AIAA Paper 96-0581, 34th Aerospace Sciences Meeting, January 1996

DESIGN AND TESTING OF A 3-D.O.F. WIND-DRIVEN MANIPULATOR

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ABSTRACT

The Wind-Driven Dynamic Manipulator is a robotic device used to execute multidimensional maneuvers and measure forces on aircraft models in a wind tunnel. Tunnel freestream kinetic energy is used to power the device. This paper describes the design, testing and use of a pitch-yaw-roll version of the device in a 2.1m x 2.7m wind tunnel at speeds up to 33 m/s. Previous work using 1 and 2-d.o.f. devices is summarized, where high--rate pitch with step and multiple-harmonic waveforms, coupled pitch-yaw maneuvers, and small-amplitude oscillations have been demonstrated. Results from adaptive pitch tracking are shown. Design tradeoffs and the construction of the 3-D device are discussed. Flow interference is shown to be negligible. Step-response experiments at high and low angle of attack are demonstrated. Pitch-yaw-roll motion histories are presented. The device is statically unstable in roll, but roll stabilization by feedback control enables pitch-yaw maneuvers. Feedback control also enables steady testing at low and high angles of attack with a slender sting mount.

INTRODUCTION

Over the past three years, we have developed a device which enables wind tunnel testing of aircraft models in complex maneuvers and opens up ideas for extracting dynamic stability derivatives. This is the Wind-Driven Dynamic Manipulator[1]. Ref. 1 summarizes the problem of simulating coupled-axis maneuvers using traditional stiff-armed manipulators: a device strong and powerful enough to perform high-rate motions about multiple axes without trajectory errors becomes more intrusive to the flow than the model itself. Such a device also transmits reactions to the tunnel supports, requiring modifications to the tunnel structure.

The WDM integrates digital control systems with aerodynamics to enable new types of aerodynamic measurements. As shown in Fig. 1, the device holds the aircraft model on a pivoting lever arm with wings at its other end. The power for the device comes from the test section freestream The device is light and the wings respond at high rates to excitation about their pitch axes from servo motors. Position and attitude feedback from the model enable adaptive compensation of trajectory errors after a few repetitions of a specified maneuver. As we will demonstrate, this approach also has an unexpected side benefit: it can alleviate the problem of model vibration which plagues high-angle of attack experiments.

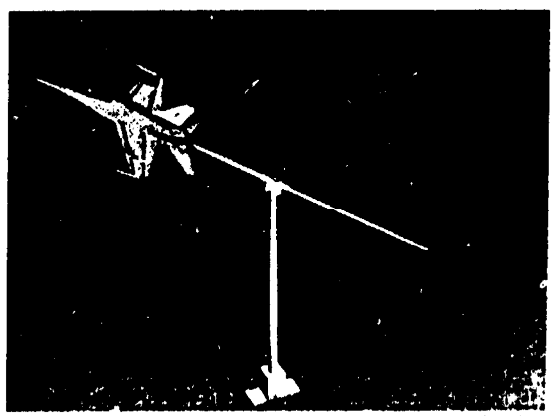

Figure 1: Solid rendering of the design drawings of the three degree of freedom Wind-Driven Dynamic Manipulator with a 1/32-scale F/A-18 model. Each control wing has a servo motor to change its pitch. The boom rotates in the roll bearing and the post rotates in the yaw bearing at the base.

PREVIOUS WORK

Ref. 1 surveys other techniques for unsteady aerodynamic testing. Briefly, the approaches consist of either cam-driven periodic motions or motions using stiff-armed manipulators driven by hydraulic or electric motors and gears[2-9]. Tethered testing[10] and free-flight testing[11] in wind tunnels are also performed with specialized facilities and expensive models.

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Ref. 12 describes the concept of the WDM. A pitch manipulator[1] demonstrated the ability to repeat square-wave, sinusoidal and multiple-harmonic motions. Ref. 13 showed flow visualization results during large-amplitude, quasi-steady pitch-yaw maneuvers using a 2-d.o.f. device. Even at a reduced frequency of 0.03, violent vortex interactions not seen in steady-state testing were captured quantitatively. Ref. 14 showed first measurements of dynamic stability derivatives using the pitch manipulator and Ref. 15 discussed the control system for the device. Ref. 16 presented an adaptive control system and Ref.17 summarized six applications of the device: dynamic pitch variation, multiple axis maneuvers, exploration of vortex interactions, measurement of rate effects, measurement of steady forces and moments, forced broad-band excitation to determine stability parameters and development of flight control laws. Fig. 2 shows an open loop response to a specified pitch testing trajectory. Fig. 3 shows the beginning of the adaptive tracking, and Fig. 4 shows the trajectory achieved after the adaptive tracking has converged to the specified trajectory.

