Program of Research in Flight Dynamics
The George Washington University
at
NASA Langley Research Center

NASA Cooperative Agreement NCC1-03004

FINAL REPORT

For the Period

January 1, 2003 through September 30, 2005

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OVERVIEW

The program objectives are fully defined in the original proposal entitled "Program of Research in Flight Dynamics in GW at NASA Langley Research Center," which was originated March 20, 1975, and in the renewals of the research program from January 1, 2003 to September 30, 2005.

The program in its present form includes three major topics:

1. the improvement of existing methods and development of new methods for wind tunnel and flight data analysis,

2. the application of these methods to wind tunnel and flight test data obtained from advanced airplanes,

3. the correlation of flight results with wind tunnel measurements, and theoretical predictions.

The Principal Investigator of the program is Dr. Vladislav Klein. Two Graduate Research Scholar Assistants (M. M. Eissa and N. M. Szyba) also participated in the program.

SPECIFIC DEVELOPMENTS

Specific developments in Aerospace during the period January 1, 2003 through September 30, 2005:

1. <u>Data Analysis of highly swept delta wing aircraft from wind and water tunnel data</u>

   a) Wind tunnel experiments were performed on the 18% scale model of the F-16XL aircraft in the NASA Langley Research Center 14x22 Foot Subsonic Wind Tunnel in 1997 and 2004 and included static tests and dynamic forced oscillation tests in roll, pitch and yaw angles. Data were collected with varying mounting techniques for both static and dynamic tests. Data from static tests were used to compute non-dimensional aerodynamic derivatives with respect to angle of attack and sideslip angle. Results varied for different mounts and Reynolds numbers.

   The measured data from forced oscillation tests were obtained at different angles of attack, amplitudes, Reynolds numbers, and frequencies. Some of the tests were performed with initial offsets in either roll or yaw angle, for roll or yaw oscillations, respectively. Harmonic analysis was applied for obtaining the in-phase and out-of-phase components of aerodynamic coefficients. Responses varied with amplitude, Reynolds number, frequency, and mounting method. In general, decreased model accuracy was observed at angles of attack greater than 30°. Increased higher harmonic in the math model improved accuracy for large amplitude and offset data. Harmonic analysis as well as power spectral analysis indicated an increased measurement noise at these low amplitude oscillations.

   Frequency dependence was observed mostly between 20° and 50° for all components in pitch, roll and yaw oscillations. For frequency dependent data a two-step linear regression algorithm was used to obtained parameters in an unsteady aerodynamic model. The static coefficients computed from forced oscillation tests were compared to static coefficients measured from static tests. Axial and normal force coefficients from pitch oscillations had high model accuracy. Rolling moments coefficient had the highest accuracy for roll oscillations when the linear model was used. There was some variation in results between small and large amplitudes. 30° amplitude oscillations at zero offset had high model accuracy, but the necessity for higher order terms in harmonic analysis brought into question the applicability of the relationships between the first order Fourier coefficients and the aerodynamic coefficients. The variation or the non-dimensional time constant showed an increased unsteady effect between 35° and 45° angle of attack. Very few yaw oscillations had acceptable unsteady model accuracy.

The results from wind tunnel data are summarized in NASA TM and M.S. Thesis (see Publications 1 and 2). Some examples are included in Figures 1 to 4.

b) The problems of general methodology for testing and data analysis were addressed using data from water tunnel tests. These tests were conducted with a 2.5% scale model of the F-16XL at Rolling Hills Research Company to identify nonlinear and unsteady aerodynamic model parameters. Although forced oscillation tests were performed about all three-body axes, only roll axis oscillation data were analyzed.

Harmonic analysis of the small-amplitude oscillatory data was performed on single oscillations formed by averaging 30 cycles of data. This analysis provided a basis for the nonlinear analysis. Harmonic analysis was also applied to the large amplitude data.

