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Aerodynamic Parameter Measurement Using the Wind Driven Manipulator: Inverse Force Measurement on Wings

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ABSTRACT

Inverse force measurement using a wind-driven dynamic manipulator is explored. Using system identification techniques, the WDM offers a method of measuring forces and moments on wind tunnel models during rapid, multi-axis maneuvers. Previous work has shown the measurement of dynamic stability parameters for small disturbances using the WDM. System identification has been used to construct simulations of WDM behavior in order to match desired and actual maneuver trajectories. Here the nonlinear behavior of a pitch manipulator is measured over a range of model loads and attitudes. A look-up table constructed from these data is used to measure quasi-steady forces and moments on a rectangular wing and a delta wing. The WDM is used to hold models steady in a wind tunnel under feedback control, at various attitudes. Each model is taken through a range of attitudes, and the control input needed for equilibrium is recorded. By repeating the experiment with 3 model-mounting positions, a set of 3 simultaneous equations is generated for the lift, drag and pitching moment at each angle of attack. The technique is successful in measuring the lift of a rectangular wing and a delta wing. Measurement resolution was inadequate to resolve drag and pitching moment accurately in these tests. Methods for measuring these are discussed. Continuous force measurement from repeated maneuvers is discussed.

NOMENCLATURE

θ	WDM Boom Angle
α	WDM Wing Relative Angle of Attack ($\alpha + \theta$ = WDM wing aerodynamic angle of attack)
M_{model}	Moment generated by attached model
M_{WDM}	Net moment generated by the WDM
L_m	Lift generated by the model
D_m	Drag generated by the model
M_m	Pitching moment generated by the model
l_b	Length of model attachment boom (WDM pivot to model quarter chord)
q	Wind tunnel freestream dynamic pressure
W_m	Model weight

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INTRODUCTION

In the development of aircraft capable of executing rapid multi-axis maneuvers, measuring forces and moments during such maneuvers is a problem of interest. Modern fighter aircraft must venture into flight regimes where the aerodynamics involve substantial uncertainties[1,2]. These regimes are explored in dynamic wind tunnel tests where the model is moved through portions of multi-axis maneuvers at scaled rates, either using robotic arms[3,4], or rotary balances[5,6]. These devices typically use stiff arms to hold the model at precisely known attitudes, and hydraulic or electric actuators to move the model through desired motions, with such an abundance of power and mechanical stiffness that the displacements and resistance caused by the forces acting on the model are negligible. The forces and moments themselves are generally measured directly using strain gages and accelerometers, attached at the model mount, or to the balance. From the forces and moments, the stability derivatives, which are parameters for a state model of the aircraft dynamics, can be computed. From these state model parameters, control laws are synthesized[7]. The apparatus for achieving these is generally massive and heavy, and causes significant flow interference[8]. Specialized equipment is needed for particular motions.

The Wind Driven Dynamic Manipulator[9] (WDM) is a device which uses the energy in the wind tunnel free stream to produce the moments necessary to drive the model through desired motions. The device is intrinsically light, unobtrusive and flexible, achieving accurate trajectories using feedback control and iterative refinement rather than by brute force. As shown in Fig. 1, a 3-d.o.f. (pitch-yaw-roll) WDM[10] has 4 control wings, each driven by a servo motor about an axis through its quarter-chord. The forces on the wings are used to drive the model through desired maneuvers. The orientation of the model, the boom, the support points and the wings are determined by the specifics of the experiment, as seen further in this paper. The use of wind energy obviates the need for heavy motors and their supports. In fact the WDM transmits little of the dynamic reactions to the tunnel walls.

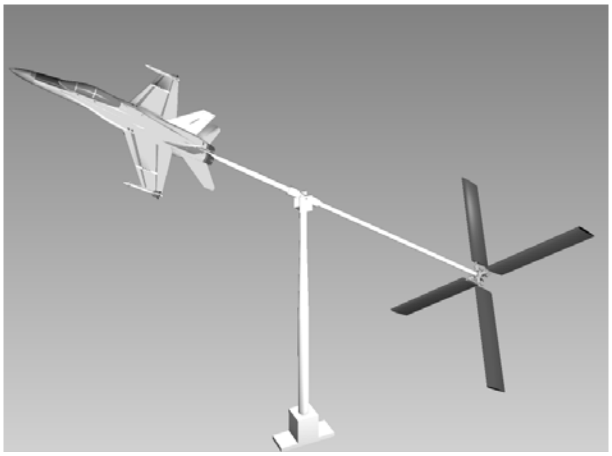

Figure 1: Pitch-Yaw-Roll Wind-Driven Manipulator used in the 7.0 ft x 9.0 ft wind tunnel.

