APPLICATIONS OF MODEL STRUCTURE DETERMINATION TO FLIGHT TEST DATA

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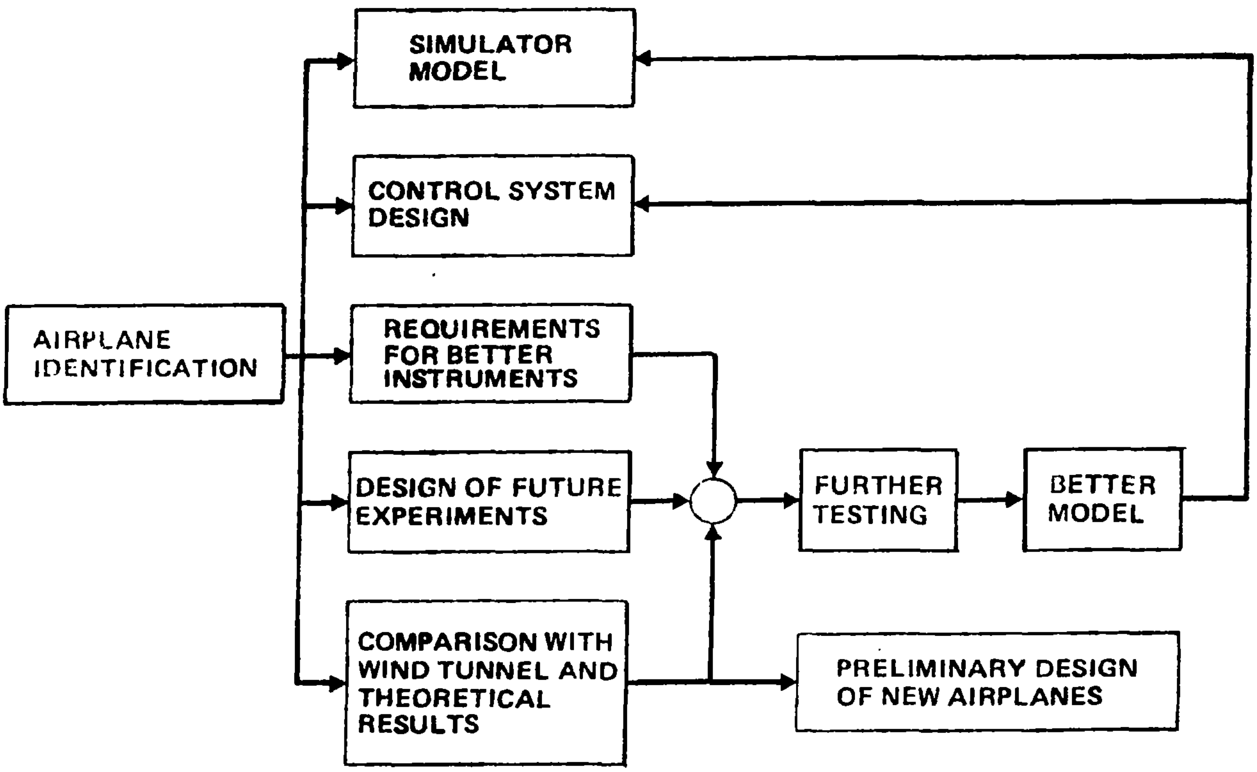
SYSTEM IDENTIFICATION DEFINED

The following definition of system identification was suggested by Zadeh[1] in 1968 and is widely accepted today. The three main objects that this definition connects are boxed. The harmonic content of the input to the system should be rich enough to excite the important modes of that system. A class of systems from which the model will be chosen is selected through engineering judgment or on the basis of a priori knowledge. Finally, the decision must be made about a decision criterion specifying which model from the class is equivalent to the physical system under test.

IDENTIFICATION IS THE DETERMINATION, ON THE BASIS OF INPUT AND OUTPUT OF A SYSTEM WITHIN A SPECIFIED CLASS OF SYSTEMS, TO WHICH THE SYSTEM UNDER TEST IS EQUIVALENT.

