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Integrated Flight and Propulsion Controls for Advanced Aircraft Configurations

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Abstract

The research vision of the NASA Lewis Research Center in the area of integrated flight and propulsion controls technologies is described. In particular the Integrated Method for Propulsion and Airframe Controls developed at the Lewis Research Center is described including its application to an advanced aircraft configuration. Additionally, future research directions in integrated controls are described.

Introduction

The research vision at the NASA Lewis Research Center in the area of integrated flight and propulsion controls(IFPC)technologies is to perform high-payoff research that is focused on the critical needs of our customers, is collaborative with our industry and university partners and includes mechanisms for effective technology transfer. The technology of integrated flight/propulsion controls is required when aircraft configurations exhibit significant levels of coupling between the airframe and propulsion systems. Recognizing that advanced configurations, such as high performance military aircraft, Single Stage to Orbit vehicles, the High Speed Civil Transport, and powered lift vehicles, would exhibit significant coupling, researchers began to develop methods for designing controls that would adequately address this coupling. Coupling can be addressed by looking at either the "inner loop" of the IFPC, generally associated with basic airframe and engine stability and limit protection, and the "outer loop" of the IFPC, generally associated with the distribution of effector power to achieve desired aircraft characteristics and capabilities.

The first significant attempt at an advanced method for designing integrated controls was the USAF Design Methods for Integrated Controls (DMICS) Program. Two separate approaches, one based upon centralized design[1], and one based upon a partitioned design approach[2], were developed and applied to an F18 configuration. Subsequently, the partitioned DMICS approach was applied in the US/UK joint powered lift program. Here the target application aircraft was a modified F16, called the E7D, for short takeoff and vertical landing (STOVL) capability. The modifications included a delta wing configuration, an ejector thrust system, a ventral nozzle, and a reaction control system (RCS). Designs were completed for a hover task and evaluated by fixed based, piloted simulation with good results[3]. A second application of the partitioned DMICS approach, with some modification, was applied to a mixed-flow vectored thrust STOVL configuration. Again fixed-based piloted simulations were accomplished[4].

NASA Lewis has taken the first generation DMICS technology and extracted the benefits of the centralized design and the partitioned approaches and combined them into an advanced, or second generation approach for integrated control design, improving upon the limitations of the DMICS approaches. The technology is called Integrated Methodology for Propulsion/Airframe Control[5] (IMPAC). This paper will describe the IMPAC method and other research conducted in support of the development of this technology. Secondly, this paper will discuss the vision of the IFPC team at NASA Lewis for future research in integrated controls.

IMPAC

A flowchart of the IMPAC design approach is shown in Figure 1. The major IMPAC design steps are (1) Generation of integrated airframe/engine models for control design; (2) Centralized control design considering the airframe and engine system as an integrated system; (3) Partitioning of the centralized controller into separate airframe and engine subcontrollers; (4) Operational flight envelope expansion through scheduling of the partitioned subcontrollers; (5) Nonlinear design such as incorporation of limit logic for operational safety; and (6) Full system controller assembly and evaluation. These design steps are briefly described in the following. A detailed description of the methodology is available in Ref. [5].

Given that integrated, nonlinear dynamic models for the system are available, the first task in the IMPAC design methodology involves generation of dynamic models to be used for control law synthesis (Block 1). These control design models are, in general, traditional linear perturbation models of the system taken at various operating points. An important issue in a centralized linear IFPC design approach is how nonlinearities of subsystems (e.g., propulsion system) will effect the validity of the centralized linear control law synthesis. Therefore, some "conditioning" of the control design models, based on nonlinear effects and control design requirements, will be required to obtain state-space dynamic models of the integrated system that will allow a "realistic" centralized control design.

The centralized control design process (Block 2) uses the full system state-space linear control design models previously developed and is based on available multivariable linear control design techniques that have the capability to meet the IFPC requirements, for example H_∞ based control synthesis techniques [6]. Design criteria formulated from system performance requirements and system open-loop dynamic studies provide the necessary control design specifications (e.g., frequency or time dependent weighting factors) for the chosen linear design technique. Because the linear control law synthesis tool may result in a high order centralized controller, controller order reduction may be performed at this point in the method. The result of this process is an operating point specific, centralized linear feedback controller for the integrated system.