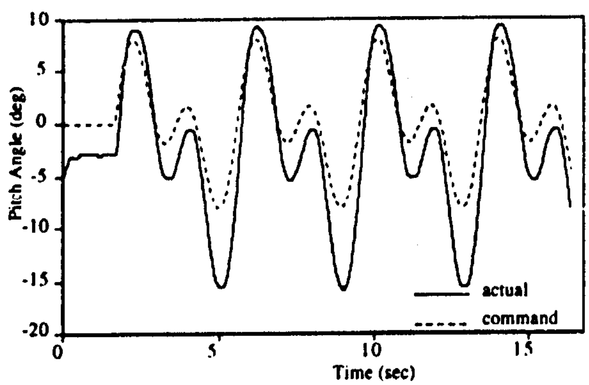


Figure 2: Pitch Manipulator trajectory tracking without adaptive control.

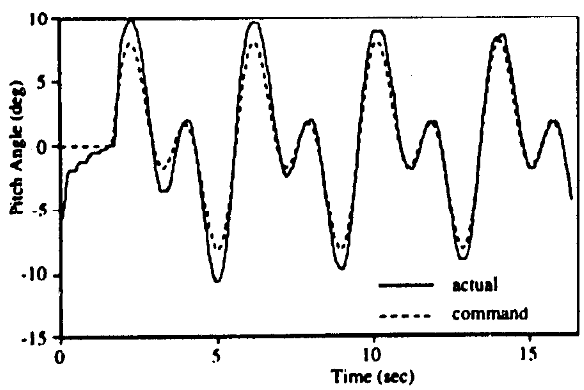


Figure 3: Pitch trajectory tracking shortly after the adaptive control is turned on.

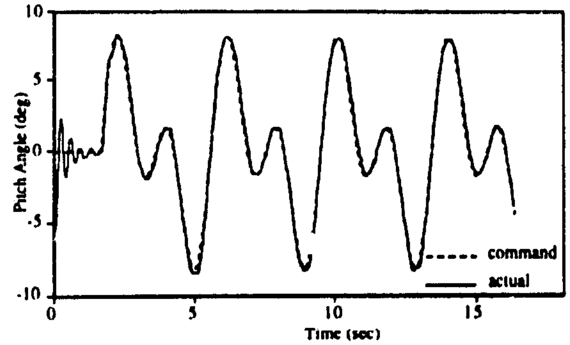


Figure 4: Steady-state pitch trajectory tracking performance of the one D.O.F adaptive controller.

OBJECTIVES

Having tested 1- and 2-d.o.f. devices, we proceeded to design a 3 d.o.f. device for the John J. Harper Wind Tunnel, which has a 2.1x 2.47m atmospheric test section. . This paper presents the design and initial testing of the 3-d.o.f. WDM. It shows the various design tradeoffs, methods of ensuring safe operation, and the testing and uses of the device. An accompanying videotape demonstrates the start-up of the device and the performance of various maneuvers.

DESIGN TRADEOFFS OF A 3-D.O.F DEVICE

Ideally, a robotic manipulator for aircraft testing should allow motion with high values of reduced frequency **k** about all six degrees of freedom. These motions would ideally include large-amplitude excitation of models of arbitrary weight and size at any tunnel speed. It should also allow measurement of forces, moments and their derivatives with high sensitivity and frequency response about all 6 degrees of freedom., and enable the execution of complex trajectories at high rates with perfect accuracy.. Below, we examine some of the tradeoffs in designing wind-driven manipulators. A design tradeoff calculation was developed using Microsoft Excel on a personal computer using several of the considerations discussed below.

Reduced Frequency vs. degrees of freedom

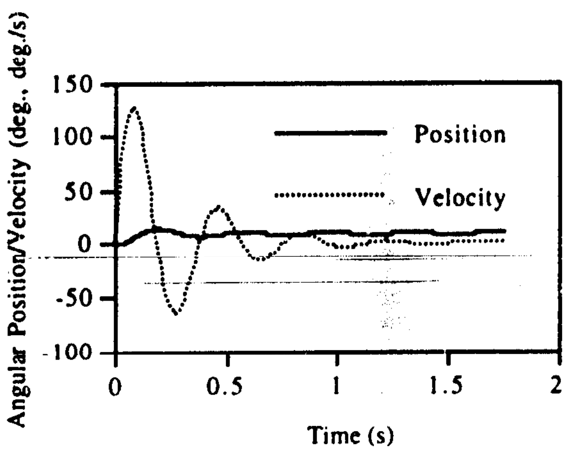
A gear in the coupling between the model mount and the control lever arm would enable high-rate motion with moderate loads on the lever arm and control wings. However, this would complicate the construction of a multiple axis device and was avoided in the design.