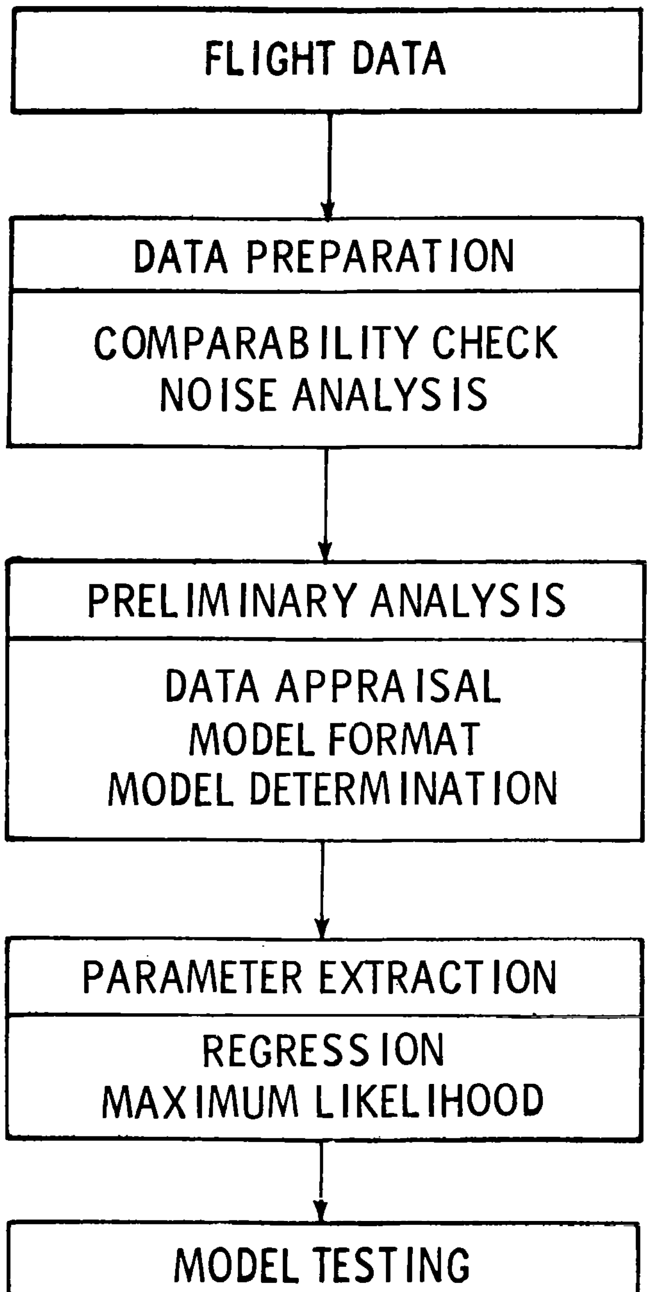
IDENTIFICATION APPLICATIONS

The benefits of airplane identification are shown here. The results of this procedure can be used in several areas indicated. They are especially important today, since modern airplanes rely upon digital control and, hence, a good mathematical model.



BLOCK SCHEME OF AIRPLANE IDENTIFICATION

Airplane identification requires several steps. This presentation will concentrate on model structure determination.



STEPWISE REGRESSION

The stepwise regression is developed from the "classical" linear regression. It allows for the selection of important terms in the aerodynamic model equation. It can show the adequacy of a linear model or a necessity for adding some nonlinear terms.

ASSUME THE GENERAL FORM OF THE AERODYNAMIC MODEL EQUATIONS CAN BE WRITTEN AS

$$y(t) = \theta_0 + \theta_1 X_1(t) + \theta_2 X_2(t) + \cdots + \theta_{Q-1} X_{Q-1}^{(t)}$$

THEN FOR EACH OF N OBSERVATIONS

$$y(i) = \theta_0 + \theta_1 X_1(i) + \theta_2 X_2(i) + \cdots + \theta_{Q-1} X_{Q-1}^{(i)} + n(i)$$

WHERE $n(i)$ IS THE EQUATION ERROR AT THE i^{th} OBSERVATION

AS APPLIED TO THE VERTICAL FORCE EQUATION:

$$\frac{2mg}{\rho V^2 S} a_Z = C_Z = C_{Z_0} + C_{Z_\alpha} (\alpha - \alpha_0) + C_{Z_q} \frac{q\bar{c}}{2V} + C_{Z_{\delta_e}} (\delta e - \delta e_0) + \text{HIGHER ORDER TERMS}$$

For the data from large amplitude maneuvers it can be beneficial to approximate the aerodynamic functions by splines rather than Taylor's series expansion. The polynomial splines are written as functions of the "+" function, $(\alpha - \alpha_i)_+^m$ for knots of α_i. This function has value $(\alpha - \alpha_i)^m$ for $\alpha \geq \alpha_i$ and has value 0 for $\alpha < \alpha_i$. In case of a function in two variables, a two-dimensional spline should be used or the data can be partitioned in one of the two variables. Data partitioning leads to a simplified model.