A general formulation of the aerodynamic model for aircraft that includes nonlinear unsteady aerodynamics was attempted. The resulting model could predict a broad class of aerodynamic responses of a rigid-body aircraft. The structure allowed easy interpretation of the model parameters by retaining conventional stability and control derivations for static and dynamic terms. Unsteady terms in the form of indicial functions were added to allow frequency dependent phenomena to be included.

Experimental data and resulting model for the rolling-moment coefficient are presented in the AIAA Paper (see Publication 3).

c) The oscillatory data obtained from the NASA LaRC 12-Foot Low Speed Tunnel for a 10% model of an F-16XL were used in previous years for mathematical modeling.

A portion of the data; however, was analyzed for obtaining a measure of their accuracy. In this analysis the accuracy of the time stamp and the sample of time fidelity were first evaluated. Then, the effect of the timing signal was investigated. In the following step, the commanded and measured input signal was compared. The last part of the accuracy assessment was the evaluation of measured outputs. A measure of precision was obtained from repeated measurements under the same conditions. For the final statement in the accuracy, the outlier rejection rules were applied. The results of the data accuracy assessment are summarized in NASA TM Report (see Publication 4).

2. Aerodynamic characteristics and instrumentation system calibration of Free Flying Aircraft Sub-scale Experimental Research Aircraft (FASER)

The FASER program was established at the NASA LaRC to provide an affordable, easy-to-modify testbed to conduct research in the area of stability and control and system identification. Since the remote-control airplane will be used in high amplitude rapid maneuvers, it was desired to have a simulation program of FASER to allow the pilot to practice the maneuvers before the actual aircraft is flown. In addition, the simulation program can be used to design the experiment and to aid control law development.

In this part of the research the existing aerodynamic model equations were updated using wind tunnel data. These data were obtained in the form of aerodynamic coefficients and their variation with the angle of attack, sideslip angle and control surface deflections. The analytical expressions for these dependencies were developed by applying the multivariate orthogonal modeling technique. An example of the resulting equations is given in Table 1.

Wind tunnel data were also analyzed for obtaining calibrations of the alpha and beta-vanes. The analytical forms of these calibrations were developed by a stepwise regression. Examples of the calibration equations are given in Table 2.

The complete results of the research conducted are in the NASA DSCB Internal Memo (see Publication 5).

3) System Identification Methodology

The past, present and future of system identification applied to aircraft at NASA LaRC were discussed in the *Journal of Aircraft* (see Publication 5).

The purpose of this paper was to present a general approach to aircraft system identification, as formulated at NASA LaRC. The paper starts with a historical survey of flight testing and stability and control parameter estimation at NACA Langley Memorial Aeronautical Laboratory, and later at NASA LaRC, which lead to the present state of the art. The individual steps in the methodology are introduced and briefly explained. Four recent examples are mostly of the methodology application are given. These examples are mostly related to problems that go beyond traditional stability and control estimation from flight data. The paper is concluded by some thoughts about the future development of the methodology.

Table1. Aerodynamic model equations for two different subspaces

$-7.5^{\circ} \leq \alpha \leq 10^{\circ} \ and -10 \leq \beta \leq 10$	
$C_D(\alpha,\beta,\delta_e,\delta_f)$	$.0405+1.6365\alpha^2+.212\alpha\delta_f+.2631\alpha\delta_e-.047\delta_e^2\delta_f+$ $.062\alpha+.013\delta_e+.1081\delta_e^2+.0426\delta_f$
$C_L(\alpha,\beta,\delta_e,\delta_f)$	$4.2977\alpha+.6275\delta_f+.2915\delta_e+.046-.608\delta_f^3-2.8714\alpha^2\delta_f$
$C_m(\alpha,\beta,\delta_e,\delta_f)$	$-.7241\delta_e-.4917\alpha-.0335\beta+.0646\delta_f-.8846\alpha^2$ $+.9092\beta^2\delta_e+.2939\beta^2-.0411\beta\delta_e-.1356\alpha\delta_f^2+$ $.0525\beta\delta_f+.0666\delta_e^2+.4455\delta_e^3-.6869\beta^2\delta_f-.0294$
$C_Y(\alpha,\beta,\delta_a,\delta_r)$	$-.35\beta+.0893\delta_r-.025\delta_a+.02965\alpha-.1662\beta\delta_r^2-.04462\alpha\delta_r+.11\alpha\beta$
$C_l(\alpha,\beta,\delta_a,\delta_r)$	$-.198\delta_a-.0411\beta-.227\alpha\beta+.24572\delta_a^3+.0272\alpha\delta_a$
$C_n(\alpha,\beta,\delta_a,\delta_r)$	$-.0435\delta_r+.0584\beta-.1181\alpha\beta+.07642\beta\delta_r^2+.02352\alpha\delta_r-.135\beta^2\delta_r$ $-.3469\alpha^2\beta+.0126\delta_a^3$

