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Expanding the Role of the Wind-Driven Manipulator

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ABSTRACT

The wind-driven dynamic manipulator is a device which uses the wind tunnel freestream energy to drive multi-axis maneuvers of test models. This paper summarizes work performed using the device in several applications and discusses current work on characterizing the aerodynamics of an X-38 vehicle model in pitch-yaw maneuvers. Previous applications in flow visualization, adaptive control and linear-domain parameter identification are now extended to multi-axis inverse force and moment measurement over large ranges of attitude. A pitch-yaw-roll version is operated with active roll to measure forces and moments during maneuvers. A 3-D look-up table generated from direct force calibration allows operation of the manipulator through nonlinear regimes where control wing stall and boom wake-wing interactions are allowed to occur. Hybrid designs combining conventional and wind-driven degrees of freedom are discussed.

INTRODUCTION

The Wind-Driven Manipulator[1] provides a means for simulating segments of multi-axis maneuvers in a wind tunnel. The version shown in Fig. 1 enables rotation about the pitch[2], yaw[3] and roll[4] axes; which may be located either through model c.g. or other points depending on the application. Position and rate errors due to the flexibility of the device and unknown aerodynamic loads are actively compensated[5] as the maneuver is refined through repetition. This eliminates the need for massive supports. Support interference is minimized, and the devices conveys minimal reactions to the tunnel supports even in high-rate maneuvers.

The WDM uses the tunnel freestream to produce forces on the lifting surfaces (control wings) which, in turn, drive the model through maneuvers. The bandwidth of the WDM is limited largely by the bandwidth of the motors used to change the attitude of the control wings. Each control wing is light, and has a symmetrical airfoil. Since the motor produces a torque about the quarter-chord (where the pitching moment is nearly zero), the response of the controlling surface is essentially the same as the response of the motor. This enables designs where the WDM drives high-rate repetitive motions. Transient maneuvers are studied by repeating them many times precisely, so that phase-resolved measurement techniques developed for periodic flows can be used. This is most suitable for subsonic tunnels with adequate run-times.

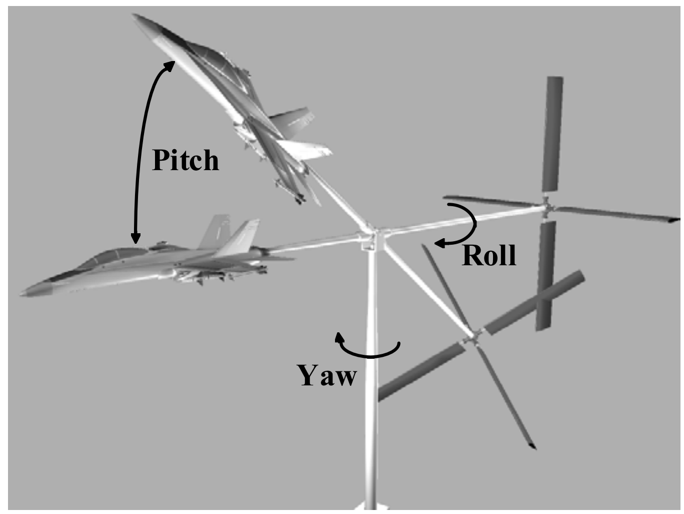


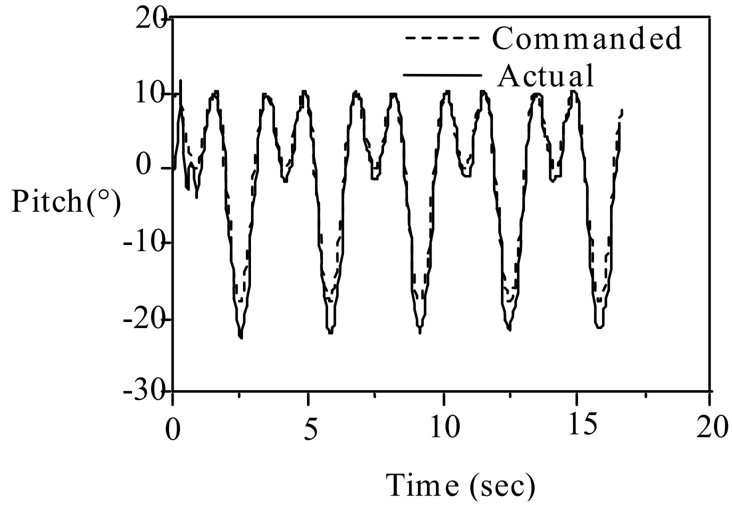
Fig. 1: Superposed frames of animation from the design rendering of a pitch-yaw-roll Wind-Driven Manipulator with a 1/32-scale F/A-18 model.