Reduced Frequency vs. Range of Motion

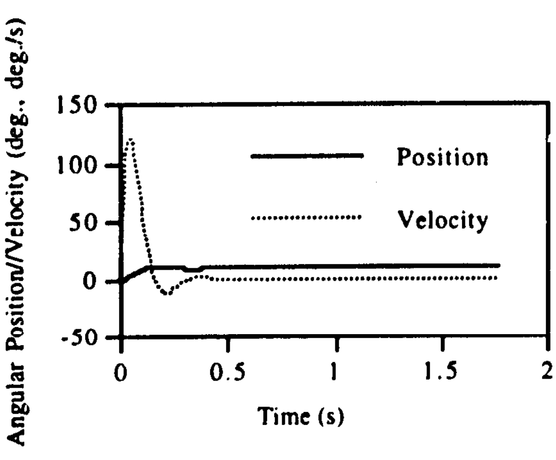
Here the tradeoff is between amplitude and frequency. This tradeoff s highly dependent on the bandwidth of the motors selected to drive the wings. The process of acquiring small motors with high bandwidth and durability posed some challenges during the project.

Boom Length Constraints

The control arm length is a complex choice. A long arm provides higher driving torque However, a longer arm limits the amplitude of motion to that which keeps the wings from hitting the walls. A long arm also has higher flexibility and lower structural natural frequency. At the same time, it has higher inertia and increases the damping in the system. The added damping increases the tracking performance of the device. Fig. 5 illustrates the effect of changes in boom length on system response to a unit step input about the pitch axis.



a)



b)

Figure 5: Angular Position and Velocity vs. Time for a Boom Length of a) 0.46 m and b) 0.92 m.

As shown in these plots, doubling the boom length reduces the time to stabilize the manipulator by more than 70%. Further increases in boom length have less dramatic effects but still prove to be significant.

Effects of Tunnel Speed

As tunnel speed U_∞ increases, the rate needed for a given reduced frequency **k** increases. However, **k** increases only linearly in U_∞ whereas driving torque increases with $U_\infty{}^2$. The added driving torque provides the extra "push" needed to drive models through higher rates. The stresses on the model and device also increase with $U_\infty{}^2$, and the cost of device failure may increase with a higher power of U_∞. The penalty of ensuring safety might offset the available-torque advantage until adequate operating experience is gained with the device.

Force Measurement vs. Flow Visualization

To visualize complex vortical flows generated during coupled-axis maneuvers, the model must execute these maneuvers repeatedly with high precision. This suggests a large manipulator whose big wings and long lever arm dominate the dynamics, with the forces on the model being kept as a small perturbation. To measure stability derivatives, on the other hand, the model must be excited at high frequency with small amplitude. The forces on the model must cause large measurable effects on the control input to the wings. The lever arm to the control wings must be short, and the wings must have short chord for fast response. Gearing the model becomes less practical in this application. Thus the requirements for high-rate, high-amplitude maneuvers are different from those for measuring dynamic stability parameters.. Interchangeable arms and wings of different sizes will enable the operator to configure the device for either type of test.

Wing Size vs. Inertia

The control wings must obviously be as light as strength considerations will allow. The device is built to survive forces exceeding those at 90° incidence at maximum tunnel speed and wing acceleration. High aspect ratio is desirable for three reasons: (i) for aerodynamic efficiency, (ii) to shorten the aerodynamic response time of the wings, and (iii) to increase roll damping, hold the model more stable and enable the adaptive control system to converge to the desired trajectory quicker. Against these are (i) the added weight of the cantilever support of high-span wings designed for high acceleration, and (ii) wing size constraining the range of motion in a test section of given size.

Model Weight

In general, the model must be as light as possible. The only exceptions are experiments where internal balances or other instrumentation must be placed inside the model. This fact poses a challenge in building models with flow or flight control devices for use with the WDM.

Model Attachment

For multi-axis, high-rate, large-amplitude maneuvers of modern aircraft, there is no unique ~~choice for the center of rotation. Thus~~ there is not much benefit ~~in going to the extreme~~ trouble of designing specific model mounts. We decided to face the problem of moving at least two degrees of freedom simultaneously to get desired acceleration vectors. This can be done by incorporating motor-driven linear degrees of freedom with the wind-driven device, once the problems of multi-axis control have been satisfactorily solved. The motors for these degrees of freedom can be located near the floor of the test section. These linear degrees of freedom are in the construction stage.