Previous Work Using the WDM

The WDM has been used to demonstrate square-wave and complex periodic pitch maneuvers using a 1/32-scale F-15 model[11], and to quantify vortex trajectories during dynamic pitch-yaw motions of a 1/32-scale YF-22 model using laser sheet video imaging [12]. These experiments showed that even when the rate of the maneuver is quite low by conventional measures of unsteady aerodynamics (low reduced-frequency), unsteady vortex interactions with aircraft control surfaces can occur during multi-axis maneuvers, with sharp variations in forces and moments expected.

In principle, the control input to the WDM, needed to drive a model through a given maneuver, contains the information needed to extract the forces and moments acting on the model. A 1-d.o.f. WDM was used in Ref. 13 to explore the measurement of dynamic stability parameters. The WDM wings and the test models were mounted on strain gage balances, and their lift curve slopes were obtained by linear regression. Test conditions were chosen so that both the test model and the manipulator wings were operating in the linear regime. The manipulator was represented by a second order linear model, and the results from the system simulation were compared with experimental data obtained using a set of calibration models. The experiments were performed with small-amplitude pitch oscillations about mean conditions. The pitching moment stiffness coefficient and the pitch damping coefficient were measured for 3 different boom lengths and compared with theoretical predictions for the models used. The results agreed within 10% error, which is very competitive with the accuracy obtained with current methods. However, it was noted that the technique required high numerical precision in the simulation for that particular experimental configuration. Basically, the difficulty was that a long boom generates large moments at the aircraft model for small changes in the control input. Thus the difference between the “model-on” and “model-off” data suffered from the uncertainty of finding the small difference between two large numbers.

Issues in Force and Moment Measurement

One advantage of the WDM in wind tunnel testing is that maneuvers can be repeated under computer control until the necessary level of perfection is achieved. This is done by monitoring the trajectory of the model in time and adapting the input to the controller until the desired trajectory is achieved. This adaptation can be done by human adjustment of control parameters [11,12], or by adaptive learning algorithms. Adaptive trajectory matching was demonstrated in Ref. 14. In either case, the final control signal contains the information necessary to drive the model through a specified trajectory. If the aerodynamics of the manipulator are precisely known, then this information can be used to derive the aerodynamics of the model being driven. The point to note here is that the model can be driven through a desired trajectory without explicit knowledge of its precise aerodynamic or inertial characteristics: the adaptive algorithm can help achieve the desired trajectory by repeating the maneuver many times. Such repetition is not difficult in a low-speed wind tunnel, where run-times are not as limited as in supersonic tunnels. Thus, in principle, forces and moments on the model can be extracted from the behavior of the WDM controller, without direct force measurement. Once the quasi-steady characteristics are shown to be reliably measurable, this force measurement can be done in continuous, quasi-steady tests without stopping the model at any condition, with the phase relationship between the model motion and the WDM control input quantified using digital signal processing techniques. And included in the system description. This can be done even during maneuvers where rate effects become important. In such regimes, the experiment can be designed to separate the time scales of the manipulator wings from those of the model. The rate effects will require modeling using unsteady aerodynamics methods.

Beneath both the control and identification problems is the need for a mathematical model of the manipulator, providing at least structure if not parameter values. The kinetics of the manipulator can be derived from first principles in the same manner as other robots[15]. Most of the difficulty lies in constructing a mathematical framework for the aerodynamics of multiple degree of freedom manipulators. Also, approximations must be made to the aerodynamic equations if the control design problem is to be manageable. The mathematical models can be validated experimentally. Actual WDM input/output measurements can be obtained through wind tunnel experiments. These data can be correlated against numerical simulations to validate and improve the model.

Experimental data obtained in nonlinear flight regimes will suffer from noise (non-repeatable events) due to buffeting and turbulence on the model and the WDM. However, by repeating the same trajectory many times, the measurement problem can be converted to one of phase-resolved signal processing. Statistical processing can be used to improve the accuracy of the data. The modeling of the pitch manipulator and the pitch-yaw-roll manipulator is detailed further in Ref. 16.

