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# DESIGN OF A CONTROL CONFIGURED TANKER AIRCRAFT

Stephen A. Walker
Headquarters, Aeronautical Systems Division (AFSC)
Wright-Patterson Air Force Base

## SUMMARY

A study was conducted to determine the benefits that accrue from using control configured vehicle (CCV) concepts and the techniques for applying these concepts to an advanced tanker aircraft design. Reduced static stability (RSS) and flutter mode control (FMC) were the two primary CCV concepts used in the design. The CCV tanker was designed to the same mission requirements specified for a conventional tanker design. A seven degree of freedom mathematical model of the flexible aircraft was derived and used to synthesize a lateral stability augmentation system (SAS), a longitudinal control augmentation system (CAS), and a FMC system. Fatigue life and cost analyses followed the control system synthesis, after which a comparative evaluation of the CCV and conventional tankers was made. This comparison indicated that the CCV weight and cost were lower but that, for this design iteration, the CCV fatigue life was shorter. Also, the CCV crew station acceleration was lower but the acceleration at the boom operator station was higher relative to the corresponding conventional tanker. Comparison of the design processes used in the CCV and conventional design studies revealed that they were basically the same.

## INTRODUCTION

In an Air Force sponsored study, conducted by the Boeing Company, a CCV tanker was designed to satisfy the same mission requirements specified for an advanced conventional tanker design. The purpose of this study was to determine the performance characteristics, control characteristics, methodology for applying CCV concepts, and the design process resulting from applying CCV concepts. In addition to RSS and FMC, the two CCV concepts applied, maneuver load control (MLC), ride control (RC) and gust load alleviation (GLA) were three other concepts given consideration.

The objectives of the study were to:

1. Define a CCV configuration

2. Synthesize a control system for the configuration

3. Compare the CCV and conventional tanker designs

To achieve these objectives, the scope of the study was expanded to include:

1. A parametric analysis to determine a nominal size, weight, and geometry for the CCV.

2. Derivation of a point design by refinement of the nominal CCV.

3. The derivation of flexible, rigid body and gust equations of motion for the control system synthesis.

4. Flying quality, fatigue and cost analysis.

The design procedure used in the study is shown in figure 1. First, the CCV was sized in a parametric study, which included two CCV concepts. Next, the CCV point design was defined; and, finally, a control system was synthesized for the point design.

Overall, the methodology used in the CCV and conventional tanker studies were the same. Equations of motion were obtained using finite element methods, and the control synthesis was accomplished using the corresponding transfer functions and root loci. Neither the finite element, transfer function, nor root locus methods are peculiar to CCV design.

## CONFIGURATION DEFINITION

### Mission and Ancillary Requirements

The specified mission requirements to which the CCV was designed are:

1. Design refuel range

2. Off-load 348,900 pounds of fuel at the design refuel range, Mach .68 and 30,000 ft

3. Personnel and cargo capability

4. Cruise speed: Mach .75

5. Rate of climb with one engine out

6. Takeoff ground roll

7. Landing ground roll

Some of these requirements are depicted pictorially in figure 2. Other quantities used to design and evaluate the CCV are:

1. Gross weight

2. Operating gross weight empty

3. Flying qualities

4. Ride qualities

5. Fatigue life

6. Cost

## Parametric Analysis

In a parametric analysis a matrix of CCV configurations was generated; and, although each configuration was smaller than the conventional tanker, each had the same mission capability. Furthermore, each configuration had the same wing loading (W/S), and thrust as the conventional tanker. Because of the application of RSS and MLC however, each configuration had less drag, a smaller operating weight empty (OWE), takeoff gross weight (GW) and wing area than the conventional tanker. From these configurations the smallest CCV tanker was selected for more detailed study and design.

The selected CCV tanker configuration was refined through a detailed design of the aerodynamic, propulsion, and structural subsystems. The result of this refinement, which was constrained by the mission requirements, was the CCV point design developed in the study.

Of the two CCV concepts used in deriving the point design, RSS had the most extensive impact on the CCV external geometry, size and weight. Reduction of the pitching moment requirements accounts for the impact of RSS because these requirements largely determine the size and location of the tail and control surfaces, and the location of the wings and landing gear relative to the center of gravity (C.G.). The influence of RSS is summarized in Tables I and II in which a comparison of various CCV and conventional tanker components is shown. (The starred items in Table I were not determined by RSS.)

