JOURNAL OF AIRCRAFT
Vol. 47, No. 6, November–December 2010

Engineering Notes

Conceptual Design of an Aerospace Vehicle Controller Using Axiomatic Theory

N. Ananthkrishnan*
Korea Advanced Institute of Science and Technology, Daejeon 305-701, Republic of Korea

DOI: 10.2514/1.C031002

I. Introduction

AEROSPACE systems are extremely involved with complex interdependencies between the attendant subsystems, making their design and engineering quite challenging. Requirements on performance, efficiency, economy, environmental effects, and issues of safety, reliability, ease of maintenance, and other factors, are usually interlinked and may often be in mutual conflict. This has led to the adoption of a systems engineering perspective to many aerospace design problems [1,2], and the development of processes, tools, and methods broadly classed as *system of systems* engineering [3]. Yet, the design and development of aerospace systems, like any other system design, must follow the natural course of ideate, analyze, check, and revise. The *ideation* phase is a creative process where the designer must make a coherent problem statement that clearly captures the design requirements, and then come up with one or more concepts that appear to meet the stated requirements. Each concept must be *realized* by one or more designs (for example, vortex lift *concept* may be realized by a canard or a strake or a cranked delta or any other design), each of which must then be analyzed and quantitative measures obtained that enable one to judge whether the design *solves* the given problem and, if so, which among the designs is the best. Almost every device available to the designer may be seen to be a realization (inverse problem), analysis (modeling & simulation) or a comparison (optimization) tool, with hardly any tool, if at all, to help the designer in the conception phase. This is of concern, especially when the concept is innovative, not merely an improvement, but a radical departure from existing conceptual approaches to the problem. Admittedly, the conception process is highly subjective, depending on the creative powers of the designer and his/her ability to integrate knowledge in diverse disciplines. Yet, a systematic basis to help the designer eliminate faulty concepts and narrow down the field to good designs will be of immense value in curtailing development time and cost, and in yielding a superior product.

Precisely such a systematic approach to design based on a few fundamental axioms, called the axiomatic design theory, has been developed by Suh [4]. In essence, the problem statement is captured in a set of functional requirements (FR) in the functional space, and the design is defined as a mapping from the functional space to the physical space which consists of a set of design parameters (DP). The axioms, and corollaries derived from them, deal with the choice of FRs, the corresponding DPs, and the nature of the mapping between them. Besides applications in several branches of engineering [5], axiomatic design theory also provides a scientific basis for design education [6].

The aim of this paper is to introduce axiomatic design theory to aerospace systems by way of a modest example of conceptual design of an aerospace vehicle controller. As will become clear in the following, this does not refer to "control system design" in the traditional sense; rather, it focusses on concept-level decisions to be made by the system designer before the task of controller realization (followed by analysis) is handed over to the control design team.

II. Axiomatic Design Theory

Axiomatic design theory is concerned with the functional requirements (FR), design parameters (DP), and the mapping between FR and DP from functional space to physical space (the design itself). There are only two axioms, which may be stated as below [4]:

1) Axiom 1 (the Independence Axiom): *Maintain the independence of FRs*.

2) Axiom 2 (the Information Axiom): *Minimize the information content of the design*.

Axiom 1 requires the FRs to be independent of each other. Further, it is desirable that the design is uncoupled in the sense that each DP affects only one FR. However, in case an uncoupled design is not possible, independence of FRs must be ensured by decoupling. This is stated in the Corollary below [4]:

1) Corollary 1 (Decoupling of Coupled Design): *Decouple or separate parts or aspects of a solution if FRs are coupled or become interdependent in the design proposed*.

FRs that are not independent or whose precise value does not matter except that they need to lie within a specified range may be classified as constraints instead. Axiom 2 leads to the following corollary [4]: [Minimization of FRs] Minimize the number of FRs and constraints. These principles will be illustrated on the conceptual design example in this paper.

2) Corollary 2 (Minimization of FRs): *Minimize the number of FRs and constraints*.

These principles will be illustrated on the conceptual design example in this paper.

III. Problem Statement

The problem is to design a controller that will take an aerospace vehicle (see Fig. 1a) powered by a liquid ramjet engine from 2.1 M, 1.4 km altitude to cruise at 3.0 M, 14.5 km altitude safely, with maximum engine efficiency, in the least possible time. Clearly, the controller must integrate both flight dynamic and propulsive aspects. Control action may be obtained by varying the fuel injection at station 5 and the nozzle throat area at station 8. Saturation and rate limits on fuel injection and nozzle throat area change are specified. Measurement of static pressure at station 4 is available, and air data sensors provide free stream Mach number, altitude, and angle of attack/sideslip information. Additional sensors may be placed (but are not recommended) upstream of the combustor, and no sensors are to be placed in the hot engine flow.

