B-52 CONTROL CONFIGURED VEHICLES:

FLIGHT TEST RESULTS

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SUMMARY

This paper summarizes recently completed B-52 Control Configured Vehicles (CCV) flight testing, and compares results to analytical predictions. Results are presented for five CCV system concepts: Ride Control, Maneuver Load Control, Flutter Mode Control, Augmented Stability, and Fatigue Reduction. Test results confirm analytical predictions and show that CCV system concepts achieve performance goals when operated individually or collectively.

INTRODUCTION

In July 1971 the Air Force Flight Dynamics Laboratory (AFFDL) initiated the B-52 phase of the Control Configured Vehicles (CCV) program in conjunction with The Boeing Company, Wichita Division. The program objective was to validate that the CCV concept is operationally practical and results in significant performance benefits on large flexible aircraft. The program was conducted under Contract F33615-71-C-1926 and included analysis, development, and flight validation of four new CCV system concepts. The systems developed were: Ride Control (RC), Flutter Mode Control (FMC), Maneuver Load Control (MLC) and Augmented Stability (AS). The Fatigue Reduction (FR) system, developed during the Load Alleviation and Mode Stabilization (LAMS) Program, Reference 1, was also evaluated during flight testing to validate compatibility with the four new CCV systems.

The Air Force participated in the performance of the program by conducting the analysis and development of the Ride Control concept at the AFFDL Advanced Development Project Office.

This paper summarizes the flight test portion of the program. The CCV tests, completed in November 1973, validate for the first time the CCV system performance and compatibility of multiple CCV systems. Actual benefits obtained by flight test are compared to the analytical predictions, thereby validating both the system performance and the analytical design techniques.

FLIGHT TEST SCOPE

Flight testing was conducted in two time periods. The Ride Control system was tested from 8 January through 9 February 1973. The remaining CCV systems were tested between 18 July and 11 November 1973. A total of 35 flights were flown, comprising 122 flight hours.

System Performance Goals

The CCV System performance goals outlined below were validated during the flight test program:

- A 30 percent reduction in vertical and lateral RMS acceleration in turbulence with a Ride Control system
- Meet MIL-A-8870 flutter damping criteria (g = .03) at 10 knots above the basic airplane flutter speed with a Flutter Mode Control system
- Reduce wing root bending moments during maneuvers with a Maneuver Load Control system by 8.2×10^6 inch-pounds, which is equivalent to a 10 percent reduction in maximum design load
- Provide acceptable flying qualities at a flight condition with neutral static stability with an Augmented Stability system
- Reduce fatigue damage rates at critical wing and fuselage locations with a Fatigue Reduction system
- Meet performance goals of each individual system with multiple CCV systems operating

Test System Configuration

Analytical studies were conducted to determine surface placement and size for each CCV concept and to evaluate the potential of various configurations to meet performance objectives. Existing B-52 control surfaces used for CCV functions are elevators and rudder. New additional surfaces consist of three segment flaperons, outboard ailerons, horizontal and a vertical canard. Figure 1 shows the surface arrangement and usage for each concept. The three segment flaperon replaces the existing inboard flaps.

The CCV systems were individually designed to achieve the specified performance objectives. Various system combinations were then analyzed and parameters were adjusted as necessary to meet objectives. A block diagram of the five B-52 CCV systems in presented in Figure 2. The angular rate and linear acceleration sensors associated with these systems are illustrated in Figure 3.

All new systems except the FMC were implemented on two onboard TR-48 analog computers. The FMC was hardwired. The FR system employed system hardware developed during the LAMS program. The fly-by-wire (FBW) system, also developed during the LAMS program, was used for pilot maneuver and flying qualities

evaluations. Figure 4 shows the modified test aircraft.

Validation Plan

The flight validation plan was structured around the types of flight test generally required in any large flexible aircraft test program. In addition, specific flight tests for math model accuracy determination were conducted. Five distinct categories of tests were accomplished: (1) flutter evaluations to determine the character of an artificially generated flutter mode and flutter mode control system validation, (2) control effectiveness evaluations to determine the aerodynamic characteristics of the new control surfaces, (3) in-flight dynamic response evaluations to determine the accuracy of the math model, (4) maneuver testing to determine flying qualities of the CCV systems and validation of the maneuver load control and augmented stability systems, and (5) low-level turbulence response evaluation to validate the ride control system and CCV systems compatibility with critical airframe loads and ride quality. Comparisons of actual test data and analysis predictions were made in all categories.

The matrix of test conditions developed to evaluate and validate system performance is shown in Figure 5. The three different fuel configurations are representative of a light weight B-52 with normal center-of-gravity (c.g.), a medium weight B-52 with a c.g. 7 percent aft of the current aft limit, and a heavy weight B-52 with normal c.g. Selected CCV systems were evaluated at various fuel configurations, test altitudes and airspeeds which best represent the true operational environment on the B-52 aircraft.

