Measurement of Longitudinal Aircraft Stability Parameters in the Wind Tunnel Using a Wind Driven Manipulator*

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ABSTRACT[1]

A wind driven dynamic manipulator is used to derive stability parameters of a lifting configuration in a wind tunnel. The parameters are deduced using system identification techniques from the dynamics of the manipulator with and without the configuration attached. The need for direct measurement of forces is obviated. The manipulator is represented by a second order linear model in the identification. This model is validated by comparing results from the actual system with a mathematical simulation of the manipulator. The measurement technique is validated by comparing pitch damping and stiffness for a set of calibration specimens to the values predicted from the specimen geometry. The results demonstrate that stability parameters of aircraft models can be measured conveniently by this technique.

NOMENCLATURE

Symbol	Definition
Θ	Pitch Angle

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Θ_i	Pitch Angle at Time Step i
q	$\frac{d\Theta}{dt}$
α	Angle of Attack
M	Pitching Moment
M_Θ, M_q, M_ϕ	$\frac{\partial M}{\partial \Theta}, \frac{\partial M}{\partial q}, \frac{\partial M}{\partial \phi}$
M_0	Nominal pitching moment
$M_{q+\dot{\alpha}}$	$\frac{\partial M}{\partial q} + \frac{\partial M}{\partial \dot{\alpha}}$
L	Lift
L_α	$\frac{\partial L}{\partial \alpha}$
C_{L_α}	Wing Lift Slope
C_{M_Θ}	Pitching Moment Stiffness Coefficient
$C_{M_{q+\dot{\alpha}}}$	Pitch Damping Coefficient
k	Constant Parameter
N	Block Size for Sampled Data
q_∞	Freestream Dynamic Pressure
U_∞	Freestream Velocity
l_{arm}	Length of Model Arm
S	Area of Model Wing
ϕ	Wing Incidence Angle
ϕ_i	Wing Incidence Angle at Time Step i
J_{total}	Total Moment of Inertia of Manipulator and Model about Pitch Axis
c	Wing Chord
τ_L	Time Constant for Unsteady Lift

Subscripts

W	Refers to Manipulator Alone
m	Refers to Model Alone

W+m   Refers to Manipulator/Model Combination

INTRODUCTION

The subject of this paper is the measurement of displacement and rate derivatives of aircraft configurations, in particular for longitudinal dynamics. The Wind Driven Dynamic Model Manipulator (WDM) enables rapid and precise coupled-axis motions of the model[1,2] without heavy motors or large support interference. On conventional stiff-armed manipulators, the model dynamics are derived directly from measured forces and moments, a process which requires complex balance instrumentation. On the WDM, the dynamics of the model can be extracted from the control input, without the need for direct force measurements; this is the primary focus of this paper.

Current Technology for Aircraft Stability Parameter Measurement[3]

Experimental Techniques

Designing control laws for aircraft requires measurement of the parameters which appear in the equations of motion for an aircraft. Typically, these parameters are reduced to a non-dimensional form and, for the case of linear dynamics, are commonly called the stability derivatives. A number of means have been devised to determine the stability parameters. These methods include static balances, forced oscillation rigs[4,5], rotary balances[6], flight tests, and flexible sting rigs[7]. Static balances measure only the derivatives that relate geometric angles to forces and moments. These derivatives are called the aerodynamic compliances because they are analogous to the spring constants in a spring-mass oscillator.

Forced oscillation rigs can be used to determine a large number of parameters, including aerodynamic compliance and damping, if enough oscillation frequencies are used. Most forced oscillation rigs measure forces directly using load cells or strain gages mounted on flexures. Generally, forced motion rigs only execute sinusoidal oscillations and are best applied only to identification of linear systems. Rotary balances have been proven useful for measuring loads induced by angular rates. Most of these facilities are driven by large motors and perform repeated rotational motion.