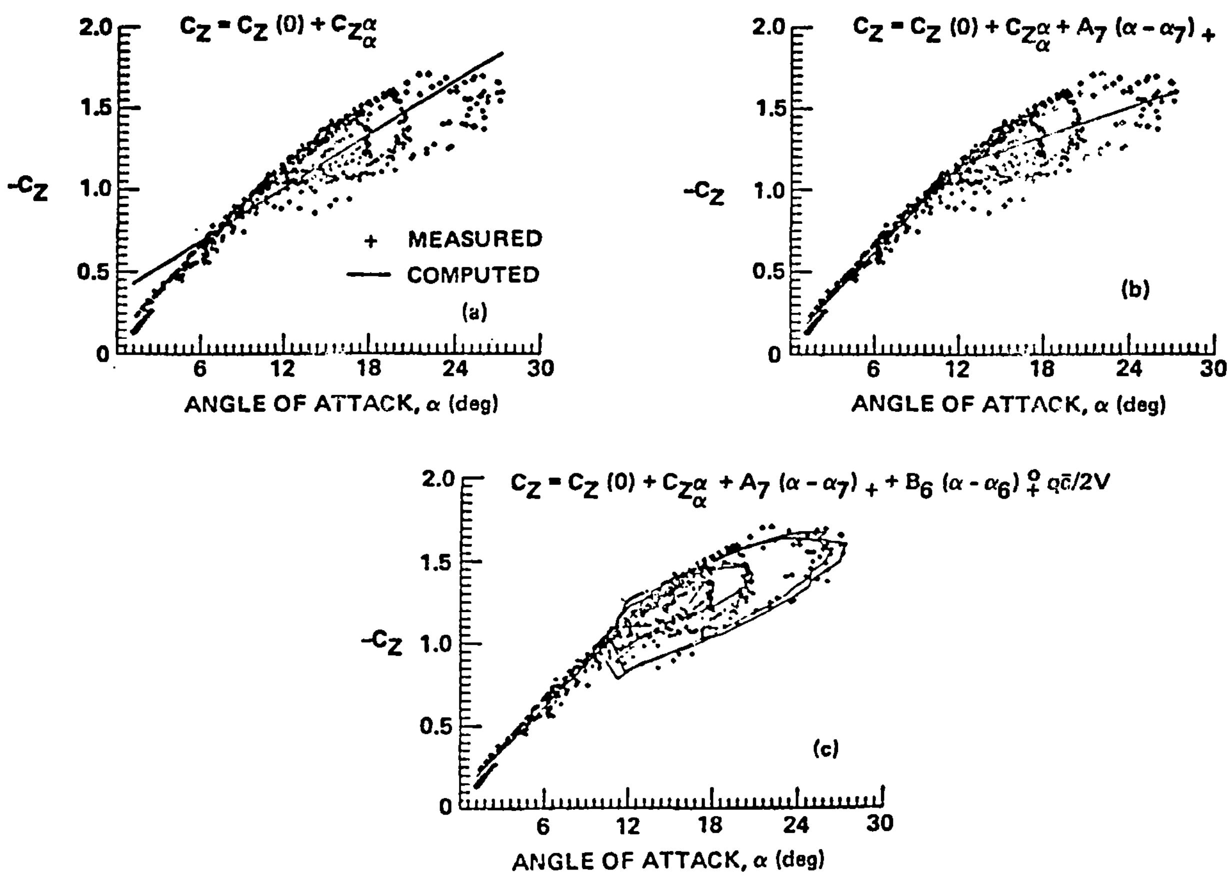
- ANOTHER REPRESENTATION OF NONLINEAR MODEL IS A SPLINE REPRESENTATION:

$$C_Z = C_{Z_0} + C_{Z_\alpha}\alpha + \sum_{i=1}^{k} C_{Z_{\alpha_i}}(\alpha - \alpha_i)_+ + C_{Z_q}\frac{q\bar{c}}{2V} + \sum_{i=1}^{k} C_{Z_{q_i}}(\alpha - \alpha_i)_+^0 \frac{q\bar{c}}{2V} + C_{Z_{\delta_e}}\delta e + \sum_{i=1}^{k} C_{Z_{\delta_{e_i}}}(\alpha - \alpha_i)_+^0 \delta e$$

- COMBINE DATA FROM SEVERAL MANEUVERS AND APPLY STEPWISE REGRESSION WITH POLYNOMINAL SPLINES TO COMBINED DATA SET
- COMBINE DATA FROM SEVERAL MANEUVERS AND PARTITION AS A FUNCTION OF ANGLE OF ATTACK, SIDESLIP, etc.

MODEL STRUCTURE COMPARISON AT DIFFERENT ENTRIES

The model building using stepwise regression and spline approximation is demonstrated in fitting of the vertical force coefficient. The first three entries into the regression show the effect of each term selected and the improvement in the fit to the data.