Previous methods of simulating maneuvers in wind tunnels[6-10] use rigid mounts to eliminate errors in model position and attitude. Usually this requires heavy mounting arms, and powerful hydraulic and/or electric drives, and generally cause some concern about support interference. Multi-axis systems designed along these principles generally require excitation forces that are far larger than the aerodynamic forces and moments produced by the test specimen in order to achieve high bandwidth. The support arm of the WDM is slender because the errors due to aerodynamic forces on the model can be compensated by feedback control. The excitation forces are on the order of the aerodynamic forces encountered by the model (since both are determined by the tunnel freestream dynamic pressure). Therefore, both the WDM and the model play comparable roles in determining the system response, improving the resolution im measuring each contribution. This offers the opportunity to measure aerodynamic forces and moments using the same system which is used to hold model attitude and perform maneuvers.

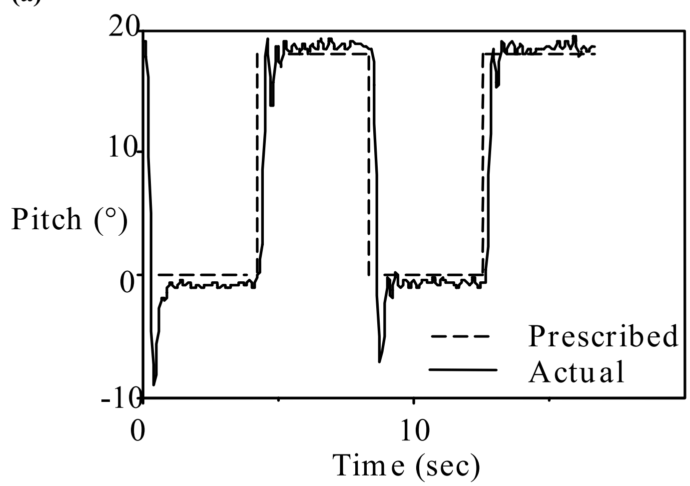
In this paper, a summary of the previous work done using the WDM is presented, before describing current efforts. The manipulator was initially used to drive specified maneuver segments. Recently, the work has focused on inverse force measurement, where the control input required to hold a given attitude or perform a given maneuver is used to extract the forces acting on the model, as well as to develop dynamic system descriptions.

SUMMARY OF RESULTS

Figure 1 shows two superposed frames of an animation used by the second author in 1995 to validate the design of the pitch-yaw-roll wind-driven manipulator for the John J. Harper 7' x 9' wind tunnel. The computer graphics rendering was developed from the design to test test section clearances and motion ranges. A 1/32-scale F-A-18 model is shown in a body-axis sting-mount configuration at the end of a long boom. The boom is driven in pitch, yaw, and roll by the 4 independently-controlled wings at the end of a lever arm. Each wing is balanced at quarter-chord, (the location of the aerodynamic center and center of pressure of each wing in incompressible flow) so that the torque required to hold a given attitude is minimum. Each wing is driven in pitch by a servo motor, and its instantaneous attitude with respect to the boom is read by a controller. This moves the model through specified maneuvers, repeatedly. The instantaneous boom pitch and roll, and the yaw of the pivot, are read from encoders at the boom fulcrum. The digitizing rates are well above the Nyquist frequencies[11] of the various time-dependent processes involved. By monitoring the actual maneuver history, and referring to functional forms of the aerodynamic behavior of the control wings, the actual trajectory is brought as close to the desired one as motor bandwidth and power will allow. Since the maneuver can be repeated precisely through many cycles in a short time, conditional sampling and phase-resolved ensemble-averaging techniques used in periodic flow measurements can be applied directly to the flow over a model executing arbitrary maneuvers. The flowfield around the model during such maneuvers can be measured using planar, or even single-point diagnostic techniques. Alternately, knowledge about the response of the manipulator itself, and the aerodynamics of the control wings, can be used to measure the forces and moments acting on the test model during arbitrary maneuvers. A third feature is that the WDM allows the use of flexible arms, and accounts for the errors due to flexibility. The obvious advantage of this is that the support arms can be slender and light, enabling fast actuation without large flow interference. Vibrating booms also enable separation of the frequency ranges of model motion for dynamic parameter identification. These features take the WDM well beyond the capabilities of previous technology in wind tunnel testing. Results from each of these capabilities are shown in this paper, and the corresponding references for detailed documentation are given. The 3-d.o.f. manipulator is an outgrowth of developments presented in Refs. 1-5. In this paper, we review several of the demonstrated capabilities of such devices, and present other directions of progress. Recently, papers have appeared at SAE and AIAA conferences[12-13] claiming a "novel device" which appears to be an imitation of the WDM, made without acknowledgement or reference to our work, which was presented to these authors in the years before these papers. These papers cite "future work" which might approach the state of WDM technology demonstrated in 1992 or 1993[2] , but suffered from "stair-like motions"[13] which appear to have resulted from inadequate understanding of the design parameters.



(a)



(b)

Figure 2: Trajectory Tracking with 1-DOF Pitch Manipulator Using PID Control with (a) multiple harmonic input and (b) square wave input. Ref. 2.