$10^{\circ} \leq \alpha \leq 20^{\circ} \ and -10 \leq \beta \leq 10$	
$C_D(\alpha,\beta,\delta_e,\delta_f)$	$-.257+1.99\alpha+.404\alpha\delta_e+.558\delta_f^2+.118\delta_e^2-.73\delta_f^3-.185\alpha\delta_e\delta_f$
$C_L(\alpha,\beta,\delta_e,\delta_f)$	$-.003+1.36\delta_e-.654\alpha\delta_f-.71\alpha\delta_f^2+.142\delta_e\delta_f+.513\delta_f+6.895\alpha$ $-11.892\alpha^2$
$C_m(\alpha,\beta,\delta_e,\delta_f)$	$.348-.8249\delta_e-3.12\alpha+2.183\alpha\beta^2+1.32\alpha^2\delta_e+1.776\alpha^2+.8948\delta_e^3$ $+.722\alpha\delta_e^3$
$C_Y(\alpha,\beta,\delta_a,\delta_r)$	$-.31\beta+.09679\delta_r+.81\alpha\delta_r-.417\alpha^2\delta_r+3.376\alpha+.381\alpha\beta^2-.2025\alpha\beta+$ $.396\beta^2\delta_r-.08982\beta\delta_r^2-.0061\delta_a^2+15.41\alpha^3-.2764-.262\beta^2-.1127\delta_a$ $-1.643\alpha^2\delta_a-12.7\alpha^2-.069\delta_r^3$
$C_l(\alpha,\beta,\delta_a,\delta_r)$	$-.131\delta_a-9.1\alpha^2\beta-.368\alpha\delta_a-.037-.7591\alpha\beta^2-.00896\delta_r^2+1.731\alpha^2\delta_a$ $-.661\beta+4.24\alpha\beta+3.59\beta^3+.127\beta\delta_a^2-.04\alpha^2\delta_r-.045\delta_a\delta_r^2-.0054\delta_a^2$ $-.004\beta\delta_a\delta_r-1.3773\alpha^3+.306\alpha$
$C_n(\alpha,\beta,\delta_a,\delta_r)$	$-.089\delta_r+2.59\beta^3-.328\alpha^2\delta_r+.196\alpha-.1138\beta^2+.1582\alpha^2\delta_a$ $-7.23\alpha^2\beta-.013\alpha\delta_r^2-.0007\delta_a\delta_r-.888\alpha^3-.02836-.083\delta_a^3$ $+3.622\alpha\beta-.457\beta+.056\beta\delta_r^2+.2837\alpha\delta_r+.0463\delta_r^3-.09\beta^2\delta_r$ $-.0136\delta_a\delta_r^2+.013\delta_a$