A. Functional Requirements

For the given problem statement, the FRs, without the benefit of axiomatic design theory, may be listed as below:

1) *Performance*: Take the vehicle from initial flight condition to final (cruise) flight condition in minimum time.

2) *Efficiency*: Maintain the terminal shock as far forward in the intake duct as possible to maximize intake total pressure recovery; and keep the fuel–air ratio (F/A) below the stoichiometric limit to

Received 1 March 2010; revision received 10 June 2010; accepted for publication 14 June 2010.

*Research Professor, Division of Aerospace Engineering, KAIST, 373-1 Guseong-dong, Yuseong-gu; drakn19@kaist.ac.kr. Associate Fellow AIAA.

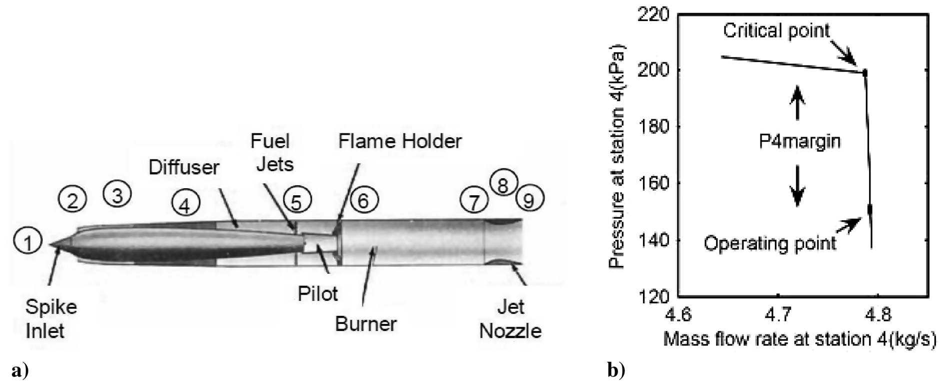

Fig. 1 Part a shows a schematic of the vehicle and engine, and part b shows a definition of intake safety factor $P4_{\text{margin}}$.

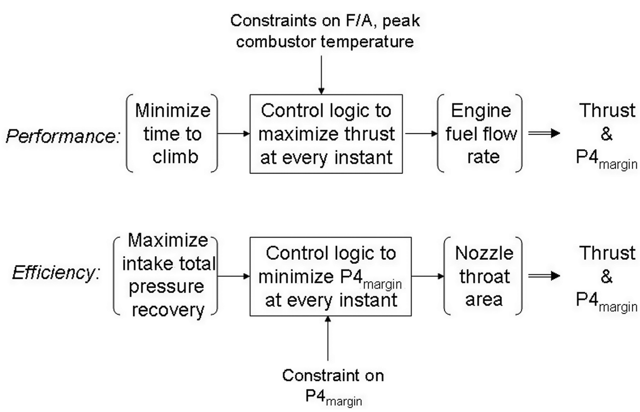

Fig. 2 One possible conceptual design solution.

ensure no unburned fuel is exhausted (so that cruise range may be maximized).

3) *Safety*: Maintain the terminal shock sufficiently aft in the intake duct so that it is not pushed out of the duct inadvertently by disturbances leading to instability (unstart/buzz); keep F/A above the lean blowout limit; and ensure peak combustor temperature does not exceed the upper limit.

The intake shock position may be quantified in terms of a factor called $P4_{\text{margin}}$, defined in Fig. 1b, which is a typical supersonic intake characteristic plot [7]. Points to the left of the critical point represent unsafe, subcritical operation where the terminal shock has emerged out of the duct; the reduction in mass flow being due to spillage. The near-vertical line is the safe, supercritical region. $P4_{\text{margin}}$ is the pressure $P4$ reckoned from its value at the critical point, positive in supercritical, and negative in subcritical regions. Larger positive $P4_{\text{margin}}$ implies lower pressure $P4$, terminal shock deeper inside the intake duct, and poorer total pressure recovery, hence worse efficiency. The best efficiency is clearly obtained at the critical point, but that is at the verge of unsafe, subcritical operation.

B. Design Solution

An apparently reasonable solution to this controller design problem is as shown in Fig. 2. In this, the performance FR#1 is met by a logic to control the fuel flow rate, and the efficiency FR#2a is satisfied through control of nozzle throat area. The other FRs are converted to constraints on these two control design problems. Two obvious problems emerge: One, closing of two control loops requires at least two independent measurements, and while $P4$ may be used to close the efficiency loop, there is no sensor for feedback in the performance loop, which must then be operated open-loop.[†] Second, each of the controls, fuel flow rate and nozzle throat area, affects both the thrust and $P4_{\text{margin}}$. Trying to maximize the thrust will lead to heavy surges in fuel flow rate limited only by the F/A and peak combustor temperature constraint which are usually beyond the constraint imposed by $P4_{\text{margin}}$. The nozzle throat area will therefore open up (as against close to maximize the efficiency) to meet the $P4_{\text{margin}}$ safety constraint, which also reduces the thrust. Besides the fuel flow and throat area working at cross purposes, if the throat area change is saturation- or rate-limited, the $P4_{\text{margin}}$ constraint cannot be held, and the system is at risk of going subcritical, a known fact [8,9].

