The Design of Rotary Wing Aircraft – The Combination of Disciplines - A University Perspective

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Abstract

The role of design has always been central in aircraft education and research. Indeed, it forms the main coordinating theme throughout the aerospace industry. It is therefore of major importance that the formative years of undergraduate and postgraduate engineering education should be firmly grounded in a full appreciation of the design process. Apart from the immediate payoff of how industry operates, the aspects of design have the unique ability to link all of the separate disciplines into the final air vehicle and thereby provide the holistic interpretation of these subjects.

The mechanism of teaching the basic aerospace topics and their mutual interaction has been under major review at Southampton. This has been evolving over a number of years and has led to several initiatives funded by the government and industry.

The paper will discuss how the design process has been used to provide a central spine to the course structure and how recent IT developments have allowed a full appreciation of aircraft design and development to be achieved in the minds of students from the initial need to the specification and then to the various design phases. Finally the students are now able to proceed with their design to the stage where they can be viewed as a mock-up; then moving to a full flying test programme on a simulator with the ability to review the flight data and to make appropriate modifications.

Further development of these facilities has led to the process being extended to areas of postgraduate research. Operational situations have been used to test aircraft behaviour on the simulator. The ease with which the test conditions can be synthesized has permitted the influence of these operations on the air vehicle design to be rapidly assessed. In this way, the loop can be closed from aircraft design to the operational need.

An example of this is presented as helicopter operation from the rear flight deck of ships. The aerodynamic interaction and the use of simulation in providing the air vehicle behaviour can influence the aircraft design and that of the ship from which the aircraft is operating.

The paper will outline the various ways in which we have refined the use of these techniques in design teaching and also how they are providing an important feedback mechanism for research into rotary wing operations.

Introduction

The word design has many perceptions but, as an example, the Oxford English Dictionary provides the following starting point.

Design - Contrivance in accordance with a preconceived plan.

This definition makes the essential point that there are constraints placed on the concept at the outset and the eventual result of the work must satisfy these requirements. The idea that a designer has complete freedom to do as they please does not really fit in with the above definition. The concept of engineering design at least must follow this principle since the ultimate goal is a saleable product, which fits the customers' needs. Bankruptcy is the only other option!

The development and production of an aircraft (or in fact, any commercial product) generates a broader demand for design processes than is normally recognised. Design may be thought to apply purely to the product itself and the design process to conclude with the emergence of a saleable item (even if that item is subsequently refined in the light of experience). Furthermore, it may be thought that the design process is relevant to the product solely to achieve its efficient operation - in the case of an aircraft, to enable it to meet certain combat requirements, to transport cargo or passengers or to perform other operations with optimum economy.

Only rarely now are commercial products produced in limited quantities by isolated individuals or very small groups. Modern mass-production processes, particularly in engineering, tend to require the resources of sizeable organisations. Each organisation generates design needs far beyond the immediate considerations of any current product. As for the product itself - in a competitive, fast-moving commercial environment, the chances of it having been designed in isolation, as a new venture, will be extremely slim. Most products are developed from an earlier version (perhaps in competition with someone else's) or to form part of a range of products which share some common characteristics.

Figure 1 - House Style - Great Western Railway

The most successful companies recognise the complexity of design (in all its forms), exploit design as a valuable resource and duly allocate responsibility for design management at senior level. Design is applied to every aspect of the company's operation - its products, working environments, communications, vehicle liveries and particularly to anything which provides an opportunity to make a company "statement". What may be termed “House Style”.

It could hardly have been coincidence that the greatly admired Great Western Railway (GWR) steam locomotives shared impressive visual characteristics (including the predominantly green livery) - their mechanical qualities representing perfectly the dignity and the pride of their owners. Figure 1 shows an example of a prairie tank locomotive of GWR. The chimney and safety valve are typical of GWR.

Where design is effectively managed, the product, the company and its image are almost one and the same thing. Such breadth of design activity is more than cosmetic. It indicates a pursuit of excellence and calls for more than forward (or single-dimension) thinking. It demands all-round awareness which demolishes old established working boundaries. When complete, most aircraft are not only identified by maker and operator, but they also carry numerous instructions for the purposes of safety and efficiency. It is an important fact that the clearer are those requirements, the less problematic will be their introduction into service.