MODEL SELECTION CRITERIA

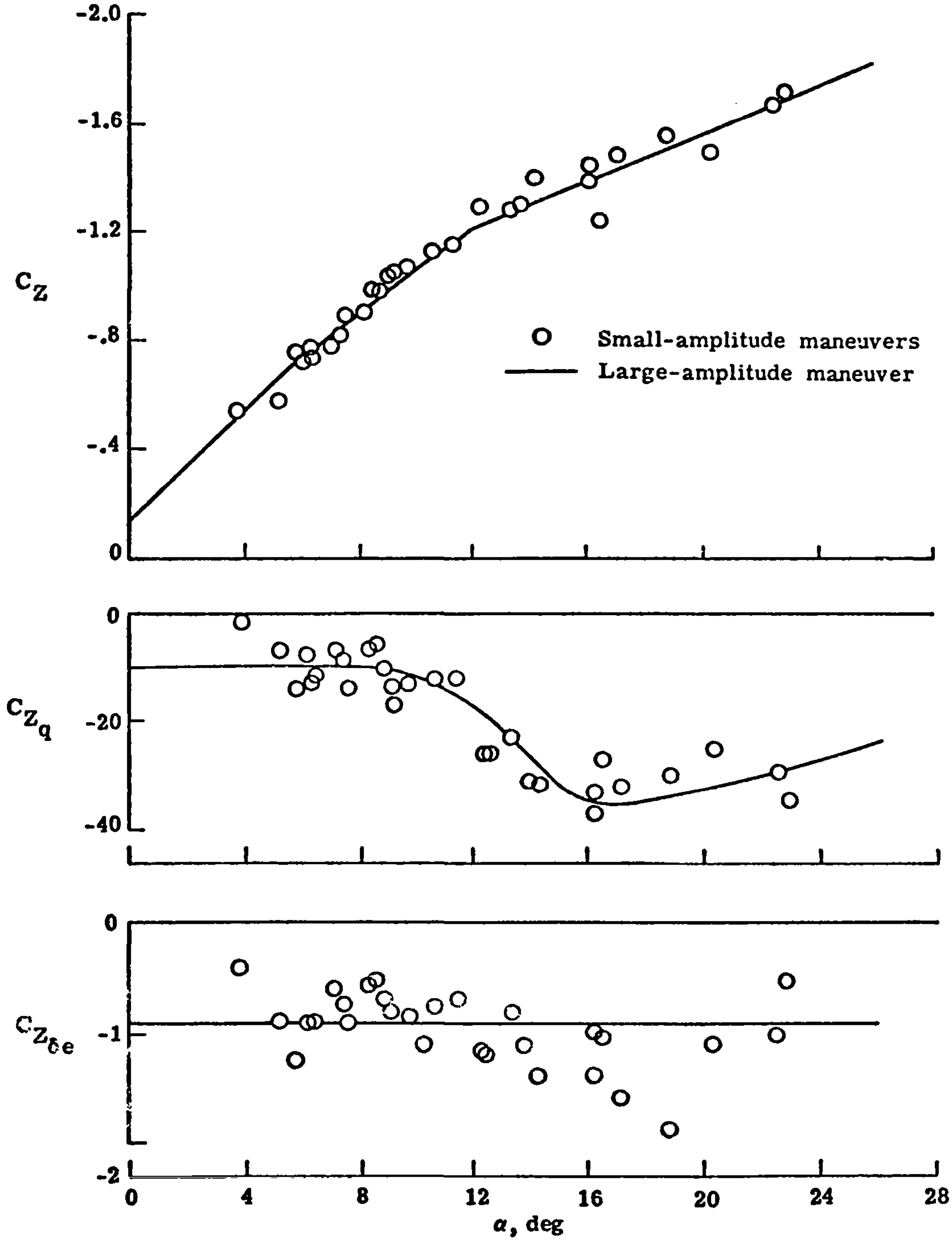
The stepwise procedure continues in selecting terms as long as they are statistically significant. But for the selection of an adequate model several criteria should be considered.

THE ACTUAL TERMS SELECTED FOR THE FINAL MODEL DEPEND ON SEVERAL CRITERIA:

- THE PARTIAL F VALUE F_p OF EACH TERM SHOULD BE GREATER THAN 5
- THE F STATISTIC SHOULD BE MAXIMUM FOR THE FINAL MODEL
- R^2, THE SQUARED MULTIPLE CORRELATION COEFFICIENT, SHOULD BE CLOSE TO 100 PER CENT FOR THE FINAL MODEL
- THE RESIDUAL SEQUENCE SHOULD BE RANDOM AND UNCORRELATED

