GARTEUR GROUP FOR AERONAUTICAL RESEARCH AND TECHNOLOGY IN EUROPE

ORIGINAL: ENGLISH

GARTEUR FM(AG08)/TP-088-2

May 22, 1995

GARTEUR Open

Flight Control Law Process Model for Use in the GARTEUR Action Group - 'Robust Flight Control in a Computational Aircraft Control Engineering Environment'

J P Irving

GARTEUR aims at stimulating and co-ordinating
co-operation between Research Establishments and Industry
in the areas of Aerodynamics, Flight Mechanics, Helicopters,
Structures & Materials and Propulsion Technology

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List of Abbreviations

ALN	Alenia Un'Azienda FINMECCANICA S.P.A.
AS	Aérospatiale
AVRO Intl	AVRO International Aerospace
BAe	British Aerospace
CCL	Cambridge Control Ltd
CERT	Centre d'Etudes et de Recherces de Toulouse
CIRA	Centro Italiano Ricerche Aerospaziali S.p.A.
DAA	Daimler-Benz Aerospace Airbus
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt (German Aerospace Research Establishment)
DRA	Defence Research Agency
DUT	Delft University of Technology
FAC	Fokker Aircraft B.V.
FFA	Flygtekniska Försöksanstalten (The Aeronautical Research Institute of Sweden)
FMV-F-FL	Försvarets Materielverk (Defense Material Administration)
INTA	Instituto Nacional de Técnica Aerospacial (National Institute for Aerospace Technology)
LiTH	Linköping University
LUT	Loughborough University of Technology
NIVR	Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart (Netherlands Agency for Aerospace Programs)
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory, The Netherlands)
ONERA-CERT	Office National d'Etudes et de Recherches Aérospatiales (National Institute for Aerospace Research and Studies)
ONERA-IMFL	Office National d'Etudes et de Recherches Aérospatiales (National Institute for Aerospace Research and Studies)
ONERA-SALON	Office National d'Etudes et de Recherches Aérospatiales (National Institute for Aerospace Research and Studies)
SMA	Saab Scania AB, Military Aircraft
UN	Università di Napoli "Fedirico II"
UNED	Universidad Nacional de Educación a Distancia

Summary

BAe (MAD) are members of the GARTEUR Flight Mechanics Action Group (FM-AG08) on 'Robust Flight Control in a Computational Aircraft Control Engineering Environment (CACEE)'. As part of the work of this Group, MAD were tasked with identifying the processes, methods and tools used in the design, assessment and clearance of Flight Control Laws (FCL). The results of this survey would form part of the definition of the requirements for the CACEE.

Although the work of this GARTEUR Action Group is specifically related to Flight Control, it is the intention to keep the CACEE that supports the Flight Control Law process as generic as possible. This will allow the use of the CACEE in a wide variety of applications, including those outside of the aerospace industry.

This report defines the process model for use in GARTEUR FM-AG08. It covers all tasks involved in the total process, and the associated tools. The methods used in the design and assessment steps of the process model will be listed separately by INTA from Spain. The major problem areas of each Action Group member, within the process, have also been identified. This will help in scoping and directing the effort in the development of the CACEE. Finally, a number of requirements for the CACEE which arise from this process model have been listed.

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Glossary

AG	Action Group
CACEE	Computational Aircraft Control Engineering Environment
FCC	Flight Control Computer
FCL	Flight Control Laws
FCS	Flight Control System
FFT	Fast Fourier Transform
FM-AG08	Flight Mechanics Action Group Number 8
FOC	Final Operational Clearance

FRD	Functional Requirements Documents
GARTEUR	Group for Aeronautical Research and Technology in Europe
GRT	Ground Resonance Test
HQ	Handling Qualities
PIO	Pilot Induced Oscillations
PSQS	Preliminary System Qualification Statement
Reqts	Requirements
SCT	Structural Coupling Test
Specn	Specification

Amendment History

Issue	Reason for Change	Date	Author
1	Original Version	April 1995	J.P.Irving

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1. INTRODUCTION.

GARTEUR is an organisation of European Research Establishments who collaborate on non-competitive research projects, mutually beneficial to the aerospace industries of the member countries. The research is carried out by Action Groups (AGs), and BAe (MAD) are members of the Action Group on 'Robust Flight Control in a Computational Aircraft Control Engineering Environment (CACEE)' (FM-AG08). As potential users of the CACEE, MAD were tasked with identifying the processes, methods and tools used in the design, assessment and clearance of Flight Control Laws (FCL). The results of this survey would form part of the definition of the requirements for the CACEE.

The aim of this report is to describe the process model of the FCL design and clearance activities. The model covers all tasks involved in the total process, and the associated tools. The methods used in the design and assessment steps of the process model will be listed separately by INTA from Spain. The report also aims to identify where major problems exist within the process, which will help to direct effort in the development of the CACEE.

Although the specific aim of this GARTEUR Action Group is to look at the Flight Control Law process, it is intended that the scope of the CACEE is as wide as possible. Therefore, the process model described in this report is meant to be generic to a number of control system design functions, rather than just aircraft Flight Control.

2. THE FCS DESIGN AND CLEARANCE PROCESS MODEL.

2.1. General Description.

The FCS design and clearance process model derived in this work is split into three levels, each of which are described below. The model covers FCL activities only (NOT the whole FCS) throughout the life of a project, from development through to its delivery into service, including:-

- control law design, assessment and specification, for both the rigid and flexible aircraft regimes (i.e.the closed-loop interaction between the airframe and the FCS)
- specification of hardware requirements (e.g. actuators, sensors, etc.)
- support and involvement in Structural Coupling Tests (SCT)
- support to, and definition of, Flight Control Computer (FCC) rig tests
- support and analysis of flight testing
- major interfaces with, and constraints from, other disciplines.

The process model has been developed based on a military aircraft FCS. Although some members of FM-AG08 are civil aircraft manufacturers, the military process model does cover civil aircraft in principle; from a process point of view, the tasks that make up the total process are very similar between the two but design criteria, rules and even methods differ. For example, there are fewer analytical design criteria for the Handling Qualities (HQ) of civil aircraft, and so much greater emphasis is given to the results of piloted simulation in the design phase than is the case for military aircraft.

Another difference between the two is in the maturity of the control laws at first flight, and the duration of the development updates thereafter. In the military application, the first flight control laws cover only a basic configuration, and limited functionality. Many additional updates, adding significant functionality, are required in the development up to the release to service. This typically takes several years. For civil aircraft, the first flight control laws are very close to the production version, and the development phase up to service lasts approximately one year, with perhaps only one control law update.

2.2. Definition of Terms.

The process model within this report contains several terms which require clarification as defined within Table 1.

2.3. Level 1 - High Level Overview.

The Level 1 FCL process model is shown in Figure 1. This shows the top level tasks involved in the FCL design and clearance process and the interfaces with other functions throughout the life of a project. Each task shown on this level of the process model corresponds to an FCS design phase, each one adding additional functionality to the control laws, until the final production standard is reached (step 9).

Figure 1 should be interpreted as follows. The disciplines on the left side of the Figure are the major interfaces with the process. The boxes along the bottom of the Figure are the main tasks that make up the overall process. Into each of these go two vertical lines. The line on the left represents inputs to the task, and the one on the right represents outputs. If a discipline has an input into a task, then this is represented by an arrow on the left vertical line, beneath the horizontal line corresponding to the discipline. An output to a discipline is represented by a similar arrow on the right vertical line. A comment is included to indicate the nature of the input or output. For example, the Systems Test disciplines has an output from the first task ('Feasibility Study'), which is initial test requirements for the hardware.

Although not explicitly stated in the Figure 1, at the end of each of the phases, a review will take place. Depending on the results of this, it may be necessary to return to an earlier phase and repeat it.

The number of control law updates shown in Figure 1 is based on military aircraft, and will vary depending upon the nature of the program. As stated above (Section 2.1), the number of updates for a civil aircraft program will be considerably lower (perhaps even zero).

2.4. Level 2 - Medium Level.

The Level 2 FCS process model is shown in Figure 2. Level 2 breaks down the very general high level tasks in Level 1 into a small number of more detailed tasks. This level gives a general view of the processes that make up the overall FCS design and clearance process. The relationship between Levels 1 and 2 is illustrated graphically in Figure 2. A more detailed description of the relationship may be found in Appendix A, which also describes the purpose of each of the Level 1 phases, together with the main inputs/outputs.

It is assumed that some of the tasks performed during the control law assessment (e.g. stability assessment and simulations) will be included in the design of the control law for evaluation. Thus, although not explicitly included in Figure 2, the control law design steps are an iterative process with design AND some assessment, until a satisfactory design is reached and a 'full' assessment performed.

2.5. Level 3 - Detailed Level.

Level 3 deals with the detailed tasks that make up the FCS design and clearance process model. Figures 3 to 14 show the tasks that constitute each of the Level 2 tasks, and a description of each is given in Appendix B. Note that steps 5 to 9 are merely repeats of steps 3 and 4. Some tasks require inputs from many disciplines (e.g. Step 1.14, 'Optimise

Configuration', which requires specialist inputs to cover FCS, Flight Mechanics, Powerplant, etc.). These interfaces are highlighted in Appendix B.