Mechanical Engineering Design

The Engineering Design process has been the subject of analysis for a number of years. Many attempts at formulating a ‘design process’ have been made, but they are usually based on speculative principles that are supposed to give definitive solutions. Examples have been tried but are unable to solve design problems and have therefore been discarded. These and other attempts have been made to produce a usable system but the analysis of a design engineer’s thought process has always been difficult to achieve. The problem with any system that tries to establish a pre-determined thought process is that it is by nature very restrictive, the very thing that needs to be prevented. However there are several points in the thought process which can be identified. Whilst design is a constant procedure of speculation, evaluation and providing solutions, there are always fundamental decisions to be made throughout the process. These fundamental or key decisions must therefore be identified and made from the initial concept through to the conclusion of the design process. The Key Decisions together with all subsequent minor decisions formulate what follows in the design process. Most of the Primary Key Decisions can be made as a result of the 'Requirement' but these decisions will inevitably lead to other areas where Key Decisions will have to be made. For instance, detail design as part of an overall project, can be a process of constant optimisation, the starting point of which can be influenced by many sets of circumstances. However it is probable that a Primary Key Decision will have been made before the process can start and several more will have to be made as the design progresses. The experience of the 'Designer' or Design Team can be a vital factor in the process. If the criteria involved in the requirement have been met previously by the Designer or Team, experience gained on similar work can be extremely useful. However this 'previous experience' may also be a serious obstacle. It is sometimes taken for granted that if it worked before, it will work again. This assumption can lead to disastrous consequences, as the controlling circumstances may not be exactly repeated.

Analysis of the Engineering Design Process

The following phases of the Engineering Design Process are shown schematically in Figure 2.

Requirement This is determined by the customer and will formalise the need.

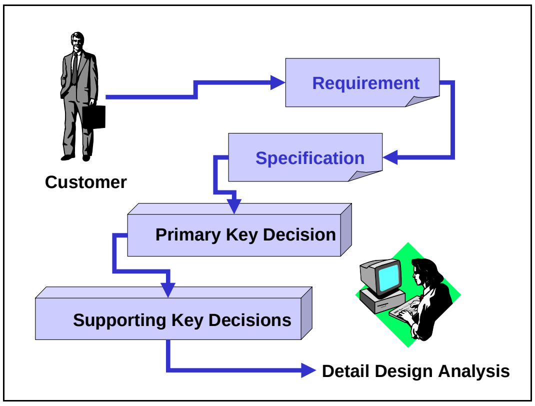

Figure 2 - Engineering Design Process

Specification The formal process that identifies and sets out the parameters developed from the Requirement. These parameters need to be identified and complied with in order to satisfy the requirement.

Primary Key Decision This is the decision following which the basic form of the design is frozen and on which all subsequent design considerations are based. It is essential that the Primary Key Decision is carefully considered and researched. Preliminary analysis and evaluation is usually necessary before the point is reached where the Design is frozen.

Supporting Key Decisions These are based on the Primary Key Decision and are therefore a means of progressing the design.

Detail Design Analysis Emphasis is placed on linking the design process to manufacture and creating the schemes that will eventually lead to the component drawings being produced.

Interface with manufacture The interface is usually the manufacturing drawings that will be used to produce the components. This process will of course include the assembly and sub-assembly drawings. However if parametric CAD/CAM software is used as the interface, actual hard copy detail drawings may not be necessary for actual manufacture, but they still may be required for legal purposes. The component can be drawn on CAD transferred into CAM and then downloaded straight into a CNC machine – see Figure 3.

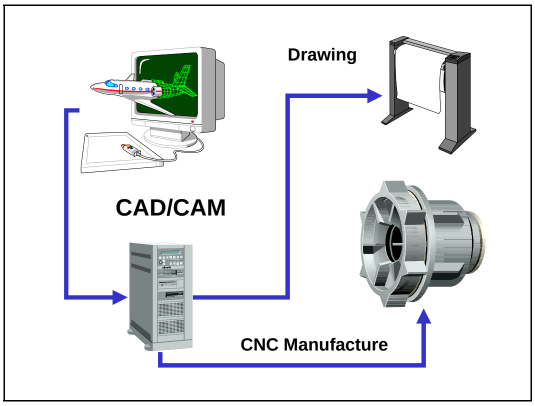

Figure 3 - Interface with Manufacturing

All of the above are necessary steps in the Engineering design process. If any areas are omitted then the process will be more open to failure. Many classic mistakes have been made because Key Decisions have not been correctly identified and implemented. In addition, Engineering Design should always be linked to eventual manufacture; it is impossible to separate the processes. If this is not the case then it is possible that expensive errors will result and also second best manufacture will take place.