OBJECTIVES

In this paper we begin developing the knowledge base needed to use the WDM for force measurement during maneuvers. The moment characteristics of a pitch manipulator are measured, for different boom angles and wing angles of attack. This includes the nonlinearities due to operating the control wings at high angles of attack, as well as the drag and interference effects of the WDM structure. As an illustration, we explore the measurement of quasi-steady forces and moments on simple wing shapes, over a range of angle of attack. A rectangular wing of aspect ratio 3 and a delta wing of aspect ratio 2.29 are used.

The quasi-steady relationships provide insight into the various aspects to be considered. Once this is done, the quasi-steady relation can be assumed to hold for rates of motion whose time scales are far longer (i.e., frequencies are lower) than the response times of the flow and the WDM control system.

MEASUREMENT TECHNIQUE

The experiments are conducted in the 42.0 in x 42.0 in Aerocontrols wind tunnel at the School of Aerospace Engineering. The pitch manipulator is shown in Fig. 2. Servo motors attached to the boom drive the control wing angle of attack using linkages. The device is controlled using a Pentium-based computer. The WDM control software records commanded and actual angles of the model boom and the WDM control wing angle of attack.

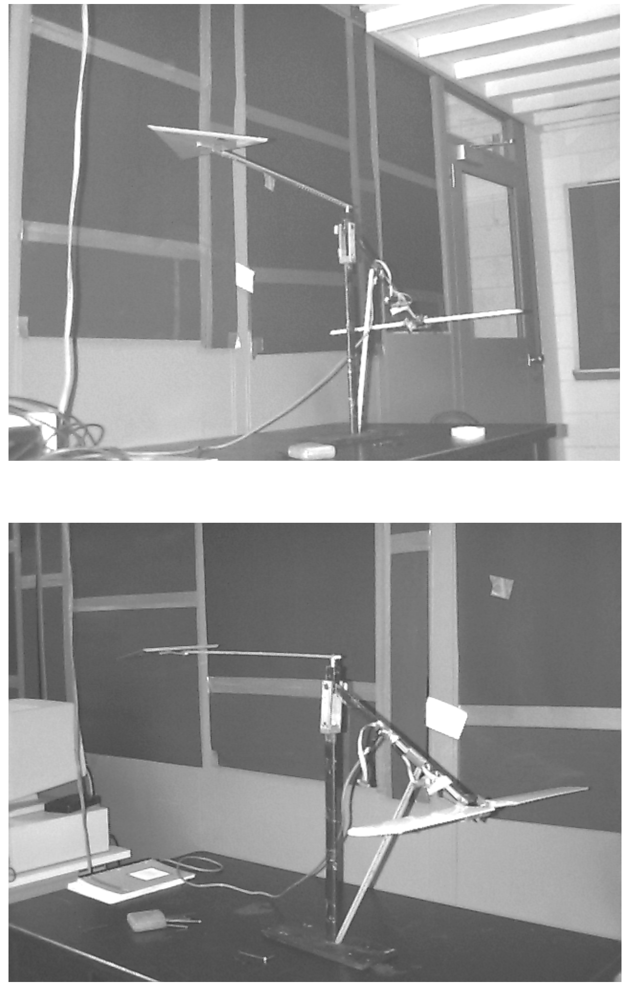

Figure 2: Pitch Manipulator used in the present experiments (with delta wing model attached)

Using a feedback control loop to hold a model steady at a commanded boom angle, the combined effects of the model-generated moment and the WDM-generated moment must sum to zero, i.e.

$$M_{model} + M_{WDM} = 0$$

The moment due to the model can be reduced into components due to the lift, drag, pitching moment and the weight of the model.

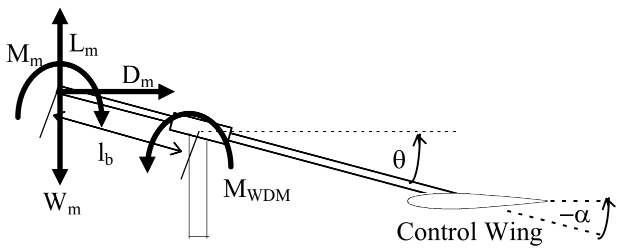

Figure 3: Geometry of the 1-DOF WDM force and moment balance with model attached

Given the geometry in Fig 3, the net moment generated by the model is

$$\begin{aligned} M_{model} &= -L_m \cdot l_b \cdot \cos(\theta) - \\ & D_m \cdot l_b \cdot \sin(\theta) - M_m \\ & + W_{model} \cdot l_b \cdot \cos(\theta) \end{aligned}$$