In sizing the CCV the only factor attributed to MLC was a 10 percent reduction in wing weight because it was assumed that any higher stresses occuring in the lighter wing structure could be alleviated by an active MLC system. However, for the reason discussed subsequently a MLC system was not synthesized for the CCV, eventhough the assumption of a 10 percent reduction had been applied to the point design.

## Point Design Description

The most prominent feature of this design, illustrated in figure 3, is the absence of a horizontal tail. Other design features include a low wing and four engines, of which two are wing and two are fuselage mounted. A tricycle landing gear and a boom operator station located in the aft fuselage section also characterize the configuration. Pitching and rolling moments are obtained from the wing mounted elevons, and the rudder is used to generate yawing moments. Because of RSS, the airframe is statically unstable at some heavy gross weight conditions which includes the takeoff condition.

The CCV point design represents an attempt to maximize the size and weight reductions; and the resulting size reduction may be observed in figure 4, in which the external features of the CCV and conventional tankers are compared.

TABLE I

CCV AND CONVENTIONAL COMPARATIVE SIZE

| ITEM | CONVENTIONAL | CCV |
|---|---|---|
| WING AREA ($FT^2$) | 10,640 | 8,984 |
| WING SPAN (FT) | 275. | 251.4 |
| FUSELAGE LENGTH (FT) | 197. | 125. |
| FUSELAGE MAXIMUM DIAMETER (FT) | 18. | 18. |
| HORIZONTAL TAIL ($FT^2$) | 2,310 | 0 |
| VERTICAL TAIL ($FT^2$) | 1,173 | 571.2 |
| CRITICAL ENGINE MOMENT ARM (IN) | 767. | 300. |
| DESIGN WEIGHT (LB) | 1,000,000. | 835,900. |
| OWE (LB) | 334,100 | 250,300. |

TABLE II

CCV AND CONVENTIONAL WEIGHT COMPARISON

| ITEM | CONVENTIONAL WEIGHT (LB) | CCV WEIGHT (LB) | $\Delta$ (LB) |
|---|---|---|---|
| WING | 120,370 | 82,650 | 37,720 |
| HORIZONTAL TAIL | 12,200 | 0 | 12,200 |
| VERTICAL TAIL | 7,070 | 3,430 | 3,640 |
| FUSELAGE | 52,900 | 35,660 | 17,240 |
| SURFACE CONTROLS | 9,730 | 6,590 | 3,140 |
| HYDRAULICS | 5,160 | 5,080 | 80 |
| AIR CONDITIONING | 2,070 | 1,190 | 880 |
| LANDING GEAR | 46,790 | 39,110 | 7,680 |
| OTHERS | 73,500 | 73,950 | -450 |
| WEIGHT EMPTY | 329,790 | 247,660 | 82,130 |
| DESIGN WEIGHT | 1,000,000 | 835,900 | 164,100 |

CCV MODEL

The equations of motion used in the control synthesis included rigid body and elastic structural modes of motion. Finite element techniques, a detailed treatment of which may be found in reference 1 and other sources in the literature, were used to derive the elastic equations of motion. Briefly, the finite element method is a technique in which the structure is modeled by a finite number of nodes (fig. 5) connected by beams or plates which act as structural springs. The structural motion is described by the displacement and rotation of the nodes, at which the forces and moments are assumed to be applied.

For lifting surfaces, an aerodynamic finite element method called the double lattice technique (ref. 2) was used, and the application of this technique entailed dividing each lifting surface into a finite number of trapezoids (fig. 5). A set of coefficients relating the velocity normal to the element and the lift on the element is provided by the method. Also produced by the method is the dynamic coupling between elements which for example, describe the wing-fin coupling responsible for the flutter mode.

Ordinary differential equations in time with coefficients that are functions of geometry are obtained from the application of the finite element technique. From a procedure for simplifying the equations and a Boeing Company transfer function computer program, the corresponding transfer functions used in the control synthesis were generated. Although the original equations represented as many as seventeen degrees of freedom, only seven degrees of freedom were used in the control synthesis; and these consisted of three rigid and four elastic (structural) modes of motion.

