Design and Evaluation of a Multi-Surface Control System for the CCV B-52

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This paper summarizes an analytical study conducted by the Control Configured Vehicles (CCV) technical staff to synthesize a CCV Multi-Surface System (MSS) for the CCV B-52 airplane. Quaratic optimal control theory was used to design a multiple-input, multiple-output controller for the lateral-directional axis. The controller used five sensors and four aerodynamic control surfaces to reduce accelerations and stresses on the B-52. This paper covers the design requirements, and constraints, design procedure, and the study results. The results show that the MSS performs better than the individually designed concepts of Ride Control and Lateral Augmented Stability (RCS/LAS).

Nomenclature

A = second-order coefficient
A_1 = second-order response coefficient
A_2 = second-order measurement coefficient
B = first-order coefficient
B_1 = first-order response coefficient
B_2 = first-order measurement coefficient
C = zero-order coefficient
C_1 = zero-order response coefficient
C_2 = zero-order measurement coefficient
D = control response matrix
E = expectation operator
F = open-loop state matrix
G_1 = control input matrix
G_2 = disturbance input matrix
H = state response matrix
J = cost function
K = optimal gains matrix
K^* = fixed form gains matrix
M = measurement matrix
P = Ricatti matrix
Q = quadratic weighting matrix
q = generalized coordinate vector
r = response vector
u = control input vector
WBL = wing buttock line, WBL222 at wing root and WBL 1110 at the wing tip
WS = wing station, WS0 at the leading edge and body centerline, and WS 1385 at the leading edge wingtip.
x = generalized state vector
y = measurement vector
η = disturbance input vector

Superscripts

T = matrix transposed
-1 = matrix inverted

Introduction

THE Control Configured Vehicles (CCV) concept is to apply advanced flight control technologies to an aircraft while it is still in the preliminary design stage. Flight Control would receive equal emphasis with aerodynamics, structures, and propulsion. At this time, the Air Force and its contractors, are demonstrating, with flight tests, the improvement in aircraft performance using these new flight control technologies. The next step after flight demonstrating a concept is to incorporate the concept as one of the parameters in the preliminary design of an aircraft.

Several CCV concepts have already been analysed and proven. A Load Alleviation and Mode Stabilization (LAMS) system was test flown in 1968.[1,2] The LAMS system used spoilers, ailerons, and elevator to alleviate gust loads and to control structural modes. A Ride Control System and Lateral Augmented Stability (LAS) system were flight tested early in 1973.[3] The RCS reduced turbulence-induced structural motion at the pilot station on a B-52, by using canards to provide the additional flexible mode damping to the structure. The LAS provided Dutch roll damping to improve aircraft handling qualtities.

Three more CCV concepts were flight tested in late 1973 and will be reported on by late 1974. A Flutter Mode Control system damped out wing bending and torsion using flaperons and ailerons. A Maneuver Load Control system reduced wing root bending moment by reshaping the wing loading distribution using flaperons and ailerons. An Augmented Stability system allowed the center of gravity of the airplane to be moved aft to the point of neutral static stability, while the flight control system provided the adequate handling qualtities.

The purpose of the MSS was to obtain an airplane with better performance than the CCV airplane, which had its concepts designed independently. The MSS was designed for the NB52E AF 56-632 airplane, whose modifications include flaperons, outboard ailerons, partially inactive spoilers, a vertical canard, and two horizontal canards, see Fig. 1. The CCV airplane had only two lateral-directional systems, the Lateral Augmented Stability system (or yaw damper), and the lateral-directional Ride Control System. The lateral MSS had five surfaces available to it, while the CCV system used only two surfaces.

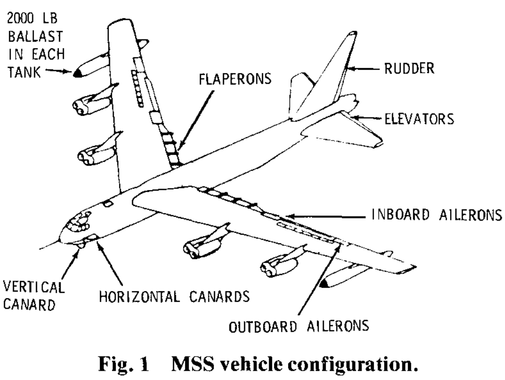

Fig. 1 MSS vehicle configuration.