Summary

To summarise, the area that needs most careful consideration is the Primary Key Decision. All subsequent work relies entirely on the expertise and knowledge of the person or persons making this decision. All subsequent detail design is locked into an almost irreversible process once the Primary Key Decision has been made and implemented. The area that involves the Primary Key Decision has therefore to be identified and very careful attention paid to the solution. Once this step has been taken, all subsequent supporting decisions can be addressed in a carefully selected sequence.

It is at this point that the design will be linked to manufacture. This involves making sure that what is designed from here on is not only capable of being manufactured but is the most cost effective and efficient means of manufacture available. This means that the materials and manufacturing process or processes have to be implicit in the design and must be within the capabilities of the supplier. It is of course possible that several alternative means of manufacture of components may be possible and these processes need to be identified at this point. Each component in the design needs to have a possible source of supply. Components can of course be specifically manufactured and unique to this particular assembly, or alternatively may be best purchased from a supplier as completed 'off the shelf' items.

The above process will usually result in a prototype from which subsequent production components can be evolved. It may be necessary to produce several prototypes, encompassing alternative detail designs or manufacturing processes. It is however unlikely that the original Primary Key Decision will be changed as this would involve a new thought process all the way through from the start of the project.
Engineering Design can be compared to compiling a crossword, it involves formulating inter - linked questions and answers to achieve an overall result.

Applications to Teaching

The above discussion shows that the ability to combine often-conflicting aspects of a design to satisfy a supplied specification is a natural occurrence in many types of subject area. This is particularly true for engineering. With this in mind, any future developments of teaching methods, with particular emphasis on higher education, will require the emerging graduate to be skilled in the integration of various subjects contributing to the overall design exercise. This is of particular prominence in the aircraft industry where work practices have moved towards the Integrated Project Team. Here, a team works in tandem towards a specific goal and is therefore required to be able to combine the many differing aspects into the overall vehicle. At the same time, the ability of the emerging design must always be capable of performing to the specification. This will not always be the case; in fact this is the probable situation, so the team must be skilled in how the various aspects interact to decide on the best way forward. Without a close understanding of the various technical factors and their effect on the final vehicle, this phase of the design process is not possible. It is therefore imperative that aerospace engineering courses contain a high proportion of appropriate subjects and their mutual interaction.

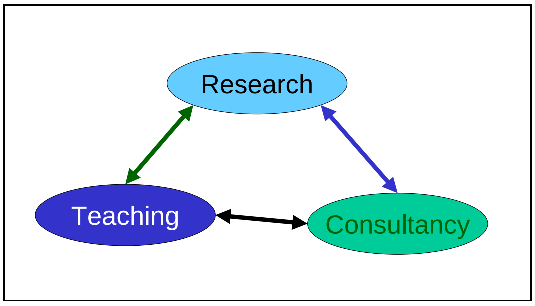

Figure 4 - Relationship of Teaching

If a teaching course is to fulfill the objectives already discussed, it is of major importance that the course content is current and contains the latest developments in the appropriate disciplines. Higher education is at its best when a threefold relationship is developed between teaching, research and consultancy. This is shown diagrammatically in Figure 4.

The course must also develop throughout the undergraduate's career. This is achieved firstly by providing firm foundations in the basic subjects. To this is added an increasing depth and scope of this knowledge. Finally, it must encourage the undergraduate in their final year(s) to develop the ability to undertake a piece of project work. The purpose of this aspect is to demonstrate the undergraduate's capability to complete this project either individually or in a team, prepare a technical presentation and to write a comprehensive but concise report. Such a scheme, over four years, is summarised below.

- Part I General Introduction
- Part II Detailed Application
- Part III Individual Project Work
- Part IV Group Project Work

In the case of an aeronautics course these can be highlighted by the following example syllabus. At the beginning there is mainly lectures and laboratory exercises. Project work forms a relatively small part of the year. As the student progresses, the course character changes towards the final year where laboratory work is virtually eliminated and specific lectured course undertaken. The majority of the work is of a project nature. This is shown schematically in Figure 5.

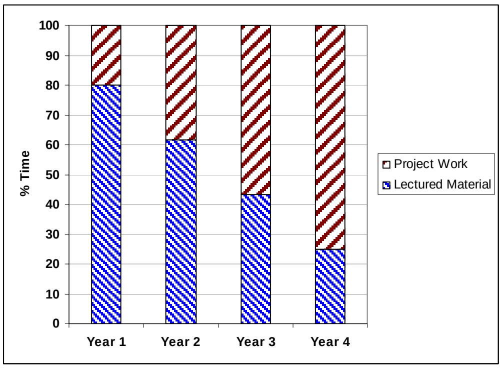

Figure 5 - Schematic of Lecture/Project Course Content

- <u>Teaching - Part I</u>

First Year - Basic Introduction

- ❑ Aircraft Operations
  This provides an understanding of the overall aerospace environment in which an air vehicle has to operate.