FMC SYSTEM TESTS

To evaluate the FMC system, a flutter mode (within the speed capabilities of the B-52 test vehicle) was created by adverse ballasting of the wing drop tanks. The left and right tanks, which normally carry 19,500 pounds of fuel each, were modified to carry 2000 pounds of lead in the forward end of each tank. At the 21,000 foot test altitude, the ballasted tanks were predicted to produce flutter at 330 knots calibrated airspeed for the light weight test configuration and 315 knots calibrated airspeed at the heavy weight configuration. Flutter was predicted to be a symmetric second wing bending and torsion mode at 2.4 Hz. Figure 6 compares actual speed versus damping (V-g) test results with analysis predictions for the light weight 260,000 pound baseline airplane. Baseline flutter was found to be approximately seven percent higher than predicted for both the light weight and heavy weight configurations.

Figure 7 shows the effects of FMC on speed versus damping characteristics and the compatibility of other CCV systems with the FMC. The test objective of flying 10 knots past flutter was achieved at both gross weights, and the FMC met or exceeded minimum damping requirements of g = .03 at all speeds. The addition of other CCV systems to the FMC further improved minimum damping at all speeds, thus validating the operational capability of the FMC with multiple CCV systems operating. A comparison of theoretical and flight test speed-

damping results with the FMC on is shown in Figure 8. The FMC generally produced greater damping than predicted by analysis. In order to achieve these performance goals, the FMC system gains were increased up to twice nominal.

RIDE CONTROL SYSTEM TESTS

The Ride Control (RC) system was validated in low level turbulence at approximately 500 feet above the local terrain. Ten minute data samples were recorded for the baseline airplane and for the RC "on". Power spectral density analyses were accomplished on the random data samples to obtain gust response parameters. Figure 9 illustrates the effect of the RC on RMS vertical acceleration along the aircraft fuselage. Results are also compared to analytical predictions. The goal of 30 percent reduction was achieved at the crew station as predicted. Test results showed less improvement than predicted at the mid body, and a greater increase than predicted at the tail. However, the proper trend was predicted. RC effects on lateral acceleration are shown in Figure 10. The goal of 30 percent reduction at the crew station was also achieved in the lateral axis. Improvements were greater than predicted at both the mid body and aft body locations.

Figure 11 shows the change in aircraft acceleration with multiple CCV systems operating. A 30 percent acceleration reduction is still achieved with all systems operating. The addition of multiple CCV systems to the RC generally produced a further reduction in aircraft acceleration. An increase in the airplane gross weight by 100,000 pounds had no significant effects on the RC operation. No changes were required to the system, and performance goals were achieved in the vertical axis, which was the only axis tested at the heavy weight condition.

During the test program, it became necessary to increase the RC system gains by a factor of two in order to achieve the performance goals.

MANEUVER LOAD CONTROL SYSTEM TESTS

The MLC was flight tested to validate performance and compatibility at the light weight and heavy weight airplane configurations. The reduction in wing loads was determined from simulated pilot electrical inputs introduced to the MLC system through the onboard TR-48 analog computers. Flying qualities were evaluated for various pilot maneuvers. Although tests were not conducted at the B-52 design load condition (maximum gross weight, low speed configuration), the MLC goal was to reduce the maximum design wing root bending moment by 10 percent, or 8.2×10^{-6} inch-pounds. Figure 12 shows a comparison of theoretical and flight test results at the light weight low speed condition. The goal of 10 percent reduction in maximum design loads was achieved as predicted.

Comparison of theoretical and flight test results for the MLC are shown in Figure 13 over a speed range representative of B-52 maneuver operation. Maneuver loads were significantly reduced over the speed range.

Compatibility of the MLC with other CCV systems is illustrated in Figure 14 for the lightweight medium speed condition. The addition of other CCV systems did not degrade MLC performance for any condition tested. No changes were required to the MLC to meet performance goals.

AUGMENTED STABILITY TESTS

The Augmented Stability (AS) system was tested to evaluate flying qualities of the medium weight airplane configuration with the c.g. shifted aft to the neutral point. The c.g. was shifted aft to 41.6 percent mean aerodynamic chord (MAC) by adverse fuel distribution. This c.g. location is 7 percent aft of the normal B-52 aft limit. The flying qualities were evaluated for various types of pilot maneuvers. Figure 15 shows a comparison of flight test and theoretical normalized pitch rate response to a step column input. The actual test data indicates good time constant correlation with less overshoot than analytically predicted.

Figure 16 indicates the decrease in stick force gradient as the c.g. was progressively shifted aft. The airplane without the AS system engaged shows very light stick forces, even at the normal aft limit of 35 percent MAC c.g. location, indicating a lower than normal artificial stick force gradient was mechanized on the FBW system. Even with these lower unaugmented airplane force gradients, the AS concept increased the force gradient a significant amount. These forces could have easily been made to meet the criteria by a FBW force gradient change and a gain change within the pilot command augmentation portion of the AS mechanization. Compatibility of AS and MLC is also shown.

FATIGUE REDUCTION SYSTEM COMPATIBILITY TESTS

The Fatigue Reduction (FR) system, validated singly during the LAMS program, was flight tested to validate compatibility with the remaining CCV concepts. The FR system was evaluated alone in low level turbulence with the light weight airplane configuration at approximately 500 feet above the local terrain. Once again, as during the RC tests, ten minute data samples were recorded for the baseline airplane and for the FR system "on". Power spectral density analyses were accomplished on the random data samples to obtain the gust response parameters. Reduction in RMS bending moments at critical wing and aft fuselage stations is shown in Figure 17 for the FR only, as well as with all systems "on" compared to the baseline airplane. With all systems "on", a slight increase in bending moment is shown at the aft fuselage location compared to the results obtained with FR "only". However, the bending moments are significantly reduced over the baseline airplane data.