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The CCV airplane had five longitudinal systems, Flutter Mode Controller, Maneuver Load Controller, Augmented Stability, longitudinal Ride Control system, and Fatigue Reduction System. The longitudinal MSS design is not completed at this time. The longitudinal MSS would in one controller perform the tasks that the longitudinal CCV systems performed separately.

Design Requirements and Goals

The first requirement of the design was that the MSS use those sensors already installed on the CCV B-52. This specially instrumented B-52 has eight normal and three lateral accelerometers. It has seven rate gyros, four in the pitch axis, two in the roll axis, and one in the yaw axis.

The second requirement of the design was that the MSS use those aerodynamic surfaces already installed on the airplane. Five sets of surfaces were available for use in the lateral-directional axis design. The rudder and inboard aileron are the same as a fleet B-52E, except for the capability of electrically commanding the actuators. For the CCV flight test program, three new surfaces were added to the airplane. A vertical "chin" canard was added beneath the pilot station. A set of three flaperons replaced the normal inboard flaps. An outboard aileron was installed outboard of the outboard flaps.

The first design goal was that the MSS should decrease the lateral acceleration due to wind turbulence at the pilot station (BS172) and at the tail of the airplane (BS1655) by at least 30%. At the same time the acceleration at the airplanes center of gravity (BS860) should not increase more than 5%. The second design goal was that the MSS should decrease the lateral stresses due to wind turbulence in the fuselage and wing by 10%. The MSS should also reduce the stress at the wing root (WS222) due to maneuvers by 10%. The maneuvers are pilot induced oscillation of the rudder or ailerons.

The MSS should have good handling qualities. The Dutch Roll damping ratio should be greater than 0.19, and the damping ratio times damped frequency should be greater than 0.35.[4] The damping ratio for the structural modes should not decrease more than 10%. The MSS should provide a gain stability margin of ±6 decibels at nominal phase, and a phase stability margin of ±60°, for nominal gain.

Design Procedure

The classical design technique is to use frequency response, root locus, and time histories to design a system by trial and error. This is a very efficient way to design a very simple system, but a very poor method of designing a complex system. The CCV systems, that were recently flight tested, were designed separately. A compatibility check of the separate functions was done after each function had been designed.

The MSS was designed using modern control theory and some classical techniques. The design was developed for one flight condition (261,000 lbs gross weight, 30% MAC center of gravity, 0.517 Mach number, 330 knots calibrated airspeed, and 2000 ft alt). The aircraft data base was provided by Boeing/Wichita and is documented.[5] The data base consisted of coefficients for the antisymmetric equations of motion. The lateral-directional degrees of freedom included 3 rigid-body modes (side translation, yawing rotation, and rolling rotation) and 27 antisymmetric structural modes. Force coefficients for side gust inputs, antisymmetric operation of the ailerons and flaperons, and operation of the rudder were also provided. Vertical canard coefficients were generated within the ADPO and integrated into the aircraft math model.

The data base was modified by transforming side translation to side velocity, and yawing rotation to yaw rate. The equations of motion are second order in terms of the LaPlace variable (s).

$$[AS^2+Bs+C]q=0 \tag{1}$$

Three computer programs were used to further manipulate the data to get an optimal control solution. The first program converts the equations of motion from the second-order matrix form to the state variable format. The second program generates the optimal gains for full state feedback. The third program generates optimal gains for measurement feedbacks.

The first digital computer program converted the second-order transfer function, Eq. (1), to the form

$$\dot{x}=Fx+G_1u+G_2\,\eta \tag{2}$$

The original data base contained 3 rigid-body and 27 structural degrees of freedom. The first computer program reduced the number of degrees of freedom down to 3 rigid-body and 5 structural. The residual effects of the structural modes eliminated did slightly modify the major modes retained in the model. The response equations are changed from

$$r=[A_1s^2+B_1s+C_1]q \tag{3}$$

to

$$r=Hx+Du \tag{4}$$

The measurement equations are changed from

$$y=[A_2s^2+B_2s+C_2]q \tag{5}$$

$$y=Mx \tag{6}$$

The states included represent rigid body motion, bending mode rates and displacements, Wagner terms, surface deflections, wind shaping, and sensor washed-out filters. The responses included are lateral stresses, lateral acceleration, washed-out sensor signals, surface deflection rates and displacements, and model following errors. Measurements included are lateral accelerations, washed-out lateral accelerations, roll and yaw rates, and washed-out roll and yaw rates.