## CONTROL SYSTEM SYNTHESIS

In synthesizing the control system no novel design techniques peculiar to control configured vehicles were used.

Transfer functions for the seven degree of freedom model and root loci were used to synthesize a logitudinal CAS, a lateral SAS and a FMC system. The criteria to which these systems were designed are given below.

### Design Criteria

The control systems were designed to existing military specifications. The logitudinal CAS and the lateral SAS designs were based on the rigid body flying quality requirements of MIL-F-8785B(ASG), and the FMC system design was based on the $1.15V_D$ criteria of MIL-A-8870, where $V_D$ is the design limit speed. The flying quality requirements are expressed in terms of adequate stability, maneuver response, natural frequency, damping ratios, time constants, and time to double; and the flying qualities are characterized by satisfactory stability, short period, phugoid, dutch roll, spiral and roll subsidence modes of motion.

### Lateral SAS Synthesis

The roll axis was unaugmented; and, hence, the lateral SAS consisted of a rigid body yaw damper only. The yaw damper, comprised of a washout circuit and a first order filter, provided the dutch roll damping required by reference 3.

### Lateral FMC Synthesis

An antisymmetric flutter analysis revealed the need for a FMC system because the free airframe failed to meet the $1.15V_D$ criterion; that is, the second structural mode fluttered at a velocity of 450 KCAS, which is below the $1.15V_D$ of 477 KCAS.

A zero root locus analysis (ref. 4) was conducted to determine the best sensor location and which of the elevons to use for flutter suppression. The philosophy of the zero root locus approach is that the distance between a sensor or surface zero and a structural pole is indicative of the coupling between the sensor or surface and the structural mode. A greater distance implies more coupling or more influence of the surface on the structural mode (fig. 6). The result of this analysis was the selection of an accelerometer location (fig. 3) and the inboard elevon for flutter suppression.

The accelerometer and inboard elevon were incorporated in the design of a FMC system, which consisted of an inner and outer feedback loop. The inner loop was the aforementioned yaw damper and the outer loop was a compensated acceleration loop that controlled the inboard elevon for flutter suppression.

## Longitudinal CAS Design

Analysis showed the absence of a longitudinal flutter problem and, hence, only a CAS design was required. Structural coupling was present in the symmetric axis, however, due to the presence of a structural pole in the vicinity of the short period poles at high speeds. Elimination of this coupling (fig. 7) was achieved by using the outboard elevon to which the structural mode was more strongly coupled. Thus, the outboard elevon provides pitch damping and attitude control as well as structural decoupling.

## Maneuver Load Control System

Steady state loads were determined for the augmented CCV on the basis of the inflight and taxi load requirements of MIL-A-008861A and MIL-A-008862A. Since the structure was adequate for the loads defined by these specifications, a MLC system was not designed.

## Gust Response And Fatigue Analyses

Turbulence response analyses were conducted to determine the fatigue and ride characteristics of the augmented CCV; and since the ride was deemed acceptable and the fatigue life satisfied MIL-A-008866A, neither a GLA nor a RC system was synthesized.

The gust analysis was conducted in the frequency domain, and the atmospheric turbulence was a von Karman power spectral density. The ride quality and the fatigue life were determined, respectively, from the turbulence parameters for acceleration (A) and fatigue damage ($N_O$).

## COMPARATIVE EVALUATION

The aforementioned mission requirements specified for the CCV and conventional tankers are also measures of aircraft performance. Although an absolute numerical comparison of these performance quantities is not generally available, a comparison based on normalized requirements is provided in Table III. A value of unity is assigned to each requirement and the performance quantities are expressed relative to this value. Since both aircraft were designed to have the same range, fuel off-load capability, cruise speed, and cargo-passenger capacity, these quantities have the same value. Values for the rate of climb, takeoff and landing ground rolls differ, however, because the corresponding capabilities were not identical for both tankers. Although both aircraft had a higher rate of climb and a shorter takeoff ground roll than required, the CCV had a faster rate of climb but a longer takeoff ground roll than the conventional tanker. Furthermore, the CCV landing ground roll equaled the slippery runway requirement, whereas that of the conventional tanker was shorter than required.

