

Computer Aided Evaluation of Aircraft Handling Qualities and
Flight Control System Robustness

Shyam Chetty and Racl J R
Flight Mechanics and Control Division
National Aeronautical Laboratory, Bangalore-17, India

Abstract

This paper describes the salient features of an interactive computer aided software package developed for the analytical evaluation of aircraft handling qualities and flight control system robustness. The package is based on MATLAB/FORTRAN and runs on IBM compatible personal computers.

Introduction

Modern high performance aircraft are designed to be aerodynamically unstable and employ sophisticated digital flight control systems onboard, to recover stability and meet the stringent performance requirements over the entire flight envelope. Performance evaluation and verification of these advanced flight control systems require analytical comparison of system characteristics to various military specifications which include flight control and handling quality specifications like the USAF MIL-F-9490D,¹ MIL-F-8785C² and the recent MIL-STD-1797.³ In addition, to guarantee flight safety, the flight control system designer must ensure sufficient robustness for the complete closed loop system against parameter variations, external disturbances and subsystem failures. These evaluations are becoming increasingly complex and difficult as the design trend towards increased control system integration, sophistication and coupling continues.

The present paper describes the salient features of the interactive computer aided software package developed for the analytical evaluation of handling qualities, generation of lower order equivalent system models, estimation of robustness margins and generation of ideal handling quality models for each phase of flight. The software package is based on Matlab/fortran-77 and runs on IBM compatible personal computers. The paper also covers certain new features/techniques used for model order reduction, evaluation

of closed loop handling quality criteria and control system robustness. Extensive use of vector optimisation techniques based on the minimisation of the Kreisselmeier's function^{4,5} is made to offer greater flexibility to the user during evaluation. Typical set of results are also presented to illustrate the capabilities of the software.

The software has been developed based on the popular MATLAB (Moler et al., 1989) Computer Aided Control System Design (CACSD) tool.⁶ The software package has a modular structure consisting of 406 Matlab macros (.m files), 32 data files (.mat files) and 5 fortran executable code segments. Special effort has been taken to make the user interface uniform and consistent over the full scope of the package. A query/menu driven input has been used, as large number of parameters have to be entered by the user during evaluation. Extensive use of default values, on screen help messages, graphic outputs and a comprehensive demonstration programme provide the necessary support to a new user. The package has been split into the following sections which are selectable from the main menu and are classified as:

- i) Model Order Reduction Techniques
- ii) Longitudinal Handling Quality Criteria
- iii) Lateral/Directional Handling Quality Criteria
- iv) Demonstration Programmes
- v) Ideal Handling Quality Design Models
- vi) Robustness Metrics

In each classification a specific criterion or technique can be selected from separate sub menus which have been organised in a tree like structure. The package can handle multiple models (at different flight conditions) and these can be specified in either the state space or transfer function formats. Time or frequency response data from nonlinear simulation and flight tests can also be used to evaluate the aircraft performance. The final results, many of which are in

graphical form, are stored in .MET files generated automatically using the Graphics Post Processor (GPP) option of MATLAB. On completion of an evaluation session, the user can select the print and output the final results to a in a sequential manner to suit his particular application.

Model Order Reduction Techniques

The following model order reduction techniques are incorporated in the package for evaluating Lower Order Equivalent System (LOES) models :

- i) Least Square Curve Fitting in the Frequency Domain - Levy's Technique and Modifications. ^{7,8}
- ii) Scalar Optimisation Technique based on Rosenbrock's Search Routine ⁹
- iii) State Space Equivalent System Procedure ¹⁰
- iv) Vector Optimisation Technique based on Minimisation of the Technique ¹¹
 - a) Longitudinal Dynamics (Second and Fourth Order Models)
 - b) Dynamics (First Second and Fourth Order Models with Extensions for Multiple Transfer Function Matching)

These techniques have been selected based on the earlier experience of researchers in this area and gives the user the choice to select the technique best suited to his particular application. The user must select the initial values with care, as most of the above minimisation techniques will tend to converge at the local minima. Single step procedures like the least square curve fitting technique can be used to obtain the starting values prior to optimisation. The other important selection the user must make is the number of LOES parameters which are to be kept fixed during the minimisation process. This mainly depends on the structure of the control system and number of plant inputs. The software also incorporates several features which enables the user to overcome some of the problems commonly encountered, like non uniqueness of solutions, interpretation of matching cost, goodness of fit required etc. Figure 1 shows the bounds on amplitude and phase error for the pitch rate transfer function as a function of frequency to which the pilot is

insensitive ⁹. The vector optimisation procedure for model reduction permits these error bounds to be explicitly included as constraints. For multiple transfer function matching the technique allows the user to minimise simultaneously the errors in each of the transfer functions. Figure 2 shows the results obtained using the model order reduction software for a highly augmented aircraft model.

Longitudinal Handling Qualities

The requirement guidance section of the MIL-STD-1797 lists several alternative short period handling quality criteria that needs to be evaluated for modern high performance aircraft. Each criterion can be selected from appropriate sub - menus by the user. Tables - 1,2 gives the details of a typical menu for longitudinal handling qualities. Figures 3 to 8 show the results obtained. The integer numbers (1 to 7) in the plots indicate the results at different flight conditions for which the evaluation was done.

Handling Qualities

The different criteria that can be evaluated using the software package are listed in Table 3. Typical results are shown in figures 9 to 11.