- ❑ Aircraft Control

  It is essential that an aircraft flies in a predictable and controllable manner. This course must provide the basic understanding.

- ❑ Design - Design, Build & Test

  This allows the student their first experience of designing on a computer and to take a design through a simple development, build and test programme.

- ❑ Mechanics of Flight

  This is the fundamental aerospace discipline. It encompasses aircraft performance and behaviour from ground roll to safe landing. It is in this course that the idea of compromise must be introduced.

- <u>Teaching - Part II</u>

Second Year - Introduction of Depth and Scope

This year is often termed the "blues year" in the accepted studies of teaching methods. The students are aware of the outside world and therefore subject to distractions. Also they have spent their school years plus the first undergraduate year in study and now have the culture shock of deeper methodology added to their workload. This brings about the idea of "conceptual overload". The pressure of learning is beginning to take its toll and the new found confidence of a year on their own gives them the impetus to drift away to other less stressful lives. It is at this point that they are given relief of this pressure by introducing them to how the various new topics are not in isolation but have a common purpose. This will demonstrate how the new-found knowledge interacts together using examples of engineering design.

The subjects covered are obvious in an aerospace context but the final topic should provide exposure to the interactions.

- ❑ Aerodynamics
- ❑ Propulsion
- ❑ Structures
- ❑ Aircraft System Design

Teaching - Part III

Third Year - Option Selection & Individual Project Work

It is at this point in the aerospace course that the undergraduate should be allowed to choose the future syllabus. Totally free choice is often not possible through time constraints but themed option selection can help avoid clashes. It is at this point that the student can stamp his or her own personality on the learning process.

- Avionics
- Aircraft Dynamics, Stability & Control
- Aircraft Design Group Project
- Individual Research Projects

- ## Teaching - Part IV

Fourth Year - Detailed and Exacting Project and Design Work

For the fourth year, which is used for Masters undergraduates, the design process should provide deep and exacting group work. They must be able to organise their work together and to keep detailed records of their progress. Reports must be of the highest standard and the resulting work will be examined under intense scrutiny. This is the point where the gloves come off and they have to deal with the design process - warts and all!

- Aircraft Design Synthesis
- Group Design Projects

The mechanism of achieving such a course development must now be defined. The exact details will depend heavily on the staff subject area, experience, and exposure to industrial work. An example of how it has been under development at Southampton is now described.

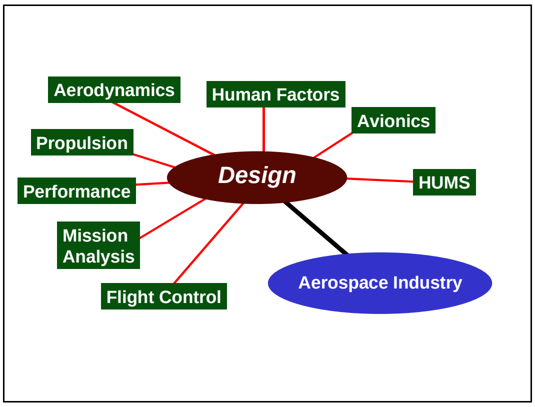

Figure 6 - Design in the Syllabus

Figure 6 shows how the design aspect interacts with the various aerospace topics, which need to be covered. It also shows the link to industry. This can take various forms of which student placements are a very important feature. If a standard approach is taken then any design will provide an amount of theoretical development, some experimental testing such as a wind tunnel and calculations confirming that the specified mission(s) can be completed. This technique falls short on two main grounds. Firstly the modern manufacturing process is not addressed in great detail and the ultimate flight testing of the final design has not taken place. By providing the means to achieve these extra goals the concept of frozen designs and feedback of actual data into the design loop can be addressed.

Figure 7 shows how the various facilities at Southampton have been assembled to provide these features.