Flight tests and free flight model tests are similar in principal. In both cases, control inputs are used to excite the system dynamics. The stability derivatives are extracted from the aircraft dynamic equations and measurements from angle, rate, and acceleration sensors. Though there is no explicit force measurement, both cases require expensive, complex test specimens. Furthermore, it is not possible to rely on flight test data if the measurements are to be used for the initial control law design during the aircraft design phase. It is essential, then, that means of testing scale models in the wind tunnel be perfected.

The use of semi-free flight techniques have been explored for the wind tunnel[8,9,10]. For example, parameters for a scale spaceplane model were measured while the model was suspended in the tunnel on a set of cables[8,9]. The technique required six component load cells, as well as accelerometers, vertical and rate gyros, and a video position measurement system. Furthermore, some of the resulting measurements did not compare well with predictions based on static balance measurements. Semi-free flight tests also generally require that a model have partly or completely actuated control surfaces, as these are often the excitation sources for the identification experiments.

Signal Processing

Processing measured data to arrive at stability parameters has been a key issue not just for aircraft but for all identification applications[11]. If measurement or process noise are significant some means of accounting for the noise, usually a stochastic approach, is employed. The techniques range from ordinary least squares fitting to the Extended Kalman Filter. A large body of work has been published on the topic during the last 30 years and extends to all identification studies.

Identifiability

Because mounting a model on a fixed axis often reduces the dynamic order of the governing differential equations, it is often difficult to completely identify some parameters. For example, the longitudinal dynamics of a typical aircraft are usually described with a fourth order linear state equation. However, when an aircraft model is constrained to rotate about its pitch axis, the angle of attack derivative $\dot{\alpha}$ and the pitch rate q are equal. Hence, it is not possible to separate the effects of q on the pitching moment from the effects of $\dot{\alpha}$. For this and similar cases, a variety of methods are often applied to the identification problem. Again taking the measurement of longitudinal derivatives as an example, it is possible to separate the effects of q and $\dot{\alpha}$ if a pitch experiment is accompanied by a plunge experiment.

Other clever approaches have been used to enhance the identifiability of stability parameters. For example, in [12], it is shown that the influence of q on the pitching moment can be isolated using a rotary balance technique whereby the pitch rate derivative (also called the pitch damping) is extracted from moment measurements for different sideslip angles.

The Wind Driven Dynamic Manipulator

The Wind Driven Manipulator is a device for executing maneuvers in the wind tunnel. It uses the kinetic energy available in the free stream to produce the moments required to move the model. Fig. 1 shows the pitch manipulator used for the experiments described herein. Fig. 2 shows single- and dual-degree-of-freedom WDMs. In Fig. 1, a small servo motor is used to set the incidence angles of the aerodynamic control surfaces, which are mounted at the end of an actuator arm. The actuator arm is attached to the model mounting block which permits rotation about its pitch axis. The model is held at specified attitudes or moved at specified rates by controlling the attitude of the control surfaces. Angular position feedback is provided for the pitch axis. By controlling the wing incidence angles, the angular trajectories of the aircraft model may be tracked. The WDM is described in greater detail in [1]. The 2-d.o.f. device in Fig. 2 extends the concept to pitch-yaw motions by adding one motor and a pair of control wings. Extension to pitch-yaw-roll requires another motor to decouple one pair of control surfaces. The use of wind energy and the long lever arms greatly reduce the weight and interference of the resulting device. Driving each control surface at its aerodynamic center requires little torque, so that small, light weight servo motors suffice. A feedback control system compensates for deflections of the device, so that complex trajectories can be specified and accurately executed. The 3 linear degrees of freedom required to complete a 6-d.o.f. device can be added using conventional traverses, because the drivers for these can be mounted close to the tunnel walls without a large interference or weight penalty.