Generation of Ideal Handling Quality Models

Most modern control design approaches require the designer to formulate an "ideal model" prior to starting the actual design process. For high performance aircraft, formulation of these low order models are crucial, and due to the large number of specifications and practical constraints which the designer must meet, this is an extremely complex task. This package allows the user to generate such models based on the airframe characteristics, flight condition and particular task. The procedure adopted for generating the optimal plant matrices is based on the simultaneous solution of a set of independent nonlinear equations. The desired specifications (including handling qualities) are formulated as a number of independent nonlinear equations containing the dimensional derivatives as unknowns which are solved simultaneously using a routine based on the secant method for finding the roots of an equation. The end

results depend on the choice of the initial values for these unknowns (dimensional derivatives) and must be systematically selected. To ensure good convergence the procedure allows the user to start with a reduced set of equations and once valid solutions are found, additional equations are added one or two at a time until all the unknowns are included. Typical specifications used are expressions for the frequencies for the dominant modes, modal phase angles between motion variables at the appropriate frequencies and gain ratios. An ideal state space model which meets all the specifications listed in the MIL - STD 1797 for a typical high performance aircraft flying at low speed and low altitude is given in Table 4. Figure 12 shows the short and long term time responses for a step input to the ideal model.

Robustness Analysis

Design of a control system is done with a nominal model of the plant. However, the control system characteristics do not remain the same in presence of uncertainties. These uncertainties are due to variations in parameters and/or unmodelled or incorrectly modelled dynamics. One of the main aims of control system synthesis is to achieve stability and good performance in face of model uncertainties. Such issues are treated via robustness analysis. We describe some methods and results of robustness analysis. Specifically the approaches based on i) singular values and eigenvalues of return and inverse return difference matrices, ii) multivariable gain and phase margins, iii) time analysis (LAATA) and iv) modal analysis. The numerical results are presented where appropriate.

Robustness Problem

When a compensator is designed using a nominal model of the plant (e.g. aircraft), the resulting feedback control system (FCS) is said to be robust with respect to class of modelling errors if it remains stable and has good performance, when the nominal model is replaced by any other model of the

discuss only stability robustness

Gain /Phase Margin issues

In a practical design it is necessary to provide reasonable stability margins, i.e.,

to provide sufficient gain and phase margins (GMPMs). For a output (SISO) system GMPMs are directly related to the variation of the so called return difference quantity $\{RD \rightarrow T(s) = 1 + \dots\}$, with RD plays important role in the assessment of the robustness of a control system. The issue in stability margin for the FCS is to determine a lower bound on the size of the smallest perturbation to the RD matrix (for multivariable systems, MVS) that will destabilize the system. It is assumed that the uncertainty introduced in the flight control system from various sources can be represented as a gain and/or phase uncertainty in each feedback loop. Therefore, the stability margin requirements of the flight control specifications determine the largest admissible gain and phase uncertainties in each loop. For the requirement is - In multivariable system, variations shall be made with all gain and phase values in the feedback paths held at nominal values except for the path under investigation. More meaningful stability margins may be defined as limits within which the gains of all feedback loops may vary independently at the same time without destabilizing the system, while the phase angles remain at their nominal values. This concept also applies to phase variations while gains remain at their nominal values. This amounts to setting the limits for independent gain and phase variations in a diagonal perturbation matrix for a multiplicative perturbation model. We can also define another approach for uniform variation of gains and phases.

Stability Margins for Multivariable Systems

We explore two approaches: eigenvalue - based and singular value - based methods to arrive at gain/phase margin limits based on Ref. [14].

Independent Gain/Phase Margins (IQMs, IPMs):

The independent gain (phase) margins are limits within which the gains (phases) of feedback loops may vary independently at the same time without destabilizing the system, while the phase angles remain at their nominal values. Let $L(s)$ be a diagonal perturbation matrix

Then IGMs are limits within which may vary independently for each i without destabilizing the system, with and $\forall i$. Similarly IPMs are limits within which may vary independently for each i without destabilizing the system while $=$ and $\forall i$.

Uniform Gain/Phase Margins (UGMs, UPMs):

The uniform gain (phase) margins are limits within which the gains (phase angles) of all feedback loops vary uniformly (as against independent ones) at the same time without destabilizing the system, while the phase angles (gains) remain at their nominal values.

In this case e and K is a diagonal nominal complex loop gain matrix.

Thus UGMs wrt the nominal loop gain $K(j\omega)$ are limits within which $b(\omega)$ may vary without destabilizing the system while $\theta(\omega) = 0, \forall \omega$.

Similarly UPMs wrt the nominal loop gain are limits within which $\theta(\omega)$ may vary without destabilizing the feedback system while $b(\omega) = 1, \forall \omega$. Based on the above definitions the robustness criteria arrived at by multivariable Nyquist theory have

been implemented in this package. 14

The combined use of IGMs, UGMs and IPMs, UPMs in an appropriate way obtains the extended stability regions beyond the usual conservative regions. However in the present case, only independent gain and phase margins have been used for seeking the stability regions.

Loop - at-a-time Approach

The single loop stability margins required in MIL-F-9490D are computed by manipulating the frequency response data base that is generated during the multivariable study of robustness. The approach is to obtain equivalent open loop transfer function for the loop in question by closing the other loops in a MVS via a connection matrix: $= \text{diag } \{1, 1, 1, 1, 0, 1, 1, 1, \dots\}$.

