ICAS-92-6.4.2

STUDY OF AEROSERVOELASTIC STABILITY ON AN AIRCRAFT

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Abstract

The disadvantageous interaction between aerodynamics, structural dynamics, and flight control system may cause aeroservoelastic instability. This becomes an increasingly important design and test consideration in the synthesis and evaluation of high authority flight control system in modern flexible aircrafts. The study on aeroservoelastic stability was made analytically and experimentally during the development of an aircraft. This paper presents some experiences gained from our study in recent years, including systematic analyses and tests on the servoelastic and aeroservoelastic stabilities and effective approaches for building and correcting mathematical model based on the ground test data. Twice improvements of control system in consideration of servoelastic and aeroservoelastic stabilities are presented.

I. Introduction

A systematic study on aeroservoelastic stability was made analytically and experimentally during the development of an aircraft. The flight control system of the aircraft consists of control augmentation system, automatic augmentation system, and polyfunctional robot pilot.

The influence of structural elasticity was not considered in the early design of flight control system. After this control system was mounted on the aircraft, the instability of longitudinal axis due to the coupling between airframe elasticity and the system was identified in ground tests. A strongly divergent oscillation of horizontal tails appeared in the frequency about 10 Hz. Because of the coupling between some elastic modes, it was difficult to get a satisfactory result by changing the positions of gyroes and accelerometers[4]. It had been predicted, in fact, with the help of a simplified analysis model in the detailed design stage of the aircraft, a structure notch filter was recommended and designed for control system[1]. The servoelastic instability disappeared when the filter had heen used. However,it had been shown by more detailed aeroservoelastic analyses that there still were potential flight instabilities within flight envelope for several configurations, which decreased the critical flutter velocity by 20%.

The detail study began with some tests to check frequency response characteristics of augmentation control blocks in the frequency range covering related elastic modes, especially, for electric-mechanical and mechanical drives. After further investigations, it was determined that the amplitude of input signal of servo-actuator in a wide frequency range 8.96 - 21.0 Hz must be less than 300 mv to avoid the disadvantageous influence of elasticity and nonlinerity, and that the dynamics of servo-valve with small input is more improtant than that of large or middle one to servoelastic stability. Another thing was to determine the relationship of sensor's output signal and elastic modes (the generalized coordinates). A high-pass demodulation filter made system unstable in higher frequency. Fourteen times,proper modifications had been tried later to compensate its disadvantageous side effect.

As a base of aeroseroelastic investigation, the structure dynamic and flutter analyses of whole aircraft are important. They require a trustworthy mathematical model of structure and aerodynamics which have been corrected or proved by a series of ground tests, such as the ground vibration test, wind tunnel test, ground closed loop test and so on. The first twenty elastic modes were used to built a longitudinal model so that all the modes of control surfaces, which are of interest in flutter analysis, were considered. The transfer function, from a unit deflection of horizontal tails to flight sensor's output at zero airspeed, was obtained in tests and used to check the final structure model.

Finally, the improvement of stability was done with a optimization of parameters of the flight control system. Not only were the stability augmentation systems altered, but also the cntrol law of robot pilot shifted properly in orde to keep the fundamental performences from changing unfavourably.

II. Aeroservoelastic Equations

In the Laplace domain, the matrix form of the generalized aeroelastic equations of motion for an aircraft with control surfaces may be written as[5]

$$(s^2[M]+s[D]+[K])\{\xi\}=q[A]\{\xi\} \qquad (1)$$

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where s is the Laplace transform variable, q is the dynamic pressure,and the vector of generalized coordinates $\xi=[\xi_s^t, \xi_c^t]$ consists of the elastic modes and control degree of freedom, respectively. The vibration's amplitude vector of the aircraft can be expressed in terms of modal degrees of freedom by

$$\{\chi\}=[\Phi s]\{\xi_s\}+[\Phi c]\{\xi_c\} \qquad (2)$$

where $[\Phi s]$ is the modal matrix of the aircraft, and $[\Phi c]$ is that of control surfaces.

Matrix [M], [D], and [K] can be obtained from the finit element analysis of structure dynamics, or / and the ground vibration test. Typically, the elements of aerodynamic matrix [A] are available as tabular functions of reduced freqency $k=\omega b/V$. To combine unsteady aerodynamic forces with the characteristics of control system in the Laplace domain, a conecpt of analytic continuation for the unsteady aerodynamics may be used[6][7].

