Aircraft Performance Benefits from Modern Control Systems Technology

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This paper discusses potential gains in airplane performance which may be offered by some applications of modern flight controls technology. The concepts examined include relaxation of inherent static stability, ride quality control, flutter margin control, and maneuver load control. A brief description of each concept, and examples of potential benefits in terms of weight and/or drag improvements, are included.

Introduction

IN conventional approaches to aircraft design, the flight control system is designed to meet specified handling requirements after the configuration is optimized to meet the mission performance requirements. The performance benefits which accrue by considering the control system design throughout the configuration studies are discussed in this paper. The approach employed to integrate control system design into aircraft design engineering, the discussion of control techniques and their impact on the design, and the performance benefits expected are elements of the paper.

Preliminary Design Approach

The conventional military airplane design process produces a configuration definition essentially as shown in Fig. 1. Military mission performance requirements such as takeoff, landing, payload/range, speed vs altitude, and endurance are assessed as the first step in establishing a new airplane configuration. Trade studies of these factors are performed and constraints applied to define a parametric airplane. This includes definition of the wing area, maximum weight, minimum weight, thrust, volume of the vehicle, etc. From this point, the propulsion, aerodynamic, and structural designs proceed, combining into a first configuration which is assessed for performance. This process is iterated several times to define a vehicle which meets all the specified mission performance requirements.

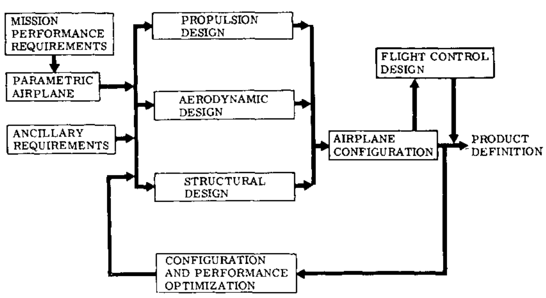

Fig. 1 Conventional airplane design cycle.

When the configuration is defined, the traditional approach then moves to system design. The various subsystem components are specified at this time. At this point, flight control design usually begins. If flight control is not considered from the outset in a design, the result can be an airplane with handling qualities which are somewhere between acceptable and unacceptable, rather than optimum. The airplane may have none of the favorable structural/aerodynamic interactions which are possible with modern control systems.

To meet the increasing demands of modern warfare, the weapons system designer presses for additional performance to obtain the needed edge for weapon system superiority. Therefore, airplane designers are building high lift/drag ratio wings, light but flexible structure, and minimum sized stabilizing surfaces. Trade studies to reduce weight, increase lift, decrease drag, and improve thrust and engine efficiency are as active today as at any point in the past. Structural, aerodynamic, and propulsion technologies are advancing and will continue to improve future aircraft.

Flight control design is an untapped area of technology for potential contribution to aircraft performance. Past applications have been to correct rigid body stability problems such as the use of yaw dampers to damp Dutch roll, thus allowing attainment of the full performance benefit of swept wings. The recently completed LAMS program proves that structural modes can be controlled to provide additional benefits in terms of structural performance, e.g., reduced fatigue damage rates during flight in turbulent air. Further

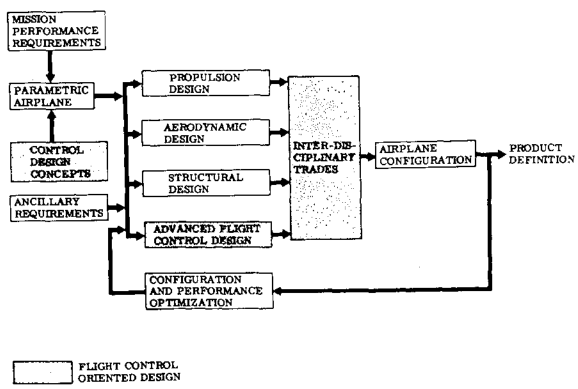

Fig. 2 Control oriented design cycle.