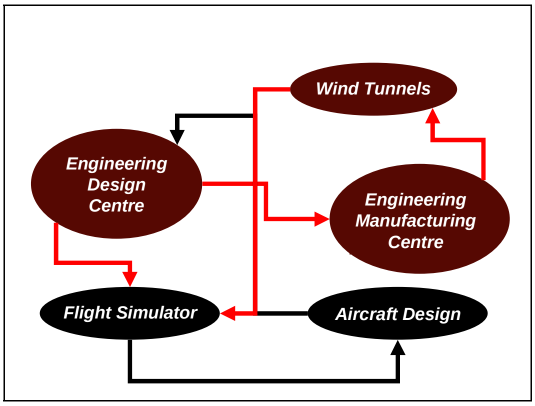

Figure 7 - Design Teaching Facilities

The flight-testing is now available using a flight simulator. A full-blown facility is extremely expensive but in recent times, PC computing power has increased and off the shelf software is readily and economically available. Add-ons are available which permit a design to be incorporated into the aircraft and indeed the scenery. This allows a specific airfield to be used or a test marker sequence to be laid out for exact testing. Also available is the ability to record the aircraft performance during the test allowing the performance to be obtained quantitatively. The Southampton facility has the provision for fixed and rotary wing controls to be used. Figure 8 shows the latter installation. Figure 9 shows two views of the simulator in action in the early development phase, one from the cockpit and one a general view of a helicopter operating from a ship.

Collective Pitch Control

Cyclic Pitch Control

Figure 8 - The Helicopter Cockpit of the Flight Simulator

Approaching an Aircraft Carrier

Flight of a Sea King past a Type 23 +Frigate

Figure 9 - Views from the Helicopter Cockpit

Figure 10 shows the interaction between the various disciplines to support the design studies on such a simulator facility. As can be seen, all of the various technical disciplines introduced during the earlier course syllabus can be included. It is at this point that the integration of the various disciplines come together. It provides the experience of working in an Integrated Project Team - preparing them for the future so that modern aerospace technology is not a surprise.

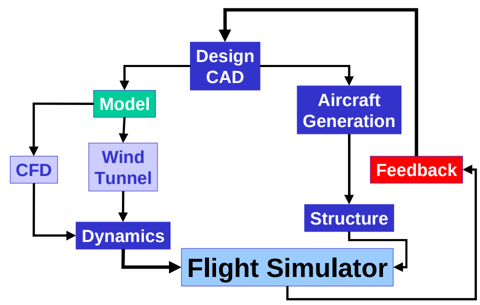

Figure 10 - Aircraft Design Interaction

Case Studies

In order to illustrate this process and how Southampton has developed its design teaching, three case studies are presented. They are of a helicopter design for specific mission requirements, two in isolation and firstly, one forming a fixed/rotary wing combination.

Queen's Flight

The first case study was aimed at replacing the Queen's Flight aircraft squadron with three aircraft:

- Helicopter – *Short Range (London – Balmoral)*

- Fixed Wing – *3,000 nm*

- Fixed Wing – *6,000 nm*

Each aircraft had a design group associated with it and all three groups interacted with the other two to provide a working combination to form the new squadron.

The helicopter design required some unexpected design decisions to be made. The flight from Kensington Palace in London to Balmoral Castle in Scotland was required to be flown in 90 minutes – which was determined by the “toilet factor”. (See Figure 11). The distance is approximately 350 nm which makes an overall speed of 240 kt necessary. This immediately put a flight speed constraint on the aircraft design which indicated that a more advanced variant was necessary. On that basis a thrust compound configuration was chosen. Propulsion was a tail mounted ducted fan with a spherical umbrella mechanism to direct the thrust laterally for yaw control. Lift compounding was not used as access to the aircraft would not be appropriate for the proposed users. The fuel requirement also had to allow the aircraft to leave Balmoral Castle and refuel at Aberdeen airport. This also formed the primary diversion.

Figure 11 - Range of Queen’s Flight Helicopter

The initial concept of the aircraft is shown in Figure 12. The fan driven compounding is shown at the end of the tail boom.

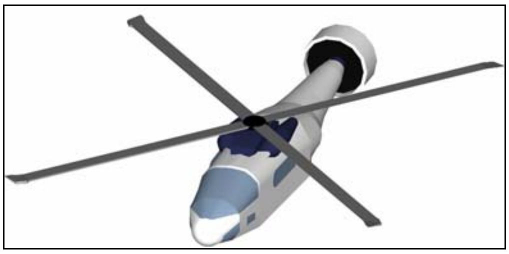

Figure 12 – Initial Concept of Queen’s Flight Helicopter

A military variant was also examined for possible product enhancement – Figure 13.