3. PROBLEM AREAS.

This section describes some of the main problem areas within the process which have been highlighted by members of FM-AG08, and are significant either because of their magnitude (and cost), or because of the lack of adequate tools.

The main problem areas are:-

1) Model consistency and configuration control, i.e. a large number of different models are produced (linear, nonlinear, simplified, etc.) and control and consistency between all is required to support a multi-user environment.
2) Investigation of structural effects on control law performance (e.g. impact of structural filters on stability margins).
3) Analysis of nonlinear stability phenomena with pilot interactions e.g. Pilot Induced Oscillations (PIOs), rate limiting, and design approaches to alleviate these problems.
4) Verification and validation of the Flight Control Computer (FCC) software against control law FRD.
5) Efficient control allocation in cases of control effector redundancy.
6) Analysis of control law behaviour (feedback) for different flight cases, loads, external stores, FCS operating modes, etc. (a very large number of cases)

These problem areas may be grouped into the following areas:-

1) Data handling and management (1,2,6).
2) Nonlinear design and analysis (3).
3) Software testing (4).
4) Vehicle performance optimisation (5).

4. REQUIREMENTS FOR THE CACEE.

In addition to the problem areas described in the previous section, several more general requirements for the CACEE (related to the process model) have been suggested by FM-AG08 members. These include:-

- The inclusion of the Group's collective experience within the CACEE. This is because a large number of steps in the process rely on designer's experience from previous programmes.
- Guidelines on why, when and how to use the different methods. This requires the CACEE to 'guide' the designer through the process, ensuring tools supported by the CACEE are not misused. Against this, the CACEE must not be too rigid, and must allow some flexibility to permit the design process to be changed if efficiency improvements are introduced (e.g. Concurrent Engineering).
- The ability to transform from one model to another e.g. nonlinear to linear.

- Automatic code generation for control law software. It should be noted that, if the code produced by such a tool was actually used on an aircraft (thus becoming safety critical), then the tool used to produce such code would itself become safety critical. This would significantly increase the cost of such a facility, compared to its cost if it were used for rapid prototyping purposes only.
- Self-checking capability for Quality Assurance wherever practical.

These general requirements, taken with the process model itself and the problem areas from the previous section, lead to the following set of requirements for the CACEE:-

1) All steps within the overall process should ultimately be covered by the CACEE. In view of the limited time and effort available however, the following areas should be given highest priority:-
   - Data handling and management (General)
   - Nonlinear design and analysis (Steps 3.18, 3.34, 3.35, 4.15, 4.24, 4.25)
   - Software testing (Steps 3.4, 4.3)
   - Effective use of control effectors available (Steps 2.12, 2.13, 2.14)
2) All interfaces with other disciplines identified should ultimately be supported. Again, limited available resource means that those associated with the afore mentioned tasks should be given highest priority.
3) All tools listed should ultimately be supported by the CACEE. Since most members of FM-AG08 have either their own tools, MATLAB or MATRIXx, priority should be given to providing an interface to these.
4) The CACEE framework should be rigid enough to prevent inappropriate tools being used for tasks, but should be sufficiently flexible to allow process improvements to be introduced.
5) The CACEE should provide an access to a 'Knowledge Base' containing the collective experience of FM-AG08 members. This should be expandable by each organisation.
6) The ability to transform between models should be included.
7) The ability to automatically produce code for control law software should be provided, with at least FORTRAN, C and ADA supported.

The mechanism for realising these requirements will not be defined in this document. These functional requirements will be contained in the Architecture Design Document, to be produced by Cambridge Control Ltd.

5. CONCLUSIONS.

This report has defined a model for the FCS design and clearance process for use in the GARTEUR FM-AG08. A set of requirements based on this model, and the experience of FM-AG08 members, has been produced. These requirements are not exhaustive. They are only those that have arisen from the definition and investigation of the processes, methods and tools used by a number of organisations in the design, development and clearance of Flight Control Laws. They are intended as an input into a formal requirements document for the CACEE, to be produced by Alenia, and the Architecture Design Document, to be produced by Cambridge Control.

TABLE 1 Definition of Terms

Term	Definition
Control Effector	Any system or surface used for control, e.g. rudder, aileron, thrust vectoring
Customer Requirements and Specification	The engineering requirements and specifications for the control system and functionality, derived from the top-level Customer requirements.
FRD	Functional Requirements Document. This is the functional specification of the control laws, as supplied to the FCC supplier. At BAe (and within the EF2000 Project) this takes the form of executable FORTRAN code. This gives rise to an unambiguous specification, and a single, central, readily portable model of the control laws.
PSQS	Preliminary System Qualification Statement. The official clearance for flight of an aircraft system (in this case the FCS).
Rig Tests	The testing performed on the FCC to ensure that it matches the required functionality, as specified by the FRD.
Structural Coupling	The closed-loop coupling between the FCS and the airframe. The potential for instability arises from the possibility of structural mode vibration being amplified by feedback through the Flight Control Laws.

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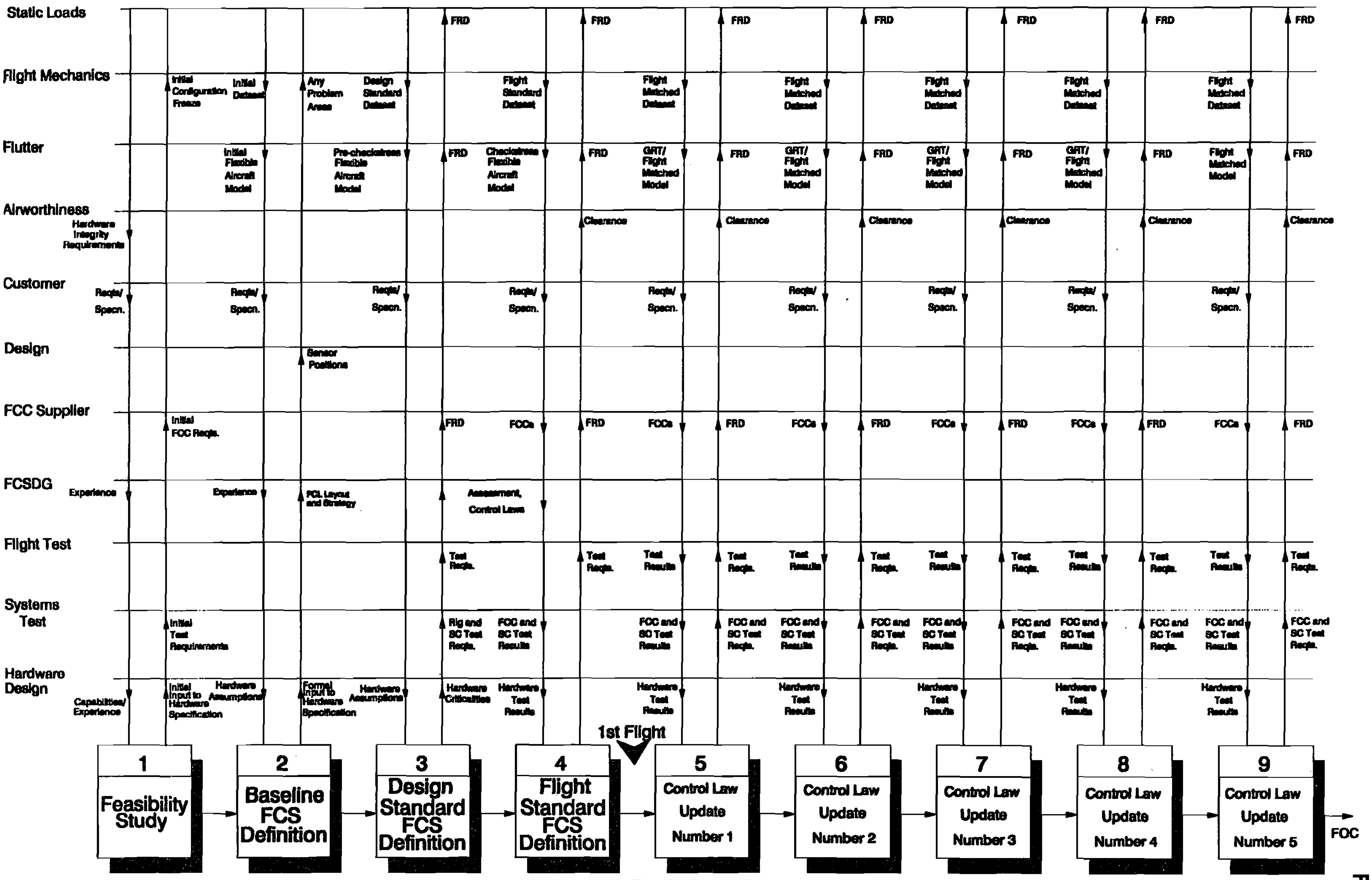
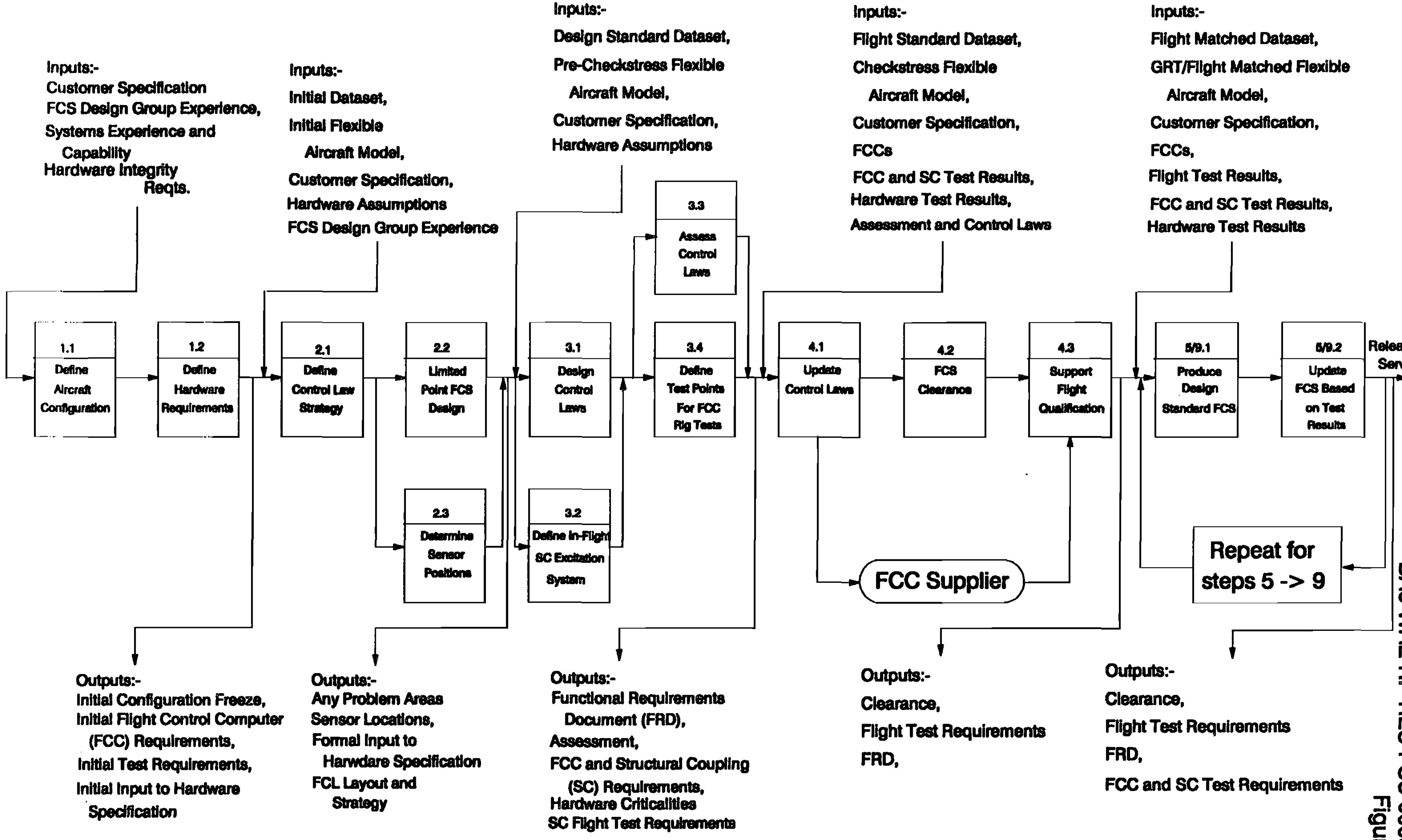