PITCH MANIPULATOR PERFORMANCE: FOURIER SERIES AND STEP FUNCTION RESPONSES Figure 2 from Ref. 2 shows the pitch history of a 1/32-scale F-15 model in the 1.07m x 1.07m tunnel. In part a), the ability to execute a programmed multiple-harmonic motion is shown: the maneuver is simple enough for a Proportional-Integral-Derivative (PID) controller to achieve excellent matching between the desired and actual maneuvers. In Fig. 2b, the response to a commanded step input is shown. By adjusting the gains of the PID controller, the overshoot is kept low, and a pitch rate of over 120° is achieved at a tunnel speed of only 13.3m/s. The continuous multiple harmonics of Fig. 2(a), and step function performance of Fig.2(b) were chosen to investigate performance of the WDM concept over the extremes of the dynamic range. Ref. 5 discusses the choice of sampling and control input rates to satisfy the relevant Nyquist criteria. Mechanical gearing at the pivot point was considered to increase the maneuver rates. However, when one studies the physical phenomena involved in dynamic stall or vortex bursting, which usually motivate high-pitch-rate experiments, it is seen that the high acceleration is needed only for a short segment of a maneuver. These segments can be more elegantly and efficiently simulated by optimizing the response to square-wave type motion commands, and using feedback control of elastic components. This is discussed below.

ADAPTIVE TRAJECTORY MATCHING At extremes of the maneuver envelope, the relationship between motor command and model movement will become nonlinear. Thus the gains needed for different portions of a maneuver will be different. Frequency-dependent phase lags complicate the picture. Under such conditions, an adaptive controller can improve the trajectory-matching performance. In Fig. 3a, the trajectory of the model (a delta wing in pitching motion) differs significantly from the desired trajectory. An adaptive algorithm[5] alters the PID gains to reduce the error (Fig.3b). After a few cycles of the maneuver, the trajectory has converged to the desired one, as shown in Fig. 3c. A corresponding algorithm for a 3-D.O.F. system poses a substantial engineering challenge because of the flexibility and coupling between axes, and the nonlinear relations over the full range of motion. This is under development.

UNSTEADY INTERACTIONS DURING SLOW MANEUVERS An important capability opened up by the WDM is that of visualizing aerodynamic interactions which may occur during aircraft maneuvers. Fig. 4, from Ref. 3 shows vortex flow features observed during a sequence of 3 video frames, as a 1/32-scale YF-22 model during a pitch-yaw maneuver with body-axis roll held at zero. The wax smoke visualization was performed using a pulsed copper vapor laser sheet and video cameras. Such maneuvers are outside the usual axis-coupling envelope, but are becoming feasible with thrust vector control and forebody control devices[6]. The reduced-frequency computed for this maneuver is extremely low[3], so that it would appear to be a quasi-steady motion. However, two highly unsteady features are observed: the sudden change in the left wing vortex structure, and the interaction of the vertical tails with the vortex system. Similar interactions are expected during pitch maneuvers of canard-wing configurations [14-15].

ATTITUDE HOLDING In high angle-of-attack experiments, vibration of the model is usually a problem unless the sting-mount is made very stiff (and bulky). The vibration is hard to eliminate, because the model is cantilevered, and even the fixed end is excited by the vibrations transmitted from the tunnel floor and supports. Experiments with the pitch manipulator revealed that vibration levels with this flexible manipulator were less than those with rigid sting mounts. This is for three reasons: a) there is no rigid connection to the floor, b) aerodynamic damping of the control wings, and c)feedback control of model attitude. Fig. 5 shows time traces of the pitch angle, showing that angle of attack change is less than 0.1 deg. except for the sharp controller jitter which can be damped out for use in actual flow measurements. The periodic vibration expected with a rigid mount is eliminated.

