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Functional Digital Aircraft: Designing Flight Controls

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Abstract:

The value of performing full aircraft simulations for ground, taxi, takeoff, and landing maneuvers with ADAMS/Aircraft has already been demonstrated. The critical design information, such as detailed landing gear characteristics, runway profiles, tire characteristics, and overall aircraft information including weight, cg, and flexibility, has been provided for in the ADAMS/Aircraft environment. This general framework can be used as a starting point to understand design issues for performing in-flight maneuvers, such as approach, climb, cruise, and general maneuvering. For flight maneuvers, the design and analysis of the mechanical components that control and stabilize the aircraft are critical. This paper addresses the overall issues with developing a flight controls module to fit within the ADAMS/Aircraft framework. Comparisons are made to the ground test process used in certification, as well as design tools that are used to assess flying qualities and flight controls mechanism performance. Relevant previous work with flight controls is cited and plans for further work are presented.

I. Background

Business issues surrounding the desire to reduce physical prototypes and physical tests have driven the automotive industry to adopt virtual prototyping tools. The ADAMS/Car product line was developed in conjunction with a consortium of automobile manufacturers to provide the ultimate virtual prototyping environment to explore performance, durability, vibration, and other design issues [1]. The ADAMS/Car software can also be viewed as a set of software tools that can be adopted to other industry processes.

ADAMS/Aircraft – Landing Gear was developed using the ADAMS/Car software as a starting point, taking advantage of the system design hierarchy, design database, user modes, and other features of ADAMS/Car [2]. Now with the release of ADAMS/Aircraft – Landing Gear, additional system level aircraft modeling is available [3]. This new modeling environment can be expanded beyond the ground, takeoff, and landing modes to encompass flight modes as well.

Many of the elements required for a flight controls design environment have been developed and proven. The impetus behind this previous work was to solve specific design problems. This previous work is now revisited with the goal of defining and assembling a complete environment for design flight control systems.

In this paper, the current design issues where ADAMS has been used are first discussed. These design issues form the basis for considering virtual prototyping tools in flight controls development. Next, some of the current testbeds for flight controls development are discussed. These testbeds provide value in the current development processes, but were not developed with the current power of virtual prototyping tools. Supplementing or simplifying these testbeds provides ample economic justification for the development of specialized virtual tools.

Finally, some of the elements of a flight controls design environment are discussed. These elements, when constructed in the same environment as landing gear and airframes, will provide a complete environment for designing the mechanical aspects of flight controls and testing a complete aircraft through flight maneuvers. Accurate flight dynamic loads can then be predicted and mechanism design issues that effect aircraft flying qualities and overall safety can be addressed *before* building physical prototypes.

II. Current Design Issues

This section presents five current flight controls design issues that can be addressed with virtual prototyping. Each of these issues has been addressed in some form with ADAMS tools.

1. Flap and Slat design

Flaps and slats are required to improve the aircraft lift at lower airspeeds found during takeoff and landing. Typical design configurations for flaps and slats include a control surface, drive mechanism, and guide mechanisms in the form of either a track or a linkage.

Flap and slat surfaces need to be rigid enough to retain their characteristic shape under aerodynamic load, but also lightweight to keep within the overall aircraft weight budget. The combination of high, variable aerodynamic loads and structural flexibility causes design problems in the guide track and/or linkage. The drive mechanism needs to be sized to handle variable loads due to aerodynamics, flexibility, and friction and binding in the track and linkage.

Data required for determining a correct flap and slat design includes:

- track shape
- aerodynamic surface shape and stiffness
- aerodynamic loading
- roller configuration
- drive mechanism configuration

Clearly, this data is contained within different design tools such as CAD, FEA, CFD (or wind tunnel data), and kinematic analysis tools. Virtual prototyping with ADAMS can bring this information together into a single design environment where tradeoffs between surface flexibility, track shape, and drive system authority and configuration can be explored.

A recent example of how ADAMS can be used in assessing these same tradeoffs is given in the SOFIA scientific aircraft door study. [4]

2. Mechanical components effect on flying qualities

The flying qualities of an aircraft are determined by a number of design parameters, primarily involving the weight, center-of-gravity location, center-of-pressure, and aerodynamic coefficients. Secondary but very important effects are also determined by the control systems themselves. With a conventional mechanically controlled actuation system for the primary controls, aircraft cables are an efficient means of transmission of control loads over long distances.

The mechanical characteristics of the cables, pulleys, and connecting mechanisms can influence how the pilot feels the aircraft response. Closed loop flight control cables must be kept in a preload condition over differential thermal expansion/contraction, cabin pressurization effects, and structural deflection. Also, the handling qualities of an otherwise excellent airplane can become completely unacceptable due to excessive friction in the cable/pulley system. [5]
So design decisions made based on packaging the actuation system through the aircraft structure can adversely effect the flying qualities.