Figure 13 – Possible Military Variant

The final design layout is shown in Figures 14-16. Figure 14 shows the CG location; the mass and balance statement formed a vital part of the design study.

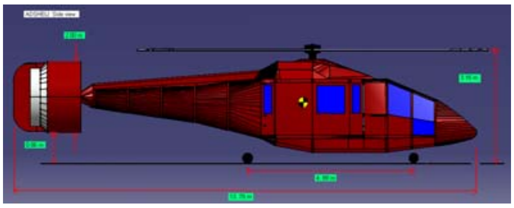

Figure 14 – Final Design – Side View

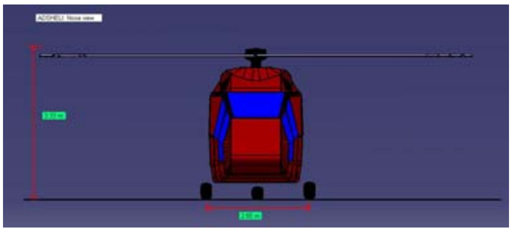

Figure 15 - Final Design – Front View

The rotor blades are presented in a “simplified form” as the overall design process was the focus. This aspect is covered in the work and the BERP type planform is used because of the higher speeds required of the design.

Figure 17 shows the ducted fan which provides the high speed required. Figure 18 shows what can be achieved regarding the final product where house style can be incorporated. Figures 19 & 20 show the structural details as constructed with a high-end CAM package.

Figure 21 shows how the internal layout forms an essential part of the work. The rule is:

The inside is always smaller than the outside!

The option of flotation bags for flights to mainland European destinations was also considered, as shown in Figure 22. Figures 23-25 show views of the aircraft whilst being flown on the flight simulator over London. The scenery was reasonably accurate but photographic scenery is now available which provides a far superior experience - as demonstrated in Figure 26.

Figure 27 shows the final brochure cover.