Here '0' in the diagonal implies that, that loop is under investigation to evaluate the stability margins, whereas the '1's' in the diagonal imply the loop closure for the remaining loops. With this connection matrix the equivalent (open) loop transfer function is evaluated for which the frequency response data base is used to compute the i th loop frequency

response as

$k_{kk}^{-1} = \{ \dots \}^{-1}$
Here k_{kk} means the (k, k) th element of the matrix. The single loop transfer function is then used to define a_1 and α_2 , namely:

$$a_1 = \min_{\omega \geq 0} |1 + g_k|^{-1}$$

similarly

$$a_2 = \min_{\omega \geq 0} |1 + g_k(j\omega)|^{-1}$$

Then the gain and phase margin formulae are applied to a_1 and α_2 to obtain the

gain and phase margins for the feedback loop in question, that is the loop for which these margins are to be evaluated. This procedure is then applied in turn to each feedback loop to obtain margins for these loops. The approach is analytically complementary to the Bode diagram method to obtain gain and phase margins and it can be used also for nonminimum phase loops without any modifications. If margins estimated by this method are greater than specified by MIL-F-9490D, then actual margins are also expected to be greater.

Modal Loop Eigenvalue [Loc]

In this approach the method described in Ref. 17 is implemented. Let the aircraft dynamics be represented as

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

Then output feedback is given as:

Here u_p is an external reference input and other variables have standard state space notation and interpretations. In eigensystem assignment, the problem is to select a \tilde{K} , the output feedback gain matrix, such that the closed loop system has desired specifications (eigen characteristics).

directions 2,3 and 4 are shown in Fig. 16. The stability boundaries are reached, at iteration 15 for direction 2, and at iteration 4 or 5 for directions 3 and 4 in gain-plane region of stability. This is supported by the behaviour of minimum singular value and the closed loop eigenvalues.¹³

b) Loop-at-a-time Results:

Loop 1 (ϕ loop):

GM = +/- 8.36 dB; PM = +/- 38.77 deg.

Loop 2 (r_s loop):

GM = +/- 13.02 dB; PM = +/- 55.50 deg.

Comparison of the above values with those of MIL-F-9490D values, shows that margins are satisfactory. However, the analytically predicted values are found to be conservative.

Case Study III:

a) Multivariable Results:

The gain-plane region of stability for a certain flight condition is shown in Fig. 17. It can be easily seen that the stability boundary in direction 1 is reached at iteration 4.

b) Loop-at-a-time Results:

Gain/Phase Margins are:

Loop Margin	FC A (Land/Appch.)	FC B (HIGH α)
1 GM	5.75	6.13
PM	55.80	32.08
2 GM	21.02	21.82
PM	59.21	58.74

For flight conditions and loops shown, the MIL-F-9490D is clearly satisfied.

c) Modal Analysis Results:

The results obtained using this package agree with those of Ref. 17. Detailed results of all the case studies of robustness analysis are given in Ref. 13.

Conclusions

In this paper the development of a computer aided software package and its validation for evaluation of handling quality criteria and robustness analysis are described. The interactive PC MATLAB/F-77 based package is validated for several flight control systems available in open literature.

References

1. Anonymous, Military Specifications for Flight Control Systems - Design Installation and Test of Piloted Aircraft, MIL-F-9490D(USAF), 1975.
2. Anonymous, Military Specifications for Flying Qualities of Piloted Airplanes, MIL-F-8785C(USAF), 1980.
3. Booz, J.E., "Relative Evaluation of MIL-STD-1797A, Longitudinal Flying Qualities Applicable to Flared Landing and Approach", AIAA Paper 88-4363, 1988.
4. Kreisselmeier, G. and Steinhauser, R., "Systematic Control Design by Optimising Vector Performance Index", IFAC Symposium on Computer Aided Design of Control Systems, Zurich, pp. 113-117, 1979.
5. Chetty, S., and Usha, U.N., "Computer Aided Handling Qualities Evaluation in the Frequency Domain", NAL-TM-SE-8902, India, 1989.
6. Moler, C., Little, J., Bangert, S., "PC-MATLAB User's Guide", Mathworks Inc., MA-01770, U.S.A., 3.5g Edition, 1989.
7. Saraswathi, L., and Chetty, S., "Longitudinal Equivalent Systems for Augmented Aircraft using Least Squares Curve Fitting Techniques", NAL PD FC 9011, Dec. 1990.
8. Ismail, S., and Chetty, S., "Lower Order Equivalent Systems for High Performance Aircraft", AMSE International Conference on Signals, Data and Systems SDS-91, New Delhi, India, Dec. 1991.
9. Moorhouse, D.J. and Woodcock, R.J., "Background Information and User's Guide for MIL-F-8785C, Military Specification for Flying Qualities of Piloted Airplanes", AFWAL-TR-81-3109, 1981.
10. Bacon, B.J. and Schmidt, D.K., "Fundamental Approach to Equivalent Systems Analysis", AIAA JI. of Guidance, Vol. 11, No. 6, pp. 527-534, 1988.
11. Chetty, S., and Lakshmi, P., "Computer Aided Evaluation of Aircraft Handling Qualities", 5th IFAC/IMACS Symposium on Computer Aided Design in Control Systems, Swansea, U.K., July 1991.
12. McRuer, D., Ashkenas, I., Graham, D., "Aircraft Dynamics & Automatic Control", Princeton Univ. Press, N.J., 1974.
13. Raol, J. R., "Robustness Analysis of Flight Control Systems-based on Singular Values/Eigenvalues", NAL PD FC 9109.
14. Ridgely, D.B., and Banda, S.S., "Introduction to Robust Multivariable Control", AFWAL-TR-85-3102, Feb. 1986.
15. Anderson, M.R., Rubin, U.H., Vincent, J.H., "Evaluation Methods for Complex Flight Control Systems", AIAA CP-89-

- 3502, 1989.
16. McRuer, D.T., Myers, T.T., Thompson, P.M., "Literal Singular Value-based Flight Control System Design Techniques", AIAA J. of Guidance and Cont., Vol. 12, No.6, Nov-Dec. 1989
 17. Srinathkumar, S., "Modal Control Theory and Application to Aircraft Lateral Handling Qualities Design", NASA Technical Paper 1234, June 1978.