3. Dynamic loads

The aircraft structural design process at many aircraft companies currently is based on the reduction of dynamic loads to a set of static loads. These static loads can then be used for element sizing and aircraft structural testing.

Typically, an aircraft is balanced in a flight configuration with aerodynamic loading and “g” loading associated with the maneuver. Worst case maneuver conditions are chosen to obtain a conservative load case, and historical factors of safety are applied for design confidence. This balanced set of loads is then reduced to a set of static loads for stress recovery and structural testing.

Although this approach has many merits, including most importantly the requirements of the FAA for certification through this approach, there are some drawbacks. A full aircraft multi-body model can provide the advantage of dynamic loads, including local inertial effects, through a complete maneuver sequence. This is increasingly important in high performance or highly reconfigurable aircraft such as the V-22 Osprey. Through this approach, worst case conditions can be found on a component basis and all structural elements can be sized consistently.

The calculation of full aircraft dynamic loads during a maneuver requires a full set of aerodynamic loading, structural stiffnesses of key components, a multibody model of the control surfaces, and the maneuver path.

4. Nonlinear control effects

Flutter is an aerodynamically induced vibration of a control surface that can quickly destroy the supporting structure. Flutter can be explored as a coupling between a linear structure and the aerodynamics of the surface with linear structural analysis tools. However, flutter-like phenomena can also occur with control surface deadband and slop effects that linear structural analysis tools cannot model effectively.

Detailed design and subsystem test information is required to assess nonlinear control effects. Also, these effects may not be noticed until system integration or some amount of flight testing. They can also occur from manufacturing tolerances or component wear.

5. Safety issues

A final example of a flight control design issue that can be addressed with virtual prototyping involves the safety certification. FAR and JAR regulations require that a pilot can safely land an aircraft even if there is a failure to a primary control system component. An example is an aileron cable failure. If an aileron cable snaps, the pilot must be able to control the plane effectively with the residual aileron control, plus rudder and elevator control.

The analysis of the aircraft flying qualities during and after a failure requires a thorough knowledge of the airplane design. A major aircraft manufacturer has used ADAMS to assess the controllability of an aircraft after cable snap, using aircraft design information. This analysis resulted in design changes to improve the pilot authority in this particular failure mode. Furthermore, the failure mode and design changes were validated with ground testing.

III. User Processes

Four traditional testbeds for developing aircraft flight controls are discussed in this section. These methods are used to understand and characterize the flight control system during development. Years ago, a co-worker at McDonnell Douglas told me that the company was in the business of making “paper airplanes”. The airplane was conceived on paper, designed on paper, and thoroughly analyzed on paper. Many of the processes for aircraft design were built around a “paper trail”. Now we can conceive of many of these same processes as automated, and can discuss a “virtual airplane”, one that is conceived, designed, and analyzed in the computer.

This section explores the key existing flight controls processes and how they might better be integrated into the functional digital aircraft concept.

1. Stability and Control Conceptual Testbed

During the conceptual design phase, aircraft models are developed and simulated to gain an understanding of the basic stability and control requirements. This analysis is typically done with preliminary design data using limited fidelity models, running in a workstation stand-alone environment.

This conceptual analysis has the benefit of setting some of the basic design parameters for the overall aircraft, such as takeoff, landing, cruise, and maneuver performance. This conceptual analysis has the limitation of providing only data output, and does not allow a pilot to interactively fly the aircraft. Also, this analysis does not provide much detail in the mechanical properties of the control subsystems.

2. Flying Qualities Testbed

During the preliminary and detailed design phase, once the basic aircraft attributes are well understood, decisions are required to support how well the aircraft handles. At this point in the development process, it is helpful to have a pilot-in-the-loop testbed that can allow tradeoffs to be made that effect the flying qualities.

A typical flying quality testbed might simulate the aircraft dynamic behavior, including aerodynamics information, and project the aircraft response on a video screen, along with gauge and dial readouts. The pilot interacts with the testbed through realistic flight control physical mockups. The control stick effect on the aircraft response is simulated through a combination of hardware mockup and simulation. Through this testbed, design parameters such as maximum allowed cable windup and maximum allowable friction can be tested and specified.

3. Control Mechanism Testbed– “Iron Bird”

During the design validation phase, and usually in parallel with building the first flight test article, a control mechanism testbed, sometimes called the “iron bird”, is assembled. This testbed provides a system level checkout of hydraulic and electrical demands to actuate the control surfaces. Typically, dummy loads are applied to the actuators to simulate flight conditions.

The construction of the iron bird is time consuming and costly, but the data it produces is essential to understand if the flight controls design is correct. There are limitations in the testing that can be done on the iron bird, most notably in the limits of the dummy loads. The flap and slat binding issues discussed earlier cannot be effectively investigated with the iron bird because there are no distributed aerodynamic loads in this environment.