LONGITUDINAL PARAMETERS FROM DIFFERENT MANEUVERS GENERAL AVIATION AIRPLANE

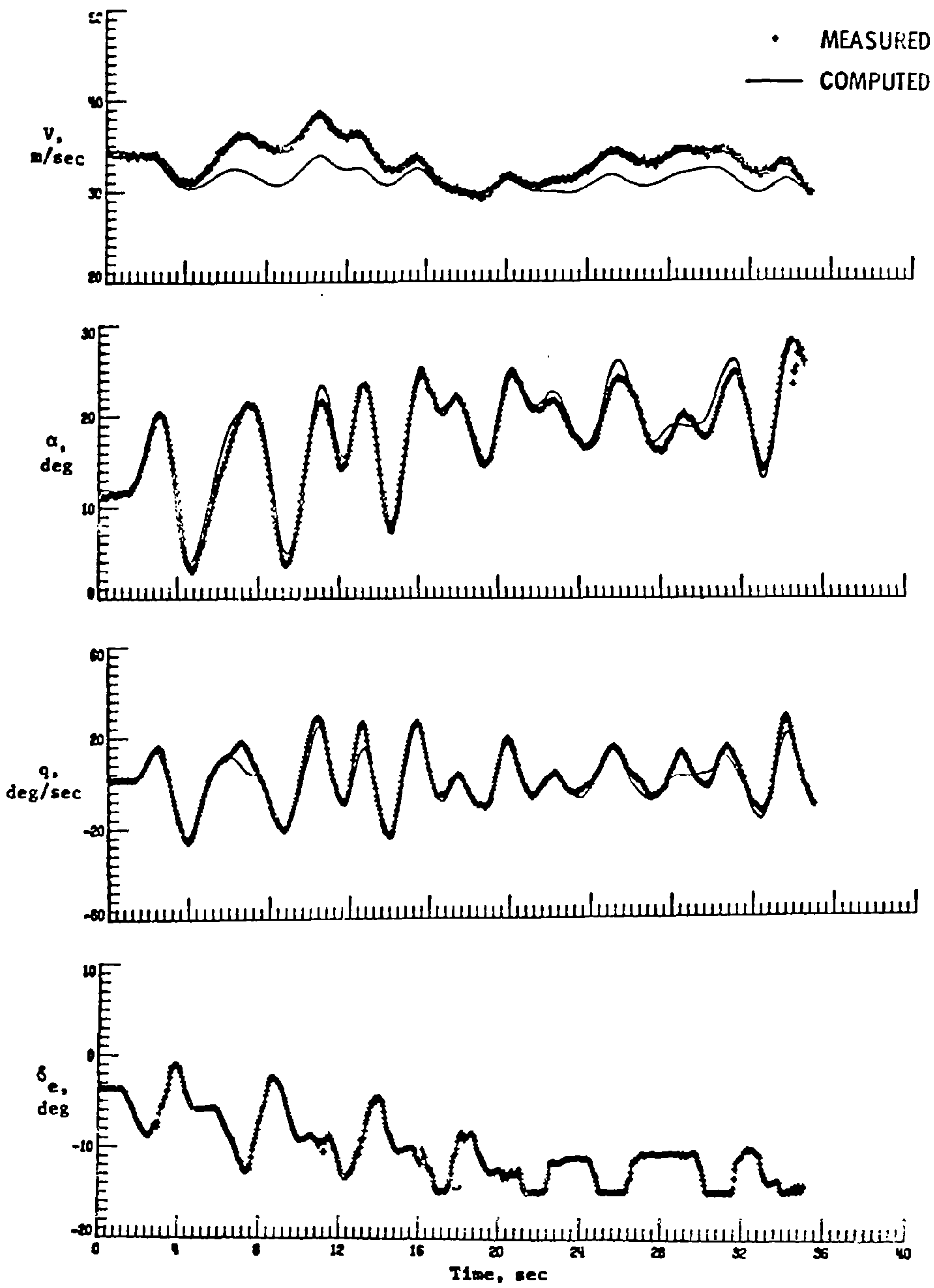
The comparison of results from small and large amplitude maneuvers is presented for the vertical force coefficient. The spline of first, second, and zero degree was used for the three functions shown.