Once an acceptable centralized controller is designed, it is partitioned into decentralized subcontrollers (Block 3) using mathematical techniques that have been developed, see for example Ref. [7]. The controller partitioning task requires that a candidate control structure for the partitioned system be specified. For example, for the IFPC problem the assumed control structure is hierarchical with the airframe (flight) control partition exercising some authority over the propulsion control partition. Comparisons between the centralized and partitioned linear controllers are made to validate the partitioning results as well as acceptability of the chosen decentralized control structure. The result of the controller partitioning task is a set of linear subcontrollers which match the performance and robustness characteristics of the centralized controller to a specified tolerance.

After completion of the operating point specific linear partitioned subsystem control design, detailed individual subsystem nonlinear control design must be performed. The first step in the nonlinear control design involves extension of the individual subsystem controllers to full envelope operation (Block 4) as defined by the system requirements. Typically this would involve gain scheduling of individual operating point subcontrollers to account for parameter variations due to change in operating conditions. It is envisioned that use of modern robust control synthesis tools to perform the linear control design tasks will reduce the complexity of controller scheduling.

The second subsystem nonlinear control design task (Block 5) involves accounting for the effects of any additional subsystem nonlinearities such as propulsion system safety limits. For example, the propulsion system would require exhaust nozzle area control limit logic to ensure that engine surge margins are maintained. After the appropriate nonlinear control loops have been designed, the subcontrollers can be validated using the subsystem dynamic models. The result of this task is the nonlinear limit and accommodation logic to be added to the full envelope subsystem controllers.

The final task in the IMPAC design approach is reassembly of the full envelope, nonlinear subsystem controllers to form the closed-loop integrated system. Evaluations of the final IFPC design can then be performed using nonrealtime simulations as well as pilot-in-the-loop (PITL) simulations. These evaluations would test the actual system performance (e.g., handling qualities) against the desired system performance specifications.

As with any design process, achieving acceptable control design using the IMPAC methodology will involve iterations through the various design steps. However, the strength of the IMPAC approach is that it considers the complete integrated system at each design step and provides the designer the means to systematically assess the level of integrated system performance degradation in going from one step to the other. The control designer can then make some "intelligent" trade-offs between controller complexity and achieved performance at each design step, thus reducing the number and severity of the design iterations.

STOVL IFPC Design

IMPAC has been applied to the design of an IFPC for the E7D STOVL configuration[8]. This configuration is shown in Figure 2. The emphasis has been a design for the transition mode of flight with a piloted, fixed based evaluation of the approach.

Figure 3 is a block diagram of the full integrated flight and propulsion control system. The main elements of the IFPC system are briefly described in the following. The airframe control subsystem consists of the following four main sections: the pilot gradients and command limiting, the lateral controller and limit logic blocks, the longitudinal measurement blending, controller and limit logic blocks, and the airframe trim schedules. The pilot gradient and command limiting block provides rate and range limits and scales the pilot effectors to appropriately sized commands. The resulting commands are then passed to both the lateral and longitudinal controllers. The lateral control system maintains closed-loop control of roll rate, yaw rate and the sideslip angle using the ailerons, rudder, and roll and yaw RCS. The longitudinal control system maintains closed-loop control of pitch angle and rate, forward velocity and acceleration, and the flight path angle using the elevons, aft nozzle angle, ventral nozzle angle, pitch RCS, and thrust from the aft and ventral nozzles and the ejectors. The trim schedules provide the nominal steady state operating point information for all of the actuators, including the nominal thrust values. The limit protection scheme bounds the hard actuator limits for both the lateral and longitudinal controllers and provides limit information back to the nominal controllers to prevent integrator windup and to maintain closed-loop stability while trying to maintain closed-loop performance.

The engine control subsystem acts on thrust commands from the longitudinal control system. The airframe trim schedules also provide thrust trim commands and gain scheduling variables to the engine subcontroller. The engine subcontroller consists of the following four main sections: the fan speed schedule, the nominal engine controller, the safety and actuator limit logic, and the thrust estimator. The fan speed is scheduled as a function of the total commanded thrust. The nominal engine controller maintains closed-loop control over fan speed and the three estimated engine thrusts (aft and ventral nozzles and ejectors). While fan speed is measured directly, a measure of actual engine thrust is not available, so a nonlinear static model of the engine provides estimates of the engine thrusts given the available engine information. The engine achieves the closed-loop control by manipulating the fuel flow, the ejector butterfly valve position, and the aft and ventral nozzle areas. The engine limit logic contains actuator rate and range bounds and operational limits for the engine, consisting of the accel/decel fuel flow limits, the fan stall margin, minimum burner pressure, and fan rotor overspeed. Limit information is fed back to the nominal control system to maintain stability during limit conditions. A second version of the thrust estimator is used to calculate thrust bounds based on the engine accel/decel schedule. These thrust bounds are fed back to the longitudinal controller actuator limit block to provide thrust command limits for the longitudinal controller.