Similar to an iron bird, a “virtual bird” can be envisioned to obtain flight control system information in a computer environment. This virtual bird can help supplement and reduce the cost of iron bird testing in several ways. First, a virtual bird can provide a comparison of distributed vs. point loads effects for flap and slat deployments. Second, a virtual bird can provide an effective off-line environment to “pre-test” the system to ensure load levels and operational sequencing is correct. And third, a virtual bird can provide an efficient environment for correlation of test data back to the aircraft design data.

4. Flight Testing Testbed

Obviously, an aircraft has to eventually be assembled and flown to understand it’s complete performance envelope. For the Bombardier Continental program, five aircraft are being developed for the flight test program: one aircraft is dedicated to aerodynamics and performance testing, another to systems evolution testing, and another to avionics testing. Aircraft four and five have complete interiors, and help prove out the complete manufacturing and assembly process [6].

The flight testing program is structured around a set of tests which gradually confirm and expand the operational envelope of the aircraft. Similar to the iron bird and virtual bird comparison, a virtual aircraft can provide an effective off-line environment to pre-test the system. Also, correlation between the flight test and a virtual aircraft can provide more confidence in the design data and allow a more aggressive schedule for envelope expansion.

IV. Constructing an ADAMS/Aircraft – Flight Controls Environment

The ADAMS/Aircraft environment uses the foundation established for ADAMS/Car [2]. Significant new functionality was added to this environment to simulate ground, takeoff, and landing events [2,7]. Given the discussion of design issues and test processes for flight controls, this section discusses a possible list of components, subsystems, analyses, and test rigs for the virtual development of flight control systems. The challenge remains to create parametric components that can be easily manipulated within entire control systems, and is the subject of a future paper.

1. Primary Systems

To construct the primary control systems including ailerons, elevator, rudder, and tab control, some specialized components are required. All of these components, and indeed entire control systems, have been constructed previously with ADAMS [5]. Cables should include elastic effects and in some cases the cable inertia and friction effects as well. Pulleys and cable drums should include inertia and friction effects as well. Cams and linkages are used extensively in primary control systems as well, and can be modeled with ADAMS. These elements are designed for the application, and so the ADAMS/Aircraft environment should provide an easy method to construct various mechanisms for motion transfer.

2. Secondary Systems

To construct the secondary control systems including flaps, slats, and spoilers, some specialized components are also required. Entire secondary control systems have also been previously constructed with ADAMS [4]. Flap and slat tracks should include friction effects for rollers. Various methods have been used successfully in modeling these devices, including dummy masses with point-curve constraints, and 2D contact. Jackscrew, gear box, and power control unit (PCU) models in subsystem form will also be required. Because these devices are designed and sized for the particular application, generic power drive systems should be available.

3. Additional Modeling Elements

To complete the modeling process, several additional elements are required. Stick controls and autopilot models are needed to define the longitudinal and lateral control loops. Rigid and flexible control surfaces are needed. To simplify the modeling of surfaces, predefined configurations may be helpful, such as flap modeling with Fowler flap, Krueger flap, Junker flap, and other possible selections. Aerodynamics applied as a point or distributed load are also necessary.

4. Analyses

A preliminary set of analyses that are desired include test configurations, as well as expected the aircraft operational configuration. For test configurations, setups which match subsystem and system tests such as the iron bird test rig are desirable. Also, test configurations which support either direct output or direct cosimulation with flying qualities testbeds are desirable. Aircraft tests that fully exercise the virtual aircraft in horizontal flight, steady climb to altitude, descent, coordinated turn, as well as takeoff and landing events are desirable.

5. Current architecture for development

The current ADAMS/Aircraft environment provides a strong foundation for adding flight controls capabilities. This environment provides full flexible and rigid fuselage modeling, aerodynamic capabilities, and a set of basic components for modeling mechanical subsystems. The ADAMS/Car – Standard Driver Interface may provide a starting point for exploring the required pilot control interface. Also, Autoflex capability of ADAMS version 12.0 provides a method for generating parametric flexible control surfaces.

V. Conclusions

This paper has discussed some of the issues surrounding the development of a flight controls module within the ADAMS/Aircraft environment. Design processes were discussed where virtual prototyping will continue to have an impact. Typical testbeds that are currently used for developing flight controls were also discussed, along with their limitations. The iron bird in particular is a testbed that provides valuable information on the interplay of hydraulic and mechanical systems, but may provide this information late in the development cycle when design changes are costly. Finally, some of the elements needed to model complete flight control systems with an ADAMS/Aircraft environment were discussed.

Looking ahead, customer input is needed to drive an overall environment for the design of flight control systems. A strong foundation of proven components and methods exists already.

References:

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