Acknowledgements

Authors are grateful to Dr. Balakrishna S. (former Head, FMCD) and Dr. Srinathkumar S. Head, FMCD, for their technical guidance leading to thought provoking discussions during the course of this work. Also the contributions of Ms. P. Lakshmi, Mr. Shaik Ismail and Mrs. Saraswathi L. towards the development of this software are highly appreciated

Table 1 Longitudinal Handling Qualities

-
1. Equivalent Systems
 2. Control Anticipation Parameter (CAP)
 3. Bandwidth Criterion
 4. Neal-Smith Criterion
 5. Closedloop Criterion (MIL-STD-1797A)
 6. Gibson's Criteria
 7. Pitch Rate Response Criterion
 8. C* Criterion
 9. Time Responses (Step/Impulse Input)
 10. Turbulence Response (Random/Discrete)
 11. Phugoid Damping
-

Table 2 Gibson's Criteria

-
1. Q-Theta Trends
 2. Nz Criterion
 3. PIO Criterion (Up and Away)
 4. Pitch Angle Criterion (Approach and Landing)
-

Table 3 Lateral/Directional HQ's

-
1. Equivalent Systems
 2. ϕ/β Computation
 3. Lateral/Directional Mode Characteristics
 4. Roll Rate Oscillations
 5. Roll Performance
 6. Bank Angle Oscillations
 7. Sideslip Excursions
 8. Time Responses (Step/Pulse Inputs)
 9. Turbulence/Gust Response
-

Table 4 Ideal HQ Model

Openloop Aircraft State Space Model :

FC - 0.5 Mach, h=5000 m, Level Flight

X = [alpha, q, theta, u/U0]' U = Y = [az]

[A] = $\begin{bmatrix} -0.648 & 1.000 & 0.000 & -0.127 \\ 0.452 & -0.996 & 0.000 & -0.025 \\ 0.000 & 1.000 & 0.000 & 0.000 \\ -0.042 & 0.000 & -0.061 & -0.018 \end{bmatrix}$

[B] = $\begin{bmatrix} -0.287 \\ -15.340 \\ 0.000 \\ -0.027 \end{bmatrix}$

[C] = $\begin{bmatrix} -104.11 & 0.000 & 0.000 & -20.586 \end{bmatrix}$

[D] = $\begin{bmatrix} -46.424 \end{bmatrix}$

Ideal State Space Model :

[Ai] = $\begin{bmatrix} -0.726 & 1.000 & 0.000 & -0.210 \\ -3.249 & -3.002 & 0.000 & -0.034 \\ 0.000 & 1.000 & 0.000 & 0.000 \\ 0.068 & 0.000 & -0.061 & -0.014 \end{bmatrix}$

[Bi] = [B]; [Ci] = [C]; [Di] = [D]