The WDM was initially developed to visualize and measure flows over maneuvering aircraft, and complex vortex interactions during pitch-yaw maneuvers have been documented[2]. Here we explore its application as a dynamic balance. As with any wind tunnel model support device, forces and moments can be measured using conventional sensors such as strain gauges and load cells. The usual problems of sensitivity, strength, interactions, and precise fabrication would be encountered. An alternative approach, which is potentially much cheaper and more elegant, is to use the information available from the control system during the operation of the WDM, in effect answering the question: *"what does it take to move this model through this maneuver, and why?"* There are three aspects to the answer. First, the dynamics of the WDM must be accurately determined. Secondly, it must be proven that the changes to these dynamics, caused by a test configuration of typical characteristics, can be accurately measured. Finally, it must be seen whether such measurements are valid at realistic rates of motion and in the nonlinear aerodynamic regime. In this paper, we study each of these issues. The first two issues are dealt with in detail:

the other issues are discussed, but accurate results at high rates and in the nonlinear aerodynamics regime are not proven.

Specifically, a method for determining moment coefficients for a linearized model of longitudinal aircraft dynamics is presented. A mathematical model with unknown parameter values is used to represent the dynamics of the WDM and the WDM + aircraft combination. Experiments are used to determine the unknown parameters. An ordinary least squares algorithm will be used to estimate the parameters[13,14]. Accompanying experimental data taken for a set of calibration models is presented to validate the technique. Though the experiments conducted to date only validate the linear parameter identification method, we argue that it is possible in principle to determine coefficients for a parameterization of the nonlinear aerodynamic moment functions.

The paper is organized as follows. First, a second order linear model for the wind driven manipulator is given. The model is discretized for compatibility with the digital data acquisition system. Next, the experimental procedure is presented. Signal processing and analysis of the experimental results is described. Finally, a comparison of measured and predicted pitching moments for a set of simple calibration models is given.

DESCRIPTION OF THE EQUIPMENT

1-d.o.f. Manipulator

A 1-d.o.f. manipulator with a lateral axis of rotation (pitch manipulator) is used. Dimensions are shown in Fig. 3. The control wing cross section is a NACA-0012 airfoil, chosen because of the extensive published data base on this airfoil. Position of the rotating assembly, as well as the wing incidence angle, are measured using HEDS 5040-512L quadrature encoders. The encoders provide 2048 increments per revolution, so that angles can be measured with a precision of +/- .09 deg. A Technology-80 quadrature encoder board provides the position counters for the controlling computer. The servo motor is a Futaba 138H servo for radio controlled models. Since the servo requires a pulse width modulated command signal, an interface is required between the A/D converter on the controlling computer and the servo. The data acquisition system is shown in Fig. 4.

Wind Tunnel

The experiments were conducted in the Georgia Tech Low Speed Wind Tunnel, which can produce wind speeds up to 22 m/s in its 1.07m x 1.07m test section. The tunnel fan is located upstream and the downstream end is open.

Calibration Models

To test the experimental identification procedure, a set of models were used for which the pitch stiffness and pitch damping could be easily computed. The models are drawn in Fig. 6. The wing cross section is a NACA-0012 airfoil. Lift and drag characteristics were measured on a 3-component strain gage balance and a least squares fit was used to estimate the lift curve slope, shown in Fig. 7.

The stability parameters for a nominal pitch angle of zero are easily computed. The predicted pitch stiffness, derived by multiplying the wing lift slope by the moment arm, is given by $M_{\Theta,m} = l_{arm} L_{\alpha,m}$. The pitch damping is given by $M_{q+\dot{\alpha},m} = \frac{l_{arm}{}^2 L_{\alpha,m}}{U_\infty}$. The latter can be easily derived by approximating the angle of attack induced at the wing by pitching motion as $q l_{arm} / U_\infty$. The damping term, then, is the product of angle of attack due to angular rate and moment due to angle of attack. The moment on the wing due to pure pitch in its reference frame is neglected, since the chord is short and the unsteady moment decays quickly. These two can be nondimensionalized to give

$$C_{M_\Theta} = C_{L_\alpha} \text{ and } C_{M_{q+\dot{\alpha}}} = C_{L\alpha}.$$

MATHEMATICAL FORMULATION

Continuous Time Transfer Function

In this section, a second order transfer function model whose input is the wing incidence angle ϕ and whose output is the pitch angle Θ is considered. The coefficients in this transfer function can be related to well known stability derivatives. Thus identification of this transfer function from input/output data can be used to measure stability parameters with no explicit moment measurement.