AERODYNAMIC FEATURES

Flow Interference

Wake effects on wings

Boom orientations can be configured to avoid interaction of the model wake and the control wings. Interaction may cause transient loads on the wings, which would require adaptive correction during the test. For the present device, we are using a straight boom which allows a 1/32-scale F-16 to go to 30 deg. angle of attack with 1' clearance to the tunnel roof.

Wing-Induced Velocity at the Model

The WDM has an advantage over other types of manipulators (see Ref. 18 for a discussion of support interference) because the intrusive part of the device is located far downstream of the test object. A lifting line computer program was used to calculate the velocity induced by the control wings at the model location. At a typical control wing incidence of 5°, the maximum induced angle of attack due to the four wings is less than 0.57°. This is an overestimate, because the counteracting wake effects of the control wings were neglected. At an extreme incidence of 10° and using a theoretical lift curve slope of 2π, the induced angle of attack was less than 0.75°.

Unsteady Aerodynamics

One question raised about the WDM is: "How in principle can one use a wind-driven device to study the unsteady aerodynamics of another device?" First we point out that the instantaneous angle of attack of the control wings is always held inside the linear attached-flow regime, regardless of maneuver rate: there is no advantage gained by going into the stall or the nonlinear regime if one wants to get controlled lift. The issues are the unsteady lift on the control wings due to wake-induced effects, and due to the "apparent mass" effect of acceleration. For low-speed flow, the unsteady lift is a function of the reduced frequency **k**. For the small-chord wings used, the reduced frequency is well below 0.1. The Theodorsen and Wagner functions[19] are essentially unity, so that wake effects can be neglected and acceleration effects are small but easily accounted for in simulating the wing aerodynamics. Where needed, it is a simple matter to include the wake-induced effects for thin rectangular wings.

The implications are that most phenomena of practical relevance to aircraft models are easily simulated. Recent work on roll states, wing rock, forebody/wing roll/yaw interaction, vortex bursting, and flow reattachment reveal phenomena which are seen at reduced frequencies based on model root chord and pitch (or roll) rate of 0.02 to 0.1. For a model of 0.3m root chord, with a freestream speed of 15m/s, a reduced rotation rate of 0.1 requires less than 1 radian per second, well within the capability of the 3-d.o.f. manipulator. Recent work on the roll dynamics of delta wings and wing-bodies shows significant effects at reduced rotations as low as 0.02. Even for problems requiring inclusion of the unsteady wake, the WDM offers a convenient way to get quasi-steady aerodynamic coefficients.

CONSTRUCTION

The Roll/Pitch/Yaw manipulator consists of three links, as shown in Fig. 6. Link 1 is the post which rotates in the yaw bearing at its base. Link 2 pivots in the pitch bearings at the top of link 1. Link 3 ("the boom") rotates in the four roll bearings housed in Link 2. The test specimen is mounted on the sting at the forward end of Link 3 and the control wings are mounted at its aft end. Common mode deflection of the horizontal and vertical wings results in pitch and yaw respectively while differential deflection produce roll. These inputs do not have pure influences but are coupled to other axes, particularly at large roll and yaw angles.

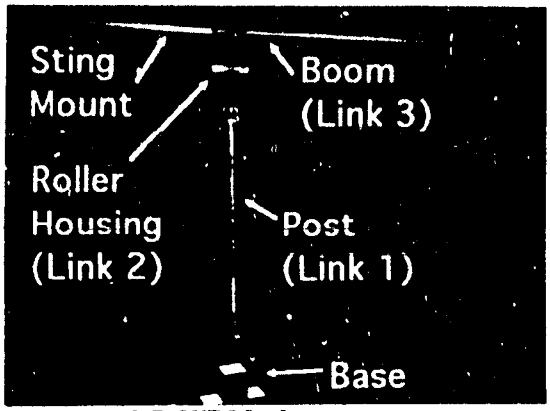


Figure 6: 3-D WDM elements

The aluminum links are attached to steel axles. The constant-chord wings employ a NACA-0012 airfoil. Foam core carbon composite construction is used, with balsa leading and trailing edges. The molded carbon-fiber spars were made in a single mold. Layers of .0035" thick carbon fiber sheets impregnated with resin were stacked and the entire mold was compressed in a vacuum bag and cured in an autoclave. The spars were bonded to the core with epoxy. A three-layer pre-cured carbon fiber skin was bonded to the outside of the wing. Glass fiber and epoxy were used to fill and shape the edges of the wing. Each wing is driven by a permanent magnet DC motor with a 76:1 zero-backlash gearbox. Motor position is provided by a magnetic quadrature encoder. The angular resolution at the output shaft of the gearbox is .074 deg. Absolute roll, pitch, and yaw angles are measured by optical quadrature encoders.