Once the WDM-generated moment is known, the model is placed at three different nominal angles of attack and the boom angle (θ) is adjusted so that the effective angle of attack is the same for each case (so that L_m, D_m and M_m are the same for the three different boom angles). The result is a system of three equations in three unknowns:

$$\begin{bmatrix} l_b \cdot \cos(\theta_1) & l_b \cdot \sin(\theta_1) & 1 \\ l_b \cdot \cos(\theta_2) & l_b \cdot \cos(\theta_2) & 1 \\ l_b \cdot \cos(\theta_3) & l_b \cdot \cos(\theta_3) & 1 \end{bmatrix} \begin{bmatrix} L_m \\ D_m \\ M_m \end{bmatrix} = \begin{bmatrix} M_{WDM,1} + W_m \cdot l_b \cdot \cos(\theta_1) \\ M_{WDM,2} + W_m \cdot l_b \cdot \cos(\theta_2) \\ M_{WDM,3} + W_m \cdot l_b \cdot \cos(\theta_3) \end{bmatrix}$$

In this paper, the boom length is held constant for simplicity. Generally, several advantages can be gained by varying the boom length. For instance, the resolution on the force measurements can be varied. Since the contribution to the overall moment scales with the boom length, the lift and drag forces can be mechanically amplified by placing the model on a longer boom. Lengthening the boom gives a larger incremental change in moment for the same change in lift, making the force easier to discern within the fixed resolution of the WDM. A long boom also serves to reduce the aerodynamic interference effects of the manipulator.

Calibrating the WDM-Generated Moment

The net moment generated by the WDM is a function of the boom angle, the angle of attack of the control wings, and the Reynolds number:

$$M_{WDM} = M_{WDM}(\theta, \alpha, \mathrm{Re})$$

The Reynolds number is expected to be important in determining the effects of boom drag and unsteadiness. In this paper the WDM moment is calibrated directly against known moments. A string attached to the end of the boom is taken out through the tunnel roof and used to support known weights outside the wind tunnel. Both positive and negative loadings were used. The wing angle of attack required to support given moments at various boom angles was measured. The measured boom angles and control wing angles of attack were recorded for each calibration run. This is shown in Fig. 4.

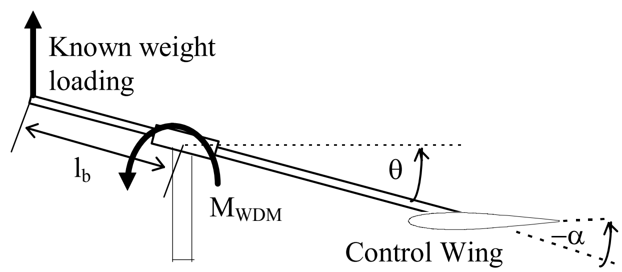

Figure 4: WDM-Generated moment direct calibration setup

The result is a look-up table that gives known moment loading as a function of boom angle and control wing angle of attack. This calibration combines the effects of the control wings and the WDM weight into a single calibrated table, allowing for any interference between the control wings and the support structure. This table can then be used to give the corresponding net WDM-generated moment with a model installed. Fig. 5 shows extracts from the look-up table. The WDM response is relatively linear when the control wing angle of attack is below stall, and becomes more quadratic as the magnitude of the angle exceeds 10°, the approximate stall angle. The control wing may generate less lift, but more net moment as the drag contribution increases past the stall. Therefore, the curve is expected to separate into a linear (un-stalled) segment and a more quadratic (stalled) segment. The apparent break in slope near the negative moment loading regimes is attributed to the effects of the boom wake and other interference on the control wings.