The analytical predictions for bending moment reductions with all systems "on" at the same wing and fuselage locations are compared with actual data in Figure 18. The FR compatibility tests generally produced results greater than the analytical predictions. No changes were required in the FR system to enable achievement of the compatibility goals.

CONCLUSIONS

The flight test results from the B-52 CCV program have validated, for the first time, that significant performance benefits are achievable when the CCV concept is utilized.

The CCV systems proved to be operationally practical, both individually and collectively, at the gross weights, airspeeds, and altitudes tested.

The baseline mathematical models and theoretical predictions differed, in some cases, from the actual flight test data. Even with these differences between the math model and the actual airplane, the CCV systems met their individual and collective performance goals without system redesign. This result indicates that math model inaccuracies, which are inevitable in any airplane design program, can be compensated for by careful and deliberate design of the CCV systems. Simple gain changes, such as those required during the FMC and RC flight tests, to enable a system or combination of systems to meet the performance goal are considered to be a minor modification.

The results of the B-52 CCV program indicate that existing analysis techniques and performance prediction methods are indeed sufficiently accurate to permit incorporation of CCV concepts into future large aircraft designs.

FUTURE RESEARCH

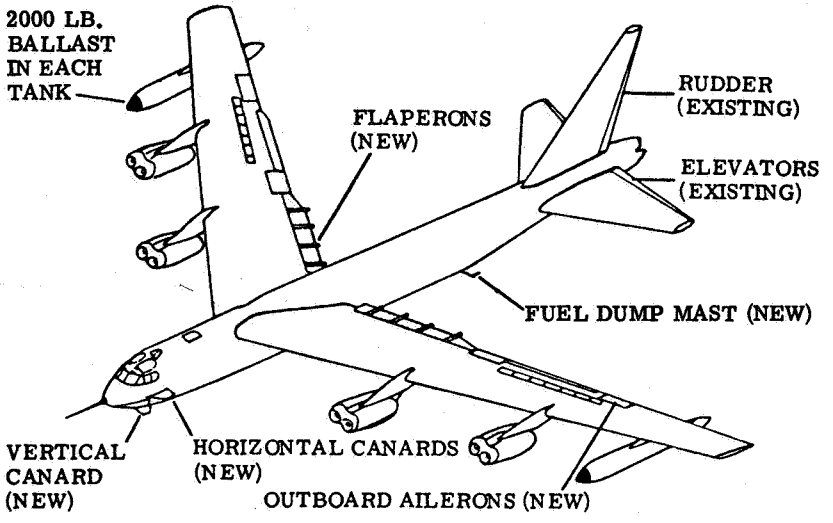
As pointed out in Reference 2, the basic criteria for establishing acceptance of a new technology such as CCV is that: (1) the system meet predicted performance, (2) the system be operationally practical, (3) the system be reliable and safe, and (4) that it be cost effective. The B-52 CCV program has contributed significantly in establishing acceptance of CCV for large military aircraft by validating that predicted performance can be achieved over a limited operational range.

Future research efforts should primarily be concentrated in the two remaining areas. Since CCV technology is dependent on the concept of fly-by-wire, efforts should be focused on development of a highly reliable fly-by-wire system for large flexible aircraft. To validate that the technology is safe and cost effective, a technology demonstrator aircraft is needed which incorporates the full concept of CCV in the preliminary design. This test vehicle should be configured to demonstrate total dependence of the structural and aerodynamic design on the CCV concept.

REFERENCES

1. "Aircraft Load Alleviation and Mode Stabilization (LAMS)," AFFDL-TR-68-158, December 1968, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio.

2. Holloway, R. B., and Shomber, H. A., "Establishing Confidence in CCV/ACT Technology." Presented at the NASA Sponsored Symposium on Advanced Control Technology and Its Potential for Future Transport Aircraft, Los Angeles, California, 9-11 July 1974.



SURFACES	CCV CONCEPTS				
	RCS	FMC	MLC	AS	FR
RUDDER				X	
ELEVATOR			X	X	X
FLAPERON		1 SEGMENT	X		
OUTBOARD AILERON		X	X		X
HORIZONTAL CANARD	X				
VERTICAL CANARD	X				