For the augmented aircraft, the servo induced control deflection $\{\Delta\xi_c\}$ has to introduced as additional degree of freedom for each control surface. The additional generalized deflection of control surfaces due to the modal motion through flight control system may be written as

$$\{\Delta\xi_c\}=[R]\{\xi_s\} \qquad (3)$$

Where [R(s)] is a coupling feedback matrix. The element $R_{ij}(s)$ means the change of generalized deflection of the i-th control surface excited by the j-th mode.

With the help of a transform matrix [T], It can be proved that the aeroservoelastic equation of motion can be expressed in the same form as the equation (1)

$$(s^2[\tilde{M}]+s[D]+[K])\{\xi\}=q[\tilde{A}]\{\xi\} \qquad (4)$$

where

$$[\tilde{M}]=[T]^t[M][T] \qquad (4a)$$

$$[\tilde{A}]=[T]^t[A][T] \qquad (4b)$$

and the transform matrix [T] is a function of the coupling feedback matrix [R]. The difference between [T] and unity matrix show the influence of control-structural modes coupling. The vibration's amplitude vector of the aircraft is

$$\{\chi\}=[\Phi s]\{\xi_s\}+[\Phi c]\{\xi_c\}+[\Phi c][R]\{\xi_s\} \qquad (5)$$

To use equation (4), the following are noteworthy:

(1) The flight control sensors, such as gyros and accelerometers, are senseless of the modal motion of control surfaces. That is, the sensors are not on control surfaces and $[\Phi c(p)]$ are zero, where p is the point which is not on control surfaces. Which leads to a non-diagonal matrix of the generalized masses.

(2) The hinge moment of control surfaces must be zero in the determination of the control feedback matrix [R].

(3) A hydranlic servo-actuator with mechanical position feedback does not exhibit a constant stiffness or damping for all excitation frequencies[8].

By matrix algebra, equation (4) can be rewritten as:

$$\{\xi_s\}=-[W][R]\{\xi_s\} \qquad (6)$$

Compared with the equation (3), the relationship above corresponds to the the closed loop control system with feedback [R(s)]. [W(s)] represents the transfer function matrix of elastic aircraft. It may relate to [R] partly, but mainly decided by the characteristics of structure dynamics.

It is convenient to divide the coupling feedback matrix R as follows

$$[R]=[Ha][Hc][Hs] \qquad (7)$$

where [Ha] is a diagonal matrix and composes of the transfer function of mechanical transform system such as servo-valves and hydraulic actuators. [Hs] describes the relationship between sensor's output and generalized coordinates, meanwhile,[Hc] represents the fundamental control law.

III. The Mathematical Model

The mathematical model used in aeroservoelastic analysis must represent every contribution to the dynamic behaviour of the aircraft's structure and the control system. For the convenience of analysis, one model may be seperated to several submodels. According to the dynamic peculiarity of each sub-model, there were three sets of model sorted in our work.

- The first set, whose theory is complete relatively, is based upon the theoretical analysis and further corrected by test data. This set may include the unsteady aerodynamics model, structural dynamic model, and the transfer function of the part of control system which only consists of electric elements. The linear approaches can give a good approximation. It should be mentioned, that the sufficiently accurate model, not the conservative model in the meaning of conventional flutter estimate and control system design, is necessary.
- The second set is semiempirical model. The relationship between flight control sensor's

output and the structural mode's input, the freqency response of servo-valve and hydraulic actuator belonged in this set. Although there may be some approaches to discribe the dynamic characteristics, those are not so complete and exact or so easy to be used like the first set mentioned above. For this set, two different models, but comparable with each other, were built theoretically and experimentaly, respectively.The further mathematical model that was chosen and corrected with extensive experiment or other additional tests. One must be sure, that the dynamic model of the worst possible case is introduced into the analysis.

For example,the frequency characteristics of the servo-valve change with amplitude of input signal. This had attracted our attention. For the control system design in lower frequency range, a second-order system, even a first-order system, gives a good approximation to input signals at all amplitude, but this may cause a unconsevative estimate on aeroservoelastic instability due to the error of phase lag in higher frequency range. It had been shown that dynamic characteristics with small signals are more important than others.

Another example is the hydraulic actuator dynamics, these are highly nonlinear depending on preloading, amplitudes, input and service condition.

- The last set is a model based on measured data. Since it is difficult to describe the inverse transform of driver stick force theoretically. The test data are used directly.

