Concept: Aircraft Design

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1. Definition and Introduction

Aircraft designers innovate solutions that meet the requirements that are specified by customers for flight vehicles. Design is the process whereby the concept for a new aircraft is born, and developed to the point where it is shown to be feasible to build, and viable to operate safely. Aircraft design starts with some well-considered guesses about what can be achieved, and then develops through a systematic process. At the end of the first pass of this process, the results from the design are checked against the requirements, and the initial guesses are refined, and innovations added, until the design is found to be appropriate for the specified needs. Following this conceptual design process, the uncertainty in each step is reduced through analyses and test results of increasing sophistication, in a Preliminary Design iteration cycle. The preliminary design is subjected to stringent scrutiny, before going on to use much more expensive and extensive analyses and synthesis to develop the detailed design. Modern design cycles take the process through a detailed consideration of the entire life-cycle of the proposed vehicle, estimating the business case for the project in as detailed a manner as possible. Model tests, and construction of protptypes, precede the development of the machine tools and production facilities for routine production. Designers must stay involved in the process through the end of flight testing the initial vehicles from the production line.

2. Steps in Conceptual Design

Conceptual design is an iterative process. We start with a guess of the payload fraction, which is the payload weight divided by the takeoff weight of the aircraft. This guess and a few other thumb rules are based on the benchmarking process, where the designer starts with data on what has already been proven feasible, and then projects what will be possible. Based on these decisions, the fuel load required to meet the range requirement is determined. By the time this is done, all other weights have been guessed or determined, except for the structure weight. The structure fraction, which is the structure weight of the aircraft divided by the takeoff gross weight, is then compared against the minimum structure fraction that the designer believes to be essential to build the vehicle using the technology that will be available. If the available fraction exceeds the minimum, then the design is basically feasible. Otherwise, the payload fraction must be reduced, or some other way found. Beyond determining this basic feasibility, the designer determines the parameters needed to ensure stability and controllability of the vehicle, so that small disturbances do not upset the equilibrium of its flight, and yet there is enough power available to control the vehicle through the most demanding maneuvers that are anticipated. It is after all these are done that the designer must decide the external configuration of the aircraft, and then its internal layout. Below we take each of the stages of the design process in turn.

2.1. Requirements Definition

The first step in designing a flight vehicle is to define why it is needed, and what it must do. A thorough analysis of what would attract customers and make the vehicle succeed in its market, and a good understanding of why existing solutions or competitors solutions will not meet these needs, leads to a careful definition of the actual requirements. While exceeding these requirements in the design sounds good, it may be a fatal mistake in the marketplace to exceed the requirements by a long margin, because this usually comes at some high cost. The example of a new airliner is used in the following, because most people have seen airliners and many have flown on them. The aircraft developer company conducts discussions with the airlines, which are their prime customers, to decide where the best market opportunities may be. They also conduct their own surveys of demographics and economics, to better understand the passengers who will buy the airline tickets and travel on the aircraft. Predictions of economic growth, the availability and costs of different fuels, the opening or closing of routes, and the prospects of making sales to various airlines and other customers of the design, all enter the Requirements Definition. A few examples of questions to answer are: What should be the passenger capacity of the vehicle? What airport landing field lengths are available, and what are weight limit, noise and curfew restrictions at the various airports that are essential? What flight speed is best?

2.2. Benchmarking

As part of the research done to define requirements, the capabilities of existing vehicles, and the projected capabilities of technology available by the time the vehicle must be built, are laid out. These data give the designer a good set of upper and lower bounds, to reduce the uncertainty in making decisions during the design process. Below we will see where the benchmarks come into play.

2.3. Mission definition

Based on the requirements definition, a reference mission for the vehicle is carefully developed. This again must be developed to pose the right requirements.

2.4. Payload Estimation, or What Do You Mean You Can't Carry Us All?

All the items that must be carried on the mission will come into this category whether they pay or not. In the case of passengers, baggage and other such variable items, statistical averages must be used, knowing that enough margin must be allowed for extreme combinations. For instance, if you have an airplane that can carry X passengers and their baggage for a certain distance, and one day the requirement is to carry an entire pro football team and their heavyweight wrestler friends on a skiiing vacation high up in the mountains under icing conditions, you will be in an uncomfortable situation unless you have planned for enough margin.

2.5. Initial Weight Estimation

There are many ways of doing the first weight estimation, and this is usually an eye-opener to students. One cannot estimate all the other things such as wing area and engine thrust unless one knows the total weight, so one cannot wait until the end and sum up all the components. Instead, a quick estimate is needed at the beginning. This is generally done by benchmarking, or seeing what happened when other people in the past set out to design vehicles in the same general class. How much was their payload, and what was the total weight? The ratio of payload to total weight is the Payload Fraction. Once one obtains a reasonable estimate for this, one simply divides the payload by this to get the first estimate of total weight. This will be refined as all the component weights come in, much later.