All data acquisition and control functions are accomplished on an Intel Pentium-based computer. Two interface boards are used. A four-axis encoder interface provides position measurements. Servo motor position control is provided by a four axis controller board. This board receives the motor encoder signal and sends torque commands to the motor. The servo control loop is separate from the WDM control loop and is processed by a Western Digital servo control system.

MODELING THE ROLL/PITCH/YAW MANIPULATOR

Details of the modeling and control software are given in Ref. 20. The equations of motion were derived using an iterative method common to robots. Because it produces a step-by-step development which eases the process of checking for arithmetic errors, the Iterative Newton-Euler method was chosen over a Lagrangian approach. The iteration was carried out symbolically, resulting in a closed-form dynamic solution[20]. The equations governing the aerodynamics of the manipulator were substituted for the end effector forces produced by the iterations.

Several aerodynamic and kinematic interactions are involved in the 3 d.o.f. WDM. An example is the change in direction of the lift vectors for the wing pairs when a roll angle is applied. When there is no roll angle, the gravitational moments can be countered by the horizontal wings. However, when a roll angle is applied, the normally vertical wings must be used to oppose the yaw resulting from inclination of the horizontal pair, and both wing pairs must be used to make up the deficit in pitching moment caused by inclination of the lift vector. A second important aerodynamic interaction is the yaw/roll interaction. In the early stages of WDM development, we encountered resonant oscillations when the natural frequencies of a flexible boom were excited. In designing the 3 d.o.f. WDM, such problems were avoided by using steel tubes of varying diameter.

CONTROL

The first set of experiments, described only qualitatively, used a roll feedback stabilizer and open-loop pitch and yaw inputs. A second set of tracking experiments were carried out using a simple linearizing control. The performance of the tracking control was poor, calling for a more sophisticated solution. The development of the software framework in which to embed the control algorithm accounts for a large part of the time invested in the 3D WDM thus far, and it is outlined here.

Control Software

The software consists of a controller segment and a user interface. The controller segment accepts trajectory commands from the user interface, measures the feedback signals, and computes a set of servo commands which it transmits to the servo control board. The commands from the user interface come directly from joystick or from a combination of sine-wave inputs (one each for the roll, pitch, and yaw axes). The controller segment also passes the feedback signals to the user interface for performance analysis. The user interface performs all initialization functions, accepts control parameters from the user, starts the control functions, and monitors emergency and non-emergency shutdown requests. The user interface also provides real-time graphic displays of commanded and actual trajectories, both for the servo and the manipulator joint angles.

Essential to the ~~adaptive controller is the~~ ability to calculate rate data (velocities and accelerations). However, the standard PC clock is accurate only to about 1/16 second, too slow to allow for accurate rate estimations. In addition, due to the interrupt-driven nature of the PC, the frequency at which a software-based sampler works will vary depending on how "busy" the processor is. Therefore, the PC timer interrupt was replaced with one that is accurate to about 1/91 second. This interrupt triggers the controller segment which reads the encoders as part of its routine, thereby enabling a precise measurement of the time between samples.

Roll Stabilization

Early on in the development of the 3-DOF WDM it became apparent that the device would be unstable in the roll axis. In order to execute even the simplest of maneuvers, the WDM needs some type of a roll stability augmentation system. This stability augmentation was accomplished using a simple proportional plus integral feedback controller.

The proportional feedback satisfactorily stabilized the device by itself but the integral compensator was needed to drive the WDM back to a zero-degree roll angle at times. Obviously, this PI controller is intended for use only in the testing stage of the WDM as the device will eventually incorporate an adaptive control algorithm. The PI controller, however, is an effective means by which the WDM can be stabilized in order to examine its behavior during basic maneuvers. In addition, the PI roll stabilizer is sufficient when only open loop motion is required.

After several test ~~runs~~ that ~~included~~ moderately quick, large-amplitude yaw oscillations, it became apparent that an additional feedback term would have to be included to compensate for yaw-roll coupling. This feedback term took the form of a derivative gain on the yaw axis. Therefore, the commanded roll would include a term dependent on the yaw rate and the yaw-roll coupling would be reduced.

Interestingly, the pitching motion of the WDM is much more strongly coupled to the roll axis than is the yaw. The reason for this has not yet been determined but is most likely due to either an asymmetry in the wings or differential motion of the motors.