MODEL VALIDATION

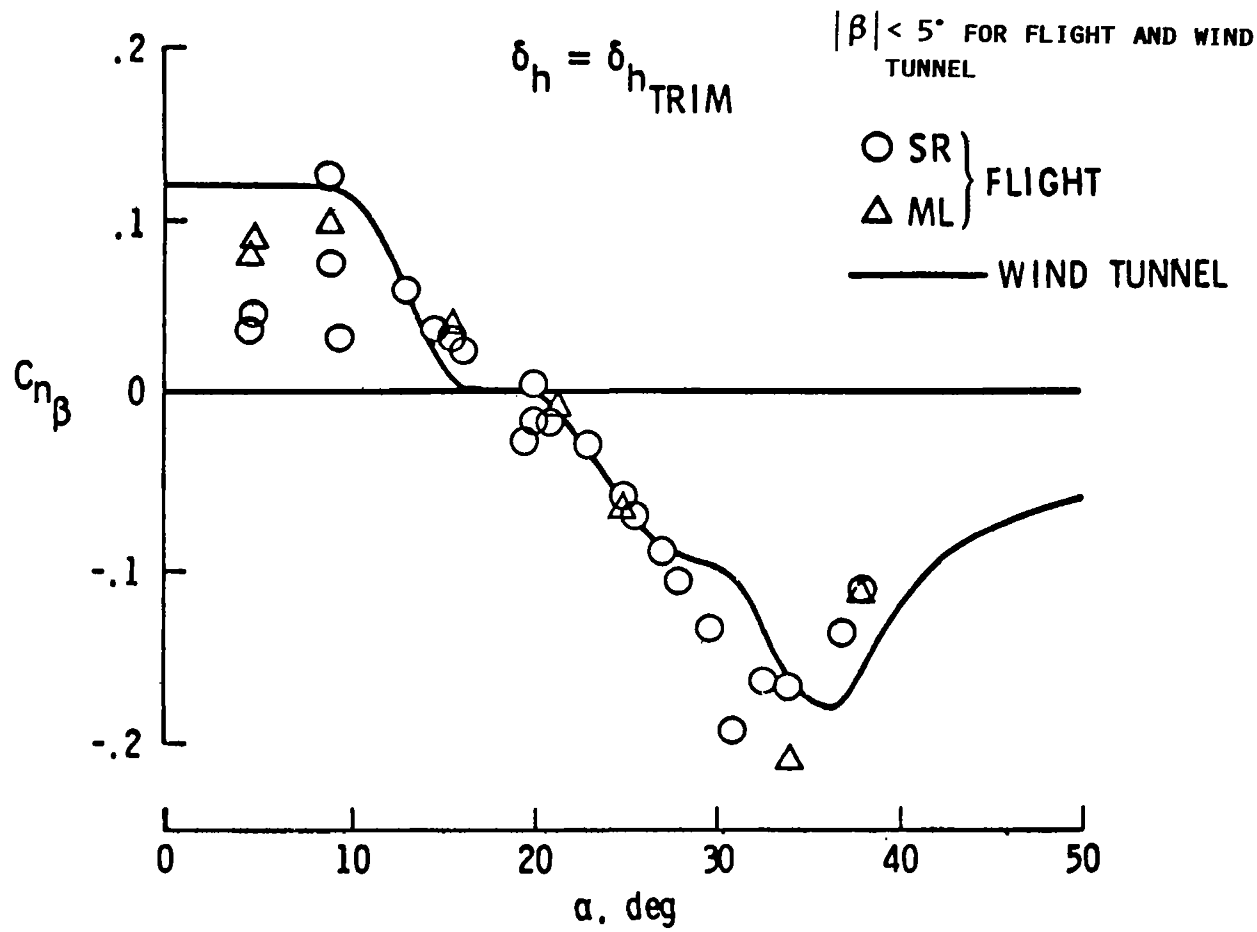
GENERAL AVIATION AIRPLANE

The model determined by stepwise regression from the data of a single large amplitude maneuver is validated by numerically integrating the equations of motion and comparing with the measured data of an independent set.



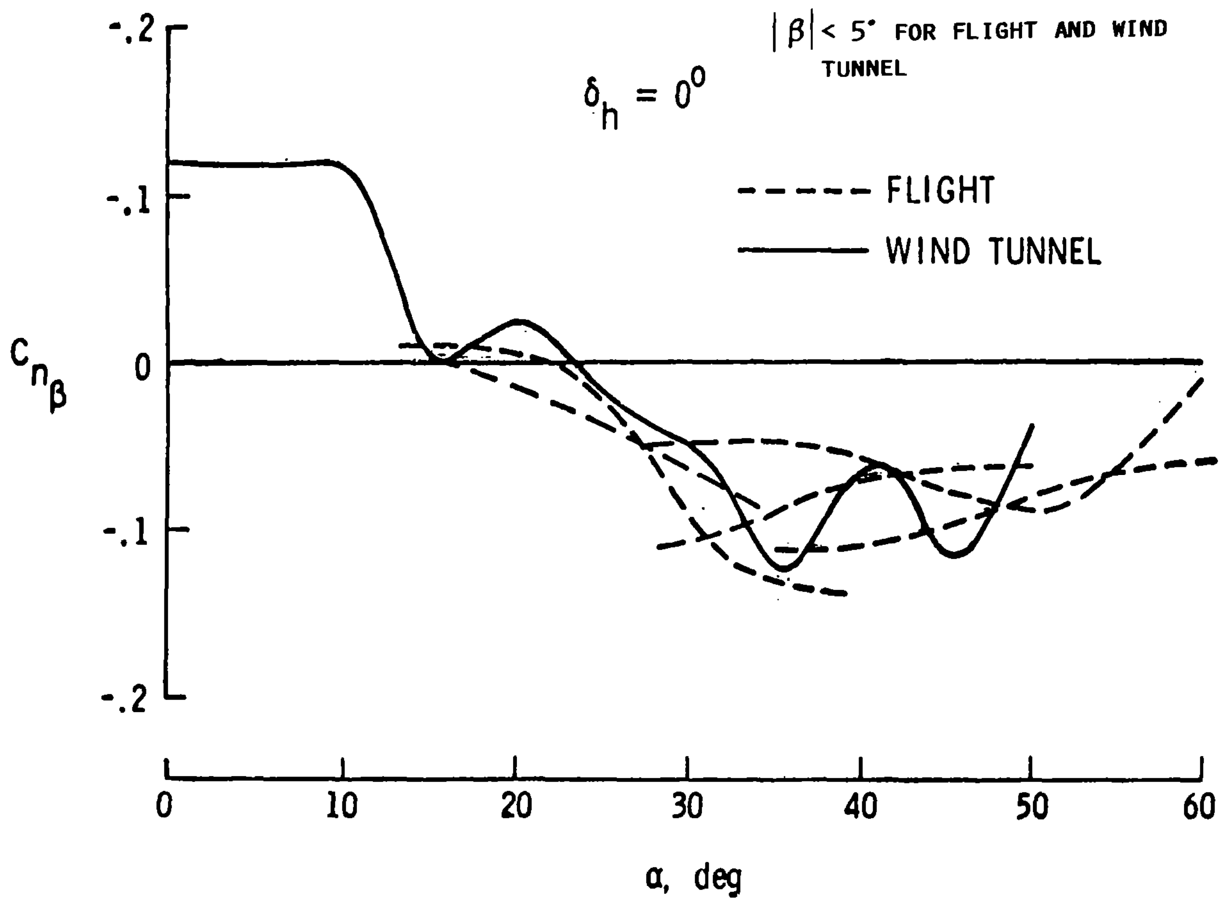
DIRECTIONAL STABILITY PARAMETER FROM LOW-AMPLITUDE MANEUVERS AND WIND TUNNEL MEASUREMENTS - ADVANCED FIGHTER

Nonlinearities in aerodynamics parameters of high-performance airplanes can be detected from the measured data by the application of stepwise regression. These results can be compared with wind tunnel measurements. The example shows the directional stability parameter plotted against the angle of attack as obtained from small amplitude maneuvers and wind tunnel measurements.