Table 2. Calibration equations for alpha and beta vanes

| Region	Relative Voltage Limits	Equation
$-7.5^o \le \alpha \le 10^o$	$\alpha_{nv} \ge .43681$	$\alpha^o = 99.539 - 201.81\alpha_{nv} - 4.2825\beta_{nv}$
$10^o < \alpha < 40^o$	$.29692 < \alpha_{nv} < .43681$	$\alpha^o = 106.98 - 229.71\alpha_{nv} + 45.279\beta_{nv}^2 - 68.554\beta_{nv}^3$
$40^o \le \alpha \le 80^o$	$\alpha_{nv} \le .29692$	$\alpha^o = 98.419 - 180.03\alpha_{nv} + 40.879\beta_{nv} - 164.08\alpha_{nv}\beta_{nv}$
$10^o \le \beta \le 30^o$	$\beta_{nv} \ge .51086$	$\beta^o = -229.29 + 640.23\beta_{nv} - 351.85\beta_{nv}^2 + 39.075\alpha_{nv}$ $- 62.05\alpha_{nv}\beta_{nv}$
$-10^o < \beta < 10^o$	$.42711 < \beta_{nv} < .51086$	$\beta^o = -11741.1 + 7222.2\beta_{nv} - 15273\beta_{nv}^2 + 11031\beta_{nv}^3$ $+ 60.448\alpha_{nv} - 170.78\alpha_{nv}^2 + 176.99\alpha_{nv}^3$
$-30^o \le \beta \le -10^o$	$\beta_{nv} \le .42711$	$\beta^o = -148.06 + 456.25\beta_{nv} - 326.72\beta_{nv}^2 + 8.4967\alpha_{nv}$
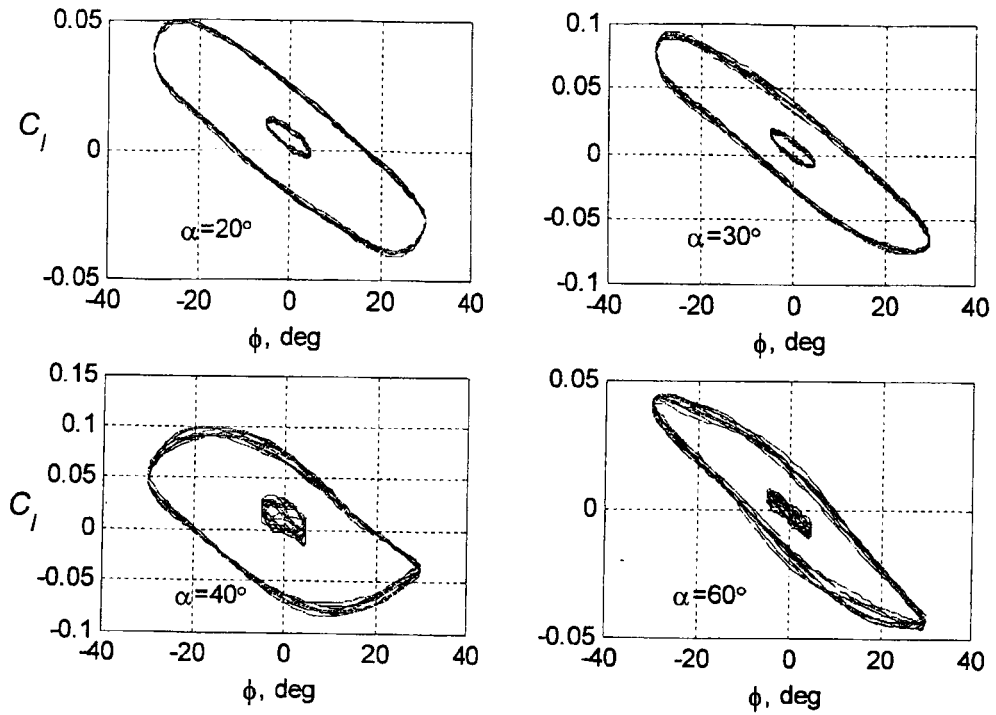
Figure 1. Effect of angle of attack and amplitude on lateral coefficient, C_l, for rolling oscillations with k = 0.171.
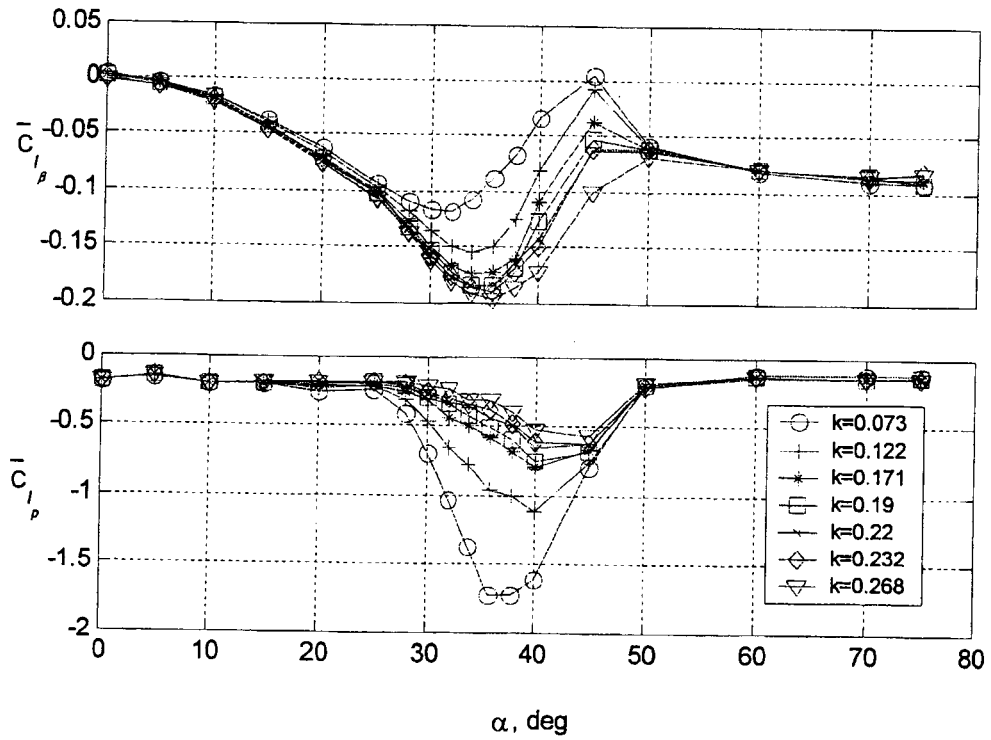