In order to evaluate the performance of the integrated control design, a piloted simulation was performed on the fixed base flight simulator[9]. The major objectives of the piloted evaluation were to assess controllability, performance and workload during a series of four flight scenarios. The four scenarios included a vertical tracking task, a combined longitudinal and lateral tracking task, an abort sequence, and a general maneuverability sequence. For the tracking tasks the pilot's objective was to maintain precise control of the flight path symbol by overlaying it on a ghost guidance symbol which is programmed to fly an optimal trajectory to a simulated landing. For the abort sequence and general maneuverability tasks, the pilot's objective was to assess the controllability and predictability of the aircraft response during excessive excursions from the nominal flight path.

Two pilots, one with V/STOL and powered-lift aircraft experience, and the other with extensive fighter aircraft experience, performed piloted, fixed-based simulation evaluations of the IMPAC design. Example aircraft response time histories for the vertical and combined tracking tasks are shown in figures 4 and 5, respectively. As seen from Figure 4, the IFPC design tightly acceleration and velocity commands. the flightpath command is also tracked well, although there is some delay in response due to control communication delays. There is some initial pitch deviation due to deceleration command which the pilots felt could be bothersome in instrument flight. The results in Figure 5 also show tight tracking of the velocity command as well as the bank angle and heading commands. The very small sideslip response indicates good turn coordination which will result in significant reduction in pilot workload.

The pilot comments revealed good vertical flightpath tracking with excellent decoupling from velocity and lateral response. Also, the comments reflected a good capability to maintain steady deceleration while tracking the ghost symbol to a simulated landing. The pilots could successfully perform abort sequences and large maneuverability changes without loss of control predictability or excessive workload. There did exist, however, uncommanded pitch deviations due to coupling with flightpath and acceleration commands. These pitch deviations could become objectionable in moving base simulation and indicated a need for better pitch regulation in the integrated control design. Some pitch deviations occurred due to coupling of pitch and deceleration commands caused by actuator saturations from the engine control. Overall, the integrated control design gave successful performance in its first piloted simulation of the STOVL maneuvers, and this study assisted in revealing improvements for an integrated control redesign.

Current and Future Directions

Currently, the NASA Lewis IFPC program is progressing on three fronts. First, we are continuing to develop the IMPAC method by additional research into the application of genetic search algorithms to integrated control. Here the idea is to apply genetic approaches to improve the partitioning phase of the design by improving the optimization approach.

Second, we are emphasizing transfer of the basic technologies demonstrated in the IMPAC STOVL application to the private sector. These specifically include the H Infinity design experience gained, some new and effective ways to handle integrator windup and actuator saturation in multivariable systems, and the IMPAC method itself.

Third, we are beginning a program to develop a software based tool that will embody the IMPAC philosophy for integrated controls design. It is the vision that this software package will establish an architecture that will not only encompass the IMPAC approach but also will include other design methods that have been proposed for application to integrated controls design. For example, NASA Langley has developed excellent tools for the automated design of flight control systems. These tools are based upon several years of research in areas such as Direct Eigenvalue assignment[10], and Stochastic Optimization Feedback/Feedforward Technology (SOFFT)[11]. These technologies, particularly SOFFT, could be used within the IMPAC framework to perform the centralized design and potentially the partitioning phases, or in a stand alone mode for flight controls. Finally, it is believed that a careful architecture definition and the availability of embedded expert design advice would make such a software design tool a powerful and extremely useful capability. This would establish a de facto standard to help focus future integrated controls tools and methods development for maximum impact at minimum investment.

In the future, we see three important needs in the area of integrated controls. The first, as already discussed, would be the completion of a prototype software design capability for integrated controls. It is obviously highly desirable that this design capability reduce design process time and yield much more robust control designs. Additionally, and perhaps more importantly in the long run, such a design capability should enable a new level of interaction between advanced configuration designers and flight/propulsion subsystem specialists. In the future, advanced configurations could begin to emerge that exploit high degrees of coupling, enabled by robust IFPC. It is the opinion of the authors that the past practice in advanced designs resulted in compromised designs that avoided coupling. This was an admission that in the past it was too difficult or too complex to perform successful integrated designs. Such a new capability would free the advanced designer to look for and achieve potentially radical designs that would represent significant improvements in performance.