TABLE III

COMPARISON OF CCV AND CONVENTIONAL TANKER PERFORMANCE

| PERFORMANCE QUANTITY | CONVENTIONAL PERFORMANCE | CCV PERFORMANCE | $\frac{\text{CCV}}{\text{CONVENTIONAL}}$ |
|---|---|---|---|
| RANGE | 1 | 1 | 1 |
| FUEL OFF-LOAD | 1 | 1 | 1 |
| PERSONNEL-CARGO CAPACITY | 1 | 1 | 1 |
| CRUISE SPEED | 1 | 1 | 1 |
| ENGINE OUT RATE OF CLIMB | 2.1 | 4.2 | 2 |
| TAKEOFF GROUND | 1.2 | 1.1 | .92 |
| LANDING GROUND ROLL ($\mu$ = .1) | 1.1 | 1.0 | .91 |

Also compared were the flying quality, flutter, ride, fatigue, and cost characteristics of the two tankers. Except for the roll performance specification which neither aircraft met, the augmented aircraft satisfied all of the flying quality requirements. The roll performance specified by reference 5 is for 30 degrees of bank angle in 2.5 seconds, but the CCV and conventional tankers required 2.7 and 3.75 seconds, respectively, to reach the 30 degrees. Both tankers exceeded the flutter requirements and both had satisfactory ride qualities. However, the CCV crew and boom operator station accelerations were respectively 34 percent lower and 15 percent higher than the corresponding conventional tanker accelerations. From a fatigue life analysis it was learned that the CCV and baseline tankers accumulated 57 and 44 percent, respectively, of their design fatigue lives. Finally, a cost summary comparison, based on the purchase of one hundred tankers, revealed that the CCV will cost 20 percent less (fig. 8).

One of the most important comparisons was between the GW and OWE of the two aircraft. The CCV was 16 and 25 percent lighter in GW and OWE, respectively. The primary importance of these lighter weights is in the potential economic advantages. For example, a 25 percent OWE reduction offers a significant benefit to commercial airlines which may be occasionally confronted with low load factors.

It is important to note that the above comparisons were based on a single CCV design iteration and that additional iterations could alter the performance and other characteristics of the aircraft. Nevertheless, these comparisons provide a valid basis for the conclusions that follow.

## CONCLUSIONS

From the results of the CCV and Conventional Tanker studies the following conclusions may be drawn.

1. Significant reductions in GW, OWE and cost are the major benefits resulting from the application of CCV concepts to transport type airplanes.

2. Of all the CCV concepts, RSS has the most extensive impact on the airplane configuration arrangement design and produces the largest reductions in weight and drag.

3. The 16 and 25 percent reductions in GW and OWE are representative of the maximum reductions possible for the specified mission.

4. The application of CCV concepts will not necessarily improve all of the aircraft performance quantities. For example, the 16 percent CCV weight reduction was accompanied by longer takeoff and landing distances, and a reduced fatigue life. However, additional design iterations could shorten the ground roll distances; and the fatigue life could be improved by structural redesign or the inclusion of other CCV concepts such as MLC.

5. The utility of CCV concepts are mission sensitive. For example, analyses determined that GLA and RC systems were unnecessary, but a low level mission which would increase the probability of encountering larger gust intensities could reverse these results.

6. A CCV is an airplane the design of which is based on

a. The waiver of the free airframe logitudinal static stability requirement.

b. The use of control systems to perform new tasks such as MLC, FMC, GLA and RC.

7. Although active controls were included in the preliminary design stage, the preliminary design process for the CCV is standard in that, first, the airframe is statically designed after which active control systems are designed.

8. New handling quality criteria are needed because a demarcation between the short period and phugoid modes is lacking at some flight conditions for the RSS airframe.

## REFERENCES


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3. Military Specification - Flying Qualities of Piloted Aircraft. MIL-F-8785B(ASG), August 1969

4. Control Configured Vehicles Advanced Tanker Study, Appendix C. Unclassified. Technical Report ASD/XRL-72-44, The Boeing Company, Wichita Division, October 1972.