IV. Axiomatic Design Solution

From the viewpoint of axiomatic design theory, the above design can be seen to suffer from several flaws. For one, the FRs relating F/A, peak combustor temperature, and $P4_{\text{margin}}$ are not independent, violating Axiom 1. The selection of DPs, fuel flow rate for the performance FR, and nozzle throat area for the efficiency FR, makes the design coupled, which obviously causes a problem. Further, a key functional requirement and an important constraint on the controller design have not been explicitly included, as revealed below.

A good systems designer will appreciate the simple yet fundamental fact that the design may 1) yield a safe but inefficient and nonperforming system, or 2) a safe and efficient system that still does not perform, or 3) a safe, efficient, and performing system. In other words, there is a natural hierarachy among the functional requirements, which must be reflected in the choice of design parameters. Rather than begin with performance and efficiency as FRs and impose safety as a constraint, one must start with the safety FR upfront, then progress to efficiency followed by performance.

With knowledge, the designer will realize that the requirements on F/A, peak combustor temperature, and terminal shock position are not all independent, but can be integrated into a single DP, $P4_{\text{margin}}$. Thus, the safety FR can be met by designing suitable limits on the $P4_{\text{margin}}$. Apparently, the least permissible $P4_{\text{margin}}$ at every point would also yield the maximum possible efficiency, making it seem as if this DP also settles the efficiency FR, but that is not so because of the following requirement that was not recognized in the design of Fig. 2. Because of decreasing air density with altitude, the air mass flow entering the intake at 1.4 km is about 3 times the prescribed mass flow at 14.5 km, so the nozzle throat area must adjust from a higher value at low altitude gradually decreasing to a lower setting at high altitude to accommodate the varying air mass flow. Thus, the efficiency FR must be met by two independent DPs, the bias setting of the nozzle throat area A_8^{bias} and $P4_{\text{margin}}$. Subsequently, the performance FR can be met by additionally prescribing a desired variation of Mach number and altitude with time, which forms the third DP for this design.

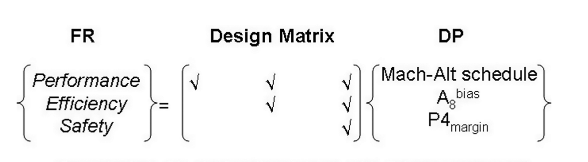

Fig. 3 Conceptual design solution using axiomatic design principles.

[†]In an academic exercise, this constraint was relaxed by assuming sensed static temperature at the nozzle throat $T8$ to be available, thus allowing the performance loop to be closed. The second problem persisted.

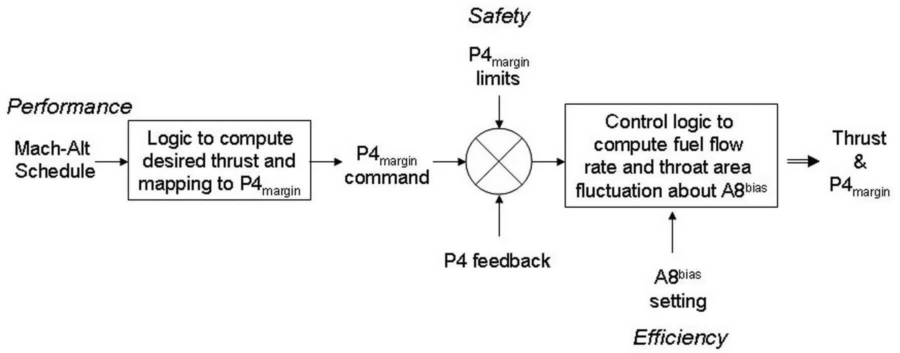

Fig. 4 Controller realized based on the conceptual design in Fig. 3.

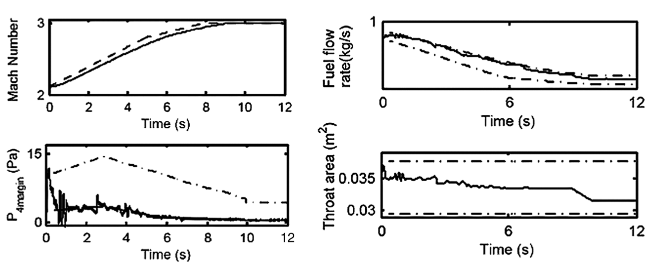

Fig. 5 Result of final design based on the conceptual design in Fig. 3.