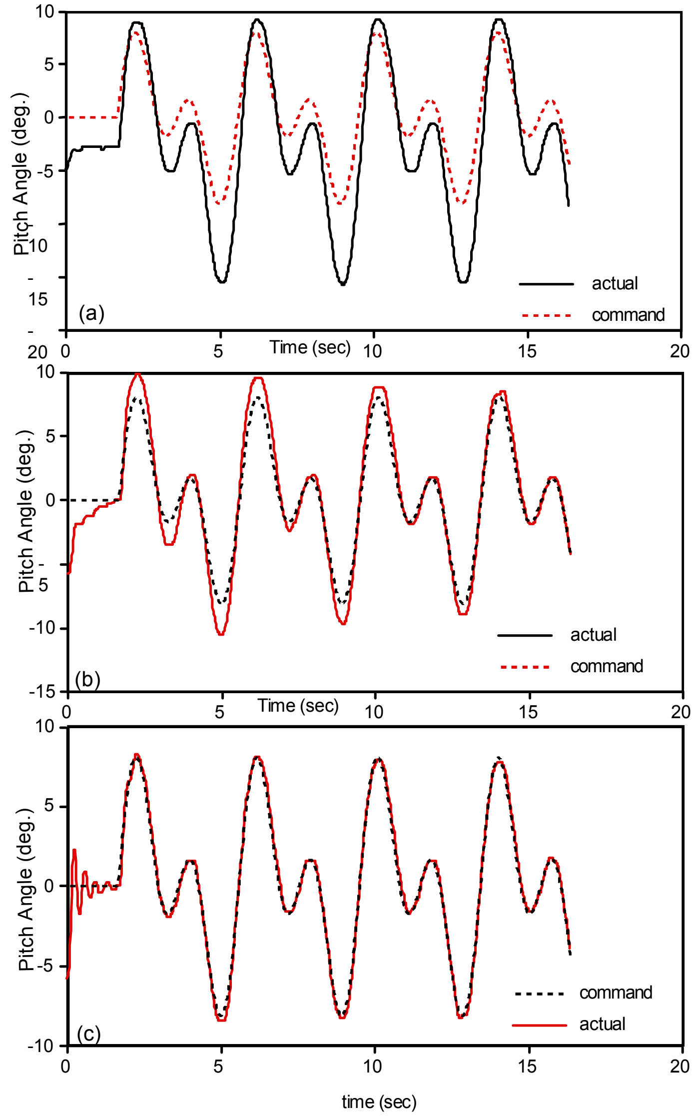


Figure 3: Performance of an adaptive controller in matching specified pitch trajectories, tested using a delta wings and a 1/32-scale F/A-18 model. (a) Before adaptive controller turned on; (b) shortly after; (c) steady-state adaptive controller performance.

ACTIVE ROLL STABILIZATION The 3-d.o.f. WDM is statically unstable in roll: this provides for greater roll control power. The device is actively stabilized in roll by the feedback circuit. Initial experiments had difficulty with this, and a few instances of uncontrolled roll, occurred, reaching roll rates of 1500 deg. /sec. before the roll limiter safety device activated, with no damage resulting to the WDM. Later experiments suffered from coupling between pitch and roll due to some asymmetries between the control wings[4] . This is seen from Fig. 6. More recent results with an improved controller are shown in Fig. 7, where roll jitter is kept to very small levels as an X-38 model is taken through pitch-yaw maneuvers.

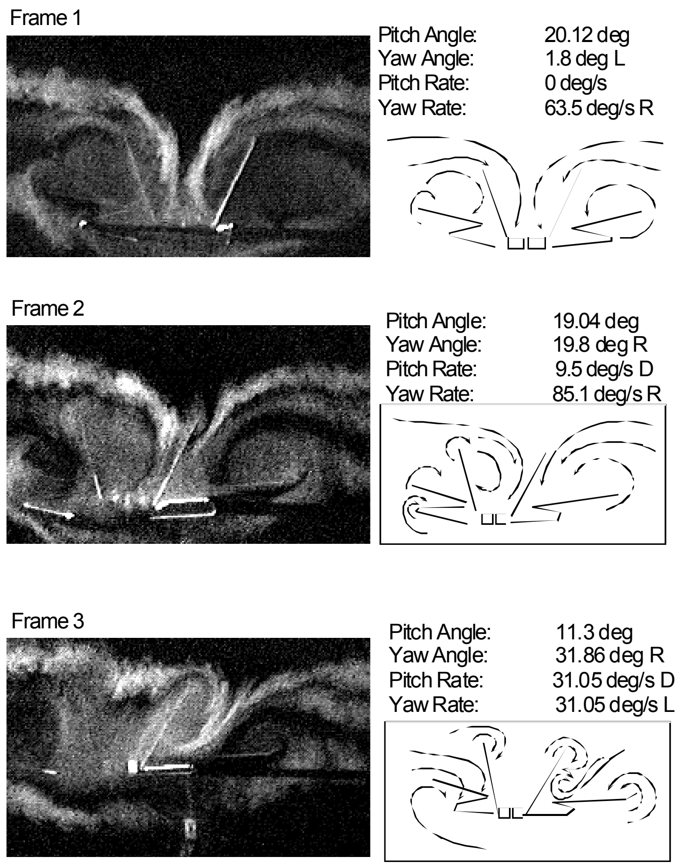


Figure 4: Laser sheet cross-flow images at the aft end of the vertical tails of a 1/32-scale YF-22 model executing pitch-yaw maneuvers. From Ref. 3.