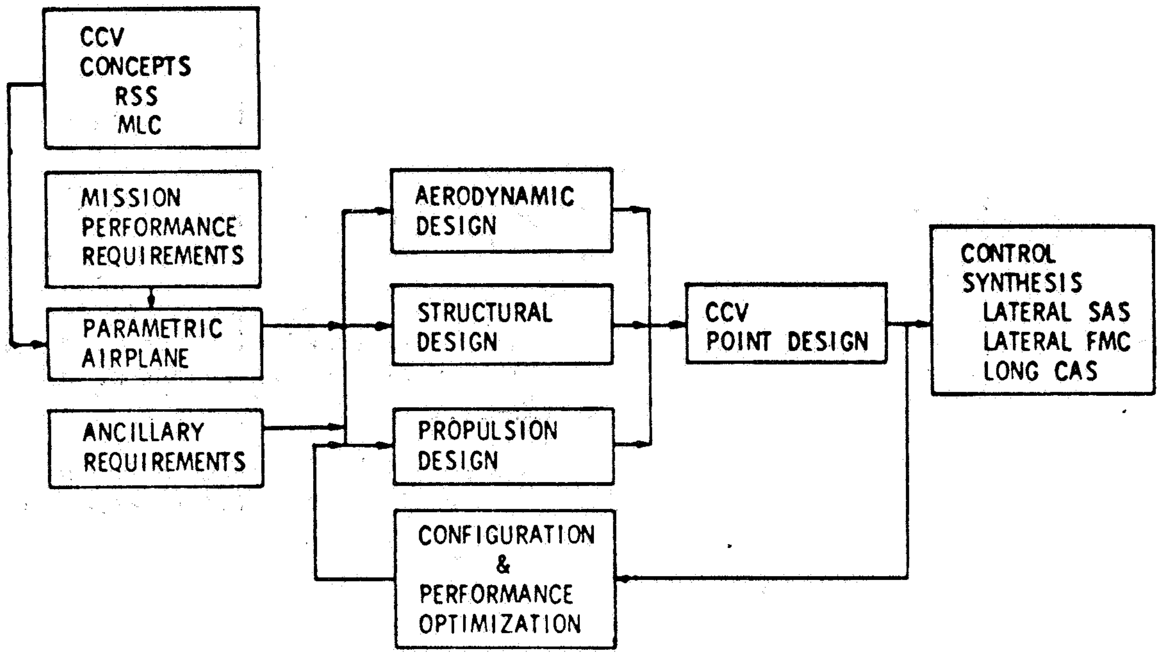


Figure 1.- CCV design process

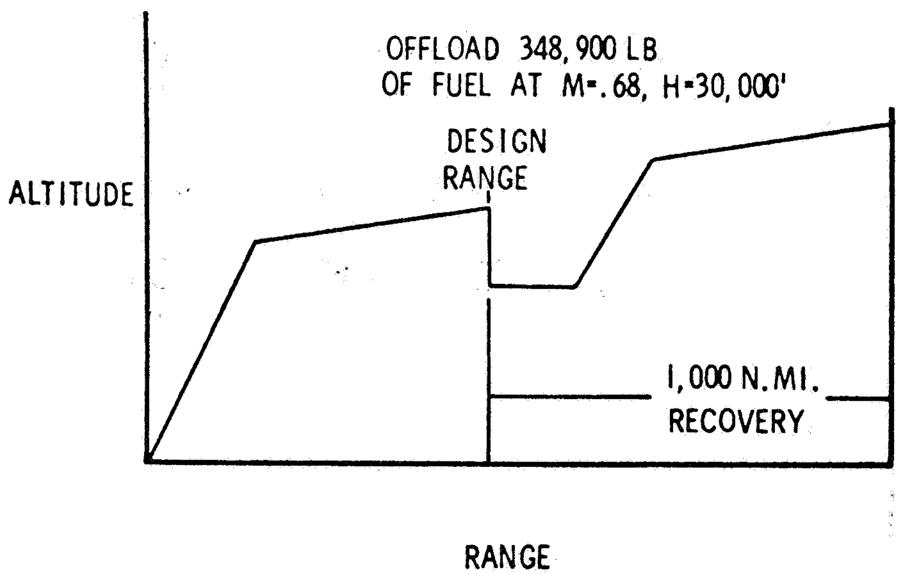


Figure 2.- Mission Profile

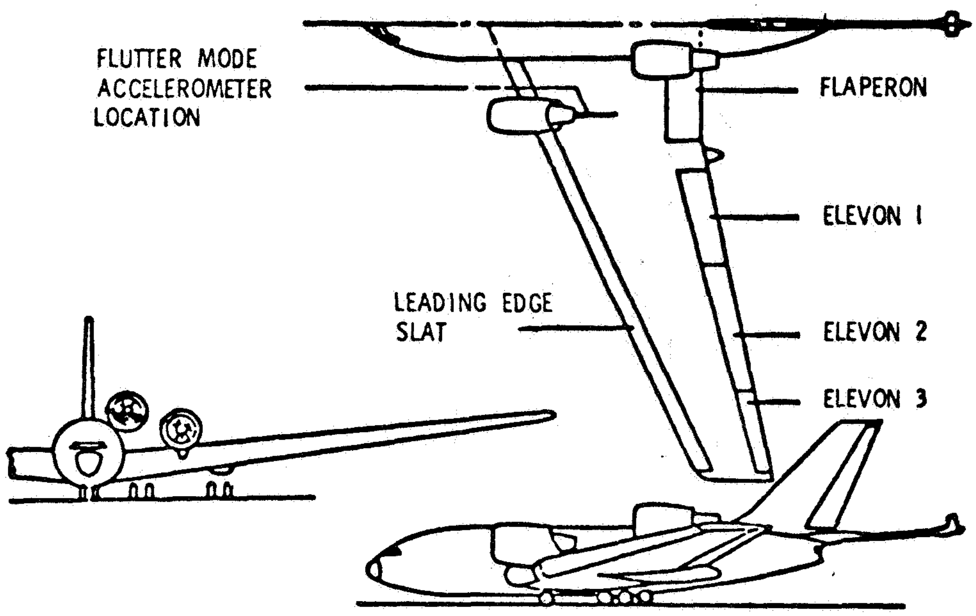


Figure 3.- CCV point design