The second digital computer program optimized the full-state feedback gains for a linear time invariant system using a quadratic cost function. The cost function was:

$$J=E[\int_0^\infty r^TQ\,r\,dt] \tag{7}$$

The optimal controls are

$$u=Kx \tag{8}$$

The optimal gains, K, are found by solving iteratively the algebraic Riccati equation

$$0=\bar{A}^TP+P\bar{A}+\bar{Q}-P\bar{E}P \tag{9}$$

where

$$\bar{A}=F-G_1(D^TQD)^{-1}D^TQH \tag{10a}$$

$$\bar{E}=G_1(D^TQD)^{-1}G_1^T \tag{10b}$$

$$\bar{Q}=H^TQH-H^TQD(D^TQD)^{-1}D^TQH \tag{10c}$$

The optimal gains K are

$$K=-(D^TQD)^{-1}[D^TQH+G_1P] \tag{11}$$

The outputs of this second computer program are the gains matrix, covariance matrices, correlation matrices, rms controls, rms measurements, rms responses, quadratic cost matrix, eigenvalues of the $\bar{A}$ matrix, and time response plots. This program was rerun with different weights in the Q matrix until the eigenvalues and responses were adequate.

The third digital computer program optimized the feedback gains using measurements instead of states

$$u = K^* y \tag{12}$$

The gains were generated in a similar way to that described for the second computer program. A frequency domain computer program was used to determine the phase and gain loci of final design.

Results

The final MSS lateral-directional configuration is shown in Fig. 2. The system has three accelerometers, a yaw rate gyro, and a roll rate gyro, as sensors. The system has four active surfaces; the rudder, differential flaperons, differential inboard ailerons, and the vertical canard. The nose accelerometer and roll rate gyro have high-pass (wash-out) filters.

The first solution obtained from the computer programs was a full-state solution of 185 feedbacks gains (37 states having 5 gains apiece). Using the weighting factors derived from the full state solution, a new solution of 50 feedbacks gains (10 measurements having 5 gains apiece) was determined. Since 50 gains is too many to implement into a system, feedback gains were deleted from the computer problem. The number of feedback gains was reduced to 9 before serious deterioration was evident. Using 10 gains, the performance was roughly equivalent to the 50 gain solution. To protect the system from steady-state errors in the sensors, various sized high-pass filters were applied to the output of the five sensors. The time constants on the wash-out filters were varied on a trial-and-error basis. Wash-out filters could be applied only to two sensor without seriously degrading the performance of the system.

The first step of going from 185 gains to 50 gains took one FFOC run, while the second step of going from 50 gains to 10 gains took 61 runs (19 runs with varied number of gains, 33 runs with varied wash-out time constants, and 9 runs with varied weightings) and 348 min of computer time.

Table 1 presents the open loop and MSS accelerations and

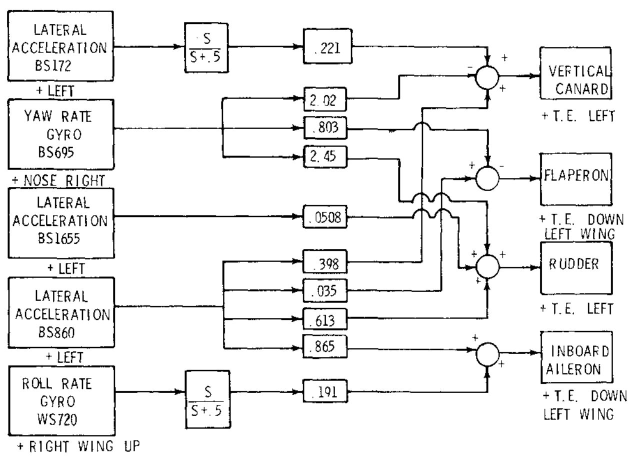

Fig. 2 Lateral MSS controller block diagram.