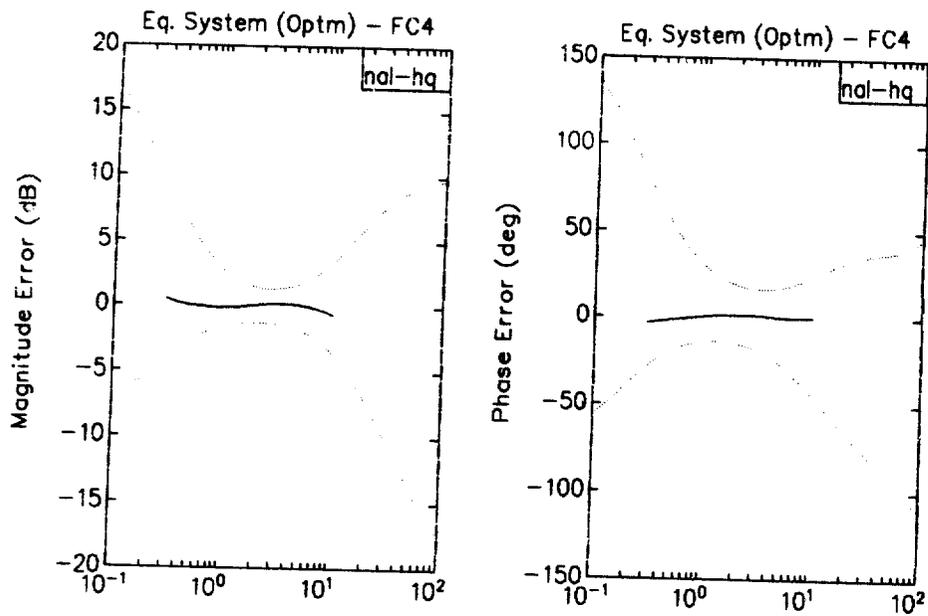


Fig. 1 LOES Error Bounds for Pitch Rate

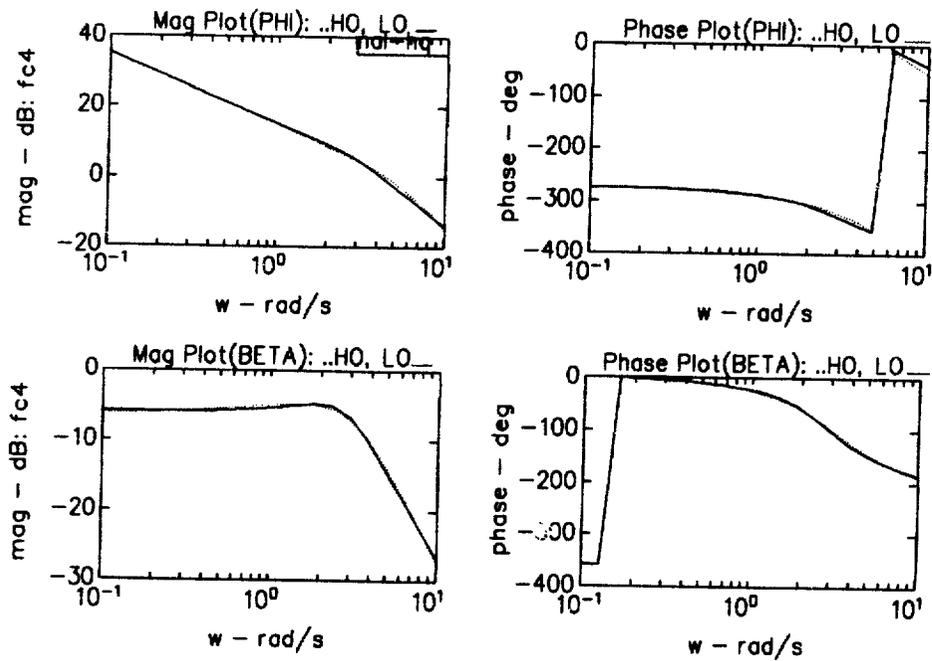


Fig. 2 Frequency Response Comparison for Lateral/Directional Axes

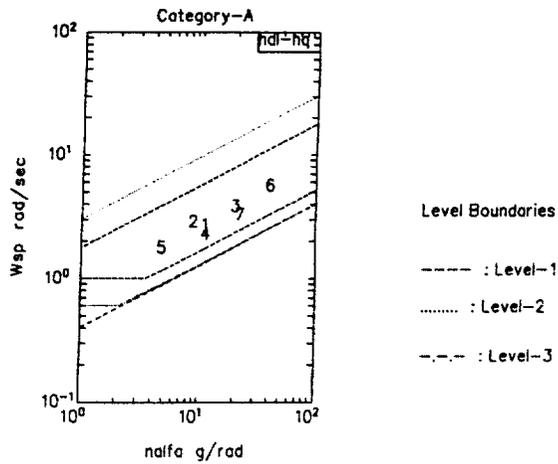


Fig. 3 Short Period Frequency Bounds

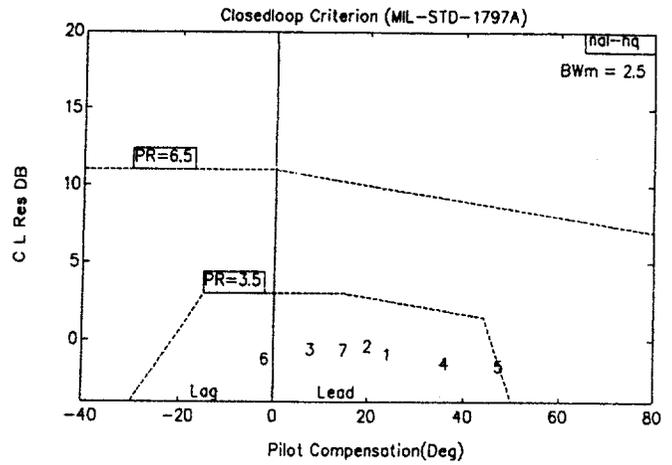


Fig. 4 Closedloop Criterion (Neal-Smith)