Figure 1.- B-52 Test Vehicle Configuration

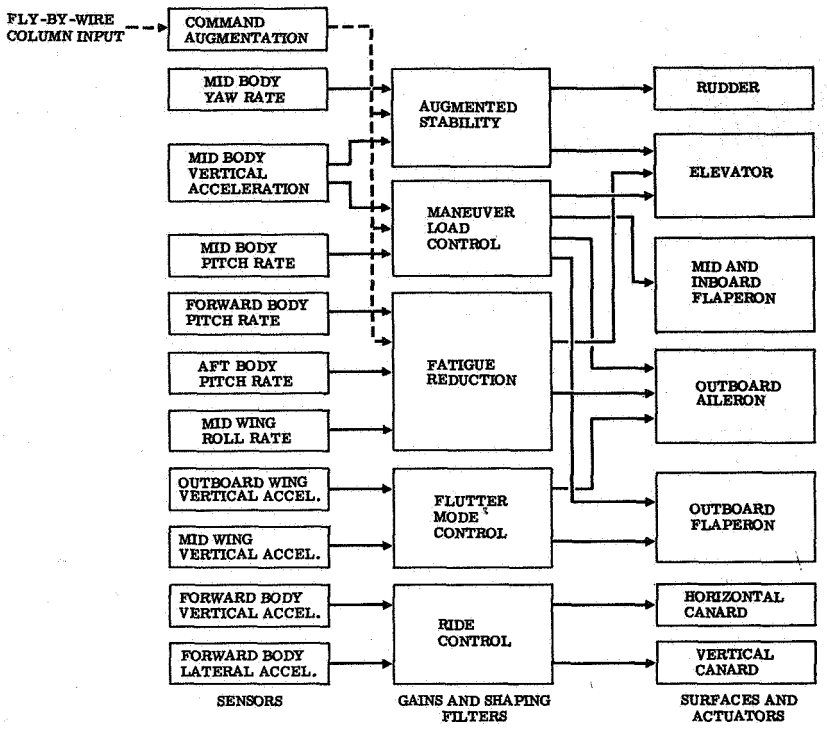


Figure 2.- B-52 CCV Systems Block Diagram

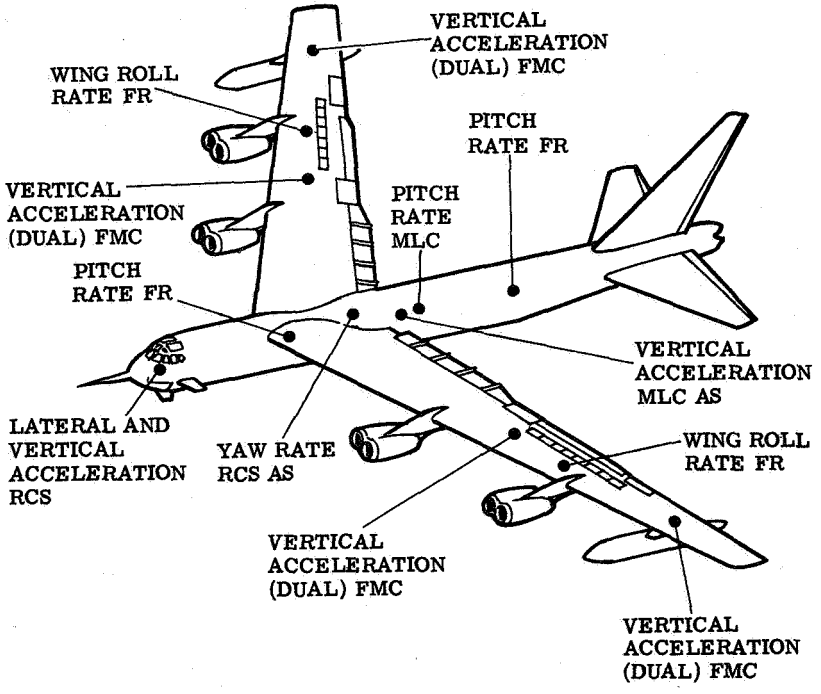


Figure 3.- B-52 CCV Systems Sensors

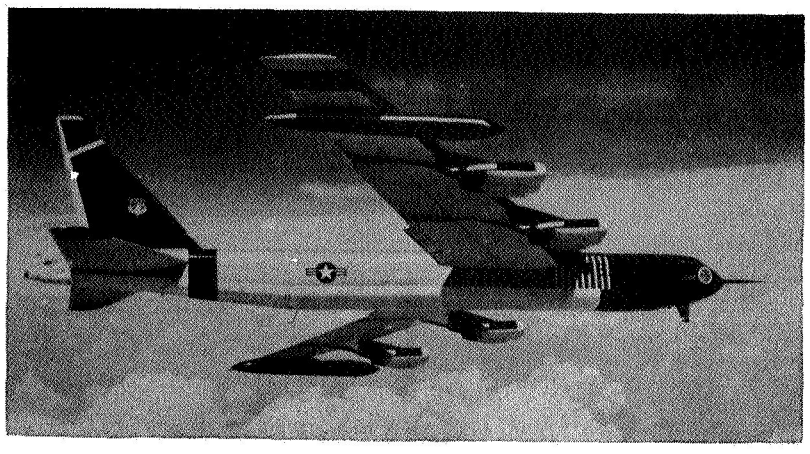


Figure 4.- B-52 CCV Test Aircraft

FUEL CONFIGURATION		ALTITUDES, FT.	AIRSPEEDS, KCAS
LIGHTWEIGHT, NORMAL C. G. 260,000 LB.	1	500 AGL, 6000, 21000	225 → 390
MEDIUM WEIGHT, C. G. AFT OF LIMIT 300,000 LB.	2	21,000	225 → 363
HEAVYWEIGHT, NORMAL C. G. 360,000 LB.	3	500 AGL, 6000, 21000	225 → 383