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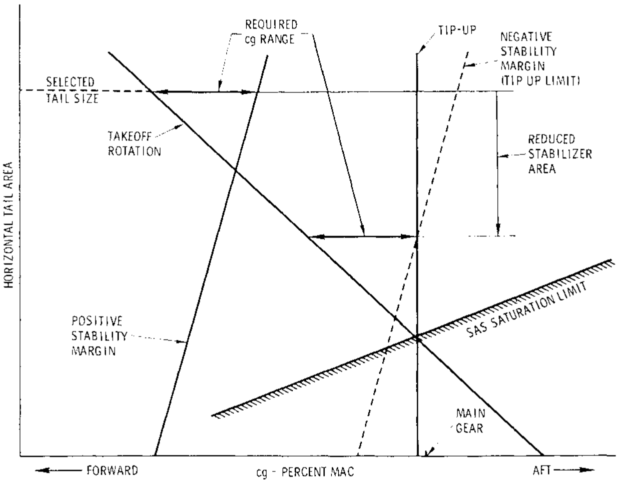

Fig. 3 **Horizontal tail sizing factors.**

information is contained in Report AFFDL-TR-68-158, "Aircraft Load Alleviation and Mode Stabilization (LAMS)," December 1968.

Current analytical studies predict even more significant advances in airplane performance through added dependence on the flight control system. Full benefit of modern flight control and design techniques can be obtained only if the airplane is initially configured using these advanced techniques. Retrofit can obtain only partial success.

The design method proposed in Fig. 2 capitalizes on the flight control potential through application of interdisciplinary trade evaluation considering advanced flight control concepts. The changes from the conventional design approach are shown by the shaded areas. Advanced control concepts are considered with the mission requirements to establish expanded bounds for the parametric airplane. Control system usage impacts the areas of propulsion, aerodynamics, and structures. Therefore, the advanced flight control design is shown associated with these elements. Configuration and performance optimization proceeds as in conventional design, resulting in an airplane configuration which may be unconventional.

Control Technology Concepts

A number of control technology concepts can be considered for application in the proposed design approach. Four examples are discussed below to indicate potential benefits. The concepts are 1) relaxation of inherent static stability, 2) ride quality control, 3) flutter margin control, and 4) maneuver load control.

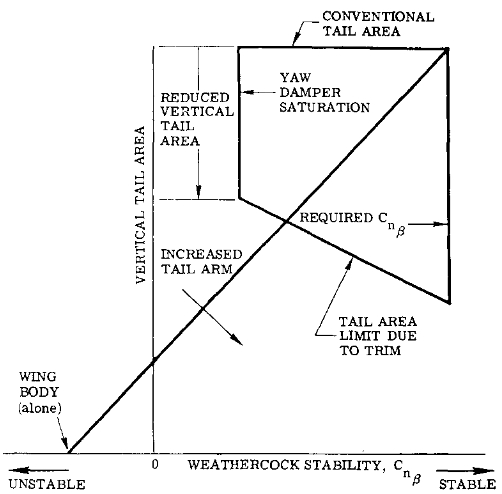

Fig. 4 **Vertical tail sizing factors.**

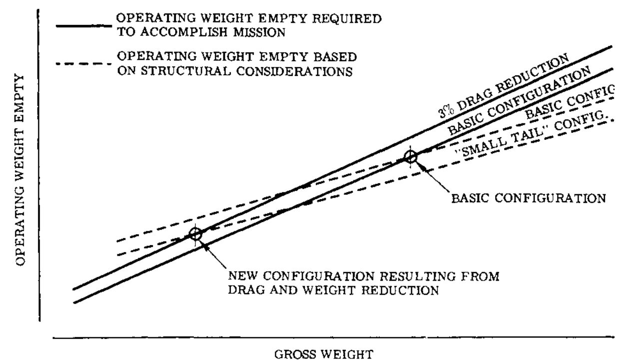

Fig. 5 **Weight benefits from relaxed static stability.**

Relaxation of Inherent Static Stability

A significant performance gain is achieved if horizontal tail size is reduced and longitudinal stability regained by augmentation. The minimum acceptable tail size is that required to provide adequate trim throughout the flight envelope, and to assure that the pitch stability augmentation system (SAS) does not saturate in any anticipated level of turbulence. The horizontal tail size is a function of the tail power required to rotate the airplane for takeoff. At more forward c.g., the tail power required for rotation increases, and hence the tail size must increase.