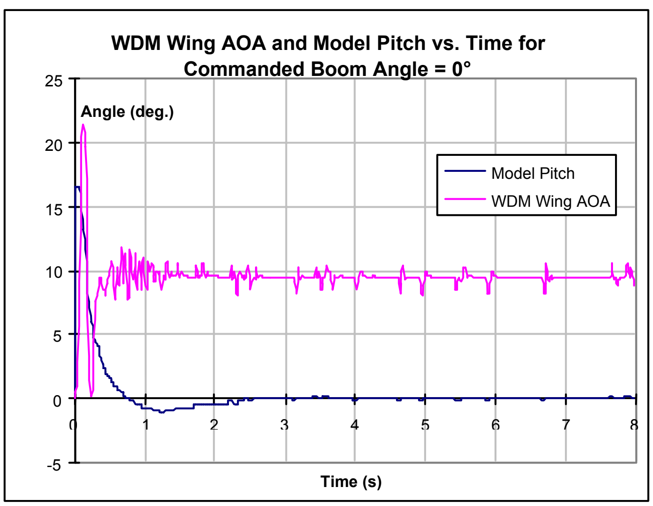


Figure 5: Model attitude holding: time trace of jitter of a pitch manipulator holding a rectangular wing in a wind tunnel.

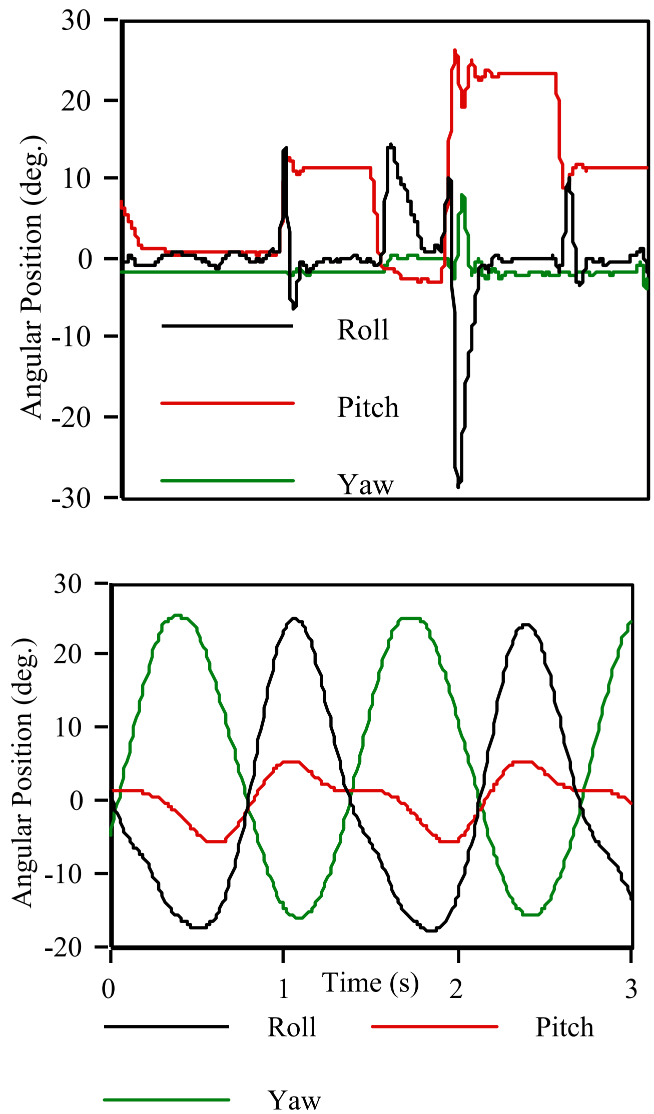


Figure 6: Roll error during pitch-yaw maneuvers of a 1/32-scale F-16 model. From Ref. 4.

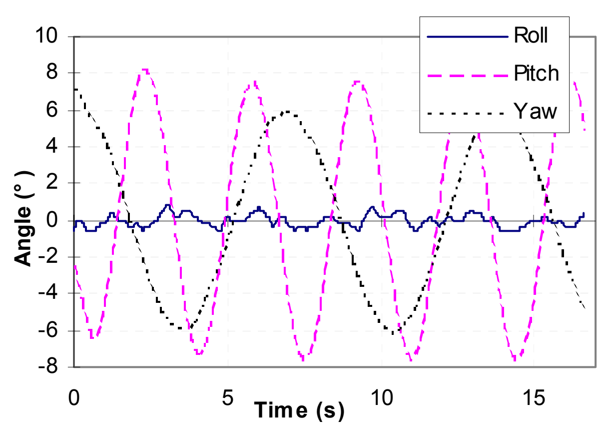


Figure 7: Roll jitter during pitch-yaw maneuvers with an X-38 model.

DYNAMIC PARAMETER IDENTIFICATION: LINEAR REGIME The above results on active feedback control illustrate that a combination of empirical feedback and aerodynamic modeling can be used to decide the control wing attitude needed to achieve a given model orientation and motion rate, through changing flowfield conditions. This fact can be turned around to use the control wings as sensors, with their attitude and trajectory converted to the aerodynamic forces and moments on the test model. This has several uses.

To measure stability parameters of an aircraft model about a given steady-state flight condition, the model is held at a mean attitude, and small-amplitude perturbations of the control wings are used to drive small-amplitude oscillations of the model. A second-order aerodynamic model of the system is developed, and the parameters dealing with the aerodynamics of the test object are derived by comparing simulation and experiment. By this technique, Magill et al[16] were able to measure the pitch damping parameters of a simple wing-tail configuration, and achieved results within 10% of the theoretical results. Here the control wing angle of attack was kept well inside the linear part of the lift curve, so that linear aerodynamics was adequate.