Figure 5.- B-52 CCV Test Conditions

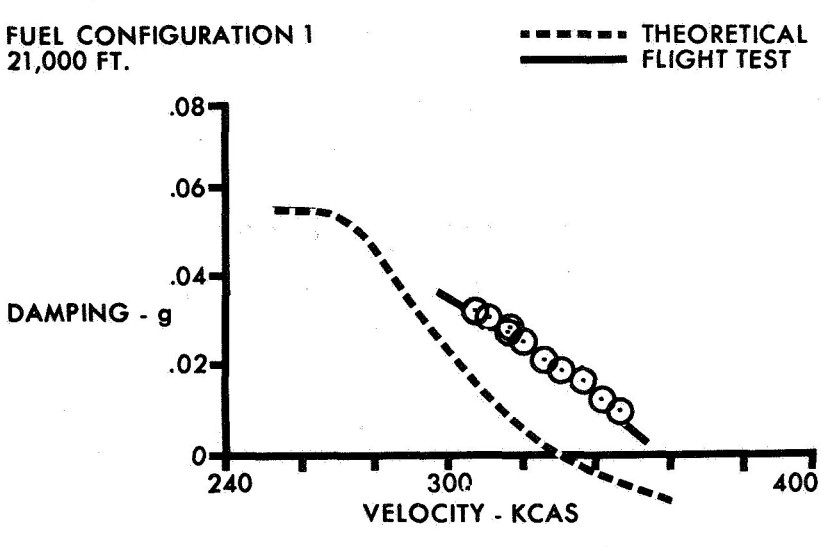


Figure 6.- V-g Comparison, FMC "Off"

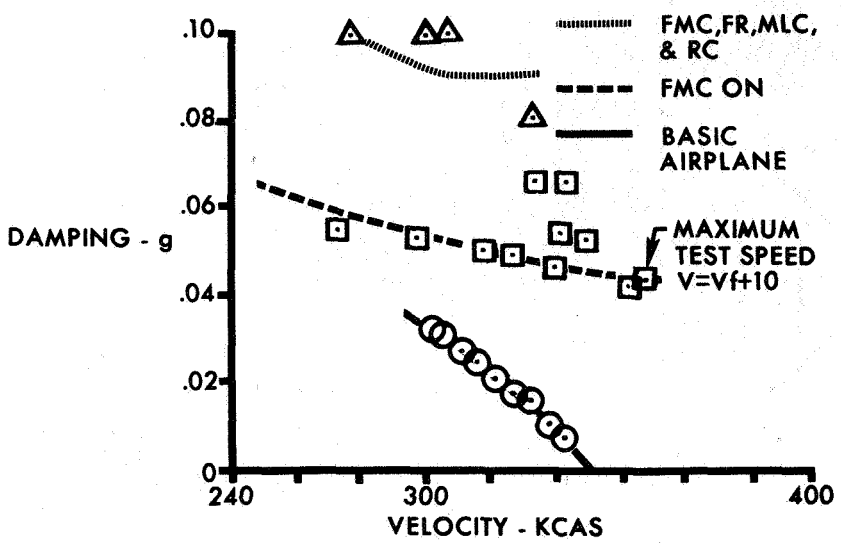


Figure 7.- Flight Test Flutter Results

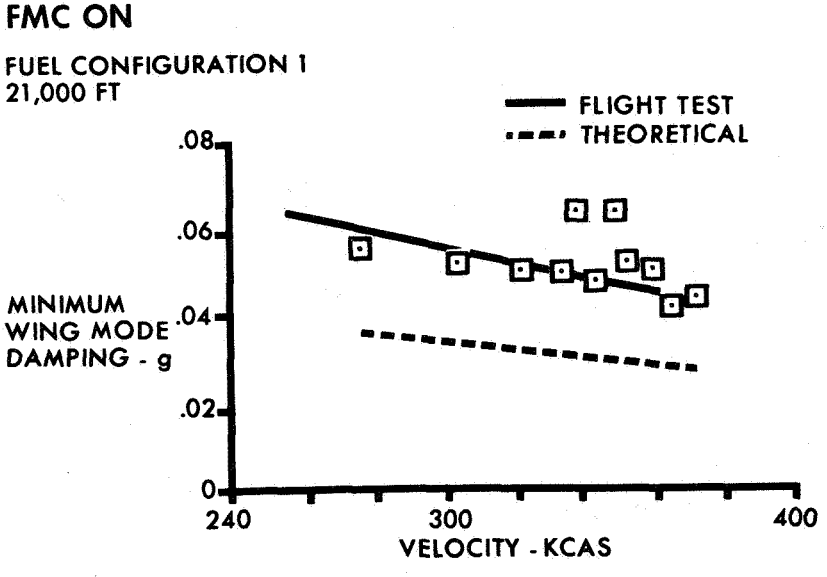


Figure 8.- V-g Comparison, FMC "On"