PROCESS MODEL LEVEL 1

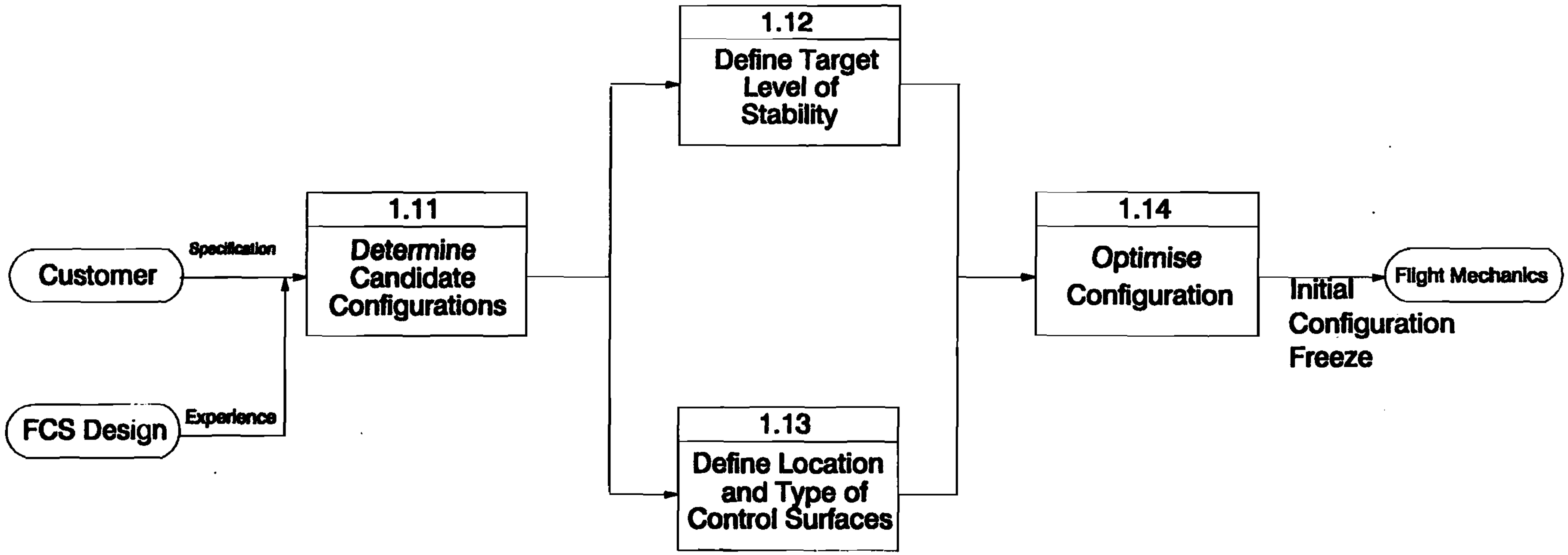
BAe-WAE-RP-RES-FCS-00593

Figure 1

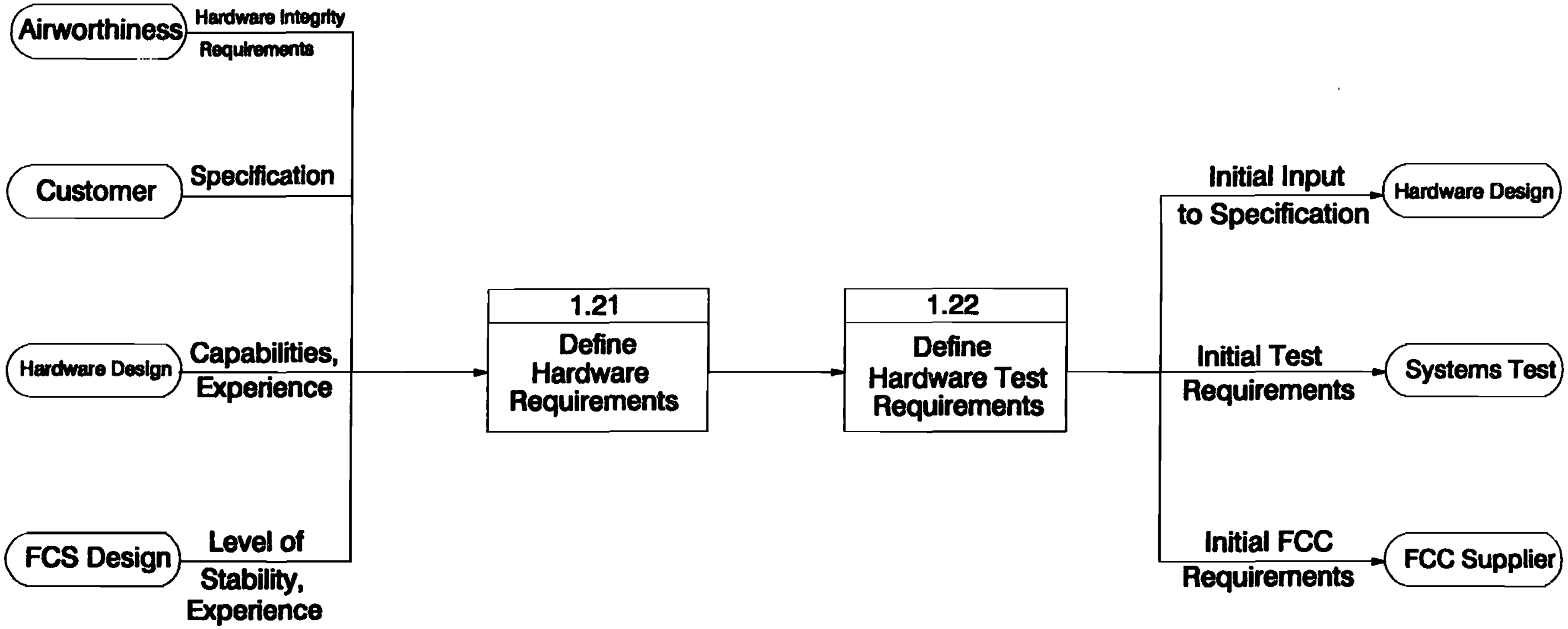


PROCESS MODEL LEVEL 2 (Appendix A)