Second, there is a need for a successful, full scale, flight demonstration of the payoff of an integrated controls design on an advanced configuration. Such a demonstration is an expensive proposition and will undoubtedly require the resources of more that a single organization resulting in a cooperative program of national or international scope.

Thirdly, the IMPAC method has been successfully applied to the "inner loop" control design problem. The next step will be to modify the approach to enable highly successful "outer loop" control system designs. This will enable the designer to attack both aspects of a complete integrated flight/propulsion control system.

Concluding Remarks

NASA Lewis Research Center (LeRC) researchers have developed a second generation integrated controls design methodology and demonstrated the methodology through integrated flight/propulsion control design for a complex Short Take-Off and Vertical Landing aircraft configuration. Current integrated controls activities at LeRC include transfer of the integrated controls technologies to the aerospace industry through contracted programs, further development of the methodology through in-house and sponsored research at universities, and development of a computer aided software design tool for integrated control system design. It is envisioned that these activities will result in industry acceptance of the advanced integrated control design techniques and will allow for radical new aerospace vehicle designs that represent significant performance improvements over current configurations.

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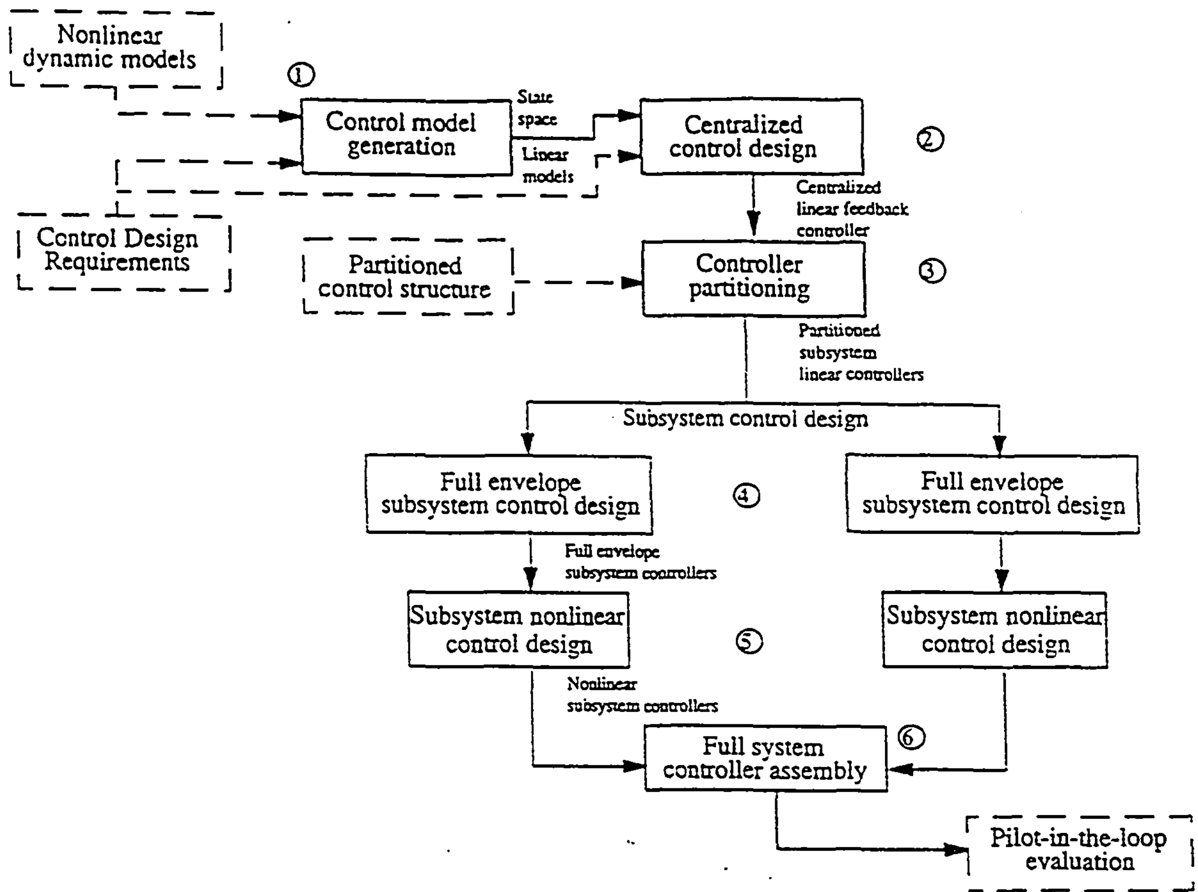

Figure 1.–IMPAC Flowchart.