Although every airplane design has different tail sizing criteria, parameters usually involved in horizontal tail sizing for conventional aircraft are shown in Fig. 3. The position of the main landing gear is indicated as a fraction of the mean aerodynamic chord (MAC). The final tail size and the final value of forward c.g. are a compromise in conventional airplane design. To achieve a useful c.g. range, the tail size and the stability margin must both be considered. The required c.g. range fixes the tail size if a specified static stability margin is to be maintained. The horizontal tail size may be reduced while retaining a fixed c.g. range by moving the aft limit of the required c.g. range back to the tip-up limit (just ahead of the main gear). The resulting negative stability margin must then be compensated for by stability augmentation.

For a given tail arm, the vertical tail area required for conventional airplanes may be set by specifying a value for the weathercock stability derivative $C_{n\beta}$ as shown in Fig. 4. By using a yaw SAS, the vertical tail area may be reduced to a minimum size determined by trim requirements and yaw SAS saturation limits.

For a conventional bomber aircraft, the horizontal and vertical tail may comprise 6% of the airplane structural weight (engines excluded). If tail size could be reduced to 50% of conventional values, the potential structural weight benefit would be more than 3%, because additional weight benefits will accrue through lighter aft fuselage structure. Since gross weight to structural weight ratios approach the value of 3 for modern long range aircraft, a savings of 3% in structural weight may easily mean savings of 10% in gross

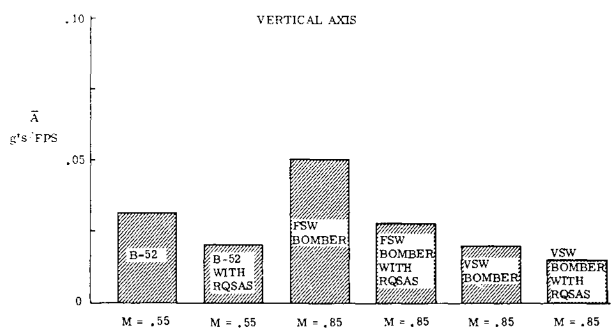

Fig. 6 **Ride quality control benefits.**

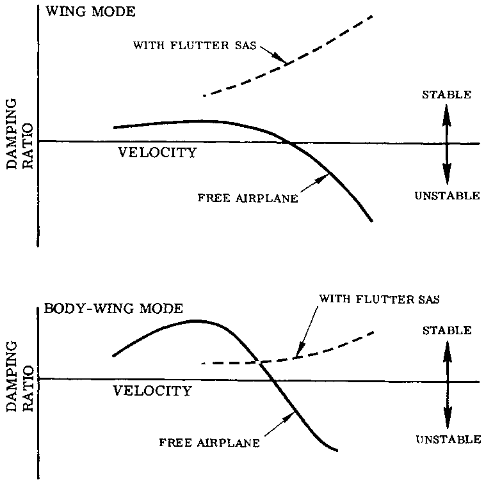

Fig. 7 Flutter margin control.

weight. Over-all airplane drag is also reduced by perhaps 3%. Combined drag and weight benefits are illustrated in Fig. 5.

For a conventional subsonic bomber such as the B-52, it is estimated that the horizontal tail size could be reduced from 900 ft^2 to 500 ft^2 by moving the c.g. aft to the neutral point and relying on the stability augmentation system to restore static stability. Assuming the vertical tail size can be reduced proportionately, the reduction in tail areas represents about 3% drag reduction, and 9% reduction in operating weight empty (16,000 lb). This is equivalent to an 11% reduction in gross weight (53,000 lb) to perform the same mission.

Ride Quality Control

Modern control system technology has more direct bearing on airplane configuration in some instances. For example, if an airplane has a high-speed low-altitude mission requirement, the proper application of control technology to improve the airplane ride quality will yield a wider range of satisfactory configurations. Ride control may allow a fixed-sweep-wing airplane to accomplish the mission that only a variable-sweep-wing airplane could do without ride control SAS. A typical example of the ride quality improvement available through a ride control SAS is shown in Fig. 6.