BAe-WAE-RP-RES-FCS-000593
Figure 2



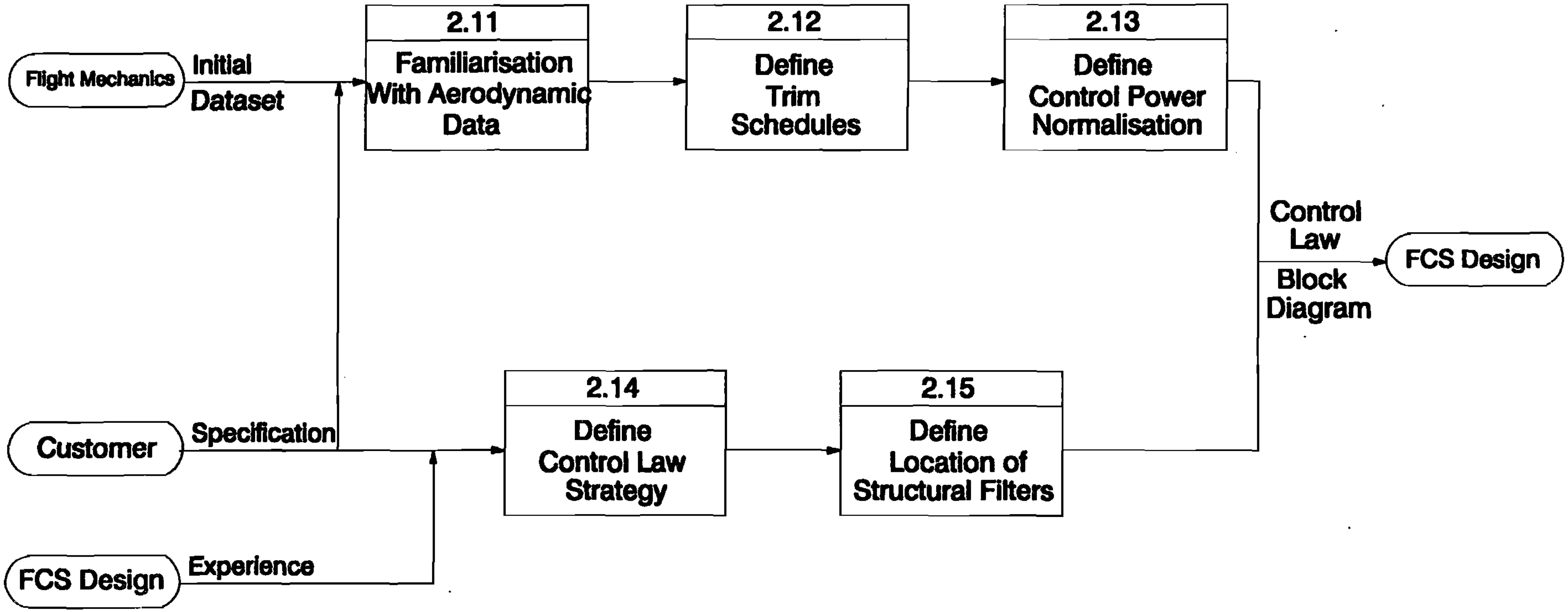
PROCESS MODEL LEVEL 3 - Step 1.1 : Define Aircraft Configuration
(Appendix B, Page 1)



PROCESS MODEL LEVEL 3 - Step 1.2 : Define Hardware Requirements

(Appendix B, Page 2)

BAe-WAE-RP-RES-FCS-00593
Figure 4

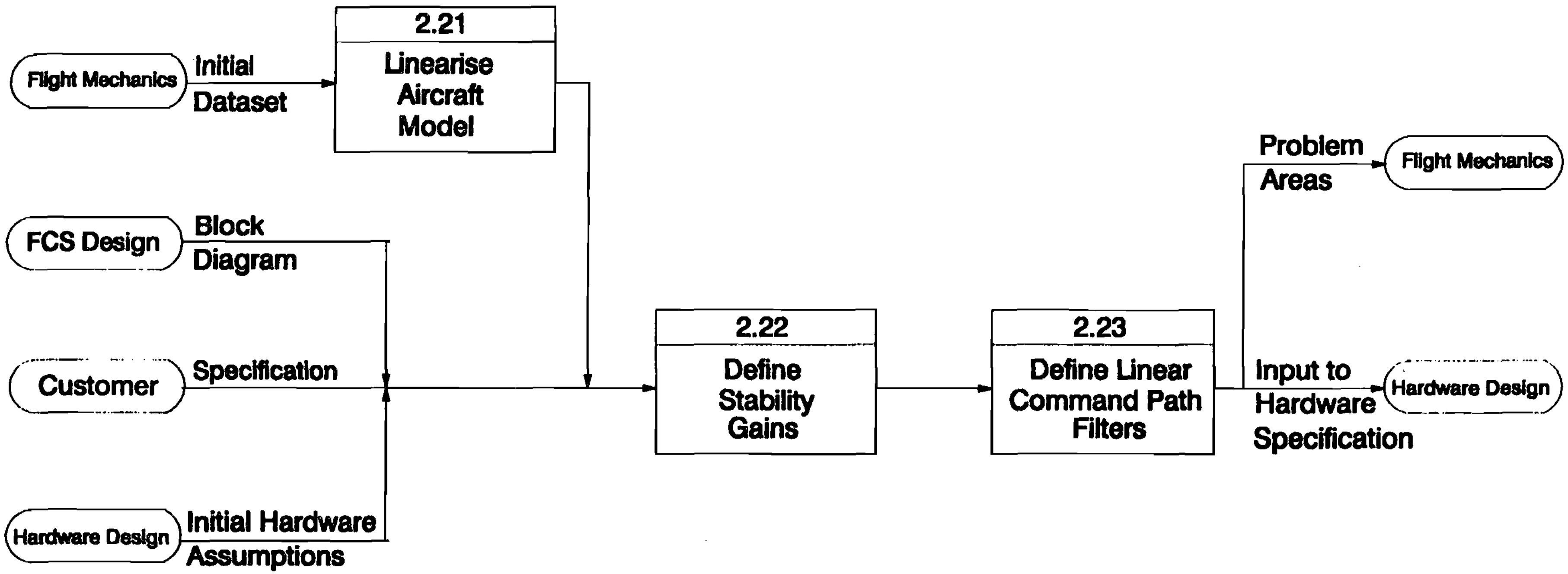


PROCESS MODEL LEVEL 3 - Step 2.1: Define Control Law Strategy and Structure

(Appendix B, Page 3)