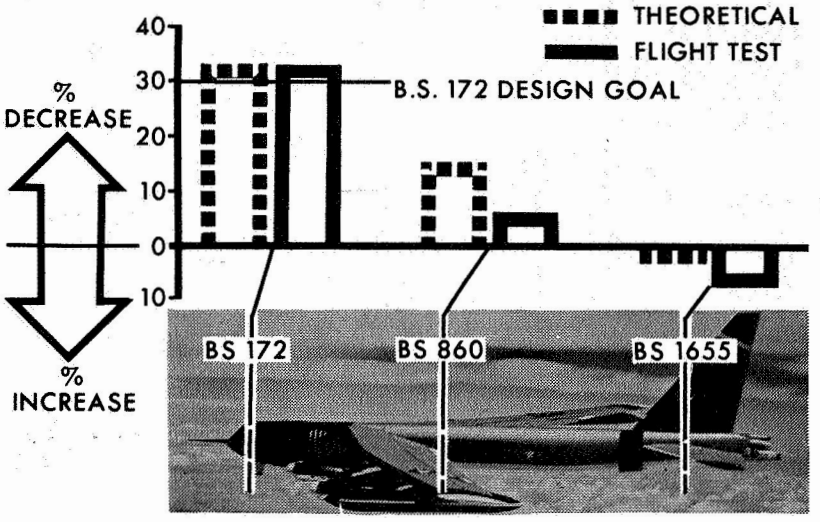


Figure 9.- RC Effect on Vertical Acceleration

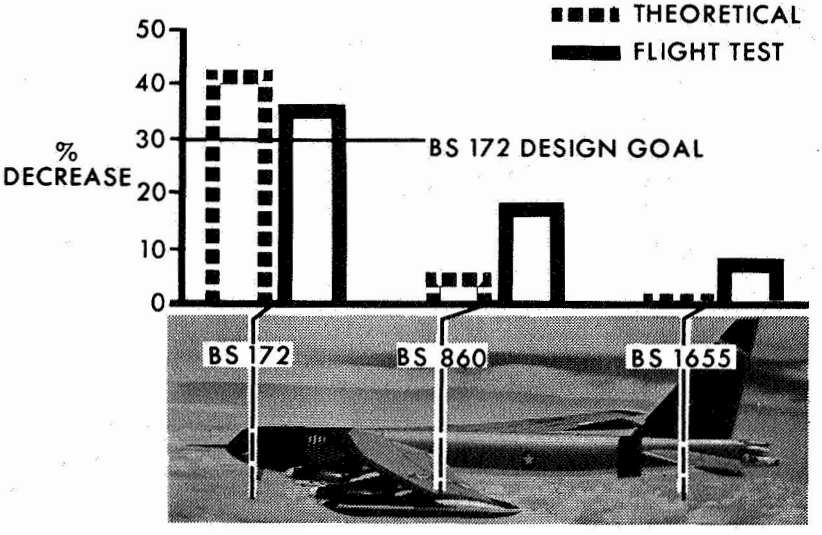


Figure 10.- RC Effect on Lateral Acceleration

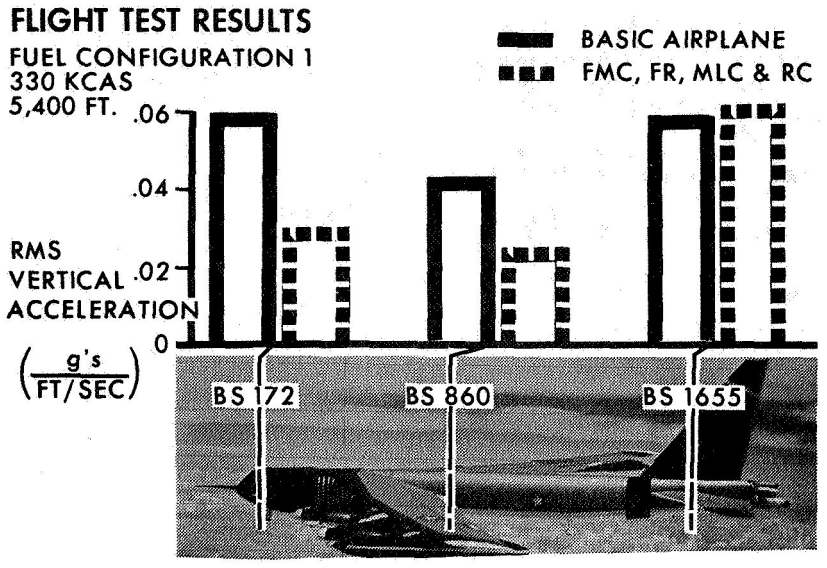


Figure 11.- Ride Quality Compatibility

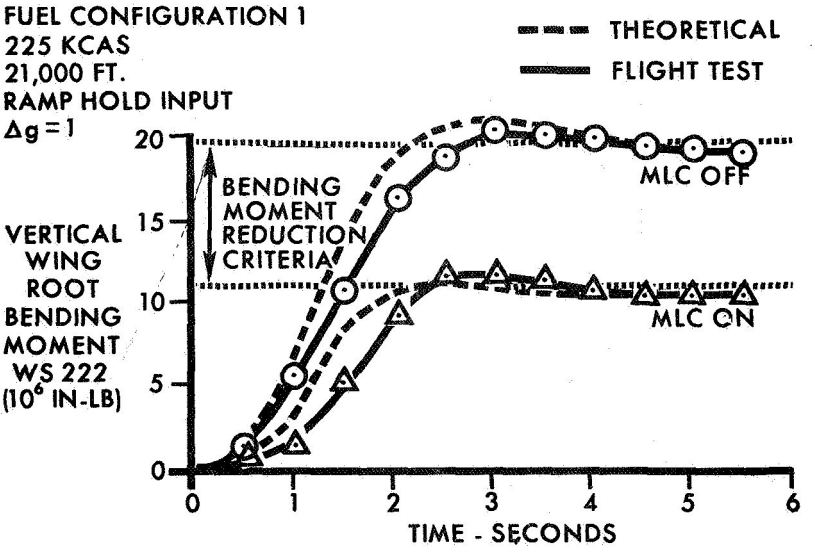