The 1-d.o.f. WDM shown in Fig. 3 is used for reference. The transfer function is described briefly here: a more detailed theoretical formulation is given in [15]. The equation of motion is derived from a simple torque balance,

$$J_{total}\ddot{\Theta} = M(\Theta, q, \phi).$$

The unsteady aerodynamics of the control wings are fast compared with the dynamics of the whole manipulator. The time constant for the decay of the unsteady lift is approximated by $\tau_L = \frac{c_W}{U_\infty}$. With a wing cord of 11.4 cm and a freestream velocity of 17 m/s, the time constant of the unsteady lift is .0067 s, about 10 times faster than the dynamics of the rotating assembly. Thus the pitching moment depends only on the instantaneous effective angle of attack of the control wing. The instantaneous effective angle does, however, depend on the angular rotation rate, so the pitching moment does depend on q.

If the moment function $M(\Theta, q, \phi)$ is assumed to be a linear function of the angle and angular rate, the resulting differential equation is

$$\ddot{\Theta} = \frac{M_\Theta}{J_{total}}\Theta + \frac{M_q}{J_{total}}q + \frac{M_\phi}{J_{total}}\phi + \frac{M_o}{J_{total}}. \qquad (1)$$

The transfer function from ϕ to Θ, then, is

$$\frac{M_\phi / J_{total}}{s^2 - (M_q / J_{total})s - (M_\Theta / J_{total})} \qquad (2)$$

The experimental technique relies on the fact that the moment slopes M_Θ and M_q can be separated into a component due to the manipulator and one due to the model.

Since the wing incidence angle has been taken as the input, the dynamics of the servo motor play no part in the identification experiments. The next step is to find a discrete time equivalent transfer function since all data acquisition and system identification will be performed digitally.

Discretization of Transfer Function Model

Normally, when discretizing a continuous system, it is assumed that the input to the system is sampled and may or may not pass through a zero order hold (see Fig. 5 a and b). Since the output of the servo is being sampled, the situation in Fig. 5c is actually the arrangement for identification. However, for high sampling rates, the system in 5c can be approximated with the one in 5a. This is possible because the high frequency content of the input associated with sampling (5a) is attenuated by the low pass characteristics of the system, and thus the outputs of 5a and 5c will be about the same. Thus the remainder of the derivation will proceed as if the input is passed through a sampler before entering the system under investigation.

Proceeding with the discretization of the continuous system, the impulse-invariant z-transform of (2) has the form

$$\frac{k_\phi z^{-1}}{z^{-2} - k_1 z^{-1} - k_2}.$$

The corresponding difference equation in auto-regressive moving average (ARMA) form is

$$\Theta_n = k_1\Theta_{n-1} + k_2\Theta_{n-2} + k_\phi \phi_{n-1} + k_o. \qquad (3)$$

Note that in the difference equation, the term k_o has been included to account for gravity and nominal pitching moment. This is justified by noting that the offset term in (1) can be considered to be the coefficient of a second input whose value is always unity. A transfer function can be taken from this additional input to Θ and then discretized, resulting in the k_o term in the difference equation. In any case, this term is used only to account for the constant component of the pitching moment and is discarded in the measurement of stability derivatives. The method for identifying the discrete time and (ultimately) the continuous time transfer function from samples of the input and output are described in a later section.

Validating the Model

Figure 8 is used to validate the second order model. Once the manipulator transfer function parameters were identified, an input other than the one used for identification was applied to both the real manipulator and a simulation of the manipulator created in MATLAB/SIMULINK. The simulation model parameters are taken from the identified second order transfer function obtained as described below. Fig. 7 compares the response of the actual manipulator to the input against the response of the simulation to the input. A small amount of phase lag is apparent and is attributed to the neglect of the unsteady aerodynamics of the wing.