Figure 2. Variation of in-phase and out-of-phase components of rolling moment Coefficient with angle of attack. Rolling oscillations.
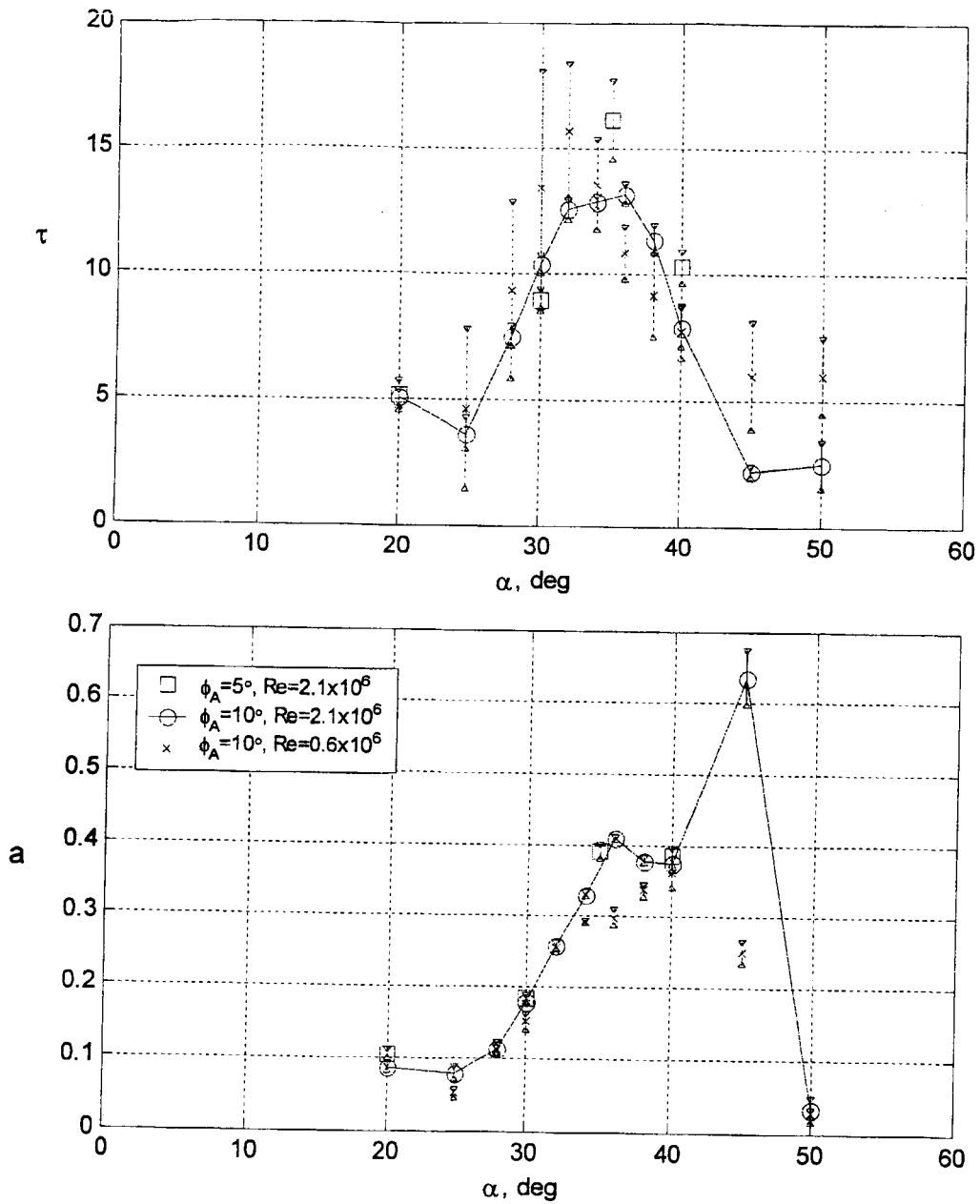