Figure 12.- MLC Performance Comparison

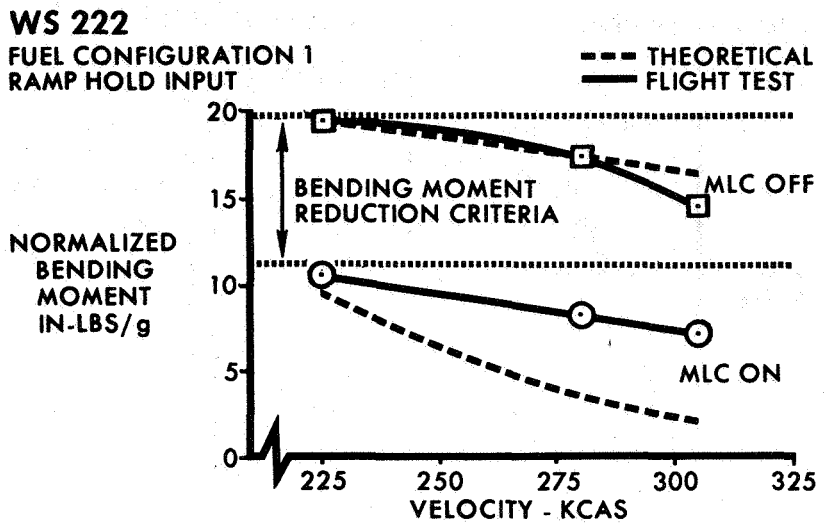


Figure 13.- Wing Root Vertical Bending Moment Reduction Versus Airspeed

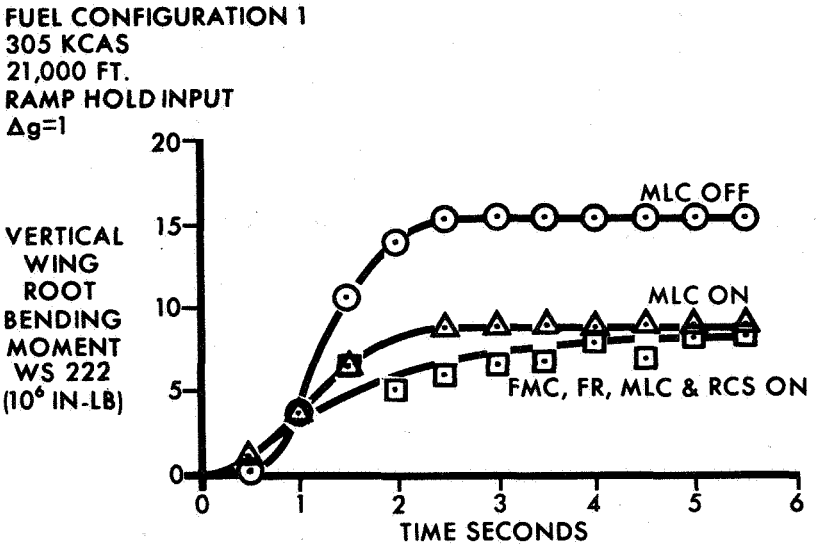


Figure 14.- MLC Compatibility

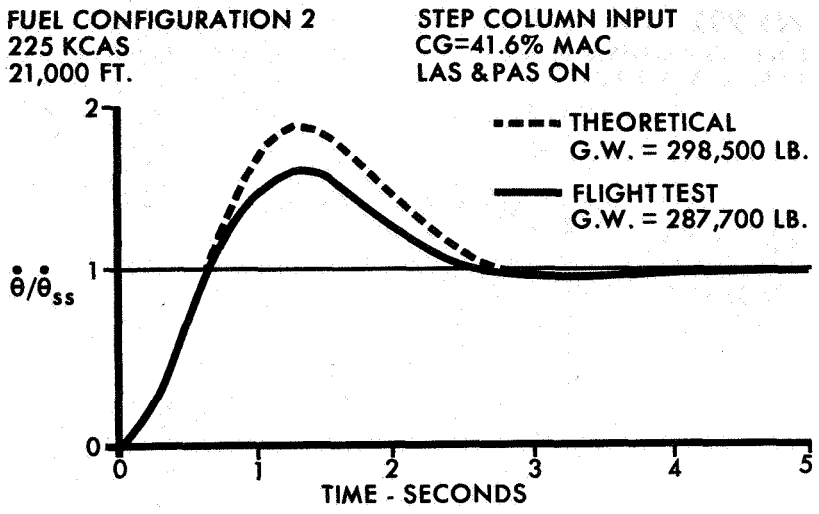


Figure 15.- AS Performance Comparison at 41.6 Percent MAC C.G.