2.6. Aerodynamic Design

Unlike other types of vehicles, aircraft operating on aerodynamic lift have a non-zero speed for minimum drag. This is because sufficient lift must be produced to balance the weight. The lift-induced drag rises at low speeds because higher lift coefficients are needed to maintain sufficient lift. At higher speeds, induced drag is low, but the profile drag rises. Thus the speed for minimum drag is the speed where the lift-induced drag and the profile drag are equal, each being half of the total drag. Higher wing aspect ratio helps to reduce induced drag coefficients and thus push the speed for minimum drag lower, while streamlining to minimize flow separation and turbulent skin friction, reduce the profile drag, and push the speed for minimum drag higher.

2.7. Propulsion design

In a first iteration, the design may be performed using an existing engine or set of engines, whose performance and fuel demands are therefore known. This process may start by estimating the thrust needed at takeoff, which is usually the most demanding situation. A condition for certification of a multi-engined aircraft is that it must be able to takeoff and return to the airfield if one engine fails at the worst possible time. A rule of thumb is that a fixed wing aircraft must have installed thrust at least equal to one-third of its gross weight. With this guidance, one can select engines, and obtain their thrust lapse rate, of the rate at which their thrust decreases as altitude increases. This is roughly proportional to air density, but may be more involved for complex engines such as turbofans.

2.8. Range

The range of an aircraft is the distance flown before the fuel reserve falls below that required to maintain sufficient margin of safety. The range is found by integrating the distance travelled per unit fuel expended per unit thrust (this is the reciprocal of the thrust-specific fuel consumption), from the starting total weight with full fuel, to the weight with only the minimum reserve of fuel left. As weight changes, the speed, altitude or both may change, so there are multiple choices of flight profile. Similarly, the endurance is given by the total amount of time for which the aircraft stays in straight and level flight before the fuel is exhausted. One choice is to fly at maximum Lift/Drag ratio, where the speed is held at the speed for minimum drag. This would give best endurance.The speed for highest range is usually higher than that for maximum endurance.

2.9. Steady Flight Envelope

Once it is determined that the conceptual design "closes" as in being able to do its mission with the given payload and speed, the limiting conditions where the aircraft can operate under steady level flight conditions, can be determined. These limits constitute the boundaries of the steady flight envelope, and and typically expressed on a chart of altitude versus speed. The maneuvering flight envelope defines the limits imposed by the "load factor" encountered during maneuvers at various altitudes and speeds.

2.10. Configuration, Stability and Control

Note that everything above was done before one had to make decisions on the configuration, i.e., how the craft looks. Now one has to decide this, so that control surfaces can be placed and sized to provide the required margins of stability and control. Aircraft are said to be stable if a small disturbance causes a restoring force or moment that returns the craft to its former undisturbed flight condition. Static stability can be ensured by placing the center of gravity ahead of the center of pressure. This also increases the amount of power required to maneuver the aircraft. High-performance aircraft such as modern fighter aircraft are statically neutral or even unstable, but are able to fly with computer-augmented flight stability, where small disturbances are immediately countered by restoring control deflections.

2.11. Structures

The vehicle must be built to be strong enough to withstand the loads that are expected, with a good margin of safety. Aerospace engineers rarely have the luxury of designing with a large factor of safety, because minimizing weight is always a priority. Thus loads must be known to good certainty. Aerospace vehicle components are designed to withstand a certain "g" level, defined as the ratio of acceleration compared to the standard acceleration due to gravity.

One way of determining whether a given design "closes" is to see what fraction of the total weight remains after all the other components such as payload, engines and fuel are accounted for. The minimum weight fraction that is needed to build a vehicle, can be estimated based on values for recent vehicles of the same general mission characteristics. For example, the best that can be done with metal structure for a large commercial airliner, may be around 27 percent. Going to composite materials for major structural components is still considered to be a risky decision, because fabricating composite parts of complex geometry is still quite difficult and prone to imperfections.

2.12. Lifecycle Cost

One way of determining the excellence of a vehicle design is to estimate the entire lifecycle cost from initial design to disposal at the end of the useful life of the vehicle.

2.13. Scale Model Validation

Once the configuration is fixed, models of smaller scale are built for various purposes. One purpose is to build models that can be tested in wind tunnels, to obtain results on the aerodynamics, stability and control that are then extrapolated to full-scale values at flight conditions. Several geometric modifications may have to be made at this stage. Wind tunnel testing helps to refine the estimate of the drag coefficient, and hence the range and fuel efficiency of the vehicle.

Other components of the design process are enumerated below:

1. Preliminary Design
2. Detailed Design
3. Production Design
4. Infrastructure Design
5. Optimization

3. Supersets

System Design, Design of System of Systems

4. Subsets

Conceptual Design, Preliminary Design, Lifecycle Cost Optimization, Detailed Design.

5. Other fields

Spacecraft Design. Systems Design. Propulsion Design. Multidisciplinary Design Optimization.

6. Notes

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7. Byline

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