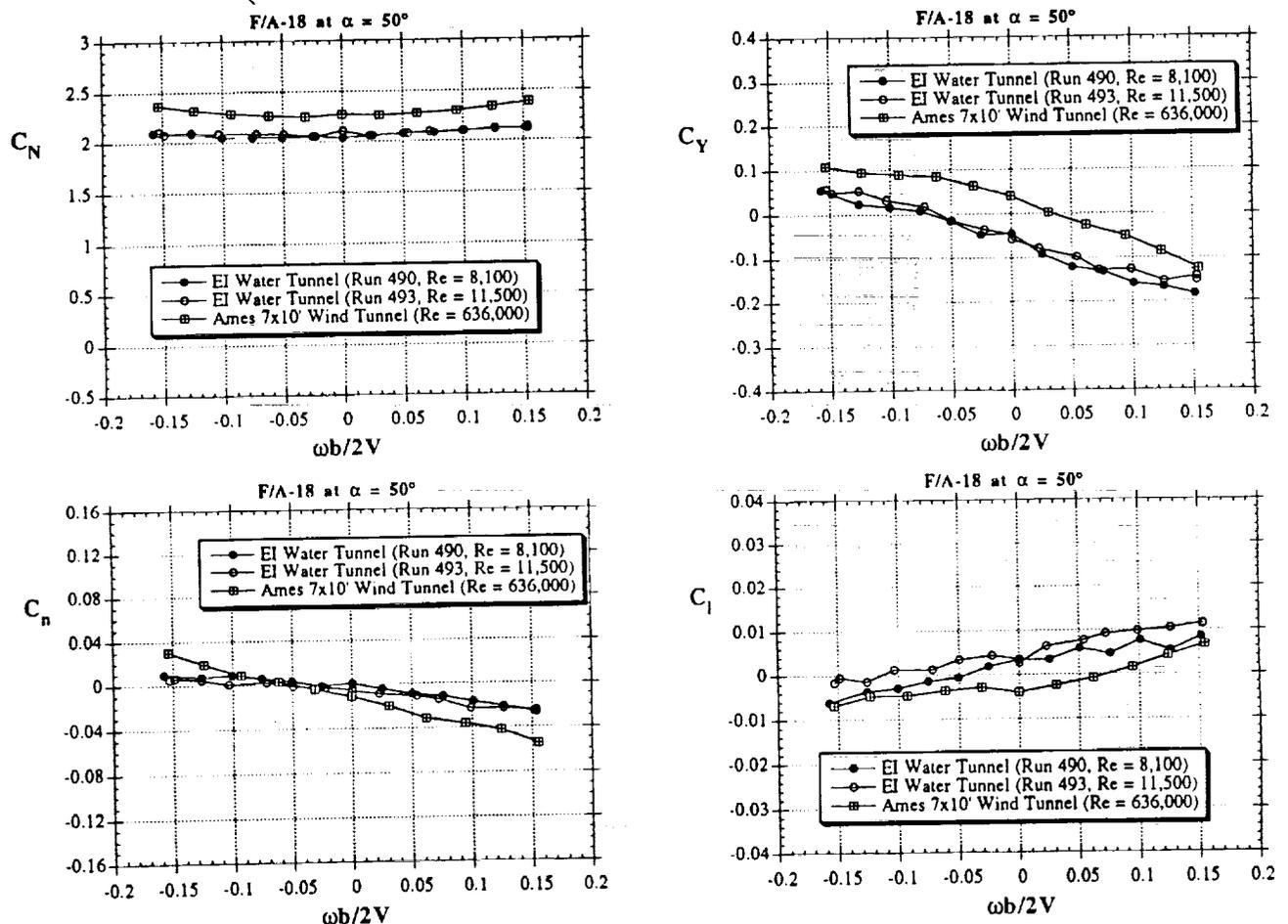
A five-component balance was designed, built and tested in the Eidetics' water tunnel. The balance was calibrated and showed good linearity and low interactions. Results of static experiments were quite satisfactory, showing good correlation with wind tunnel data of similar configurations (delta wing and F/A-18 models).

This research project also explored the use of the balance to perform dynamic experiments in the water tunnel. The model support of the Eidetics' water tunnel was improved, and both a new roll mechanism and a rotary rig were designed and built to assess the performance of the balance under different types of dynamic situations. Among the advantages of conducting dynamic tests in a water tunnel are less demanding motion and data acquisition rates than in a wind tunnel test (because of the low-speed flow) and the capability of performing flow visualization and force/moment measurements simultaneously with relative simplicity. Of significant importance is the fact that this investigation showed that the values of the inertial tares (the effect of the resistance to motion due to the mass model of inertia) are very small due also to the low rotation rates required in the water tunnel. Depending on the accuracy of the data required, these tares can be ignored, and that facilitates the testing and data acquisition process. This investigation clearly showed all the different dynamic experiments that can be easily performed in a water tunnel, and the capability of simultaneous flow visualization and F/M measurements proved extremely useful to explain the results obtained during these dynamic tests.

In general, results obtained in this contract should encourage the use of water tunnels for a wider range of quantitative and qualitative experiments, especially during the preliminary phase of aircraft design.

CONCLUDING REMARKS

- FORCES AND MOMENTS WERE MEASURED IN A WATER TUNNEL USING A 5-COMPONENT BALANCE

- IN GENERAL, THE WATER TUNNEL DATA PRESENTED GOOD AGREEMENT WITH STATIC AND DYNAMIC WIND TUNNEL DATA

- RESULTS EMPHASIZE THE IMPORTANCE OF HAVING THE CAPABILITY OF PERFORMING SIMULTANEOUS FLOW VISUALIZATION AND FORCE/MOMENT MEASUREMENTS

- THE DEVELOPMENT OF THE CAPABILITY FOR PERFORMING DYNAMIC EXPERIMENTS IN THE WATER TUNNEL, INCLUDING ROTARY BALANCE TESTS, OFFERS A WIDE VARIETY OF NEW POSSIBILITIES FOR USING THE WATER TUNNEL AS A PRELIMINARY DESIGN TOOL

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13. ABSTRACT (Maximum 200 words)

The goal of the Fourth High Alpha Conference, held at the NASA Dryden Flight Research Center on July 12–14, 1994, was to focus on the flight validation of high angle-of-attack technologies and provide an in-depth review of the latest high angle-of-attack activities. Areas that were covered include, high angle-of-attack aerodynamics, propulsion and inlet dynamics, thrust vectoring, control laws and handling qualities, tactical utility, and forebody controls.

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