Figure 8 illustrates an extension of this concept, to a case where the model is moving through a rapid maneuver. The instantaneous values of all aerodynamic parameters and their derivatives are determined from verifying the aerodynamic model for every segment of the maneuver. This maneuver is repeated periodically, with large-amplitude motion and relatively low frequency. Superposed on this maneuver is a high-frequency, small-amplitude motion, achieved through aerodynamic or electric servo control, or through elastic resonance of the boom itself. The aerodynamic forces and moments on the test aircraft model provide the forcing function for the boom vibration. This is extracted by matching the system response model with experiments. Through the use of elastic resonance, the frequency regimes of the small-amplitude perturbation and the large-amplitude maneuver can be separated widely. The large amplitude motion can then be assumed "frozen" while solving for the small-amplitude aerodynamic response. The small-amplitude motion can be assumed to be in equilibrium while solving for the large-amplitude force and moment history.

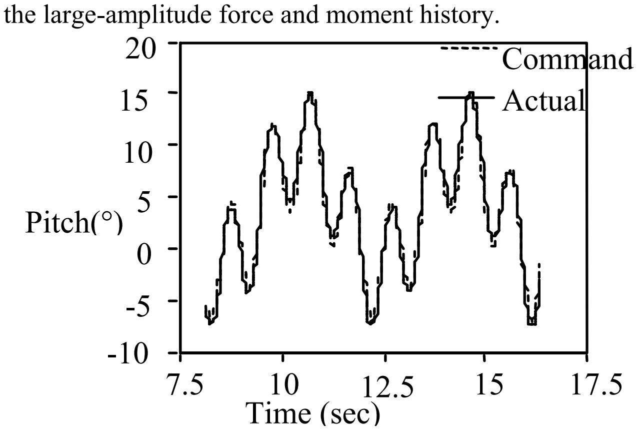


Figure 8: Superposing small-amplitude, high-frequency perturbations on a large-amplitude, lower-rate maneuver. The amplitude of the perturbation is exaggerated, and the frequency reduced for visibility.

DESIGN TRADEOFF BETWEEN RATE AND SENSITIVITY The WDM functions like an aerodynamically operated lever. To get a large force at the model end, the control arm must be long. On the other hand, to get high sensitivity to measure forces at the control wings, the model arm must be long. This was studied quantitatively by Ames[17] for a 1-d.o.f. manipulator.

STATIC FORCE AND MOMENT MEASUREMENT For the 1DWDM, The static force and moment measurement procedure is one in which the model is held at a commanded pitch angle using a PID controller. In this configuration, the sum of the moment contributions from the WDM and the model must equal zero; i.e.

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

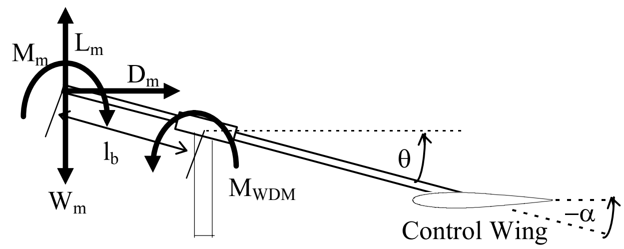


Figure 9: Geometry of the 1-DOF WDM force and moment balance with model attached

Given the geometry in Fig 9, the net moment generated by the model is

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

The control wing position required to maintain the same commanded model angle for two different nominal model angles are then compared to a previously generated look-up table generated with known weight loadings, setting up a system of two equations in two unknowns for the lift and drag. By adding a third nominal model angle, the pitching moment can be measured, as well, resulting in the following system of three equations in three unknowns:

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

These equations are used for measuring the forces on one axis (pitch). The same measurements can be mode on the yaw axis by replacing the lift, drag and pitching moment with sideforce, sideforce contribution to drag and yawing moment. The model is then placed at three different nominal sideslip angles and the same procedure is used to solve the equations.

CALIBRATING THE 3-D WDM FOR OPERATION IN THE NONLINEAR REGIME A load is applied along each component (roll was held constant at 0° for the first set of experiments) and the output from the control wings, required to maintain the commanded inputs in pitch and yaw, is recorded as indicated in Fig. 10. This process was systematically carried for the full range of angles and expected loadings and the data used to generate the look-up table. With the model installed and held at a commanded angle of attack and sideslip, the position of the control wings are used as indices into the look-up table to find the corresponding forces (now generated by the model rather than known weights).