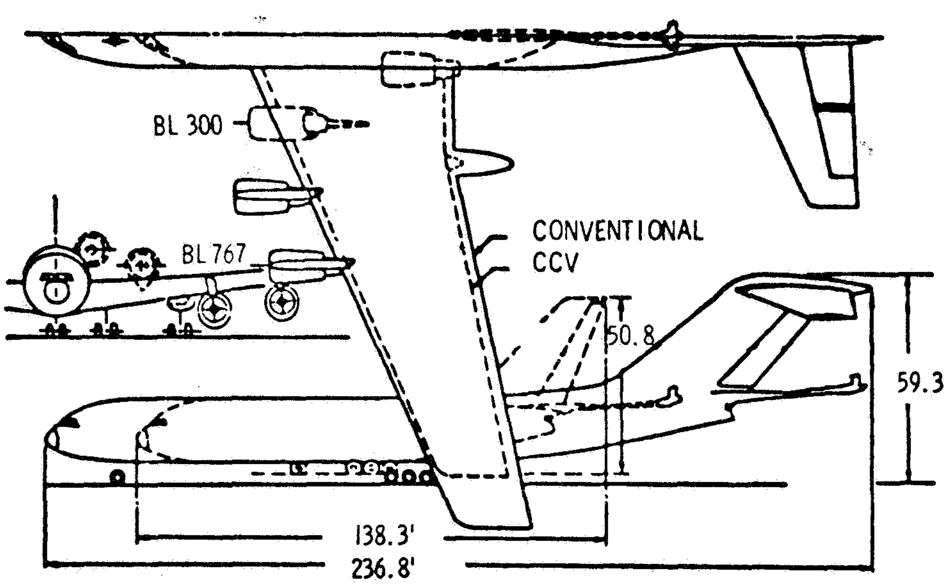


Figure 4.- Size comparison of CCV and conventional tanker configurations.

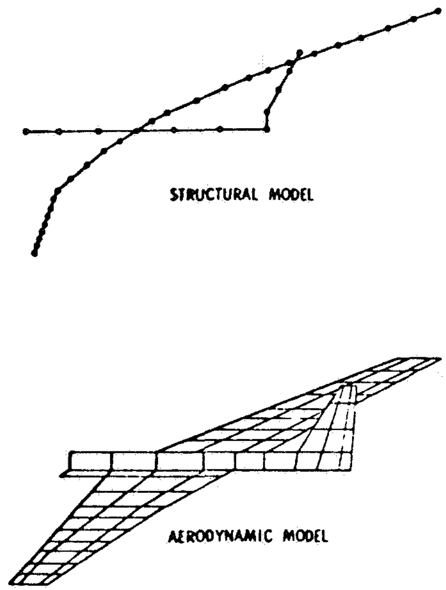


Figure 5.- Finite element models.