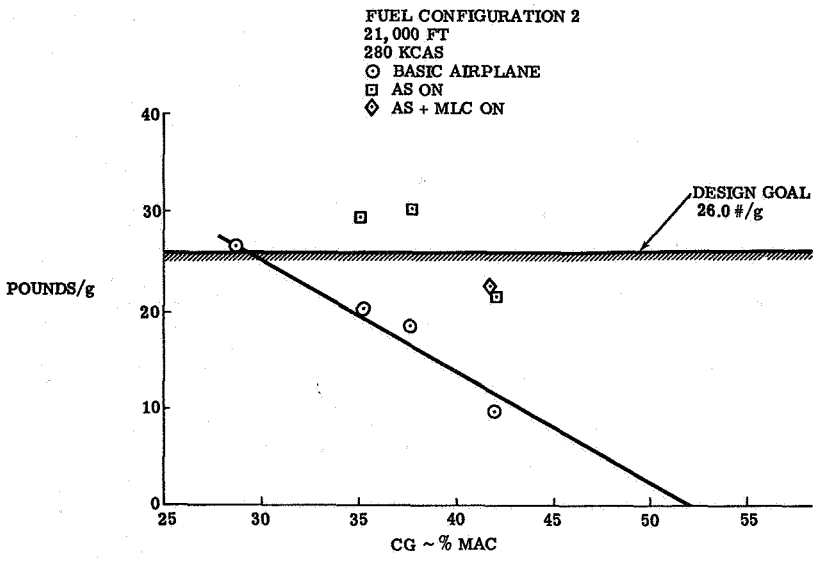


Figure 16.- Effect of C.G. on Stick Forces

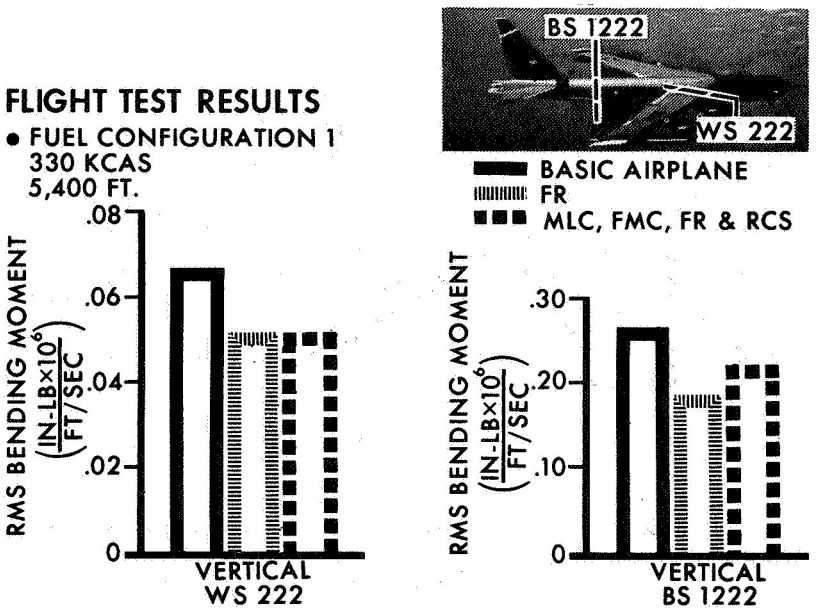


Figure 17.- FR Bending Moment Compatibility

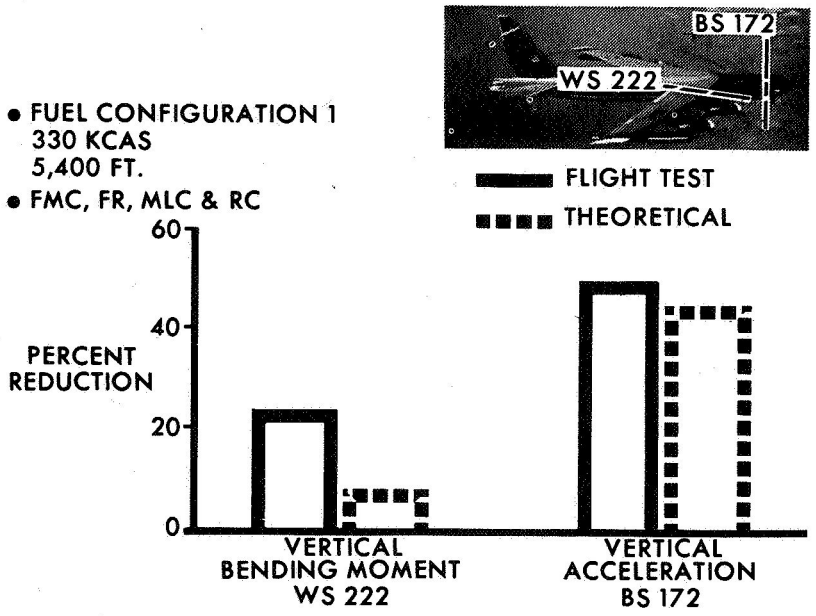


Figure 18.- FR Compatibility Comparison