SAFETY FEATURES

To prevent damage due to uncontrollable motions, several safety features were included in the design both of the software and the structure. The initial tests of the WDM were carried out using a roll stop that held the device at the zero degree roll angle. This stop consisted of a long screw that was threaded through the boom and secured to the roller housing, which could not rotate about the roll axis.

Subsequent tests utilized a roll-limiting setup which limits the WDM to a roll angle of about 4 revolutions in either direction. This setup uses the motor control cables that extend from the rear of the WDM, along the boom, and down the post. These cables are duct-taped to the boom and the post, leaving enough slack to allow for approximately 4 revolutions. The duct tape is wrapped around the boom and the post at approximately 4-inch intervals. As the WDM rolls, the motor control cables "wrap up" around the boom and begin to tighten. As the cables became taught, they transfer the load to the post and boom through the duct tape. As the cables tighten further, the tape rips and the next "stage" of tape begins to carry the load. This setup successfully prevented the motors and cables from incurring any damage during several violent, uncontrolled roll motions.

The pitching motion of the WDM is limited using a pitch stop. This stop consists of a spring loaded support that transfers the loads from the boom to the post as the WDM pitches back past about 35°. At about 45°, the spring is completely compressed and the pitching motion is stopped. The stop is adjustable so that the pitch-stop amplitudes can be changed for different tunnel sizes.

The WDM also employs a yaw stop to limit yaw amplitudes. This stop consists of a screw threaded though a slot in the base into the post. As the WDM yaws, the screw slides along the slot and is stopped at either end by an adjustable screw. The WDM is set up to yaw approximately ±30° in the John J. Harper Wind Tunnel at Georgia Tech. This amplitude is, again, dependent on tunnel size.

Two software limit-checking routines were included, as well. Hard-coded into the software is a maximum allowable motor output. Since the motors are directly geared to the wings, setting a maximum allowable motor output value is equivalent to setting a maximum allowable angle of attack for the wings. Any output values from the control algorithm that exceed this maximum allowable value are replaced with the maximum allowable value.

The software also checks the roll, pitch, and yaw angles and compares them to the maximum allowable values as hard-coded in the software. If the limit-checking routine detects an excessive amplitude, it returns the WDM to its equilibrium position in two steps. First, it calculates a trajectory to move the wings back to their zero-roll, -pitch, and -yaw positions. It then turns off the control and sends the calculated trajectory to the motors. This routine successfully returned the WDM to its equilibrium position after several large-amplitude motions.

TESTING

Running experiments using the WDM consists of four main procedures: initialization, start-up, collecting data, and shutting down. The initialization procedure consists of first initializing the three encoders (roll, pitch, and yaw) to their zero-degree position. Then, the wings are set to their zero-angle-of-attack positions and initialized. To complete the initialization procedure, the user inputs the desired gains for the PID controller and the amplitudes and frequencies of the desired motions.

Next, the tunnel is brought up to a speed of about 15 m/s. As the speed is increased, the software allows for trim corrections to account for perturbations from the zero roll angle. As the speed is increased past about 17 m/s, the pitch wings unstall and the WDM is ready for operation. At this point, the tunnel speed is increased to approximately 20 m/s and the control is turned on. Next, the WDM is put through its desired motions and the angular position data is collected by the software. When the motion ends, the software calculates a trajectory to return the WDM to its equilibrium position, much as it does when the device exceeds its allowable range of motion.

Initial Results

The 3-D.O.F. WDM has been put through several initial tests using both manual, joystick controlled input and computer controlled input. A limited amount of testing has been done using the adaptive controller. The data collected for the non-adaptive control include some interesting results.

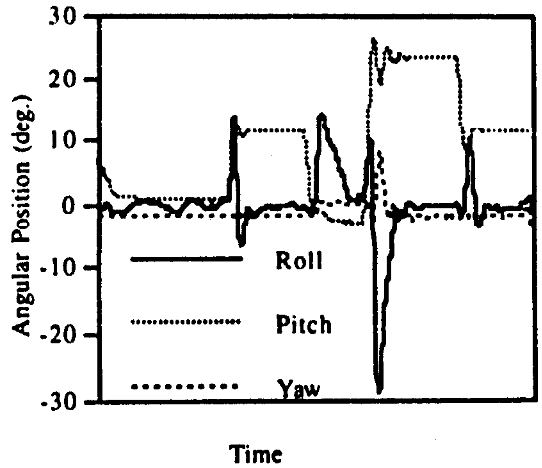


Figure 7: WDM Response to Step Pitch Inputs (over approximately 15 seconds)