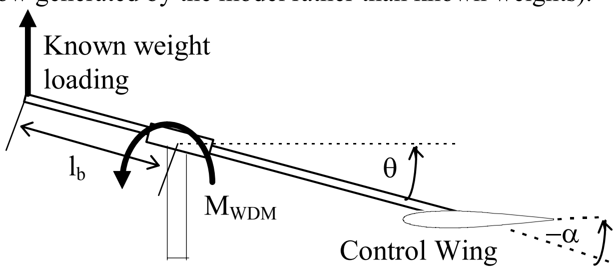


Figure 10: Illustration of Calibration Procedure of a WDM for inverse force measurement

A similar calibration is run for the rolling moments, as well. The WDM is again run through the full required range of motion, but in this calibration, the applied weights are offset and the differential as well as common mode deflection of the pitch wings (only the pitch wings are used for roll stabilization) are recorded and used to generate another look-up table.

The operating envelope of a given design can be widened by going into the nonlinear aerodynamics regime. The results are shown in Fig. 11, where the calibration of a 1-d.o.f. WDM is shown over a wide range of pitch angles. The range includes regions where the control wings are stalled, and those where the control wings are in the wake of the boom and its supports. The calibration is performed by suspending known weights from the model end of the boom and measuring the wing pitch settings needed for equilibrium at each attitude. In the linear regime of the control wing angle of attack (<12°), the moment is linear as the lift dominates the force providing the moment. As the wing passes through the stall, however, the drag begins to take over and the moment curve becomes more quadratic. Through the entire regime, however, the 1DWDM is able to maintain good control authority whether the moment is generated by the drag or lift.

LIFT MEASUREMENT ON A DELTA WING Figs. 12a and b show views of a 1-d.o.f. manipulator used to measure lift of a delta wing model in the 1.06m x 1.06m wind tunnel. Fig. 13 shows lift measurements on a finite wing, compared with the predictions from a lifting line code. The accuracy level is not as good as that available from conventional balances for this application; however it should be noted that the data are obtainable while the wing is moved through a quasi-steady sweep of angles of attack, without actually pausing at any value for any length of time. Lift measurements on a delta wing are shown in Fig. 11, compared to the empirical prediction of Edwards[18]. Here the accuracy is better, though the angle of attack range tested is fairly small.

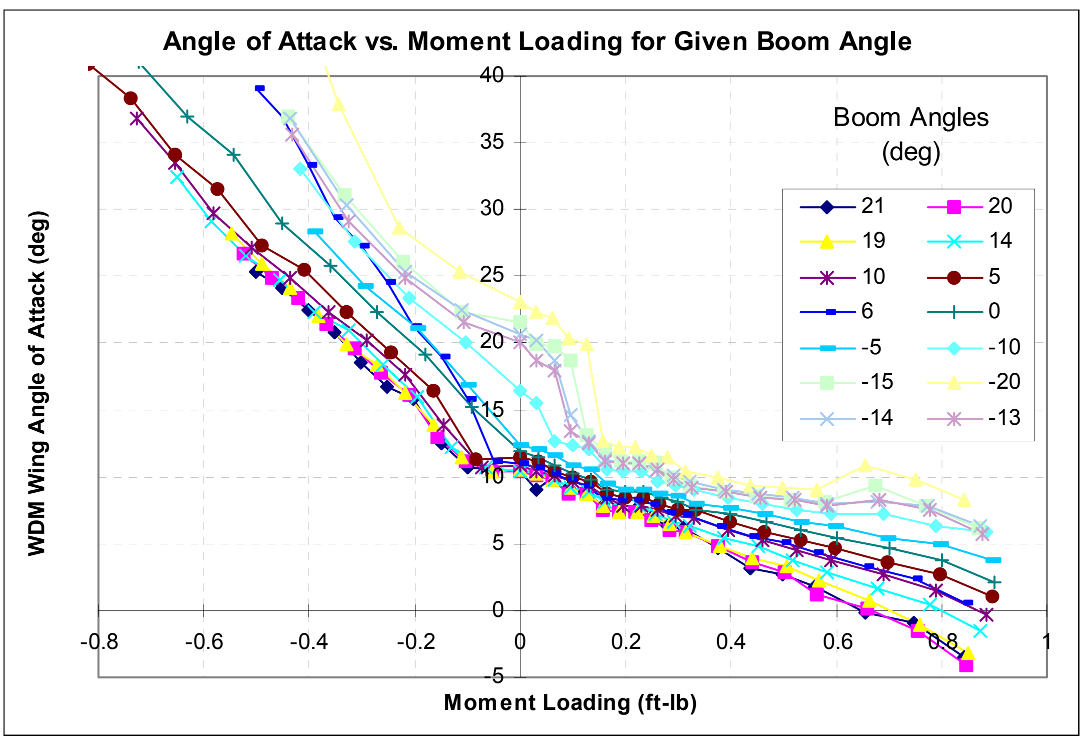


Figure 11: direct nonlinear calibration of a 1-d.o.f. WDM. The moments generated by the control wings are plotted against angle of attack for various boom angles. Regions of nonlinearity are caused by interference between boom wake and control wings, and by wing stalling. From Ref. 19.