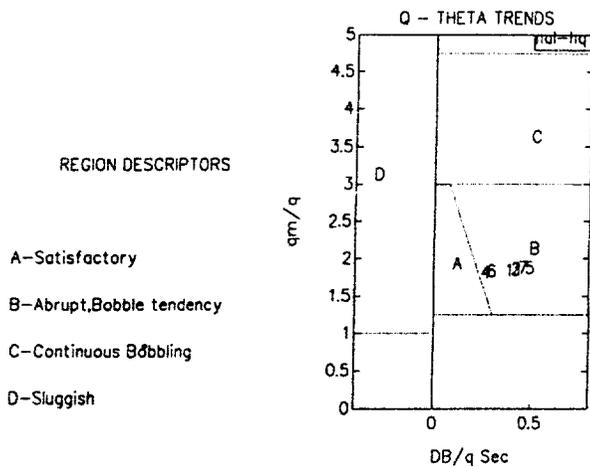


Fig. 5 Gibson's Q-Theta Trends

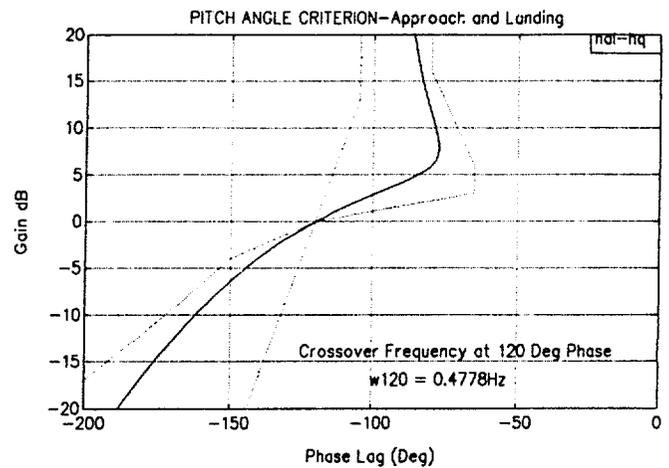


Fig. 6 Gibson's Pitch Angle Criterion

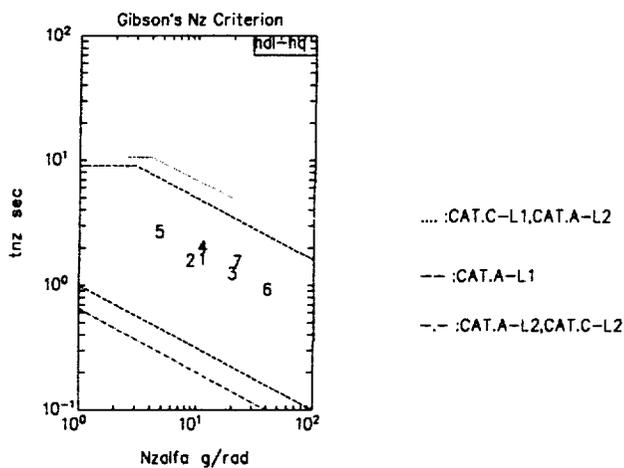


Fig. 7 Gibson's Nz Criterion

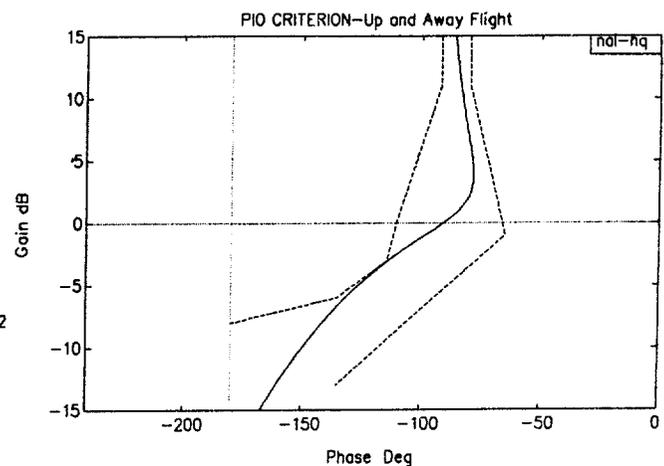


Fig. 8 Gibson's PIO Criterion

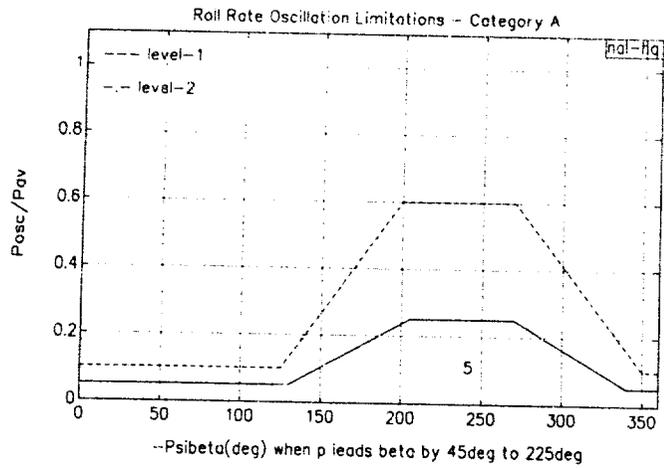


Fig. 9 Roll Rate Oscillation Criterion

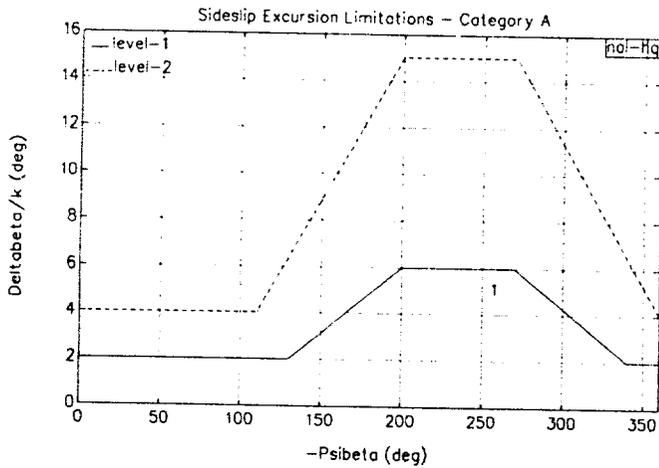


Fig. 10 Sideslip Excursion Limits

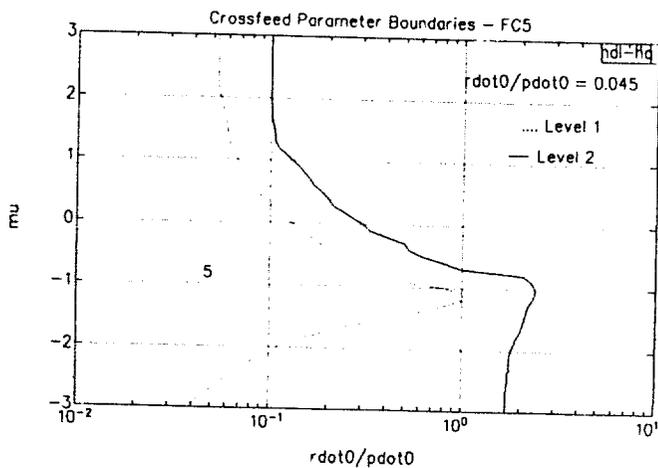


Fig. 11 Turn Co-ordination Criterion