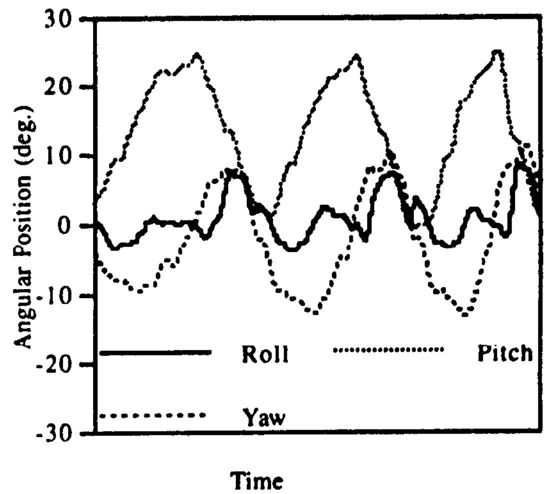


Figure. 8: WDM Response to Combined Pitch-Yaw Maneuver (over approximately 10 seconds)

Fig. 7 shows the response of the 3DOF WDM to step inputs in pitch. This experiment was run with an F-16 model attached on the sting mount. As explained above, there is still (as of this writing) a strong dynamic coupling between the pitch and the roll but the device stabilizes and is able to sustain the model at any angle of attack within its range. This is shown by the flat zones where pitch, yaw and roll are all held constant.

This capability is especially useful for static testing of models that tend to vibrate on rigid mounts. Here, with a very slender sting which minimizes flow interference, the model attitude is held stable by feedback control. Fig. 8 shows the 3DOF WDM response to a joystick-commanded combined pitch-yaw input. This is a large amplitude, low rate input over a total sampling time of approximately 10 seconds.

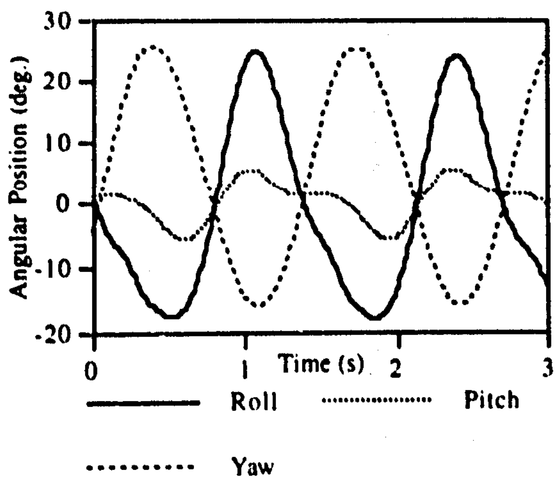


Figure 9: WDM Response to High Yaw Rate

Fig. 9 shows the WDM response to a high-rate input. Note the strong coupling between the yaw and the roll and the 90° phase lag. The derivative gain on the yaw axis had little effect in reducing this coupling, hinting again that the roll appears as a result of pitch-roll coupling.

During the testing, a slipped belt resulted in a large step roll input. The resulting roll rate exceeded 2100° /sec., with no damage. Other than this, the device has not yet been pushed to its limits.

Measurement Uncertainty

This paper deals with the development of a measurement device. Thus accuracy figures are for the data taken to date. The motors use a 16 pulse-per-revolution magnetic quadrature encoder integral to the motor and a 76:1 zero-backlash gearbox. This gives an angular resolution of 4824 counts per revolution, or 0.074° at the motor output shaft. The encoders used on the roll, pitch, and yaw axes were of the optical, quadrature type. These encoders had a 512 pulse-per-revolution output. Therefore, the angular resolution of the encoders is 512X4 = 2048 counts per revolution, or 0.176°.

EXTENSION TO 6 D.O.F.

Adding three linear degrees of freedom would enable the point of rotation to be moved to desired locations as needed for particular maneuvers. This can be done with traditional motorized traverses, with all three motors located at the tunnel floor. We are constructing these. As mentioned before, the problem of simultaneously moving several degrees of freedom and maintaining desired trajectories is more severe for the rotational degrees of freedom. Once the adaptive control system for these motions is developed, it can be extended to the full 6-d.o.f. manipulator.

SUMMARY

The design, development and testing of a roll/pitch/yaw Wind-Driven Dynamic Manipulator are described. Design tradeoffs and the construction of the device are discussed. Flow interference due to the induced velocity of the control wings is shown to be negligible. Results from adaptive pitch tracking are shown for a pitch manipulator. Step-response experiments at high and low model angles of attack are demonstrated with the 3-d.o.f. device. Quantitative pitch-yaw-roll motion histories are extracted, and the motor inputs to the control surfaces are obtained to extract forces and moments for coupled maneuvers. Pitch-yaw maneuvers with roll stabilized by feedback control are explored. Feedback control also minimizes pitch and yaw vibrations of the model, despite the use of a slender sting mount. The device also serves as a convenient way of testing models at fixed attitude without tunnel vibrations, and with feedback control of flow-induced oscillations and asymmetries. As of this writing, work continues towards perfection of adaptive trajectory tracking for the device and development of the linear degrees of freedom needed to complete a six-degree-of-freedom device.