Flutter Margin Control

A structural mode SAS may be considered for control of flutter margin. Data typical of a large supersonic vehicle are shown in Fig. 7. Considerable effort is required to achieve these benefits at a lesser weight than that of the equivalent required stiffness structure. However, in a properly integrated design, flutter control is accomplished through control surfaces already incorporated for other functions, thus minimizing the flutter SAS weight penalty. Gross weight benefits of 2–5% could result for a large supersonic airplane.

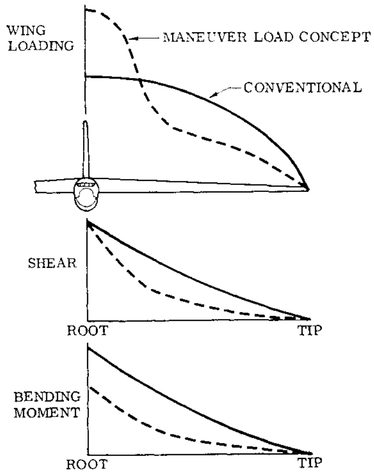

Fig. 8 Maneuver load control concept.

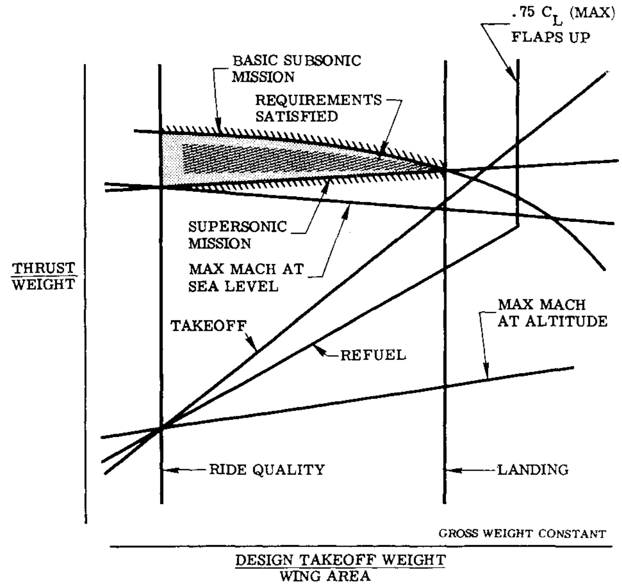

Fig. 9 Airframe and engine matching.

Maneuver Load Control

Maneuver load control may be considered as a design element to save airplane weight by reducing wing-root bending moment during pullup. The pilot must be able to pull g's to maneuver the airplane; however, the way the load is distributed on the wing makes a measureable difference in bending moment. In Fig. 8, two wing-loading patterns are presented and each will develop the commanded 1-g increment. The method allowing the inboard wing to accept the greatest load provides a wing-root bending reduction of 30% which corresponds to a potential gross weight benefit of about 2% for a B-52 type airplane. In many airplanes, the wing structure is sized by the maneuvering requirement and reduced bending moment can result in reduced wing weight.

Conclusion

In conclusion, the application of modern controls technology can expand the range of possible successful airplane designs by reducing weight and drag. A typical airframe/engine matching plot answering a specific set of ground rules is presented in Fig. 9.

The application of controls technology opens up the area of possible airplane designs by raising the "basic subsonic mission" line, by lowering the "supersonic mission" line, and by moving the "ride quality" line to the left.

The envelope of possible successful designs is opened by reducing stabilizing surfaces to an absolute minimum size through control provided stability augmentation, by relieving wing-root bending moments through maneuver load control, and by using active flutter mode stabilization to replace stiffness structure. Ride quality is achieved by incorporating a ride control SAS.

Airplane designs that employ advanced control techniques throughout configuration exercises will demonstrate the benefits to be obtained from greater dependence on the flight control system. 15–25% gross weight reductions are probably achievable, but such benefits may not be easily obtained. The configuration benefit is sensitive to design criteria and will vary according to the kind of airplane being designed and the mission assigned. Only an intensive interdisciplinary effort will yield maximum benefits.

Building airplanes using modern control system concepts as previously discussed, requires significant improvement in flight control reliability. The reliability required is expected to advance to meet the need as industry recognizes the performance to be gained by the approach. To date, however, lack of flight-verified systems has precluded acceptance of these advanced concepts. Only a vigorous developmental effort, leading to flight test demonstrations, can give the aircraft designer the confidence he needs to apply these ideas.