BAe-WAE-RP-RES-FCS-000593

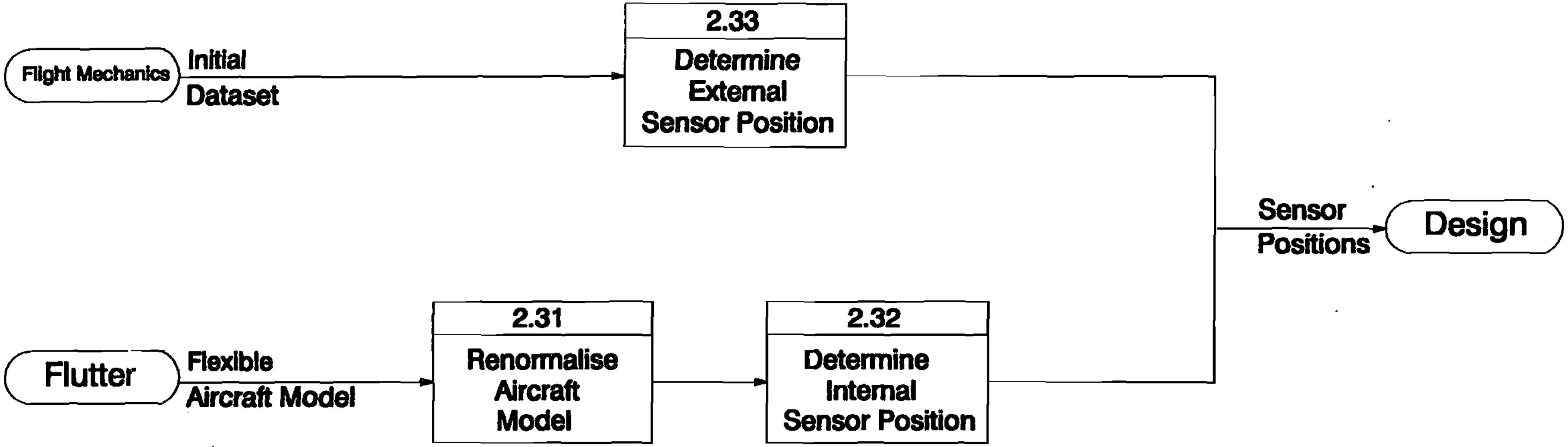
Figure 5



PROCESS MODEL LEVEL 3 - Step 2.2 : Limited Point Control Law Design

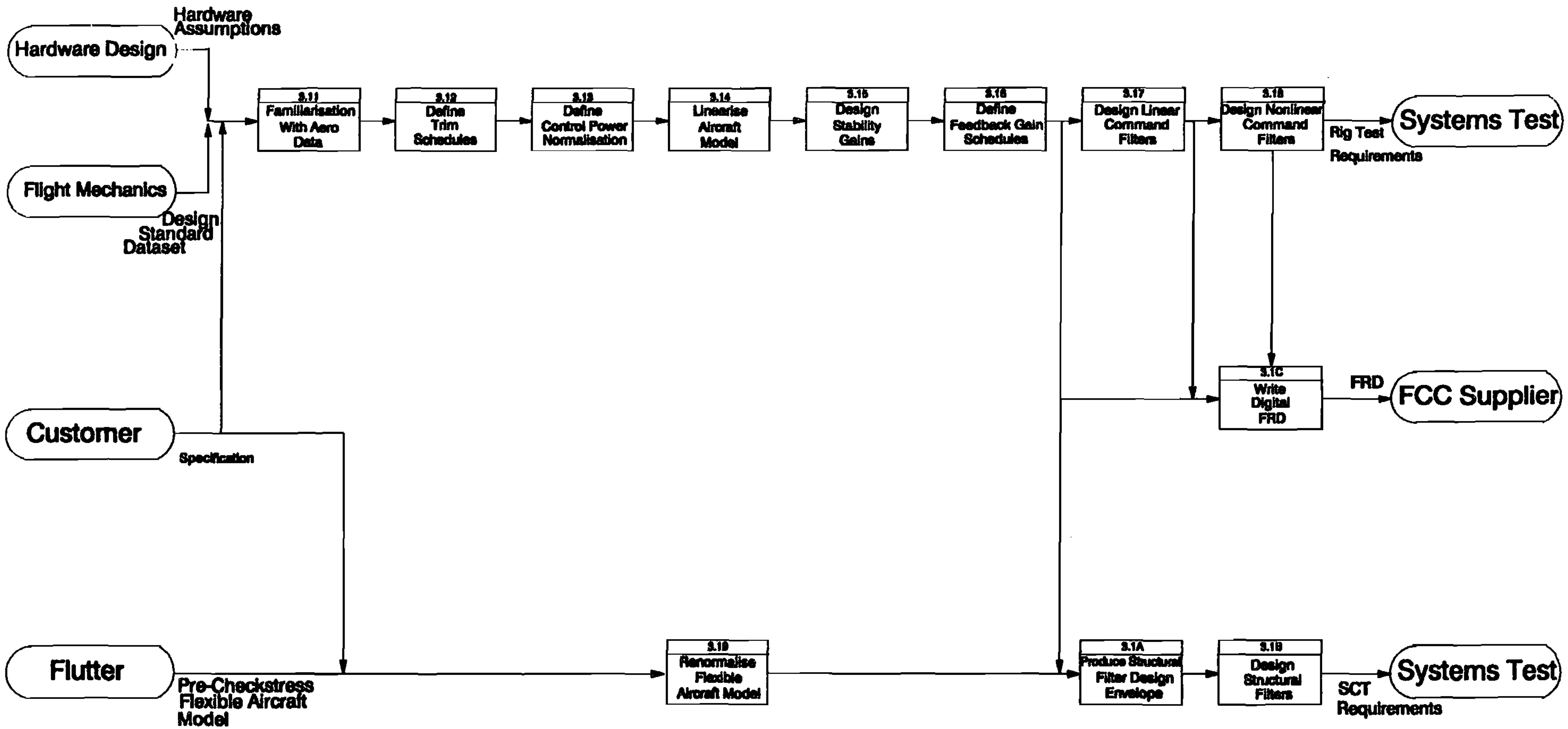
(Appendix B, Page 4)

BAe-WAE-RP-RES-FCS-00593
Figure 6

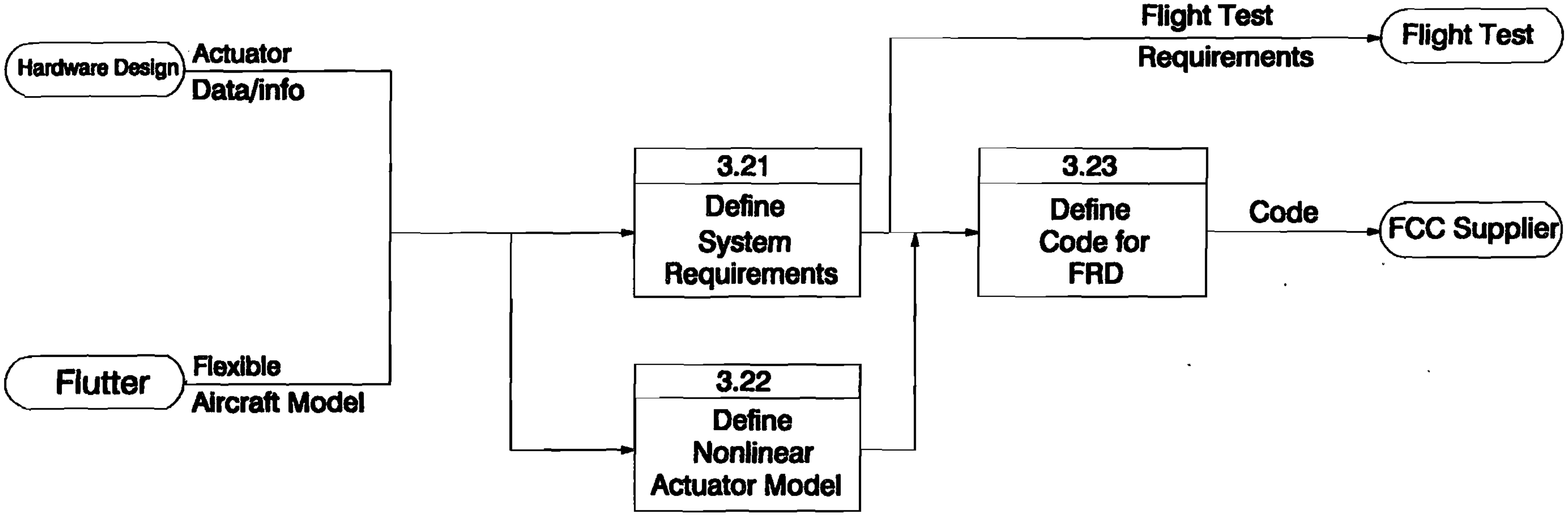


PROCESS MODEL LEVEL 3 - Step 2.3 : Determine Sensor Positions
(Appendix B, Page 5)

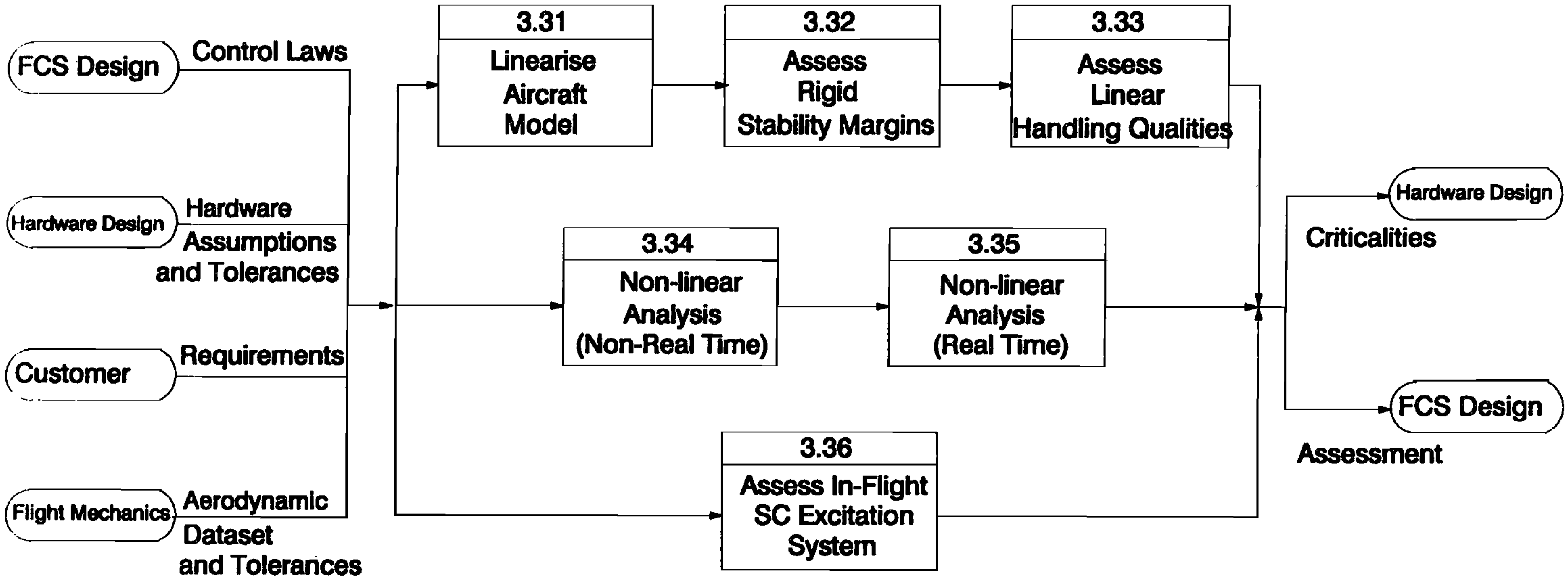
BAe-WAE-RP-RES-FCS-00593
Figure 7



PROCESS MODEL LEVEL 3 - Step 3.1 : Design Control Laws (Design Standard)
(Appendix B, Page 6)