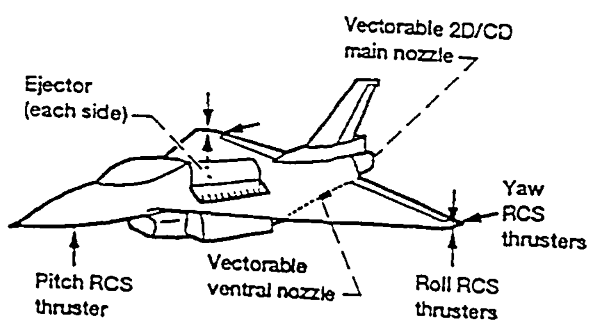

Figure 2.–E7D Aircraft Configuration.

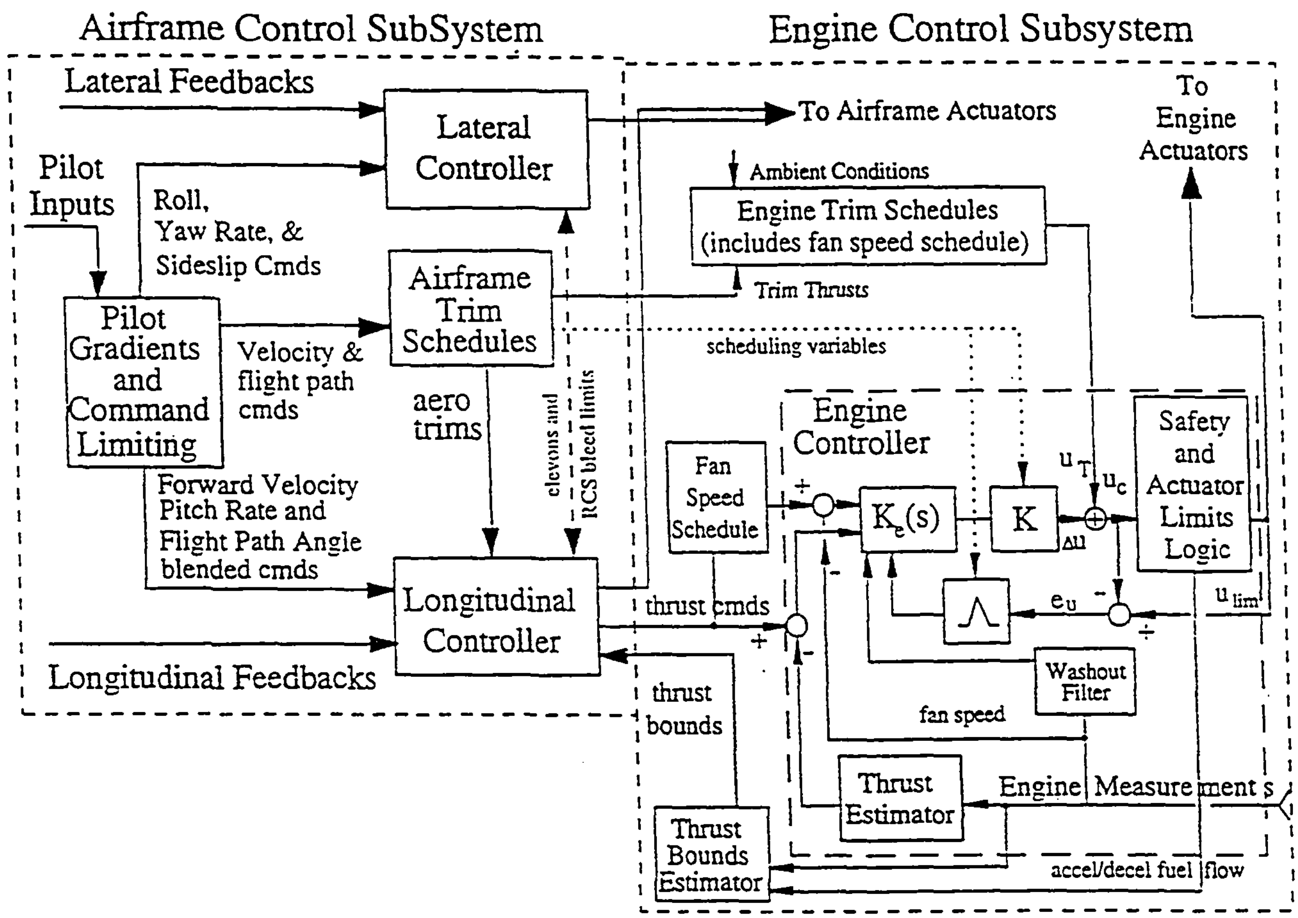

Figure 3.–Partitioned, Integrated Controller with Details of Engine Controller.