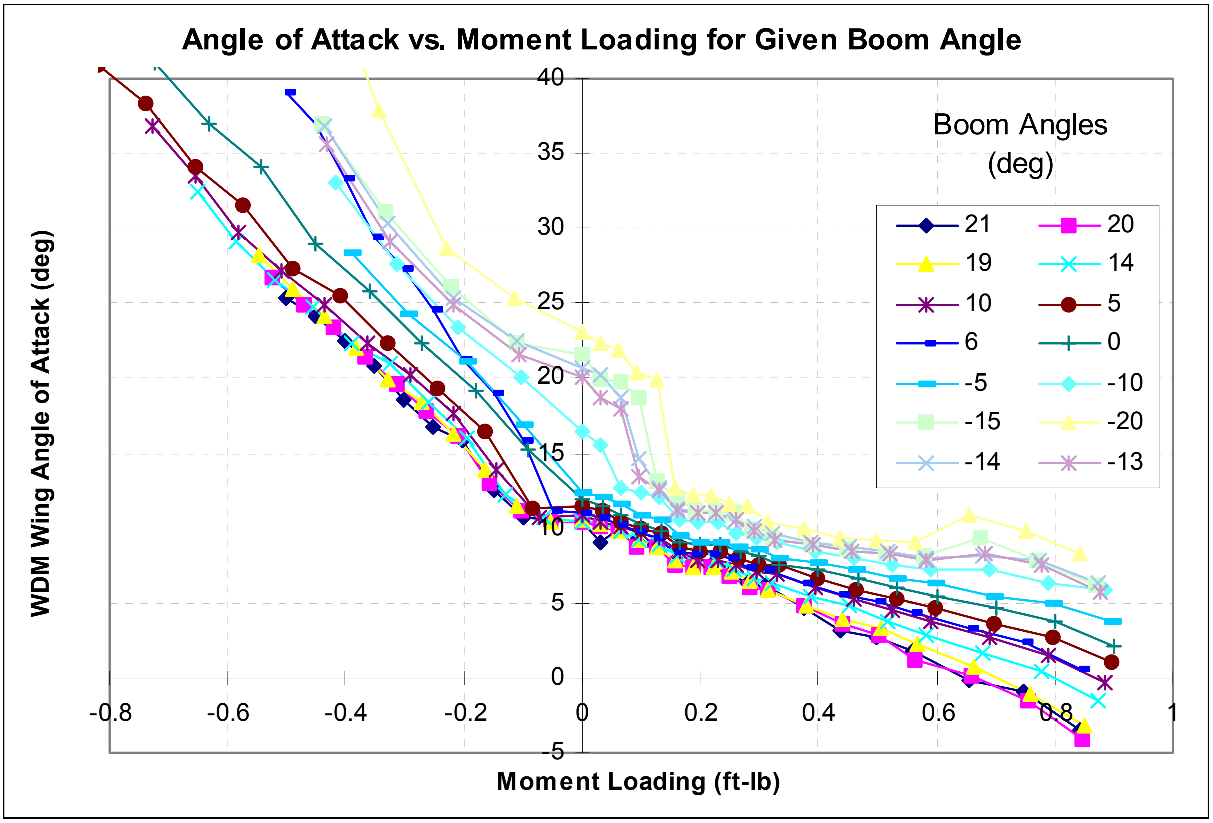

Figure 5: WDM-generated moment vs. control wing angle of attack for several commanded boom angles.

Controller Performance
The controller used for these experiments is a simple proportional-plus-integral-plus-derivative (PID) controller that assumes that the WDM-generated moment increases with increasing control wing angle of attack. This assumption is generally true: the control wings are usually pitched back far enough so that the net moment increases with angle of attack even if the wings are progressing through stall because the drag contribution increases rapidly. At some test points, the control wings could not provide enough moment to hold a model at a given angle of attack. The problem could have been resolved in most of the instances if the controller had known that it could increase the WDM-generated moment by decreasing the angle of attack of the control wings, back through the stall. A more sophisticated controller would provide better performance in this respect.

The settling time for each commanded angle of attack was on the order of two to four seconds. Fig. 6 shows a plot of control wing angle of attack and boom angle vs. time. The controller was also successful in holding steady a delta wing model at high angle of attack, as shown in Fig. 7. A very-low frequency fluctuation in the boom angle was encountered at some test conditions, perhaps due to a periodic flow interaction between the model and the boom. This is shown in Fig. 8.

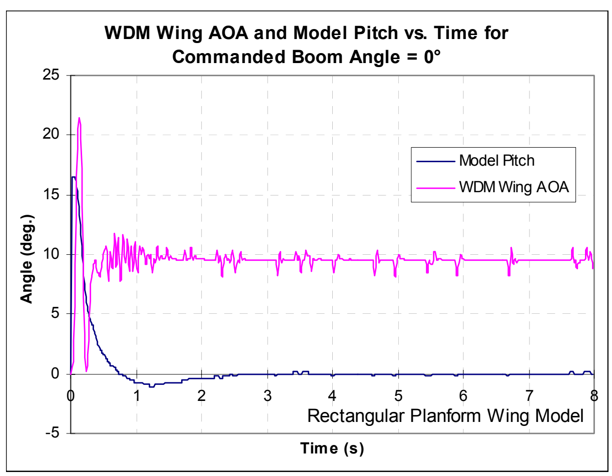

Figure 6: WDM control wing angle of attack and boom angle vs. time for commanded boom angle = 0° (rectangular planform wing model)