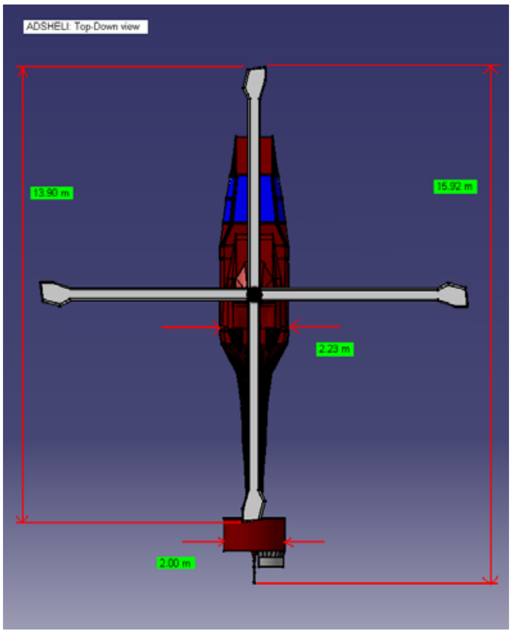

Figure 16 - Final Design – Plan View

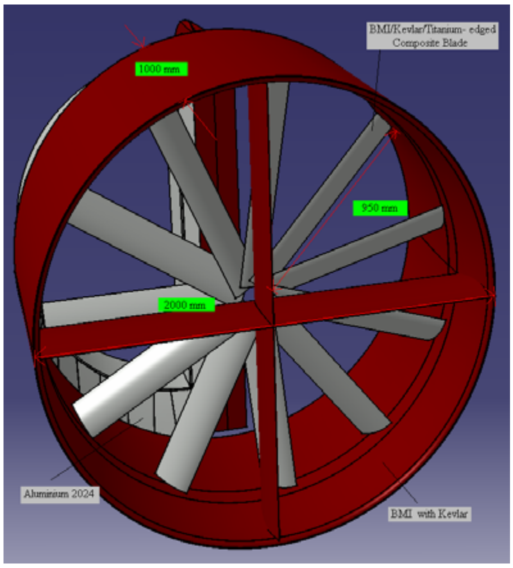

Figure 17 - Final Design – Fan Assembly

Figure 18 - Final Design – General View

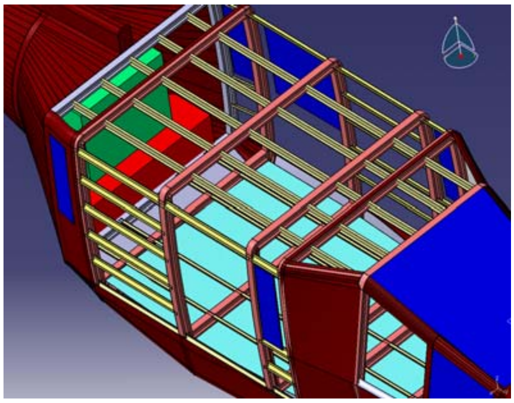

Figure 19 - Final Design – Interior Cabin Structure

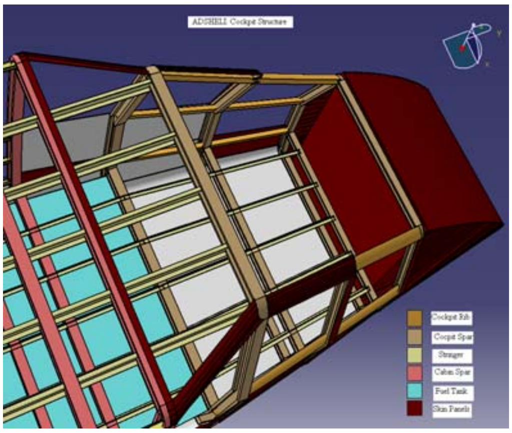

Figure 20 - Final Design – Interior Cockpit Structure

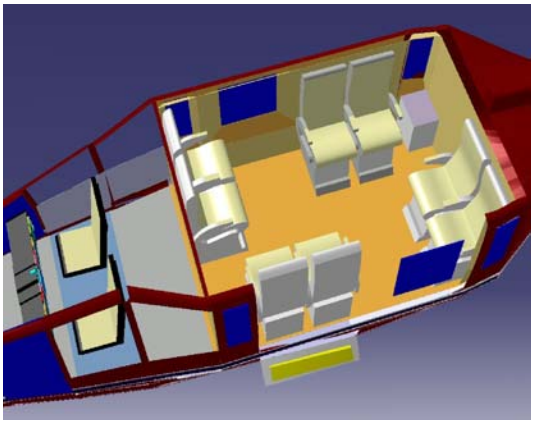

Figure 21 - Final Design – Complete Interior

Figure 22 - Final Design – Flotation Bags

Figure 23 - Simulator – General In-Flight View

Figure 24 - Simulator – In-Flight View (House of Commons)

Figure 25 - Simulator – In-Flight View (St Paul's Cathedral)

Figure 26 - Photographic Scenery of Central London

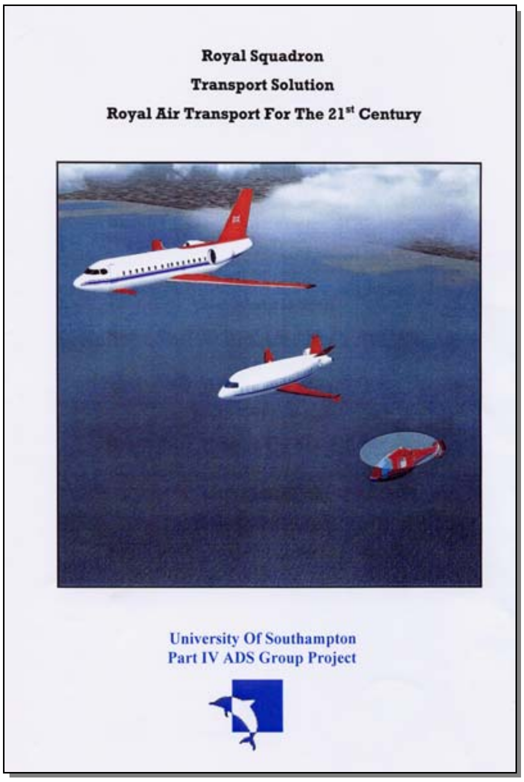

Figure 27 – Final Brochure Cover

High Altitude Rescue Helicopter

This formed an AHS Student Design theme. The high altitude requirements proved an interesting feature of this work as high hovering placed stringent demands on the tail rotor design. In addition, the design procedure could develop with newly available software. The blade construction was now part of the design brief. An example is shown in Figure 28. The final aircraft is shown in the simulator in Figure 29. This also shows a problem with some simulation packages of the undercarriage presentation. The software package "gmax" was now available to link in with Microsoft Flight Simulator and the screen view of the general arrangement is shown in Figure 30.