The mathematical model must be laid out in such a way that it can be easily adjusted to match test results. Additionally, an assumption used to build mathematical model should be mentioned. According to the opinion of Reference[11], The investigation of aeroservoelastic stability can be isolated from the rigid-body flight mechanics when rigid-body and elastic modes frequencies are separated by two octave. This condition was met in our aircraft.

IV. Scheme for Tests

At present, the stability of an aeroservoelastic system and the stable margins can not be proved only by the ground tests. The ground test is an important means of predicting instability, but it also depends on synthetic analysis. To ensure that the approach and the mathematical models used in analyses are correct, a scheme for synthetical analyses and ground tests was mapped out, which is shown in Figure 1.

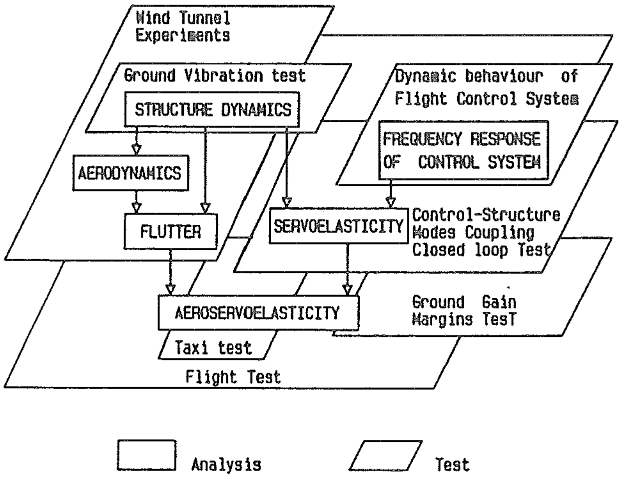


Fig.1 Scheme for ASE investigation

It was attempted that each result of analysis should be shown or demonstrated by some tests directly or indirectly. With a series of tests and their comparation with analyses, the mathematical models would be proved and corrected so that the gaps amoung diffrent specialities concerned may be bridged and the analysis error should be made as little as possible. The following ground tests had be performed:

- The ground vibration tests of the aircraft.
- Wind tunnel tests of the aircraft flutter model
- The dynamic behaviour tests of automatic flight control systems on the iron-bird platform
- Control-structural mode coupling's closed loop tests on aircraft
- Demonstration of the ground gain margins on the aircraft

Reference [3], [9], and [10] described and recommended some ground tests for servoelastic and aeroservoelastic study. It should be emphasised that each test must be designed elaborately so that the test conditions are in agreement with systematic analysis approches, and the consistence of test data must be considered.

On the other hand, the limit response of structure, such as the driver stick force and control surface oscillation, had better be determined by tests. Because a strongly oscillation was encountered by horizontal tails due to complex reasons, in the open loop case, on the iron-brid platform, an additional test had been performed on aircraft to answer the question how much signal should be allowable for input of servo-valve. it was determined that the input more than 300 mv signal could excite a dangerous oscillation in a wide frequency range 8.91-21.0 Hz, which could not be suppressed by electricity switch-off until hydraulic source was cut off.

V. Analysis Techniques

Aeroservoelastic analyses need to predict and prevent adverse interaction between automatic flight control systems and the aircraft's structural dynamics. Here, we are interested especially to evaluate the parameters which are required and used as quality indexes in concerned specification of aircraft design, such as flutter speed margins, damping requrements, gain and phase margins, and to obtain more information which is beneficial to the design and improvement of control system.

The PK method was used to determine the critical airspeed,modal damping and other flutter characteristics. This method can give results which may compare with tranditional flutter analysis without flight control system. Therefor, it is helpful to understanding the influence of flight augmentation system on the standpoint of structure engineers. The function of augmentation system is similar to dynamic correction to aeroelastic system like equation (4) did.

The Bode plot gives valuable information for improving the stability of aeroservoelastic system. With this approach, the elastic aircraft is seen as a block of control system. It is easy to obtain gain and phase margins for a given control law and flight conditions, and to determine the task of control system improvement from Bode plots. For our work, it was required that the curve of amplitude-frequency characteristics of the open loop aeroservoelastic system must be lower than the -6 db line, in the frequency range of elastic modes, at the speeds up to the aircraft's limit speed. This requirement seems harsh, but it may be practical for improving a automatic flight control system which designed without consideration of the influence of structral elasticity.