EXPERIMENTAL PROCEDURE

Identification of the transfer function parameters requires three experiments. First, the transfer function of the manipulator with no model must be determined. Second, the transfer function for the manipulator-model combination must be determined. The difference between these two transfer functions is used to compute the model's stability parameters. The final experiment is to measure the moments of inertia of the model and rotating assembly. Each is described below in detail.

Wind-On Experiments

The procedures for identifying the transfer function of the manipulator or manipulator/model combination are identical and are based on classical linear system identification techniques.

First, the manipulator was installed in the tunnel with no model attached. The tunnel speed was approximately 17.1 mps. The servo was excited with a signal containing several frequencies sufficient to excite the dynamics of the WDM. The wing and pitch encoders were sampled with a sampling period of .0164 sec., the sampling rate being chosen for convenience on the data acquisition system. A block of 2000 samples were taken. The transfer function was analyzed as described below in "Analysis of Signals".

Next, a model was installed on the manipulator. The identification procedure was repeated for the model/manipulator combination with the same sampling rate and block size as described above.

For these experiments, no control was applied to the manipulator to assure that the mean pitch angle was zero. The properties of the models being tested were known to be linear for a large range, and hence a small difference in mean angles between the experiments is tolerable. However, it will be necessary in some cases to apply a control signal, in addition to the excitation input, to assure that the mean angle of attack is that about which the linearized model is desired.

Moment of Inertia Measurement

It was shown in equation (1) that the moment of inertia of the entire rotating assembly is required in order to compute the moment coefficients from the transfer functions. The need for model inertia measurements is the chief drawback of this method, but the measurement of the moments of inertia is generally simpler than the tare experiments conducted to account for inertia on rigs such as rotary balances.

For the models used in these experiments, the moment of inertia could be easily estimated by treating the "fuselage" as a slender beam and the wing as a point mass concentrated at its quarter chord.

For the manipulator arm and wings, the task is more difficult. The wings were again considered point masses located at their quarter chord (a reasonable approximation since they are far from the axis of rotation). The arm, servo, encoder, and tail/bearing assembly is a far more complex arrangement and thus a torsion pendulum was used to measure that quantity. (The wings were considered separately because of the large damping they may add to the pendulum experiment). The torsion pendulum is simply a heavy gauge steel wire attached to a rigid mount at the top end and having the inertia in question suspended at the bottom. First, a disk of known inertia is used to find the torsional stiffness of the pendulum wire. The stiffness is easily computed from the natural oscillating frequency of the disk. Then the manipulator arm was suspended from the wire at the arm's center of gravity. Again, the frequency of rotation was measured and the inertia was computed. The moment of inertia about the pitch axis could be determined using the parallel axis theorem.

The oscillating frequencies can be observed visually with precision if the period of oscillation is long enough. For example, when the natural frequency of the manipulator/pendulum system was measured, the oscillations were observed for 200 sec. Sixty oscillations were counted. Since an observer can easily determine position at the final time within one eighth of a cycle, the period of oscillation can be measured within 1/(60*8) = .21%.

ANALYSIS OF SIGNALS

The analysis of input and output measurements to compute the discrete time transfer functions required some signal enhancement and will thus be described here in some detail.

Upsampling the Data[16]

As mentioned previously the sampling rate must be very high with respect to the dynamics of the continuous system being identified. Furthermore, it is necessary to measure the transfer functions with great accuracy since the desired parameters are computed from small differences between two transfer functions. There are several ways to increase the effective sampling rate. One way is to increase the sampling frequency. Since the position signals are discrete in amplitude, though, the sampled signal may contain sets of identical consecutive signals, even if the position is changing. Thus the signals would have to be filtered.

The approach taken in these experiments was to keep the actual sampling interval at .0164 sec., but to effectively increase the sampling rate by post-processing the measurements with a 16X upsampling filter, giving an effective sampling rate of 976.5 Hz. Since the signals are assumed to be band limited, we can accurately reconstruct 16 measurements for each actual measurement taken during the experiment. The upsampling essentially improves the integration in the discretization of the differential equation model by taking smaller time steps. In other words, the discrete time model is an approximation to a continuous time model, and by increasing the sampling rate, the approximation is improved. Then, more accurate results are achieved when then continuous time model parameters are computed from discrete measurements.