Table 1 Acceleration reduction using MSS

Fuselage Station	Acceleration Open Loop G	MSS G	Acceleration Reduction MSS %	Acceleration Reduction Goal %
BS172	0.102	0.0583	43.1	>30.0
BS860	0.048	0.0235	51.0	>-5.0
BS1655	0.196	0.121	38.3	>30.0

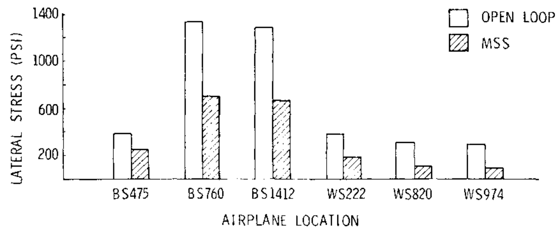

Fig. 3 Lateral stresses.

Table 2 Stability margins

Feedback loop	Gain margin db	Phase margin degree
Rudder	11.0	80.0
Flaperon	7.0	180.0
Inboard aileron	23.0	60.0
Vertical canard	43.0	45.0

the acceleration reduction that the MSS provides for a gust environment of 8 fps. All three accelerations easily surpass the required performance.

Figure 3 shows the effectiveness of the MSS in reducing fuselage and wing lateral stress in a turbulence environment of 8 fps rms. The stress reductions for the body and wing stations varied from 36.5% to 66.4%. The design requirement was that the stresses be reduced by at least 10%.

With pilot-induced oscillation of the rudder, the MSS reduced the wing root (WS222) stress to 367 psi from 723 psi, a 49.2% reduction. With a pilot-induced oscillation of the ailerons, the MSS reduced the wing root stress to 230 psi from 241 psi. This 4.5% reduction in stress does not meet the design goal of a 10% reduction. Both the rudder and aileron disturbances were simulated with white noise through a low-pass (1 sec) filter commanding 5.78° rms surface deflection.

The maximum rms surface rate for any disturbance (gust or pilot-induced) was 30.5° per sec. The range of surface rate limits was 80-120° per sec. The solution was not rate limited. The maximum rms surface displacement for any disturbance was 2.95°. The range of displacements limits was 12 to 20°. The solution was not displacement limited.

The MSS stability margins are tabulated in Table 2. The design requirement were that there be six decibels gain margin was met by all sensor loops. The 60° phase margin was met by all surface loops except the canard loop which had 45° of phase margin.

The MSS increased the Dutch Roll damping ratio to 0.71 from 0.15. The design goal was that the damping ratio be greater than 0.19. The Dutch Roll damping ratio multiplied by the Dutch Roll damped frequency increased to 0.87 rad/sec using MSS compared to 0.21 rad/sec open loop. The design goal was a value of 0.35 rad/sec or greater. The design goal of a less than 10% change in the frequency of the structural modes was met by all the structural modes. The design goal of a less than 10% degradation in structural mode damping was met by all structural modes except the sixth mode in which the MSS reduced the damping ratio by 16.1%.

The CCV concepts in the lateral-directional axis was the Ride Control System and the Lateral Augmented Stability (yaw damper) system. The Lateral Augmented Stability system used only the rudder to increase the Dutch Roll damping ratio, and the RCS used only the vertical canard to reduce accelerations and stresses. The acceleration reduction by the RCS/LAS systems at the pilot stattion was 41%, compared to 43% using the MSS.

Conclusions

The performance of the MSS was adequate. The MSS did not meet all its design goals, such as only 45° phase margin for the canard loop. The MSS showed superior performance to the RCS/LAS systems, in reducing acceleration due to wind turbulence. The MSS reduced wing root stresses due to rudder and aileron disturbances.

The main advantage of using optimal control is being able to handle multiple inputs and outputs. the optimal control automatically gives the best stable gains for the given sensors and surfaces.

A disadvantage of optimal control is that even though stability is assured, the stability margin is not assured. For example, the canard loop has a phase margin of 45°. There is no easy way of ensuring that there will be ±6 db of gain margin or ±60° of phase margin from the optimal control program except by trial and error.

A second disadvantage of optimal control is that filtering, like wash-out filters, has to be put into the program either as modified sensors or surfaces. The time constant of the wash-out (high-pass) filter can only be determined by trial and error.

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