Another useful plot used to determine the stability of a closed loop system, by the frequency characteristics of its open loop case, is the Nyquist diagram. This plot consists of a lot of loop pathes. For aeroservoelastic problem, each elastic mode is represented by a loop of Nyuist path. It not only gives the gain and phase margins as well as modal damping, but also indicates some ways for improving the system. Using the Popov criterion[2], the nonlinear stability may be considered.

All this three techniques determine stability in the frequency domain so that any oscillatary aerodynamic method and test data of frequency response of control system can be employed directly.

VI. Results

Structure Dynamics

Table 1 gives a result of structure dynamic analyses of the aircraft with full oil in the symmetrical case. Where the first twenty elastic modes ($\omega < 50$ Hz) were considered. It was found that the results obtained by the finit element method (FEM) was good fitting to that measured in the ground vibration test (GVT). To use them in aeroservoelastic analysis(ASE), some work was done. The elements of generalized stiffness matrix were corrected for the case that the natural frequency error between analysis and test was greater than 4 percent. The modal damping was fetched from the ground vibration test directly. In the further analyses, smaller structural damping values were introduced.

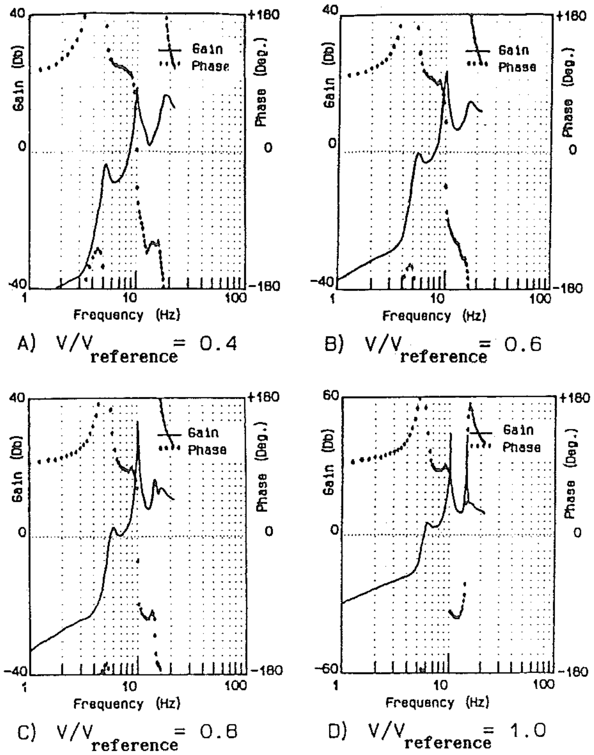
Table 1 Dynamic characteristics

Mode No.	Natural frequency (Hz)			Damp ing
	GVT	FEM	ASE	
1	4.979	4.929	4.931	0.030
2	8.842	8.857	8.763	0.021
3	9.850	9.667	9.668	0.058
4	11.342	11.475	11.766	0.065
5	-	12.771	13.839	-
6	15.469	15.936	16.305	0.033
7	20.340	19.574	19.250	0.081
8	-	21.748	-	-
9	21.737	24.540	23.325	0.109
10	-	26.876	-	-
11	27.558	31.004	27.178	0.058
12	-	33.773	-	-
13	-	36.026	36.901	-
14	43.160	38.848	40.838	0.030
15	-	40.733	-	-
16	-	44.733	-	-
17	45.105	45.902	45.904	0.045
18	-	46.755	46.667	-
19	-	47.846	47.489	-
20	-	51.019	48.433	-

Aeroelasticity

Figure 5(A) shows the V-g plot of the aircraft without control system. The first horizontal tail bending (Mode No.3, 9.85 Hz) and first fuselage bending (Mode No.4, 11.342 Hz) are the critical modes. It should be mentioned, that thus flutter characteristics just meet the design requirments, there are no more stability margins. Therefore, it was required that the basical flutter characteristics could not be changed more disadvantageously by the augmentation system.

Figure 2(A)-2(D) show the frequency response of the output signal of flight control gyroscapes to the generalized deflection of horizontial tails, at airspeed ratio 0.4, 0.6, 0.8, and 1.0. Although the flutter frequency is about 10 Hz, The second wing symmetric bending mode (Mode No.6, 15.469 Hz) was notable in aeroservoelastic analysis, because the amplitude response changed significantly with the increase of airspeed.