It was determined through the experiments that the upsampling was necessary to accurately determine the pitch rate effects on the moments, even though the position coefficients could be determined without upsampling.

Ordinary Least Squares

Taking the model (3), one can construct the matrices

$$Y = \begin{bmatrix} \Theta_N \\ \Theta_{N-1} \\ : \\ : \\ \Theta_3 \end{bmatrix}, \quad X = \begin{bmatrix} \Theta_{N-1} & \Theta_{N-2} & \phi_{N-1} & 1 \\ \Theta_{N-2} & \Theta_{N-3} & \phi_{N-2} & 1 \\ : & : & : & : \\ : & : & : & : \\ \Theta_2 & \Theta_1 & \phi_2 & 1 \end{bmatrix}, \quad \Psi = \begin{bmatrix} k_1 \\ k_2 \\ k_\phi \\ k_0 \end{bmatrix}$$

and write a matrix equation for the discrete time model,

$$Y = X\Psi .$$

Now, the estimate $\hat{\Psi}$ of the parameter vector Ψ may be calculated by a least squares projection:

$$\hat{\Psi} = \left(X^T X\right)^{-1} X^T Y .$$

From here, the inverse z-transform is used to find the equivalent continuous time transfer function. Since the manipulator dynamics are linear, the model moment derivatives may be expressed in terms of the transfer function coefficients for the manipulator and manipulator/model combination.

Computing the Stability Parameters

Having found the coefficients in the continuous time transfer function, it is now possible to calculate the stability parameters for the model. The moment derivatives are given by the difference between those measured for the model/manipulator combination and those measured for the manipulator alone:

$$M_{\Theta,m} = M_{\Theta,W+m} - M_{\Theta,W} \quad \text{and} \quad M_{q+\dot{\alpha},m} = M_{q+\dot{\alpha},W+m} - M_{q+\dot{\alpha},W} .$$

These may be nondimensionalized to give

$$C_{M_\theta} = \frac{M_\Theta}{q_\infty S l_{arm}} \quad \text{and} \quad C_{M_{q+\dot{\alpha}}} = \frac{M_{q+\dot{\alpha},m} U_\infty}{q_\infty S l_{arm}^2} .$$

RESULTS

The results of the experiments with the calibration models are shown in Table I. The measured coefficients corresponded well with the predicted values, although the stiffness coefficient was consistently measured to be lower than the predicted value, and the damping was consistently higher than predicted. The error in both parameters increased with arm length. All measurements were, however, within 10% of the predicted value.

It is believed that most of the error is due to the prediction of the coefficients rather than the measurement procedure itself. Some is due to the neglect of the "fuselage" of the calibration models in computing their parameters.

MODEL ARM	C_{M_Θ}	% error	$C_{M_{q+\dot{\alpha}}}$	% error
21 cm	3.40	2.4	3.17	4.5
29 cm	3.56	7.2	3.11	6.3
42 cm	3.59	8.1	3.08	7.2

Table I: Measured Stability Parameters for Calibration Models. Predicted C_{M_Θ} and $C_{M_{q+\dot{\alpha}}}$ for all Models is 3.32.

EXTENDING THE METHOD

So far, the wind driven manipulator has been used only to identify linear model parameters. Since fairly accurate results have been achieved for the linear case, one can expect that linearly parameterized nonlinear aerodynamic functions could be identified as well. There is certainly an ample theoretical foundation for designing adaptive identifiers for nonlinear systems. One of the chief advantages of the wind driven manipulator over other devices is that it is not limited to evaluating sinusoidal motion, which is used for identifying linear models, but can perform a wide range of motions to enable identification of nonlinear models.