ACKNOWLEDGEMENTS

This work is conducted under AASERT Grant F49620-93-1-0342 by the Air Force Office of Scientific Research, monitored by Dr. Len Sakell. Assistance from the other students in Experimental Aerodynamics in conducting the experiments, and from Mr. David Hooke of the Composite Structures Lab in the wing construction technology, is acknowledged.

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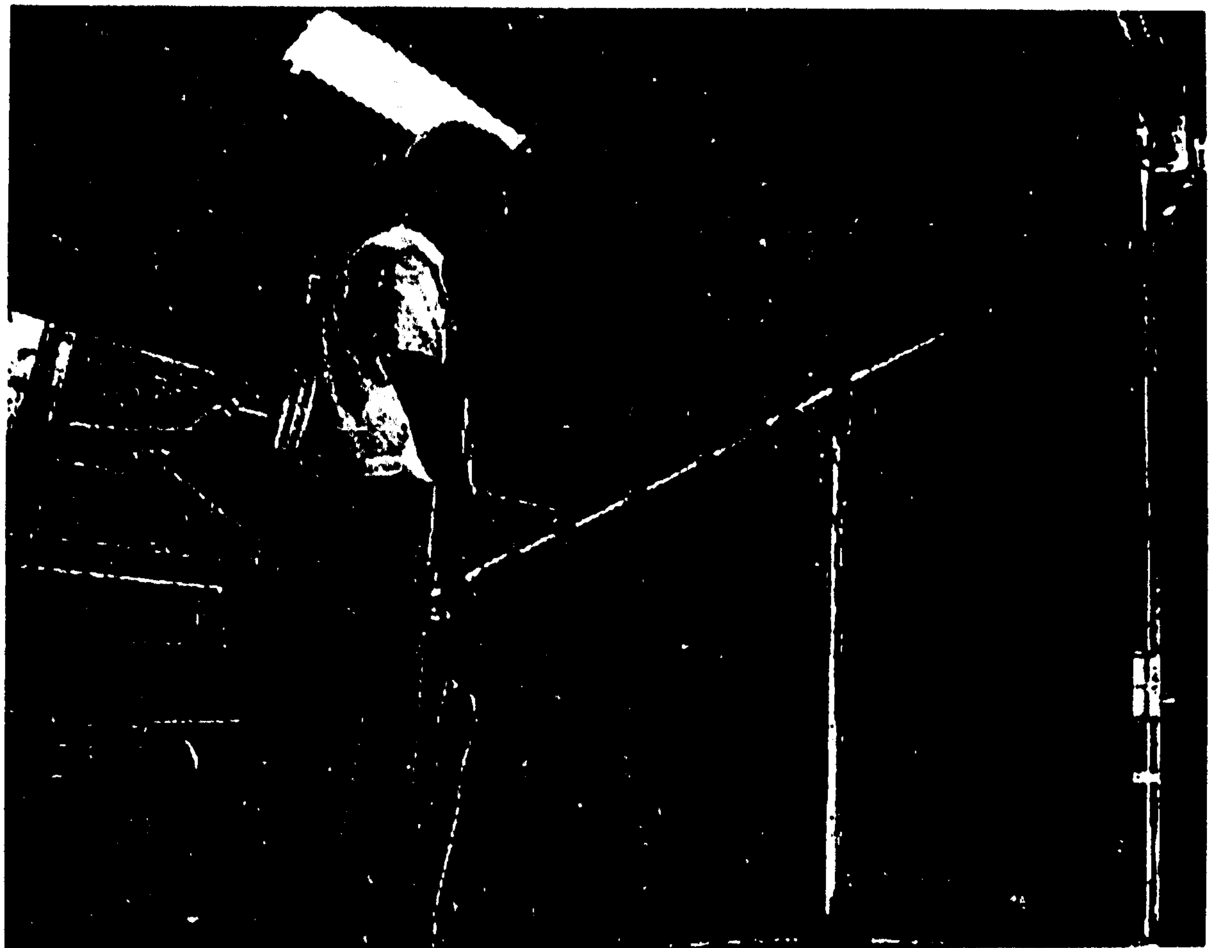

Figure 10: 3-d.o.f. WDM installed in the 7' x 9' test section of the John J. Harper Wind Tunnel, with a 1/32-scale F-16 model.