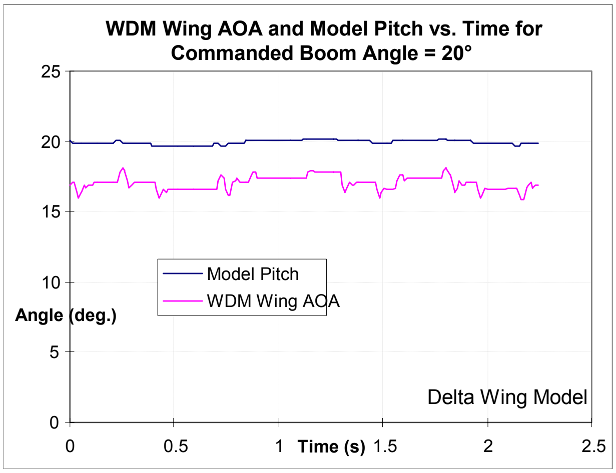

Figure 7: WDM control wing angle of attack and boom angle vs. time for commanded boom angle θ= 20° (delta wing model).

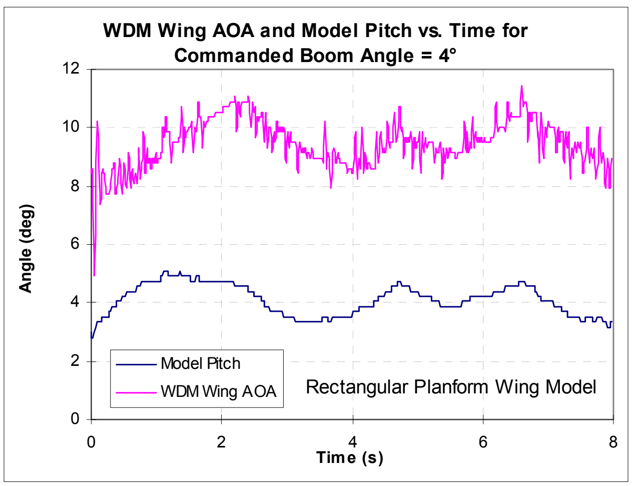

Figure 8: WDM control wing angle of attack and boom angle vs. time for commanded boom angle = 4° (rectangular planform wing model)

RESULTS

At each measurement point, the average value of α is found over the positions where the commanded and actual boom angle values are equal. The values of α and θ are then used as indices in the calibration look-up table to find the net WDM moment, which is equal to the net moment generated by the model. These data are then read into a spreadsheet, sorted according to the three different nominal angles of attack and reduced using the 3X3 matrix equations described above.

Because the model pitching moment is so small, it could not be resolved in these experiments. Further improvements on the moment resolution and control software need to be implemented before these data can be measured. The moment resolution can be improved by changing the boom lengths and the method of model mounting. A 2X2 system was used to measure only the lift and drag contributions of the model. Because there are three different nominal angles of attack, there are a total of three different combinations of the data that yield a complete 2X2 system. Solving each data point by using each combination provides three lift and drag measurements for each angle of attack, allowing for comparison between the three.

Models Used

Two different models were used to validate the WDM as a force measurement platform: a rectangular-planform wing with a NACA0012 airfoil and a flat-plate delta wing model with a beveled lower edge. These are shown in Fig. 9.

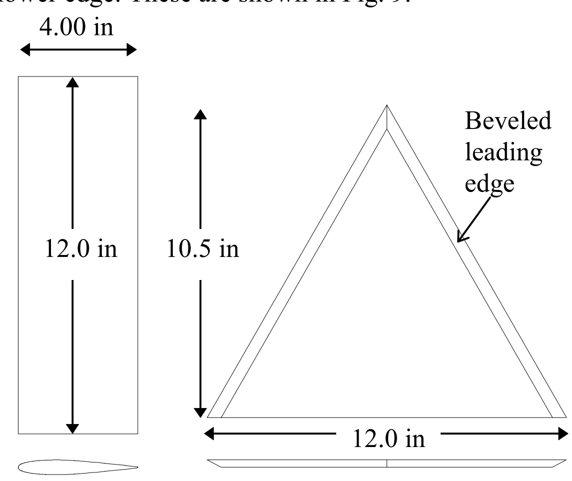

Figure 9: Models used in force measurement experiments

Rectangular-Planform Wing Model

The lift data for the rectangular planform wing are shown in Fig. 10. A 9-term lifting line solution is also shown for comparison; it is recognized that the lifting line calculation is inadequate for the small aspect ratio of the wing. The sharp peak near -10° is the result of the interference effects the WDM encounters as it pitches the model through the negative angle of attack regime. The WDM control wings are directly in the wake of the model in this range.