Effectively, this conceptual design has mapped the FRs onto the DPs, as shown succinctly by the relationship in Fig. 3. The mapping is represented in terms of the Design Matrix which can be seen to be triangular, the √ marks indicating significant interrelationship between the respective FR and DP. This triangular structure is typical of decoupled systems (obeying Corollary 1) and captures the fact that the FRs may be met sequentially by varying the DPs one at a time. Thus, once DP#3 is frozen after being selected to meet FR#3 in Fig. 3, DP#2 alone will satisfy FR#2, and so on. The constraint requiring only a single loop to be closed is in keeping with Axiom 2 which calls for minimizing the information content–using two sets of measurement where one will suffice does not lead to a "good" design.

The DPs with the constraint in Fig. 3 now form the FRs passed on to the control designer to realize this conceptual design. This is typical of the hierarchy between FRs and DPs in the design process [4]. For the record, an innovative, single-loop (to satisfy the constraint in Fig. 3) control design for this problem was successfully realized taking DP#1 in Fig. 3 as the FR, and the other two DPs as constraints, as sketched in Fig. 4. Technical details of that controller design have been reported in [10], but a few key results are reproduced in Fig. 5. The dashed Mach number line is DP#1, the set of dash-dot $P4_{\mathrm{margin}}$ lines is DP#3, with the full lines being the actual controller simulation outputs. Disturbances are because of atmospheric turbulence and pressure fluctuations internal to the engine. The variation of DP#2, A_8^{bias}, is seen in the throat area plot. The output of the controller design is the fuel flow rate schedule during flight, which now changes in such a way that the original set of performance, efficiency, and safety requirements are all met.

V. Conclusions

The example presented in this paper highlights how a highly nonintuitive but successful design can be conceived by using a few systematic principles. Note that axiomatic design theory does not provide a set of tools to compute the DPs for a problem; that is left to the ingenuity and skill of the system designer. What axiomatic theory does is to provide a set of principles that when used sensibly can help the designer eliminate faulty designs and guide him/her toward a good design like the example in this paper. A competent designer might possibly have independently arrived at the same conclusions, but then he/she would have been implicitly applying precisely the same principles as those put forth by axiomatic theory. Thus, axiomatic theory in a way merely formalizes good design thinking and should find more application in the complex world of aerospace systems.

References

[1] Moir, I., and Seabridge, A., *Design and Development of Aircraft Systems: An Introduction*, AIAA Education Series, AIAA, Reston, VA, 2004, pp. 1–65.

[2] Price, M., Raghunathan, S., and Curran, R., "An Integrated Systems Engineering Approach to Aircraft Design," *Progress in Aerospace Sciences*, Vol. 42, No. 4, June 2006, pp. 331–376. doi:10.1016/j.paerosci.2006.11.002

[3] Mane, M., Crossley, W. A., and Nusawardhana, "System-of-Systems Inspired Aircraft Sizing and Airline Resource Allocation via Decomposition," *Journal of Aircraft*, Vol. 44, No. 4, July–Aug. 2007, pp. 1222–1235. doi:10.2514/1.26333

[4] Suh, N. P., *The Principles of Design*, Oxford Univ. Press, Oxford, England, 1990, pp. 46–70.

[5] Suh, N. P., *Axiomatic Design: Advances and Applications*, Oxford Univ. Press, Oxford, England, 2001, pp. 1–124.

[6] Brown, C. A., "Teaching Axiomatic Design to Engineers-Theory, Applications, and Software," *Journal of Manufacturing Systems*, Vol. 24, No. 3, 2006, pp. 186–195. doi:10.1016/S0278-6125(06)80007-5

[7] Gupta, N. K., Gupta, B. K., Ananthkrishnan, N., Shevare, G. R., Park, I. S., and Yoon, H. G., "Integrated Modeling and Simulation of an Airbreathing Combustion System Dynamics," AIAA Paper 2007-6374, Aug. 2007.

[8] Boksenbaum, A. S., and Novik, D., "Control Requirements and Control Parameters for a Ram Jet with Variable-Area Exhaust Nozzle," NACA RM E8H24, Nov 1948.

[9] Harner, K. I., and Patrick, J. P., "Control Systems Requirements for Advanced Ramjet Engines," AIAA Paper 1878-1056, Jul. 1978.

[10] Bharani Chandra, K. P., Gupta, N. K., Ananthkrishnan, N., Park, I. S., and Yoon, H. G., "Modeling, Simulation, and Controller Design for an Air-breathing Combustion System," *Journal of Propulsion and Power*, Vol. 26, No. 3, 2010, pp. 562–574. doi:10.2514/1.42368