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Pilot and Aircraft Augmentation on the C-5

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The C-5 military transport is typical of the new generation of transports. The gross weight, large pitch, yaw inertia, and low landing speed present new problems. These problem areas are alleviated by an augmentation system, designed to improve the handling qualities of the C-5. The C-5 pilots were able to log more than 500 hr on a simulator before the first flight. This simulator was a valuable assist in the analysis and design of the augmentation systems.

Introduction

THE pilots who flew the giant C-5 on its first series of test flights were not surprised when they found it a pleasant aircraft to fly because they had already flown it 500 hr on a C-5 simulator. Described in this article are some of the approaches (both simulation and actual) used in testing a modern transport, in this case the C-5. Also discussed is the major role augmentation plays in improving the handling qualities of large aircraft.

Built by Lockheed-Georgia (with a triple-redundant augmentation system provided by Honeywell), the C-5 is typical of the new transports in which the mass has been concentrated in the fuselage to accommodate the payload. Intended for long hauls, large loads and improved economy, it has a maximum gross weight of 764,500 lb and can carry a payload of over 100 tons. Cruising at 440 knots, it has a range of up to 6000 miles, depending on the payload. Because it must be able to land on short unimproved fields, the C-5 has high lift, flaps, slats, and a low landing speed. In addition, it has a landing gear with 28 wheels, four of which are on the nose gear and six on each of the four main bogies.

C-5 Characteristics

The C-5 is representative of a new class of aircraft in which the mass concentration causes the yaw and pitch inertia to be over six times the inertia for a conventional transport. This increased inertia requires large surfaces to provide the necessary control power and handling qualities at low speed. With the very low approach speeds, the aerodynamic forces are small and the control effectiveness is reduced. The static directional stability is also reduced at low speeds so that the turn coordination is poor. Many aircraft exhibit poor coordination at low speeds, but in this case the difference in yaw inertia tends to aggravate the problem.

The increased pitch inertia in the pitch axis contributes to a lower pitch frequency and thus the requirement for pitch rate feedback in the pitch augmentation. The C-5 has rather high short-period damping ratios but the short-period frequency is close to the phugoid (long-period motion). As a consequence, the two frequencies interact and what starts out as a short-period response ends up after a few seconds in a phugoid oscillation. This phugoid is easy to control but is disconcerting to the pilot in that it gives him the impression that the aircraft is hard to trim, or that it is wandering about about a trim point. This phugoid action is also present, to a certain extent, on the glide path approach where the pilot prefers a more positive pitch response.

Preliminary Analysis

Several agencies, including NASA Ames, Cornell Labs., and the research group at Wright-Patterson have conducted studies on these problem areas. Flight test and simulator studies have been used to predict the handling qualities of large aircraft at low landing speeds (Refs. 1 and 2). These studies predicted that with proper augmentation the handling qualities would be satisfactory at the low approach speeds. Their predictions on the need for improvement in Dutch-roll damping, turn coordination, and spiral stability were very worthwhile. The importance of flight path response, the need for new handling qualities criteria, and the importance of the phugoid motion were verified on a C-5 simulator and flight test studies.

Using this simulator, augmentation configurations were evaluated early in the C-5 autopilot design. This cockpit simulator, in conjunction with analog and digital computers, video display, and audio simulation, provided a more realistic evaluation of the system. The cockpit was free to move in pitch and roll with additional motion to simulate the contact with the runway. The moving belt camera and the video display in the cockpit gave a visual display of the terrain. Either a 3-degree-of-freedom or a 6-degree-of-freedom simulation was used depending on the nature of the problem. As the pilot commanded new attitudes or throttle settings, the computers provided the proper aerodynamic effects, instrument readings and change in display. Various augmentation configurations were flown on the simulator to obtain pilot comments and evaluate system operation. A typical simulation is described in the following paragraphs.

For a takeoff weight of 450,000 lb and a center of gravity at 29%, flaps extended, the pilot trims the stabilizer for climb. The throttles are advanced to 100% normal rated thrust, and, as the airplane accelerates down the runway, the nose gear is used to steer to the centerline of the runway. At 90

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