PROCESS MODEL LEVEL 3 - Step 3.2 : Define In-Flight SC Excitation System
(Appendix B, Page 7)



PROCESS MODEL LEVEL 3 - Step 3.3 : Assess Control Laws

(Appendix B, Page 8)

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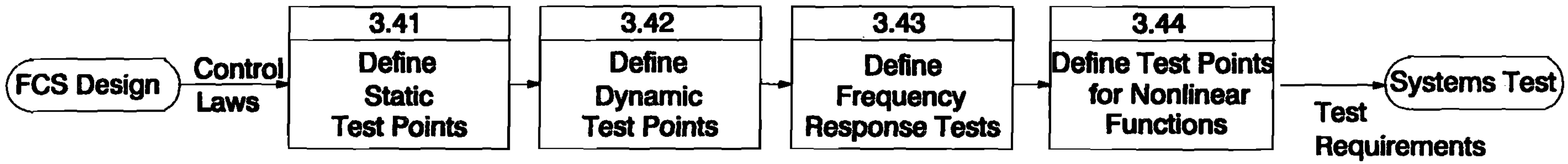
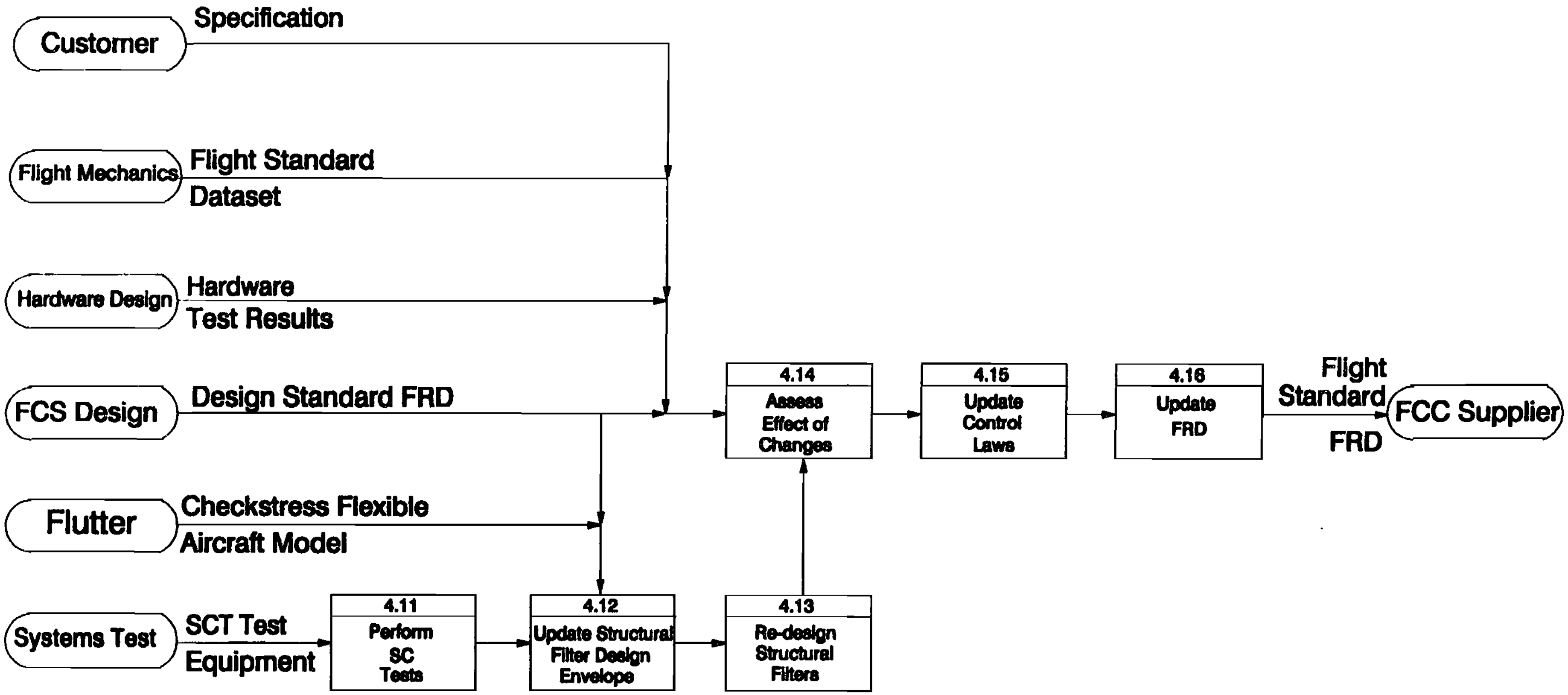
Figure 10



PROCESS MODEL LEVEL 3 - Step 3.4 : Define Test Points for FCC Rig Tests

(Appendix B, Page 9)