Figure 3. Estimated time delay and gain parameter with their 2-sigma intervals.
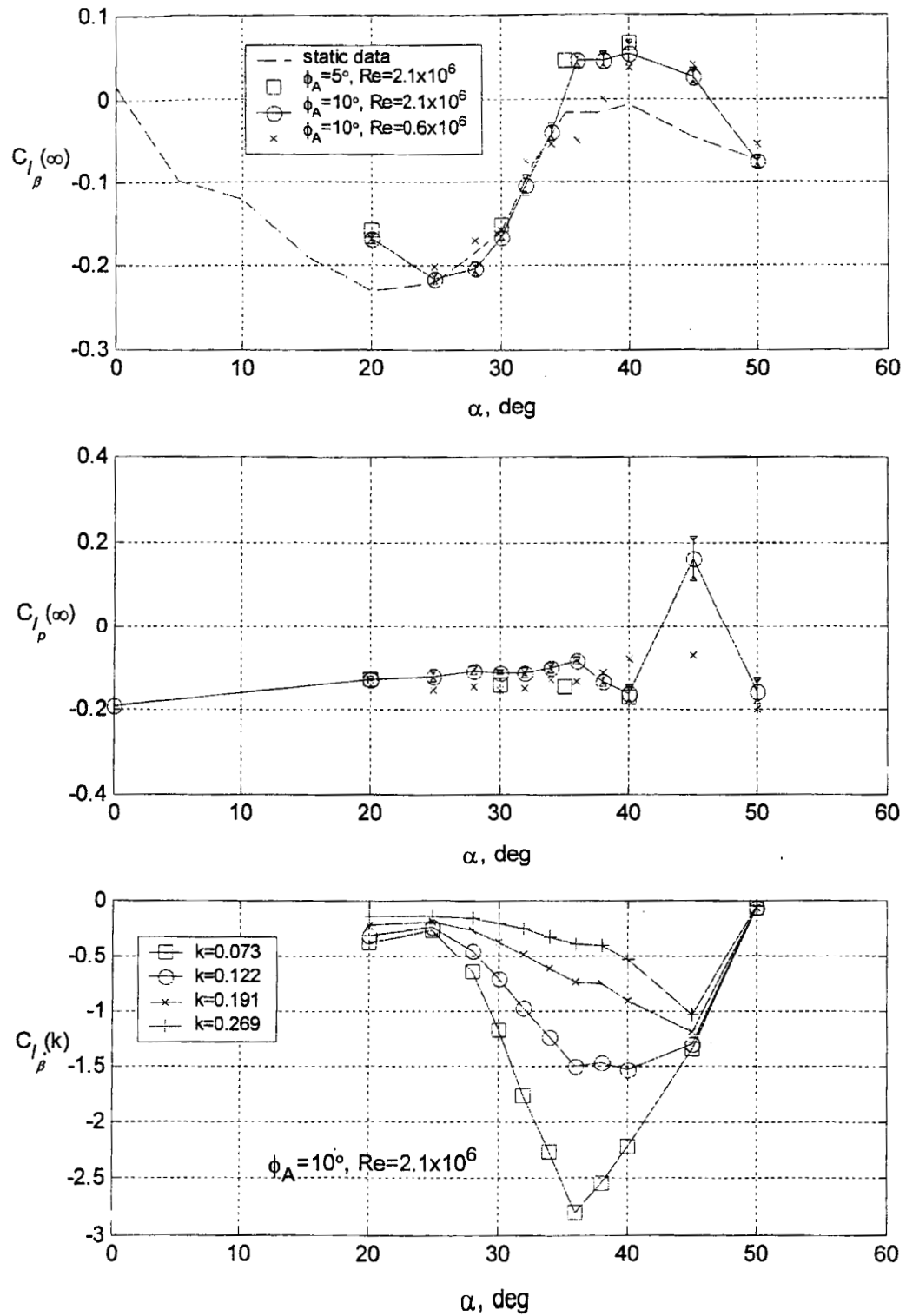Rolling-moment coefficient. Rolling oscillations.