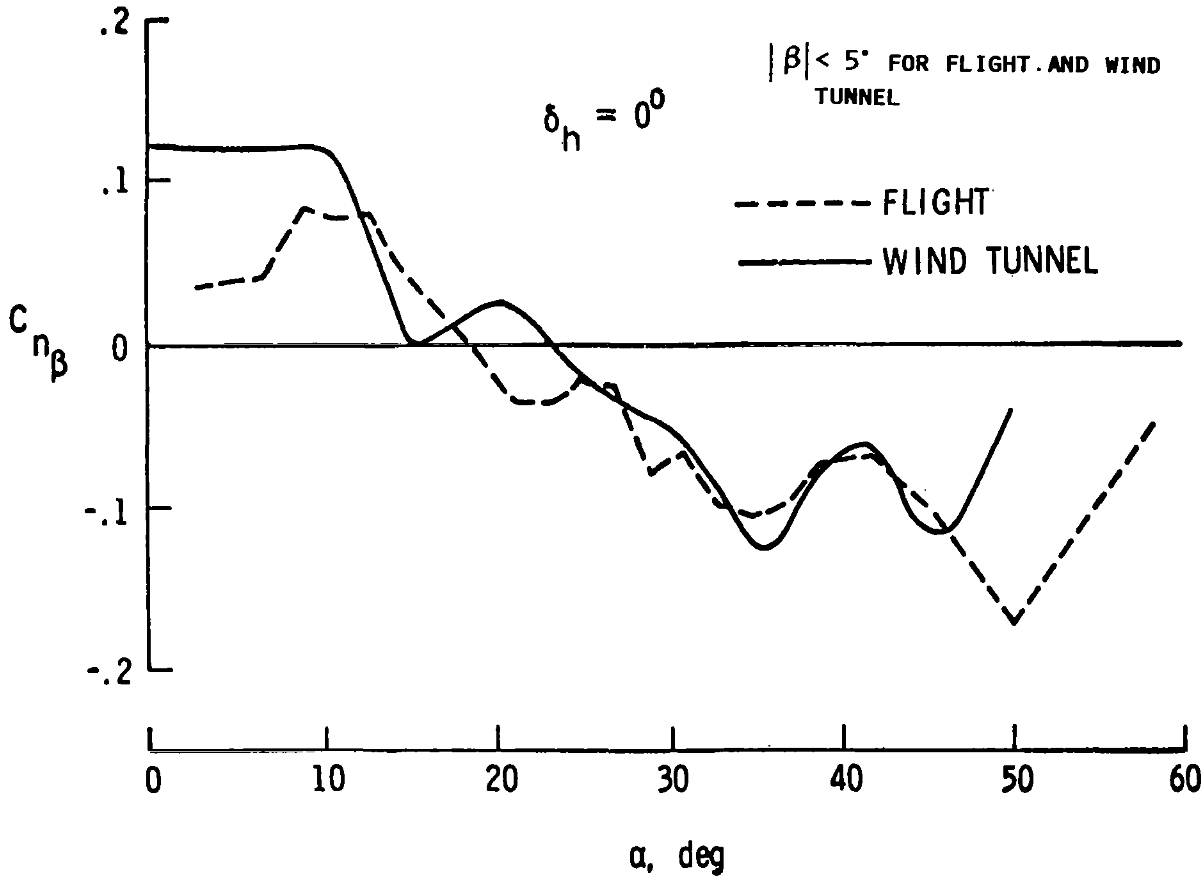
DIRECTIONAL STABILITY PARAMETER FROM LOW-AMPLITUDE MANEUVERS AND WIND TUNNEL MEASUREMENTS - ADVANCED FIGHTER (CONTINUED)

The directional stability parameter determined from five large amplitude maneuvers is compared with wind tunnel measurements.