A) $V/V_{reference} = 0.4$ B) $V/V_{reference} = 0.6$

C) $V/V_{reference} = 0.8$ D) $V/V_{reference} = 1.0$

Fig.2 Frequency response of aircraft

H.T.deflection ——▷ Output of ygroscope

Control System Dynamics

Whereas thransfer functions of all electrical blocks in the flight control system can be predicated analytically with sufficient accuracy, determination of the actuater dynamics must mainly depones upon tests.

The measurement data of the ground vibration tests, frequency respose tests of automatic flight control system on aircraft and on the iron-bird platform were used to abstract the transfer function of servo-actuator (including direction arm, rods, and other drive mechanism) under the conditions mentioned in section I above. All the tests include control surfaces. At first, the frequency response data of hydraulic servo-actuator and control surface was used to set up an analytical model. Then, the influence of elastic connection of control surface was taken out from the analytical model, meanwhile the result of associated ground vibration test is considered in the model. Figure 3 shows a example, where the analytical model, test data and mathematical model of servo-actuator without control surface are compared with each other.

Aeroservoelasticity

The gyro path has a great contribution to the coupling between structural modes and stability augmentation system dynamics. After inverstagation, it was found that the position of gyros was not so bad on the whole, but the mode of second wing bending did cause a larger output of longitudinal gyroscopes, which had been shown in the ground test of aircraft. Of course, there were other complex factors. A more important reason for the coupling was due to the use of a high-pass demodulation filter after gyroscopes in the automatic flight control system. However, it was difficult to take the filter out because of the function in lower frequency domain control.

First Improvement Fig.4(A) shows the original frequency response of gyro path. The amplifying effect and unsuitable phase in the elastic modes frequency range led to a possibility for control-structural mode coupling. In our opinion,one must be careful in matching a large amplifying effect with phase lag near 90° between main structural mode frequencies in the flight augmentation system. Another problem was that the input electic signal of the longitudinal servo-valve was greater than the allowable one, which had been found in a later ground test. Following notch filter was recommened so as to improve the servoelastic and aeroservoelastic stability

$$\frac{(\frac{S}{75.})^2 + 0.1(\frac{S}{75.}) + 1}{(\frac{S}{70.})^2 + 1.4(\frac{S}{70.}) + 1} \times \frac{1}{\frac{S}{80.} + 1}$$

which was synthesised with a simplified analysis model and there were some differences in structure dynamic characteristics between analyses and real aircraft because the prototype aircraft was not ready that time. All the same, this work improved the ground stability.

Second Improvement Although the servoelastic stability bas been proved by the ground tests after the first augmentation system improvement, in which a structure notch filter was employed in

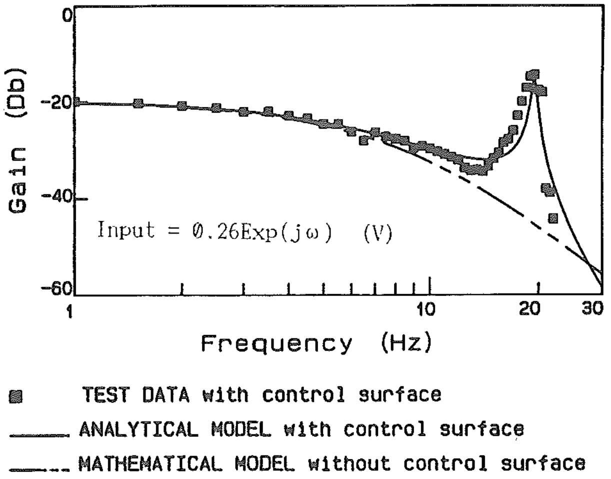


Fig.3 Transfer function of servo-actuator Including direction arm, rod, and other drive mechanism.