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ADVANCED CONTROLS
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PILOTED SIMULATION RESULTS

- Vertical Tracking Task

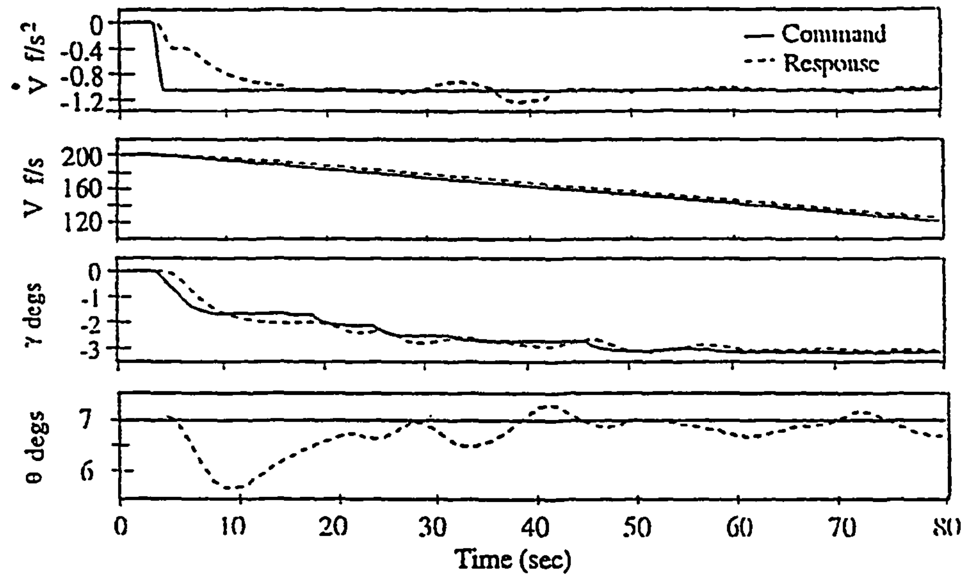

Figure 4.–Example Time Histories for Vertical Tracking Task.

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PILOTED SIMULATION RESULTS (contd.)

- Combined Vertical and Lateral Tracking Task

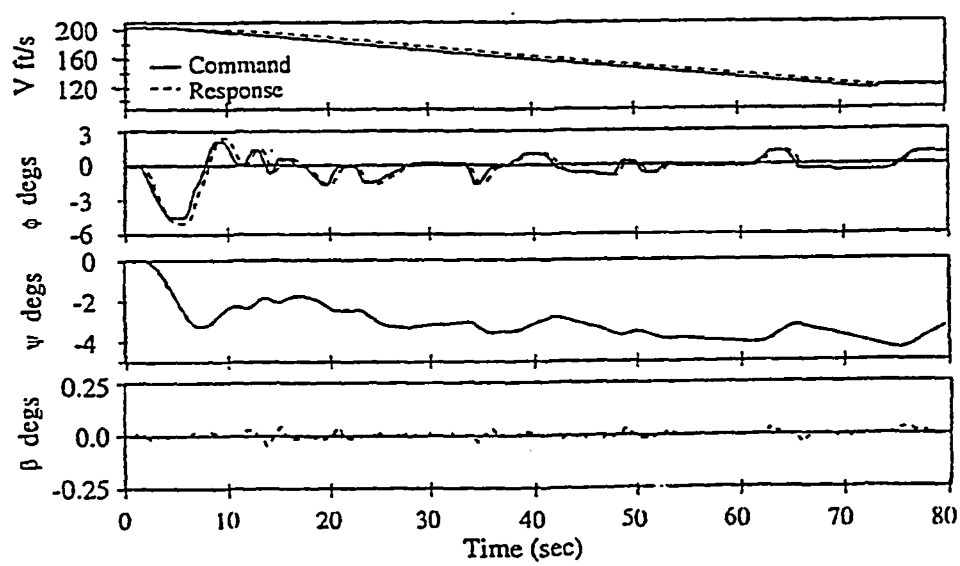

Figure 5.–Example Time Histories for Combined Tracking Task.

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