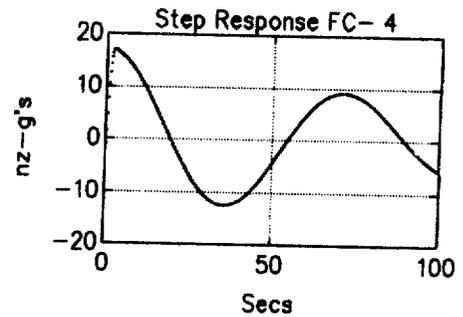
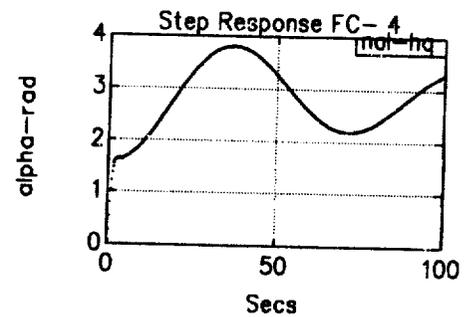
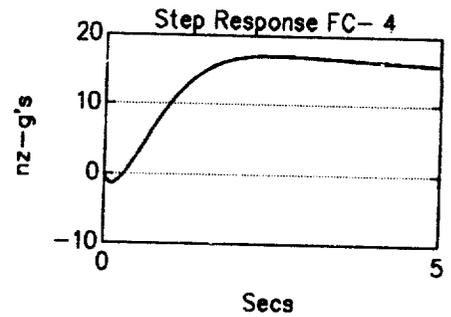
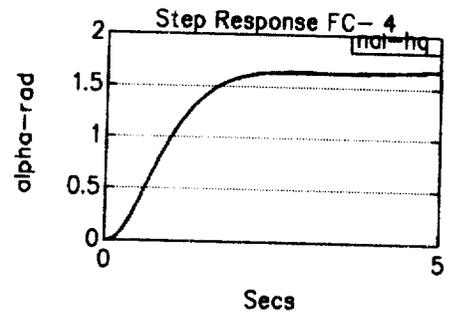


Fig. 12 Ideal HQ Model Step Responses (Short and Longterm)

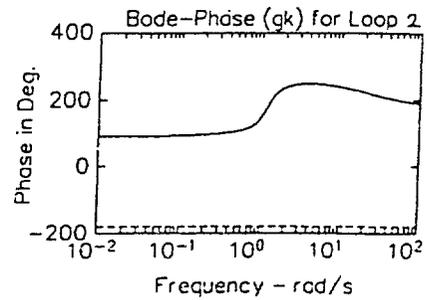
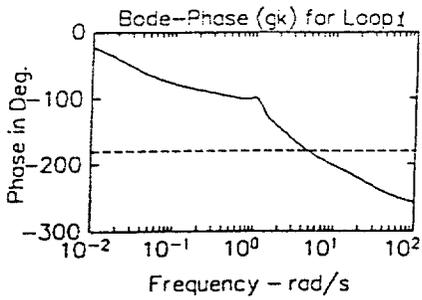
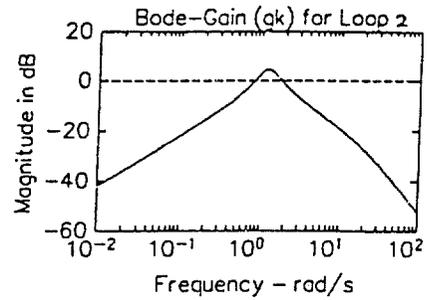
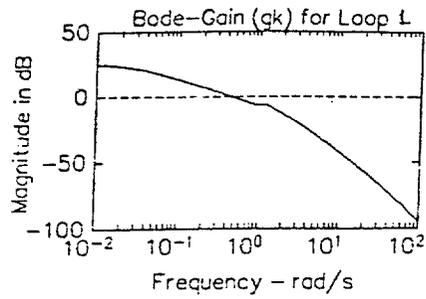
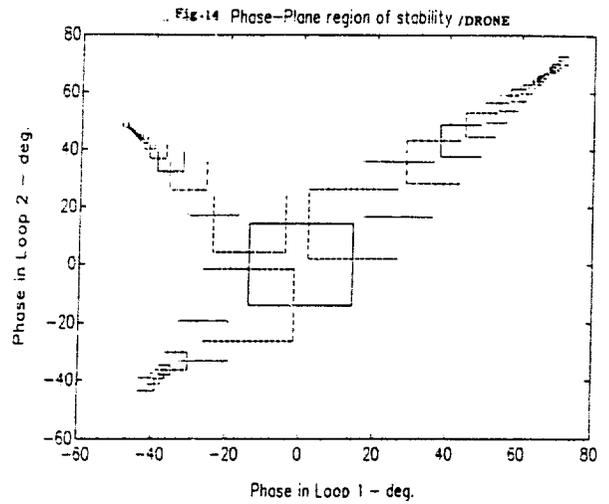
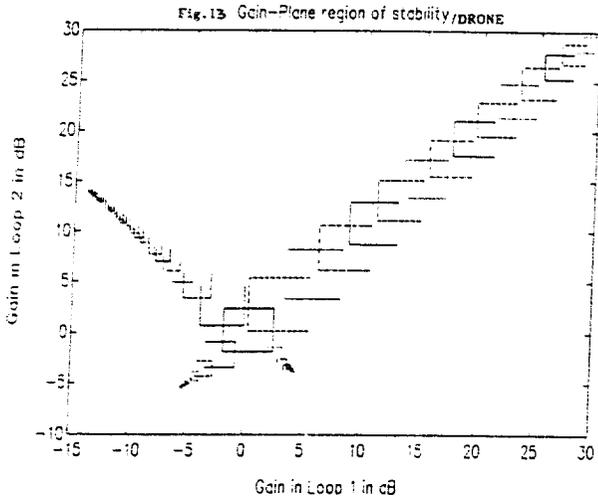
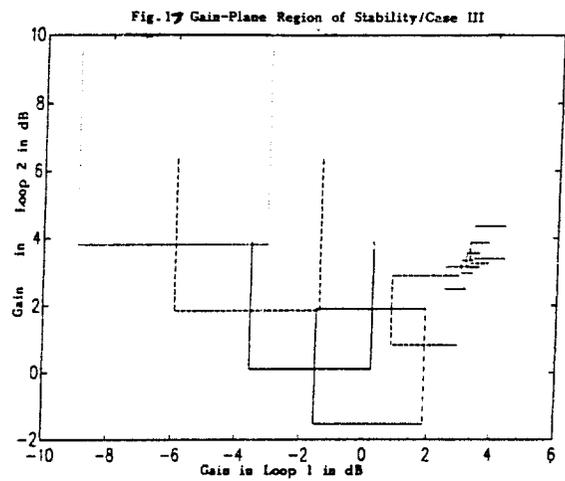
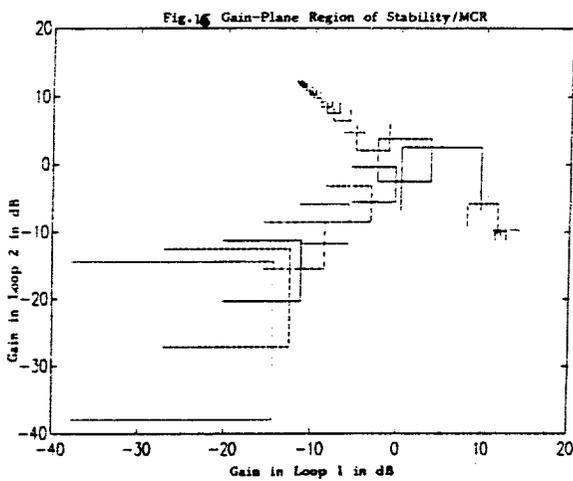