BAe-WAE-RP-RES-FCS-00593
Figure 11

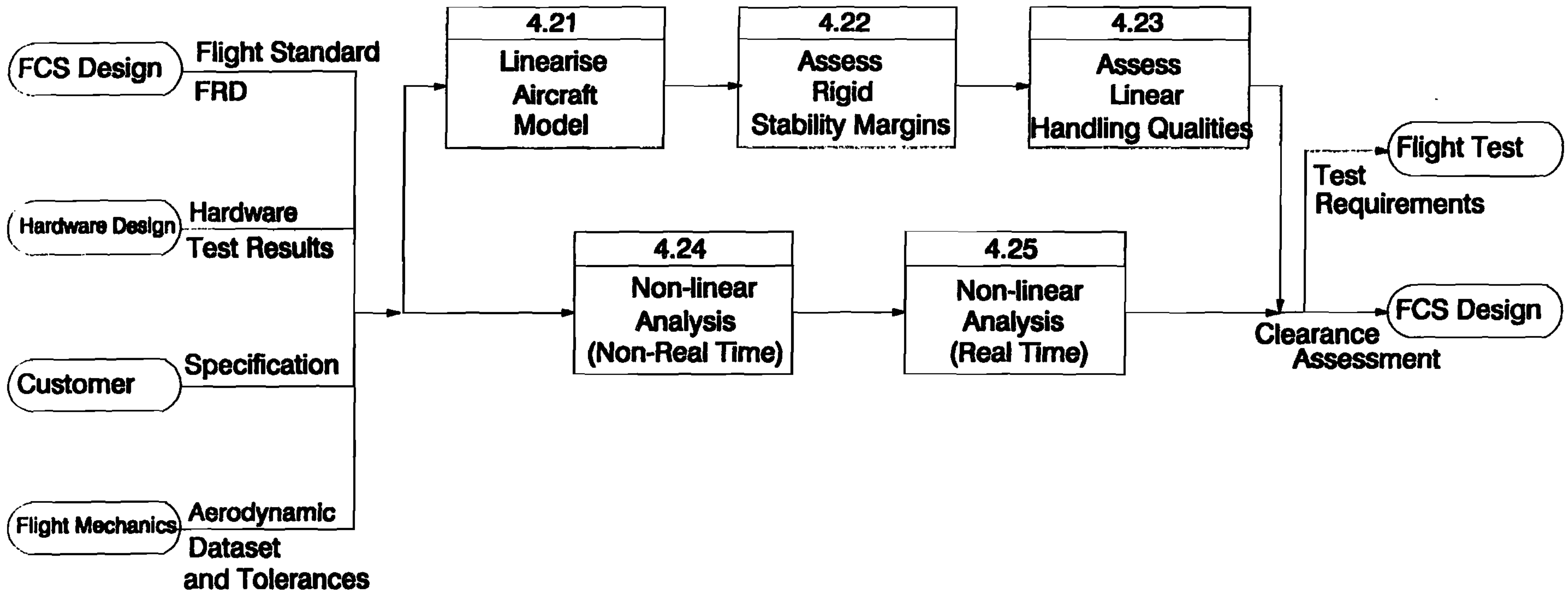


PROCESS MODEL LEVEL 3 - Step 4.1 : Update Control Laws to Flight Standard

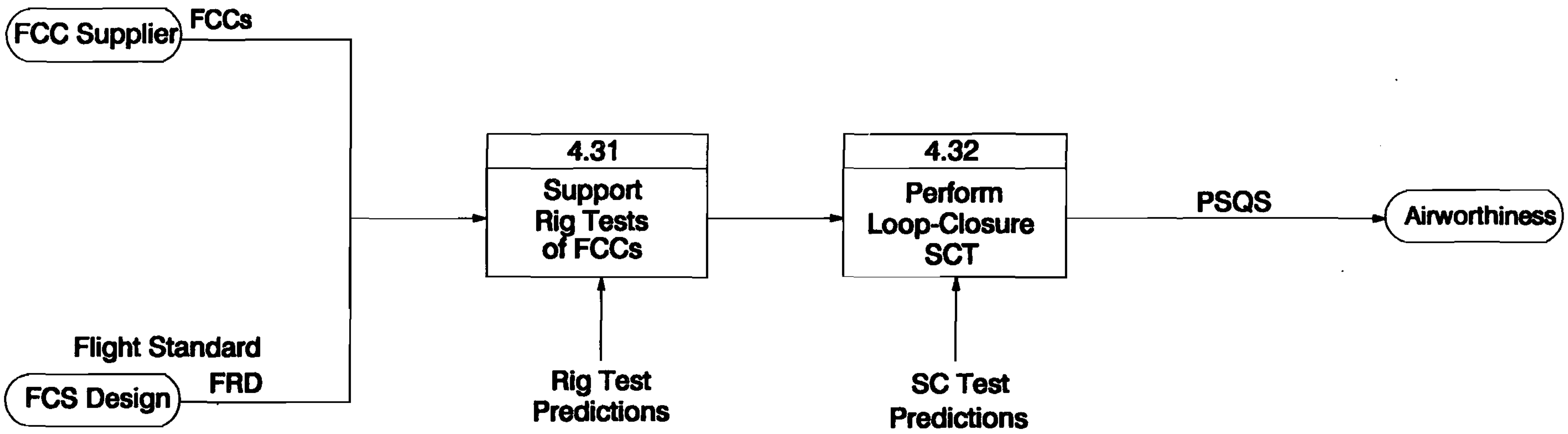
(Appendix B, Page 10)

BAe-WAE-RP-RES-FCS-00593

Figure 12



PROCESS MODEL LEVEL 3 - Step 4.2 : Control Laws Clearance
(Appendix B, Page 11)



PROCESS MODEL LEVEL 3 - Step 4.3 : Support FCS Qualification

(Appendix B, Page 12)

BAe-WAE-RP-RES-FCS-00593
Figure 14

APPENDIX A

FCS DESIGN AND CLEARANCE MODEL - LEVEL 2

1. LEVEL 1 STEP 1 - FEASIBILITY STUDY.

Step Purpose:-

- To determine whether customer requirements for a new or upgraded product could be met, with the current and predicted levels of capabilities and experience.
- If feasible, define initial aircraft configuration, and hardware and FCL performance and test requirements, together with cost estimates.

Inputs:-

- Customer specification
- Experience (FCS Design and Hardware Design)
- Hardware integrity requirements

Outputs:-

- Initial configuration freeze
- Initial FCC requirements
- Initial input to hardware specifications
- Initial indication of hardware test requirements

2. LEVEL 1 STEP 2 - BASELINE FCS DEFINITION.

Step Purpose:-

- To define control law layout and strategy
- Do sufficient initial design work to
  - highlight any problem areas within the aerodynamics
  - produce a formal input to the hardware specifications.
- To support the choice of the best sensor location to
  - minimise effect of structural coupling
  - optimise quality of aerodynamic signals (alpha, beta, etc.)

Inputs:-

- Customer specification
- Initial aerodynamic dataset (from data sheets and low speed wind tunnel tests)
- Initial flexible aircraft model
- Initial hardware assumptions (based on initial specification)
- Experience

Outputs:-

- Any problem areas in the aerodynamics and performance
- Sensor requirements (e.g. type, number, position, etc.)
- Formal input to hardware specifications
- FCL layout and control strategy

3. LEVEL 1 STEP 3 - DESIGN STANDARD FCS DEFINITION.

Step Purpose:-

- To define and assess a limited functionality FCS (i.e. limited stores fit, basic handling, no autopilot) based on design standard information (i.e. wind tunnel tests, formal hardware assumptions, etc.).
- To provide a fully defined Functional Requirements Document (FRD) to the FCC supplier.
- To define structural coupling and FCC rig test requirements.
- To design an in-flight structural coupling excitation system for flight testing.
- To identify parameters critical to FCS performance (e.g. hardware performance).

Inputs:-

- Customer specification
- 'Design' standard aerodynamic dataset
- Pre-checkstress flexible aircraft model
- Hardware assumptions (based on formal specification)

Outputs:-

- FRD to FCC supplier
- A set of control laws, with assessment (computer code, together with block diagrams)
- Structural coupling and FCC rig test requirements
- Hardware performance criticalities
- Structural Coupling Flight Test Requirements

4. LEVEL 1 STEP 4 - FLIGHT STANDARD FCS DEFINITION.

Step Purpose:-

- To update the design standard control laws (if necessary) based on flight standard information (e.g. hardware test results).
- To define, perform and analyse structural coupling ground tests and update notch filters.
- To validate the control laws against customer requirements (FCS clearance), for all operating modes, including failures, etc.
- To support the verification of the FCCs against the FRD (FCS qualification), for all operating modes, including failures, etc.
- To provide an input into the FCS PSQS.

Inputs:-

- Customer specification
- 'Flight' standard aerodynamic dataset
- Checkstress flexible aircraft model
- Hardware test results
- FCCs from supplier
- Design standard FRD
- FCC and Structural Coupling test requirements

Outputs:-

- Input into FCS clearance statement
- Flight standard FRD
- Flight test requirements

5. LEVEL 1 STEP 5/9 - UPDATE FCS FOR ADDITIONAL FUNCTIONALITY.

Step Purpose:-

- To update the previous phase Flight Control Laws to add extra functionality (extra stores, autopilot, carefree manoeuvring, etc.).

Inputs:-

- Customer specification
- 'Design' standard and flight matched aerodynamic dataset
- GRT and flight matched flexible aircraft model
- Hardware test results
- Structural Coupling ground and flight test results
- Flight Test results

Outputs:-

- Input into FCS clearance statement
- Flight standard FRD
- Flight test requirements

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APPENDIX B

FCS DESIGN AND CLEARANCE MODEL - LEVEL 3

1. LEVEL 2 STEP 1.1 - DEFINE AIRCRAFT CONFIGURATION (FIGURE 3).

Step Purpose:-

- To provide input into the choice of aircraft configuration which best meets the customer requirements.

Inputs:-

- Customer specification
- Experience

Outputs:-

- Initial configuration freeze

Interface Effects:

- FCS involvement is to aid in definition of sizes and location of control surfaces, and place a constraint on stability levels.
- Configuration definition allows:-
  - wind tunnel testing
  - design work to commence
  - flexible aircraft models to be defined (e.g. NASTRAN)

Methods (FCS involvement only):

- Experience and knowledge of hardware capability
- Analysis of control power derivatives

Tools:

- No specific tools

Constraints:-

- Task is multi-disciplinary, requiring specialist inputs to cover Flight Mechanics, FCS, Performance, Powerplant, Design, etc. Therefore a compromise configuration will be chosen which best meets all requirements.

2. LEVEL 2 STEP 1.2 - DEFINE HARDWARE REQUIREMENTS (FIGURE 4).

Step Purpose:-

- Provide a preliminary definition of hardware requirements to Systems Department, for discussion with suppliers, etc.
- Provide an indication of hardware test requirements.

Inputs:-

- Customer specification
- Experience
- Technological capabilities
- Target level of stability
- Hardware integrity requirements

Outputs:-

- Initial hardware assumptions and input to specification
- Initial indication of test requirements

Interface Effects:

- Initial discussions with hardware suppliers can commence, and draft specifications can be issued.
- Systems Test Department are able to plan initial hardware tests.

Methods (FCS involvement only):

- Experience and knowledge of hardware capability

Tools:

- No specific tools

Constraints:-

- Limitation of current technological capabilities
- Hardware speed can limit maximum allowable level of instability

3. LEVEL 2 STEP 2.1 - DEFINE CONTROL LAW STRATEGY AND STRUCTURE (FIGURE 5).

Step Purpose:-

- To define control law layout and strategy

Inputs:-

- Customer specification
- Experience of choice of control variables, states, inputs, etc.
- Initial standard aerodynamic dataset (from datasheets and low speed wind tunnel tests)

Outputs:-

- Control law block diagram, including control surface usage (i.e. trim distribution)

Interface Effects:

- Initial control law block diagram may be provided to FCC supplier for initial software design and programming.

Methods:

- Experience and knowledge
- Visualisation of aerodynamics variation
- Simple closed-loop (aircraft dynamics and control laws) simulation feasibility study

Tools:

- Visualisation tools
- Simulation tools

Constraints:-

- No structural information, so location of structural filters from experience
- Technology only allows certain states to be measured with required accuracy
- Cost and weight may make certain choices of control effectors too expensive for use as primary control surfaces e.g. leading edge flaps.