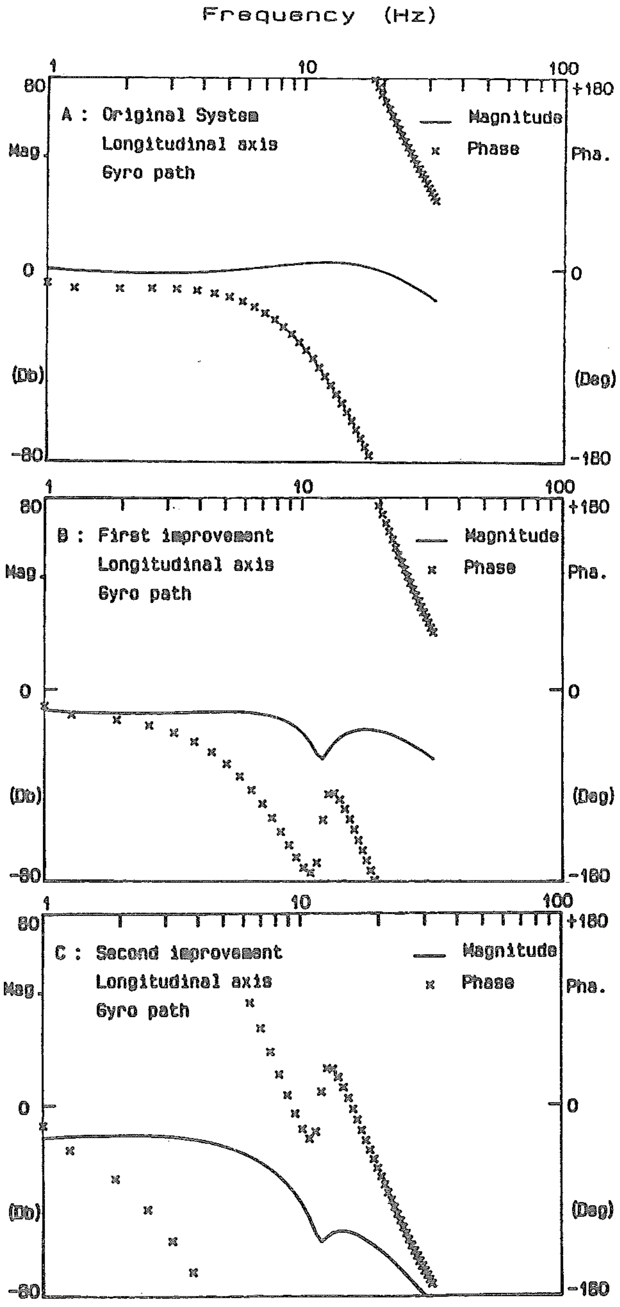


Fig.4 Frequency response of Gyro path in Augmentation system

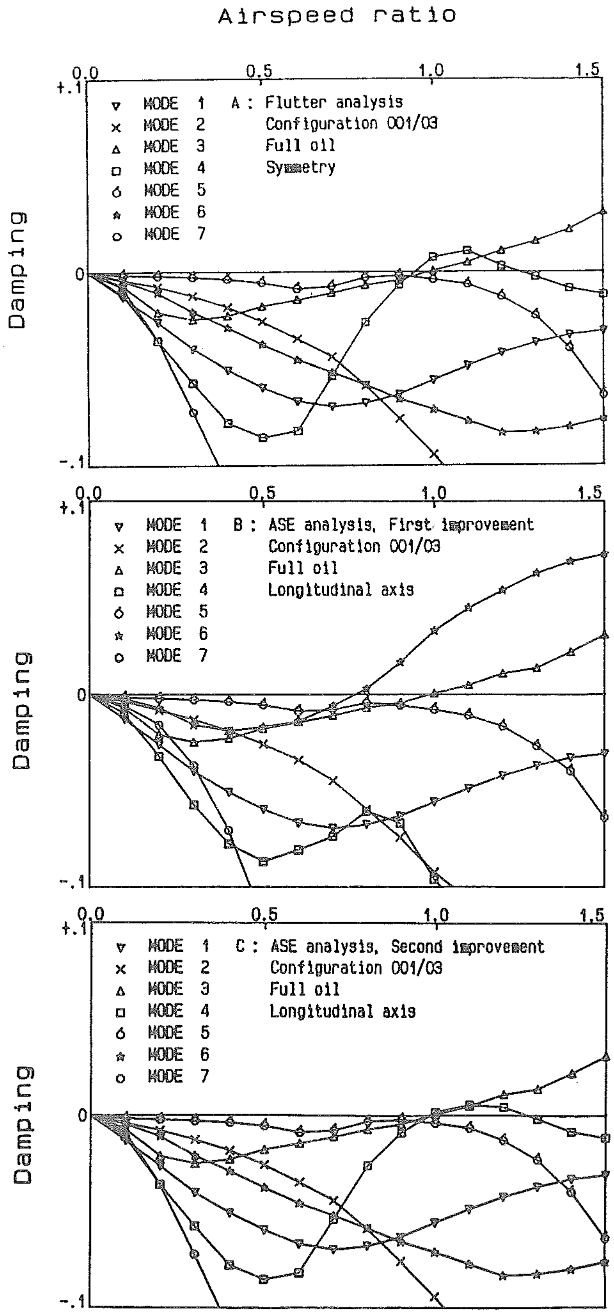


Fig.5 V-g Plots without and with Control system.