Fig. 15 Loop-at-a-time Results for Case I



Computer Aided Evaluation of Aircraft Handling Qualities and
Flight Control System Robustness

Shyam Chetty and Racl J R
Flight Mechanics and Control Division
National Aeronautical Laboratory, Bangalore-17, India

Abstract

This paper describes the salient features of an interactive computer aided software package developed for the analytical evaluation of aircraft handling qualities and flight control system robustness. The package is based on MATLAB/FORTRAN and runs on IBM compatible personal computers.

Introduction

Modern high performance aircraft are designed to be aerodynamically unstable and employ sophisticated digital flight control systems onboard, to recover stability and meet the stringent performance requirements over the entire flight envelope. Performance evaluation and verification of these advanced flight control systems require analytical comparison of system characteristics to various military specifications which include flight control and handling quality specifications like the USAF MIL-F-9490D,¹ MIL-F-8785C² and the recent MIL-STD-1797.³ In addition, to guarantee flight safety, the flight control system designer must ensure sufficient robustness for the complete closed loop system against parameter variations, external disturbances and subsystem failures. These evaluations are becoming increasingly complex and difficult as the design trend towards increased control system integration, sophistication and coupling continues.

The present paper describes the salient features of the interactive computer aided software package developed for the analytical evaluation of handling qualities, generation of lower order equivalent system models, estimation of robustness margins and generation of ideal handling quality models for each phase of flight. The software package is based on Matlab/fortran-77 and runs on IBM compatible personal computers. The paper also covers certain new features/techniques used for model order reduction, evaluation

of closed loop handling quality criteria and control system robustness. Extensive use of vector optimisation techniques based on the minimisation of the Kreisselmeier's function^{4,5} is made to offer greater flexibility to the user during evaluation. Typical set of results are also presented to illustrate the capabilities of the software.

The software has been developed based on the popular MATLAB (Moler et al., 1989) Computer Aided Control System Design (CACSD) tool.⁶ The software package has a modular structure consisting of 406 Matlab macros (.m files), 32 data files (.mat files) and 5 fortran executable code segments. Special effort has been taken to make the user interface uniform and consistent over the full scope of the package. A query/menu driven input has been used, as large number of parameters have to be entered by the user during evaluation. Extensive use of default values, on screen help messages, graphic outputs and a comprehensive demonstration programme provide the necessary support to a new user. The package has been split into the following sections which are selectable from the main menu and are classified as:

- i) Model Order Reduction Techniques
- ii) Longitudinal Handling Quality Criteria
- iii) Lateral/Directional Handling Quality Criteria
- iv) Demonstration Programmes
- v) Ideal Handling Quality Design Models
- vi) Robustness Metrics

In each classification a specific criterion or technique can be selected from separate sub menus which have been organised in a tree like structure. The package can handle multiple models (at different flight conditions) and these can be specified in either the state space or transfer function formats. Time or frequency response data from nonlinear simulation and flight tests can also be used to evaluate the aircraft performance. The final results, many of which are in