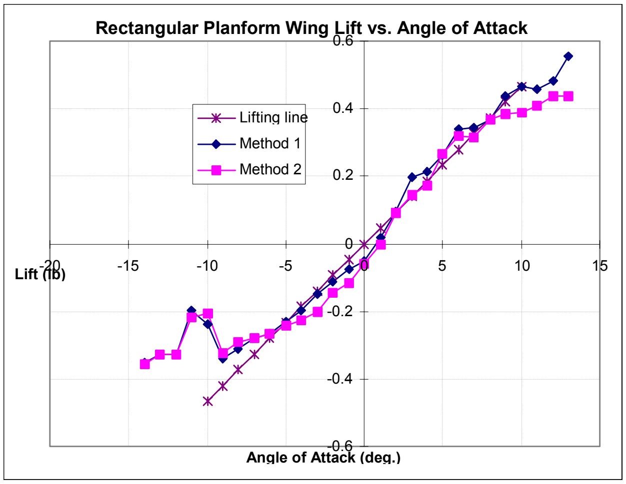

Figure 10: Measured lift curve for the rectangular planform wing model

Figure 11 shows the drag data for the rectangular-planform wing. The drag data are incorrect due to the resolution problems described. Again, the drag contribution to the overall moment is at least three orders of magnitude less than the lift contribution. As a result, small errors in the measurement lead to large errors in the reduction.

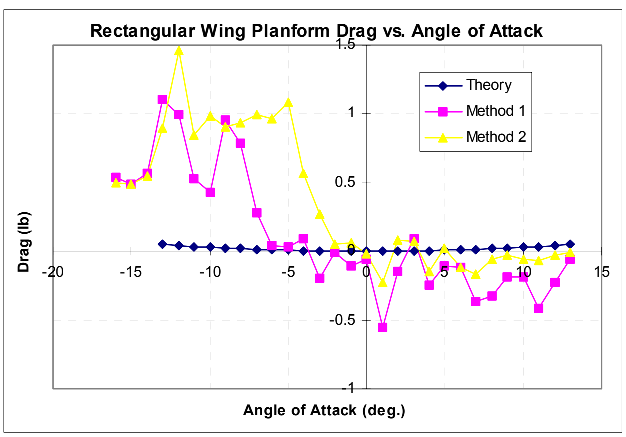

Figure 12: Measured drag curve for the rectangular planform wing model

Delta Wing Model

The lift data for the delta wing model are shown in Fig. 13, and compared with the empirical model of Edwards[17]:

$$C_L = \left(\frac{\pi}{2}\right) \cdot AR \cdot \alpha + \pi \cdot (AR)^{1/3} \cdot \alpha^{5/3}$$

The discrepancy at the negative angle of attack is again attributed to boom/control wing/ model wake interference. Figure 14 shows the drag data for the delta wing model. Again as with the rectangular-planform model, the data are poor due to the resolution problems.