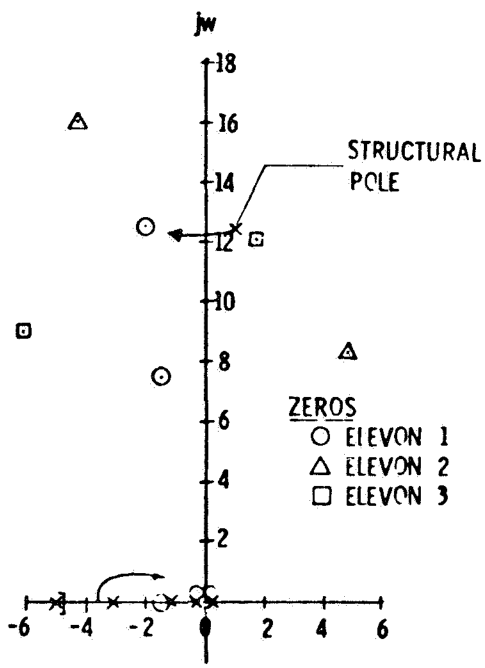


Figure 6.- Flutter control root locus with yaw damper and alternate elevon zeros.

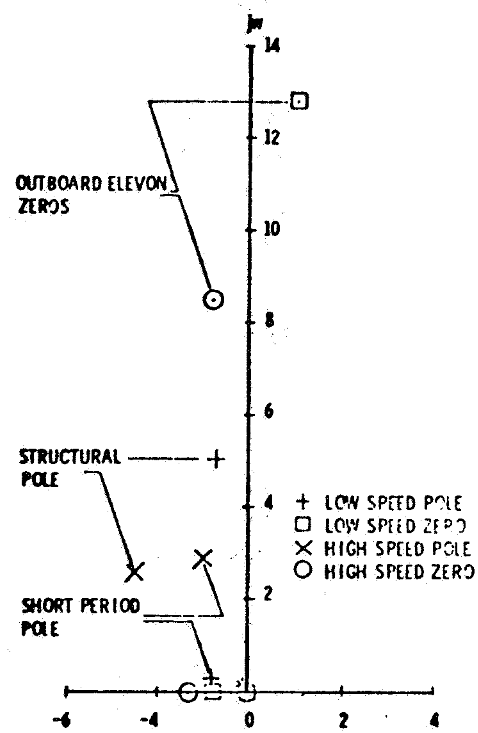


Figure 7.- Effect of speed on short period-structural coupling.

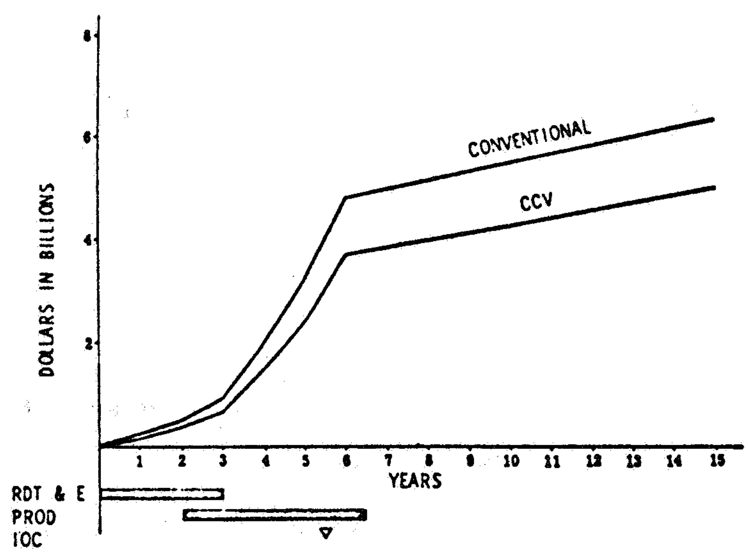


Figure 8.- Life cost comparison.



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