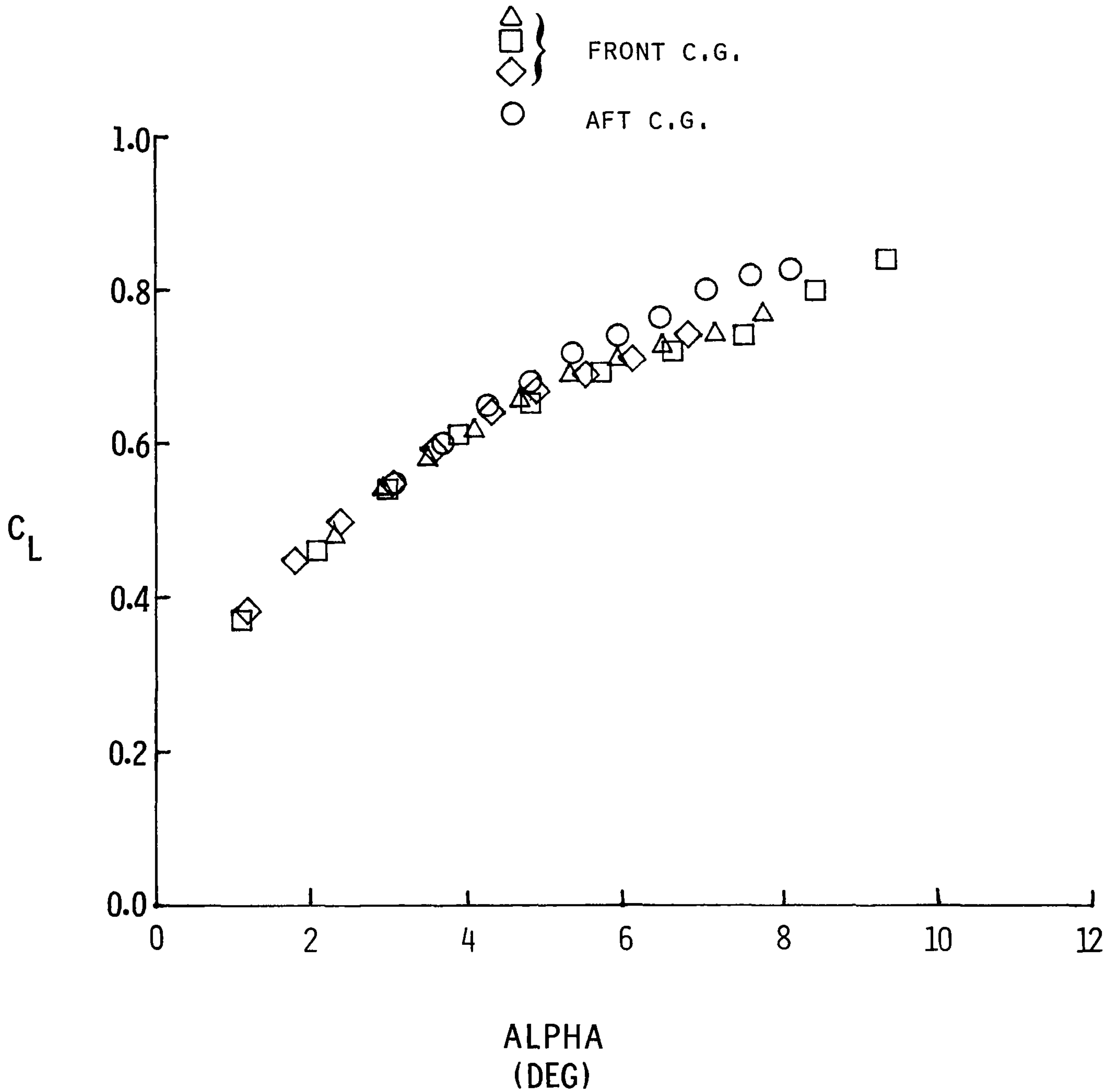
DIRECTIONAL STABILITY PARAMETER FROM LOW-AMPLITUDE MANEUVERS AND WIND TUNNEL MEASUREMENTS - ADVANCED FIGHTER (CONCLUDED)

The directional stability parameter determined from partitioned data is compared with wind tunnel measurements.



ESTIMATED LIFT CURVE FROM WIND UP TURNS — JET TRANSPORT

For the jet transport, nonlinearities in the lift curve can occur at relatively low angles of attack. Therefore, even for small perturbed maneuvers it can be necessary to use nonlinear aerodynamic model equations. The example shows the results from the wind up turns which were flown for airplane certification.



SUMMARY

The technique presented in this paper has been published in references 2 and 3.

- o INCORRECT STABILITY AND CONTROL DERIVATIVES CAN RESULT FROM AN INADEQUATE AERODYNAMIC MODEL STRUCTURE.
- o STEPWISE REGRESSION CAN BE USED TO DETERMINE THE STRUCTURE FOR AN ADEQUATE MODEL.
- o SEVERAL STATISTICAL AND INFORMATION CRITERIA NEED TO BE CONSIDERED WHEN SELECTING AN ADEQUATE MODEL.
- o FLIGHT DATA WHICH COVERS A NONLINEAR AERODYNAMIC MODEL RANGE MAY BE ANALYZED AS A SINGLE DATA SET OR PARTITIONED INTO SEVERAL DISTINCT SETS.
- o STEPWISE REGRESSION FOR MODEL STRUCTURE DETERMINATION AND PARAMETER ESTIMATION HAS BEEN SUCCESSFULLY APPLIED TO THREE AIRCRAFT TYPES (SINGLE ENGINE GENERAL AVIATION, UNAUGMENTED MODERN JET FIGHTER, JET TRANSPORT).

REFERENCES

1. Zadeh, L. A.: From Circuit Theory to System Theory. Proceedings of I.R.E., vol. 50, no. 5, May 1962, pp. 856-865.

2. Klein, Vladislav, Batterson, James G., and Murphy, Patrick C.: Determination of Airplane Model Structure From Flight Data by Using Modified Stepwise Regression. NASA TP-1916, October 1981.

3. Klein, Vladislav and Batterson, James G.: Determination of Airplane Model Structure From Flight Data Using Splines and Stepwise Regression. NASA TP-2126, March 1983.