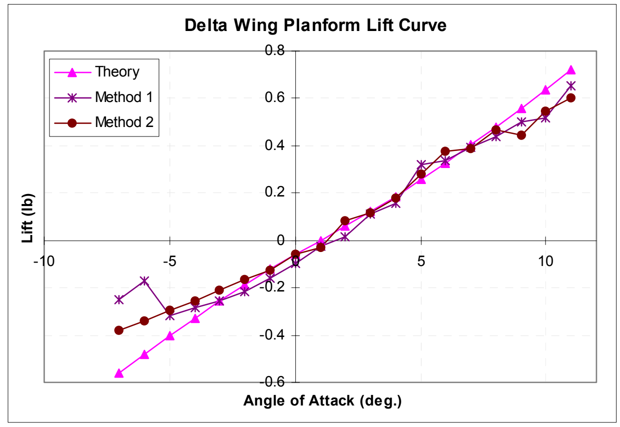

Figure 13: Measured lift curve for the delta wing model

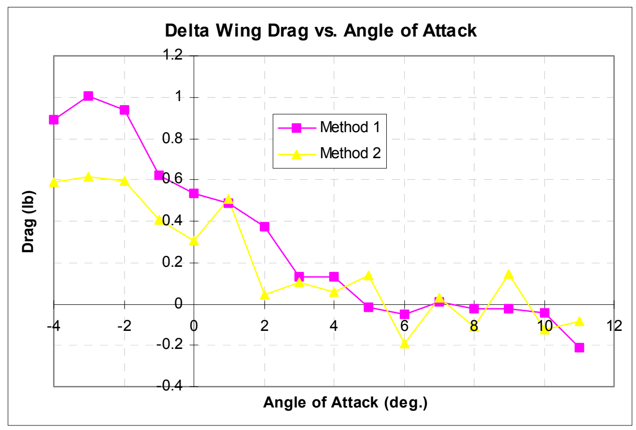

Figure 14: Measured drag curve for the delta wing model

DISCUSSION & CONCLUSIONS

It has been shown that forces on aerodynamic models can be measured using the Wind Driven Dynamic Manipulator. By inverting the control input needed to balance the aerodynamic forces and moments, direct force measurement on the model, with the complexities of wind tunnel balances, is avoided. The dominant lift forces are measured successfully over a wide range of angles of attack, going well past stall. This is done without any particular attention to keeping the control wings in the linear regime. The full nonlinear calibration of the WDM is shown, even including regimes of severe aerodynamic interference on the boom and control wings: these ranges are easily avoided when conducting actual aircraft parameter measurements.

The lift force is generally an order of magnitude greater than either the pitching moment or the drag. In addition, the lift is multiplied by the cosine of the boom angle, while the drag is multiplied by the sine of the angle, further reducing the total contribution of the drag to the overall moment. The pitching moment for most models is about two orders of magnitude less than the moment due to lift.

The solution is two-fold. By bending the boom through a right angle at the pivot and mounting the model on the vertical boom, the relationships between the moments due to lift, drag and pitching moment can be greatly altered. This is shown in Fig. 15. By changing the boom lengths, the sensitivity of the control input can be altered. For each condition, a continuous sweep of boom angles can be conducted. By this technique, a large number of test points can be obtained in a short time. In the present experiments, each value on the force vs. angle of attack plots is computed independently. The resolution of the technique also depends on the resolution of the encoders that read the control wing angle of attack.

The incremental change in moment depends on where the control wings are within their lift curve. When data from continuous boom sweeps are used, downsampling can be performed to reduce the random error. Also, when the cycle is repeated several times, the analysis is reduced to the standard problem of measuring a periodically-varying quantity, using azimuth-resolved ensemble-averaging. This will reduce the error further. These exercises are fairly obvious, and are left to later work.

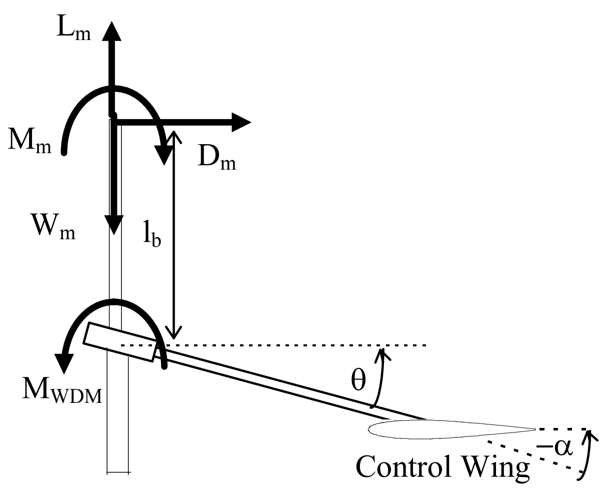

Figure 15: Concepts for varying the sensitivity to drag and pitching moment.

The larger errors at the negative angles of attack are shown in this paper to illustrate the effects of aerodynamic interference. With the boom geometry shown in Fig. 2, at negative angles of attack, the control wings come directly downstream of the wake of the model. This causes large errors in the resolution of the moment into lift, drag and pitching moment. This problem is easily avoided during actual testing of models by acquiring the negative-angle-of-attack data with the model turned upside down, or the boom bent to another orientation.

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