the longitudinal axis, Figure 5(B) shows a unhoped V-g plot of the aircraft for a typical configuration with longitudinal axis augmentation control, under the same conditions as that in Figure 5(A). Those analyses depended on a detailed linear model corrected by a series of ground tests. Based on a lot of analyses, it was believed that there were potential instabilities within flight envelope. Compare Figure 5(B) with Figure 5(A), thé critical velocity decreases by 20%, the critical mode was changed and the critical frequency was 15.7 Hz.

The second improvement was done with a optimization of parameters of flight control system. This work was confined to the elastic modes frequency range, the minimum frequency was greater than 5 Hz so that the fundamental performence of automatic flight control system designed early did not changed so much. It was required that the frequency response of open loop aeroservoelastic system must be lower than the -6 db and the centres of Nyquist loop associated with main structural mode had better be in the right half-plane, at the speeds up to the aircraft limit speed. Finally, not only the stability augmentation systems were altered, but also the control law of robot pilot shifted properly in order to keep the fundamental performences from unfavourable changing.

Figure 4(C) shows a final frequency response of control law on gyro path. The amplitude response in the frequencies after 10Hz is decreased more than that of first improvemet, and the phase lag is shifted properly.

The V-g plot and Nyquist diagram at the limit airspeed are show in Figure 5(C) and Fgure 6, respectively. These give a satisfactory results.

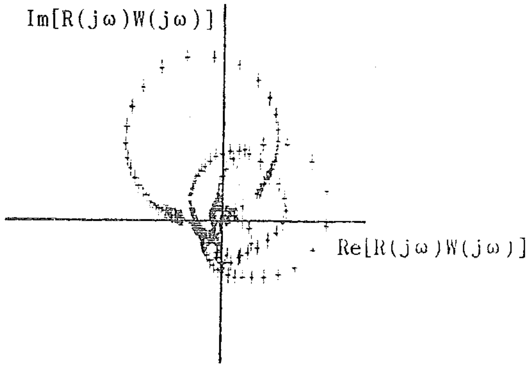


Fig.6 Nyquist Diagram (Speed ratio=0.8) with Augmentation system

References

1. Z.Congqing and C.Guibin, Aeroservoelastic analysis on an aircraft, BUAA TP, 1986.

2. Benjamin C.Kuo, Automatic Control Systems, Pretic-hall,Inc.,Englewood Cliffs, New Jersy, 1975.

3. Guan De, Aeroelastic Tests, Beijing University of Aeronautics and Astronautics, 1986.

4. T.Changhong and Z.Daquan, Initial Discussion on Aeroservoelastic Stability, BH-B3030, November 1987.

5. R. Freymann, A Method for Determining the Aeroelastic Behavior of Aircraft with Active Control Systems, ESA-TT-719, February 1982.

6. Abel I., An Analytical Technique for Predicting the Characteristics of a Flexible Wing Equipped With an Active Flutter-Suppression System and Comparison With Wind-Tunnel Data, NASA TP 1367, 1979.

7. Karpel M., Design for Active Flutter Suppression and Gust Alleviation Using State-Space Aeroelastic Modeling, AIAA paper No.80-766, 1980.

8. T.H.Beier, Prediction and Measuremant of the Dynamic Stiffness and Damping of Hydraulic Servo-Actuators,AIAA paper 77-420, March 1977

9. Felt, L.R., Huttsell, L.J., Noll, T.E. and Cooley, D.E., Close Encounters of the Aeroservoelastic Kind, AIAA paper No.78-1289, August 1978.

10. Arthurs,T.D. and Gallagher,J.T., Interaction Between Control Augmentation System and Airframe Dynamics on the YF-17, AIAA paper No. 75-824, May 1975.

11. A. Lotze, O. Sensburg, and M. Kuhn, Flutter Inverstigations on a Combat Aircraft with a Command and Stability Augmentation System, AIAA 75-1025, 1975