(a)

(b)

Figure 12: Pitch Manipulator used for delta wing lift measurements. From Ref. 19.

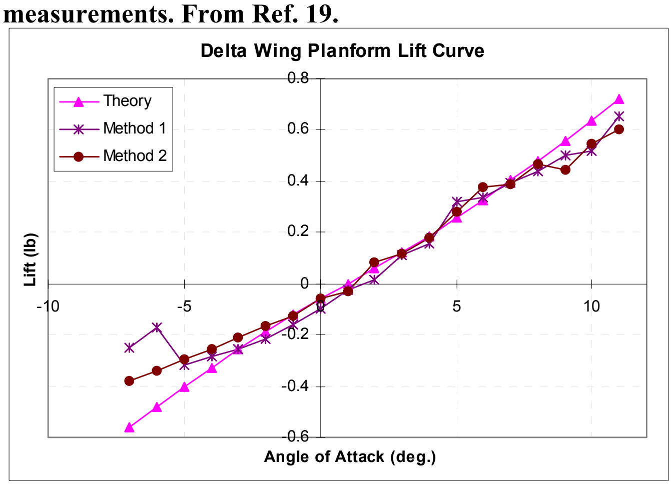


Figure 13: Inverse lift measurement on a delta wing using a 1-d.o.f. pitch manipulator, compared with empirical model of Edwards[17]. The large error at negative angle of attack is due to interference between the delta wing wake and the control wings. From Ref. 19.

MEASUREMENTS ON AN X-38 MODEL Figure 14 shows the test setup currently being used to do static and dynamic parameter measurement on an X-38 model. The model has two servo motors that actuate the flaperons on the underside of the model in either common mode or differential deflection. In this way, the flaperons are used to generate both rolling and pitching moments.

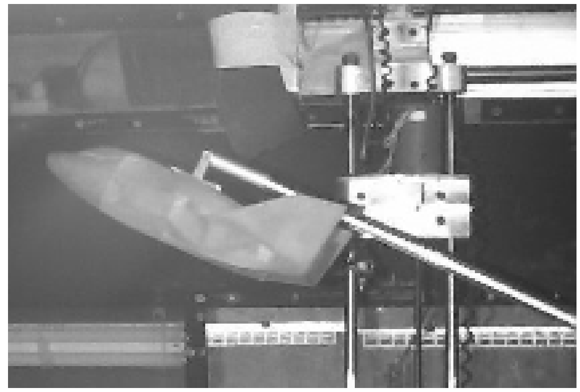


Figure 14: X-38 Model attached to the 3DWDM.

A current set of experiments is aimed at measuring these moments and the resulting forces acting on the X-38 model using the 3DWDM for both static and dynamic test conditions.

HYBRID DESIGNS Several hybrid forms of manipulators have been designed for various applications. A linear track degree of freedom is used to couple linear acceleration with roll, pitch, or yaw motions in order to simulate aircraft maneuver segments completely. Servo motors mounted directly under delta wing models are used to perform body-axis yaw during pitch-roll maneuvers driven by the WDM. The X-38 model discussed before has servo motors to deflect flaps during maneuvers for studies of flap effectiveness. All of these designs may also be combined with gears where warranted. These are some of the variants which are obvious, given the basic WDM concept.

MEASUREMENT UNCERTAINTY Three optical encoders are used to measure the roll, pitch, and yaw angles. These are optical quadrature encoders with an accuracy of +/- 0.09°. The encoder signals are counted by a 4-axis encoder board in an 80486 PC. The angles of the motors that drive the wings are measured from a 16 pulse-per-revolution magnetic quadrature encoder that is integral to each motor. The motors in turn, have a 76:1 gearbox. The angular resolution at the output to the wings is then 0.074°.

CONCLUSION

The Wind-Driven Dynamic Manipulator has been shown to enable multiple-axis maneuver simulation of models in wind tunnels. The versatility of generating arbitrary pitch waveforms was demonstrated in early tests in 1992 with a simple PID controller. An adaptive algorithm produced a large improvement in the fidelity of simulations. Pitch-yaw maneuvers used with flow visualization on swept-wing aircraft models showed transient, unsteady vortex-surface and vortex-vortex interactions under conditions which appeared nominally quasi-steady based on the low value of reduced frequency. Active-controlled model positioning is demonstrated with the WDM, with angle-of-attack oscillations kept under 0.1 degree even at tunnel speeds of 75 fps with no damping. Active roll stabilization enables rapid 3-d.o.f. maneuvers with low cross-coupling. The behavior of the WDM control wings in the linear regime has been used to perform aircraft stability parameter identification. A design tradeoff is seen between driving torque and sensitivity for force measurement: this is partially avoided by operating the control wings into the stall regime and using their drag to generate the driving torque. The envelope has been extended to the full nonlinear regime encompassing regions of boom-wing interactions using a direct nonlinear calibration technique. This has been used for force measurement on rectangular wings, delta wings and an X-38 model during quasi-steady maneuvers.

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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