Figure 4. Estimated rolling moment parameters from static and oscillatory tests.

PUBLICATIONS

1. Klein, Vladislav; Murphy, Patrick C. and Szyba, Nathan M.: "Analysis of Wind Tunnel Lateral Oscillatory Data of the F-16XL Aircraft." NASA TM-2004-213246.

2. Szyba, Nathan M.: "Unsteady Aerodynamic Modeling of Dynamic Oscillatory Wind Tunnel Data of the 18% Scale F=16XL Aircraft." M.S. Thesis, The George Washington University, 2004.

3. Murphy, Patrick C.; Klein, Vladislav and Szyba, Nathan M.: "Progressive Aerodynamic Model Identification From Water Tunnel Test of the F-16XL Aircraft." AIAA Paper 2004-5277.

4. Kim, Sungwan; Murphy, Patrick C. and Klein, Vladislav: "Evaluation and analysis of F-16XL Wind Tunnel Data from Dynamic Tests." NASA TM-2004-213234, April 2004.

5. Eissa, Mohamed M.: "Model Structure Definition and Analysis For the Wind Tunnel Force and Moment Coefficients For a Sub-Scale Research Airplane." NASA DSCB Internal Memo, August 2004.

6. Morelli, Eugene A. and Klein, Vladislav: "Application of System Identification of Aircraft at NASA Langley Research Center." *Journal of Aircraft*, Vol. 41, No. 2, January-February, 2005, pp. 12-25.