The discussion in this paper has been limited to measuring longitudinal stability parameters only, but lateral stability properties must also be identified. In persuit of that goal, a two degree of freedom pitch/yaw manipulator has already been constructed and tested, and a 3-axis roll/pitch/yaw version is planned. Hence it may soon be possible to measure not just longitudinal but also lateral stability parameters.

CONCLUSIONS

It has been shown that the wind driven manipulator can be used for measurement of aircraft stability parameters in the wind tunnel. The experiments require no explicit force measurement but rely on well understood system identification procedures. The method has been validated by comparing measured and predicted values of two longitudinal stability parameters for a set of calibration models.

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REFERENCES

1. J. Magill and N.M. Komerath, "A Wind Driven Dynamic Manipulator for Wind Tunnels", to appear in *Experimental Techniques*

2. J. Magill, L.A. Darden, and N.M. Komerath, "Visualization of Rate Dependant Vortex Phenomena During Wind Tunnel Simulation of Aircraft Maneuvers", AIAA 94-0669, 32nd Aerospace Sciences Meeting, Reno, NV, January, 1994.

3. K. Orlik-Ruckemann, "Review of Techniques for Identification of Aircraft Stability Parameters in the Wind Tunnel", in AGARD-LS-114, May, 1981.

4. E.S. Hanff, "Direct Forced-Oscillation Techniques for the Determination of Stability Derivatives in the Wind Tunnel",in AGARD-LS-114, May, 1981.

5. K.J. Orlik-Ruckemann, E.S. Hanff, and C.R. Anstey, "Wind Tunnel Apparatus for Translational Oscillation Experiments", AIAA-80-0046, 18th Aerospace Sciences Meeting, Jan 14-16, 1980, Pasadena , CA.

6. *Rotary Balance Testing for Aircraft Dynamics*, AGARD-AR-265, Report of the Fluid Dynamics Panel Working Group 11.

7. C.O. O'Leary, "Wind-Tunnel Measurement of Aerodynamic Derivatives using Flexible-Sting Rigs", in AGARD-LS-114, May, 1981.

8. S. Sasa, M. Takizawa, T. Shimomura, and O. Nonaka, "Spaceplane Longitudincal Aerodynamic Parameter Estimation by Cable-Mount Dynamic Wind Tunnel Test", *SAE Transactions*, v100, n Sect 1, pt2, 911980, 1991, p. 2017-2025

9. M. Yanagihara, S. Suzuki, S. Kayaba, K. Murota, "Estimation of Spaceplane Lateral-Directional Stability and Control Derivatives from Dynamic Wind Tunnel Tests",*SAE Transactions*, v100, n Sect 1, pt2, 911979, 1991, p. 2008-2016.

10. M.V. Cook, F. Heydari, "The Estimation of Stability and Control Characteristics of a Canard Configured Combat Aircraft Having a Swept Forward Wing", *Congress of the International Council of the Aeronautical Sciences*, 15th v1, p. 730-738.

11. K.W. Iliff, "Parameter Estimation for Flight Vehicles", *Journal of Guidance, Control, and Dynamics*, Vol. 12, No. 5, 1989, pp. 609-622.

12. W. Blake, "Validation of the Rotary Balance Technique for Predicting Pitch Damping", AIAA-93-3619, Atmospheric Flight Mechanics Conference, August 9-12, 1993, Monterey, CA.

13.J.P. Norton, *Identification*, 1986, Academic Press.

14. Gene Franklin, J. David Powel, and Michael Workman, *Digital Control of Dynamic Systems*, Addison-Wesley Publishing Co., 1990.

15. J. Magill, N.M. Komerath, and J.F. Dorsey, "Dynamics and Control of Wind Driven Manipulators", AIAA-94-3657, Guidance, Navigation, and Control Conference, August 1-3, 1994, Scottsdale, AZ.

16. Alan V. Oppenheim and Ronald W. Schaffer, *Discrete Time Signal Processing*, 1989, Prentice-Hall , Englewood Cliffs, NJ.

17 Bernard Etkin, Dynamics of Flight:Stability and Control, John Wiley and Sons, New York,1982.