4. LEVEL 2 STEP 2.2 - LIMITED POINT FCS DESIGN (FIGURE 6).

Step Purpose:-

- Do sufficient initial design work to
  - highlight any problem areas within flight dynamics
  - obtain a more accurate definition of the hardware requirements.

Inputs:-

- Customer specification
- Initial aerodynamic dataset
- Initial hardware assumptions
- Control law block diagram and control surface usage

Outputs:-

- Formal input to hardware specifications
- Identification of any problems with aerodynamics

Interface Effects:

- Formal specifications can now be issued to hardware suppliers.
- Flight Mechanics area will be aware of any potential problems with aerodynamics, allowing for possibility of fixes.
- Result will form FCS input to freeze of aircraft configuration, allowing detailed design and build work to begin.

Methods:

- Methods contained in INTA List of Methods

Tools:

- In-house tools (linear design/analysis)
- MATLAB toolboxes
- MATRIXx toolboxes
- ANDECS

Constraints:-

- Specification of minimum expected hardware performance for satisfactory control of aircraft

5. LEVEL 2 STEP 2.3 - DETERMINE 'BEST' SENSOR LOCATION (FIGURE 7).

Step Purpose:-

- To support the selection of the best sensor location to
  - minimise effect of structural coupling
  - optimise quality of aerodynamic signals (alpha, beta, etc.)

Inputs:-

- Initial flexible aircraft model
- Initial aerodynamic dataset

Outputs:-

- Required location for sensors

Interface Effects:

- Sensor position definition allows detailed design work to proceed for both internal and external fit.

Methods:

- Eigenvalue/eigenvector decomposition for renormalisation
- Evaluation of frequency responses for different sensor positions

Tools:

- SPEAKEASY/MATLAB
- In-house tools
- MATRIXx
- ANDECS

Constraints:-

- Internal 'fit' of aircraft may limit available choices of sensor location

6. LEVEL 2 STEP 3.1 - DESIGN CONTROL LAWS (DESIGN STANDARD) (FIGURE 8).

Step Purpose:-

- To design a limited functionality FCS based on design standard information.
- Provide a fully defined Functional Requirements Document (FRD) to the FCC supplier.
- To determine final structural coupling and rig test requirements.

Inputs:-

- Customer specification
- Design standard aerodynamic dataset
- Pre-Checkstress flexible aircraft model
- Hardware assumptions based on specification

Outputs:-

- Digital FRD
- Detailed structural coupling and rig test requirements

Interface Effects:

- Definition of FRD allows indication of time schedules required for:
    - Rig tests for FCC validation.
    - Structural Coupling ground Tests.
- Full control law definition allows assessment of loads, Flight Mechanics, and flutter characteristics (although flutter and loads use a simplified model).

Methods:

- Methods contained in INTA List of Methods
- Assessment methods (e.g. stability, simulation) used to evaluate control laws
- Continuous/digital effects modelling

Tools:

- In-house tools
- MATLAB toolboxes
- SPEAKEASY
- MATRIXx toolboxes
- ANDECS
- Automatic Code Generation tools

Constraints:-

- Amount of data to be organised and controlled
- Loads limits on manoeuvres

7. LEVEL 2 STEP 3.2 - DESIGN IN-FLIGHT STRUCTURAL COUPLING EXCITATION SYSTEM.

(FIGURE 9)

Step Purpose:-

- To define requirements for in-flight flutter and structural coupling excitation system, including Flight Test.
- To define FRD code for execution of system.

Inputs:-

- Pre-Checkstress flexible aircraft model
- Actuator amplitude limits

Outputs:-

- FRD code for system
- Structural coupling Flight Test Requirements

Interface Effects:

- Input to Flight Test Programme.
- Allows assessment of likely loads, flutter effects.

Methods:

- Experience and knowledge of aerodynamics and aircraft model variation.
- Time response analysis of response levels/actuator characteristics.

Tools:

- In-house tools
- Automatic Code Generation tools

Constraints:-

- Flight envelope limitations (such as alpha or 'g' limits) may prohibit some test points.
- FCC throughput capacity may limit functionality of system.

8. LEVEL 2 STEP 3.3 - ASSESS CONTROL LAWS (FIGURE 10).

Step Purpose:-

- To assess the design standard control laws against customer requirements, for all FCS states (including failures) and aerodynamic uncertainties
- To identify parameters whose value is critical to control law performance (e.g. actuators must be within spec).

Inputs:-

- Customer specification
- Design standard control laws
- Design standard aerodynamic dataset and tolerances
- Hardware assumptions and expected variations

Outputs:-

- Full assessment of design standard control laws
- Indication of which parameters critically affect stability margins and performance

Interface Effects:

- Identification of problem areas, and the required fixes (if any) for flight clearances.
- Identification of criticalities in hardware performance and their likely effect on flight clearance (e.g actuator must meet spec. or phase margin not large enough).
- Partial input into clearance statement for the system.

Methods:

- Methods contained in INTA List of Methods
- Pilot-in-the-loop simulations

Tools:

- In-house tools
- MATLAB toolboxes
- Flight Simulation facilities
- MATRIXx toolboxes
- ANDECS

Constraints:-

- Output places a constraint on the minimum acceptable level of performance from the hardware

9. LEVEL 2 STEP 3.4 - DEFINE TEST POINTS FOR FCC RIG TESTS (FIGURE 11).

Step Purpose:-

- To define test points sufficient to verify the functionality of the FCC (covering all operating modes, failures, elements,etc.)
- To define acceptance criteria for FCC rig tests.

Inputs:-

- Digital FRD

Outputs:-

- Detailed test requirements for FCC, including:-
  - the element/function to be tested
  - the required environment
  - the required equipment
  - the test methodology
  - the test procedure
  - the acceptance criteria

Interface Effects:

- Allows formal test programme to be defined.

Methods:

- Knowledge of FRD and schedules.

Tools:

- In-house tools

Constraints:-

- None

10. LEVEL 2 STEP 4.1 - UPDATE CONTROL LAWS TO FLIGHT STANDARD (FIGURE 12).

Step Purpose:-

- To update the control laws (if necessary) based on flight standard information (e.g. hardware tests)

Inputs:-

- Customer specification
- Flight standard aerodynamic dataset
- Checkstress flexible aircraft model
- Hardware test results
- Design standard FRD

Outputs:-

- Flight standard digital FRD

Interface Effects:

- Flight standard control laws allow flight clearance of loads, Flight Mechanics, and flutter.

Methods:

- Methods contained in INTA List of Methods

Tools:

- In-house tools
- MATLAB toolboxes
- MATRIXx toolboxes
- Dedicated in-house test software
- ANDECS
- Automatic Code Generation Tools

Constraints:-

- Time available
- Cost of changes

11. LEVEL 2 STEP 4.2 - FCS CLEARANCE (FIGURE 13).

Step Purpose:-

- To validate the control laws against the customer and certification authority requirements.

Inputs:-

- Customer specification
- Flight standard aerodynamic dataset
- Hardware test results
- Flight standard FRD

Outputs:-

- Clearance of FCS FRD against customer requirements, including any limitations
- Flight Test requirements

Interface Effects:

- Provide input into flight clearance.
- Imposition on Flight Test Programme of restrictions (if necessary) based on results of assessment.

Methods:

- List contained in INTA List of Methods

Tools:

- In-house tools
- MATLAB
- Flight Simulation facilities
- MATRIXx
- ANDECS

Constraints:-

- Restrictions may be placed on flight testing if necessary.

12. LEVEL 2 STEP 4.3 - SUPPORT FCS QUALIFICATION (FIGURE 14).

Step Purpose:-

- To support the verification of the FCCs against the FRD.
- To provide an input to the PSQS for the FCS.

Inputs:-

- Digital FRD
- FCC from supplier
- Rig test predictions
- Loop-closure structural coupling test predictions

Outputs:-

- Input to first flight PSQS

Interface Effects:

- Formal input into flight clearance paperwork.

Methods:

- Comparison of predicted frequency responses with experiment.

Tools:

- In-house tools

Constraints:-

- None

13. LEVEL 2 STEP 5->9.1 - PRODUCE DESIGN STANDARD FCS FOR NEXT PHASE.

Step Purpose:-

- To produce a full FCS design for the required additional functionality and/or stores fit using predicted (e.g. wind tunnel) data.

Inputs:-

- Customer specification
- Design standard aerodynamic dataset
- Hardware test results
- Structural coupling test results
- Ground Resonance Test matched flexible aircraft model

Outputs:-

- Fully defined FRD
- Structural coupling and rig test requirements

Methods:-

- As for Step 3, with the addition of analysis of flight test results via:-
  - Parameter identification for aerodynamic derivatives
  - Fast Fourier Transform techniques for in-flight SCT

14. LEVEL 2 STEP 5->9.2 - UPDATE FCS BASED ON FLIGHT TEST DATA.

Step Purpose:-

- To update the design standard FCS (if necessary) following availability of flight test data.
- Provide an input to the PSQS for the next FCS phase.

Inputs:-

- Customer specification
- Design standard FCS
- Flight matched aerodynamic dataset
- Ground Resonance Test matched flexible aircraft model
- Hardware test results

Outputs:-

- Flight clearance, and input to FCS PSQS
- Flight Test requirements