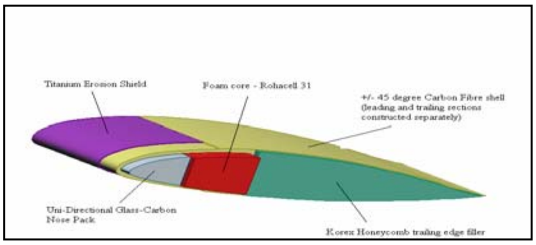

Figure 28 – Blade Manufacture

Figure 29 – High Altitude Helicopter - Simulation

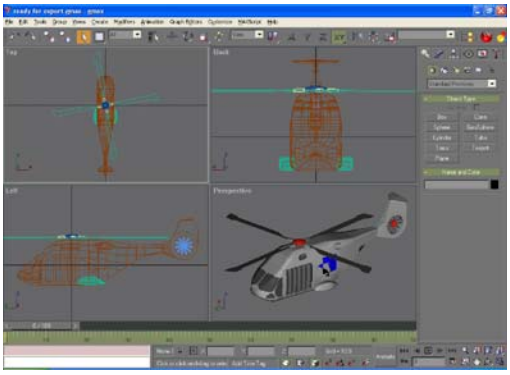

Figure 30 – gmax Design View

Figure 31 shows the aircraft operating in the mountains and demonstrates the use of weather definition in the simulator.

Figure 31 – High Altitude Helicopter – Simulator – Mountain Flight

VVIP Helicopter

The final case study is a VVIP helicopter. The early concept sketches are shown in Figure 32 & 33. These show the basic external view and that of the engine layout on top of the cabin. A three engine installation was chosen and the flow past the rotor head and engine housing was an important part of the work.

This example was not put on the simulator since a smaller number of students undertook the exercise. In addition, due to the experience of one member of the group, a CATIA based design was undertaken. Figures 34-37 show the CATIA views of the emerging design, both from an external viewpoint but also the detailed internal structure.

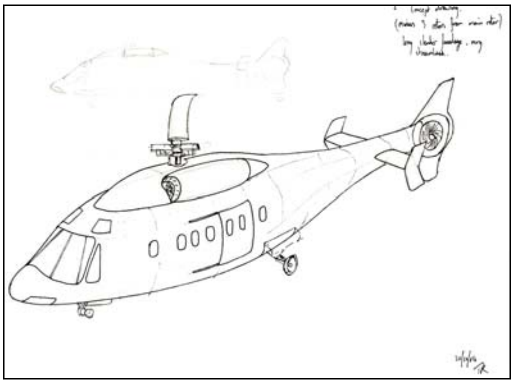

Figure 32 - VVIP Helicopter - First Sketch – General View

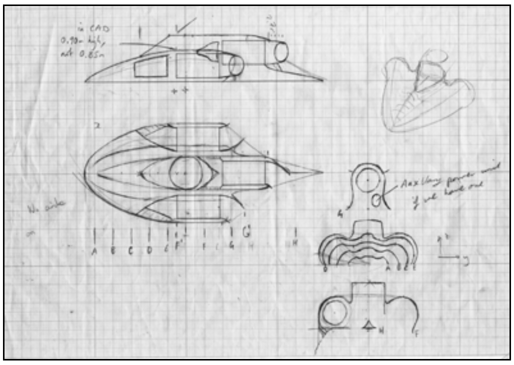

Figure 33 - VVIP Helicopter - First Sketch – Engine Deck View

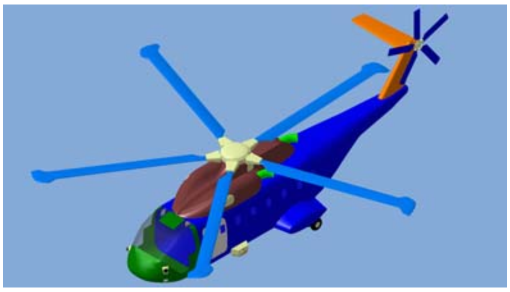

Figure 34 - VVIP Helicopter – Final General View - Front

Figure 35 - VVIP Helicopter – Final General View - Rear

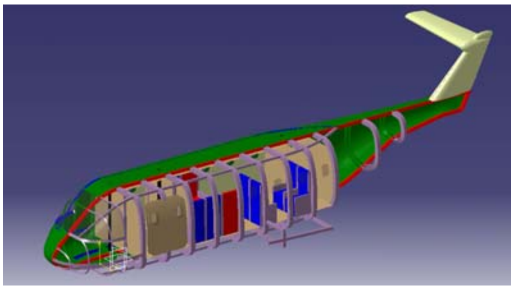

Figure 36 - VVIP Helicopter – Internal Structure View

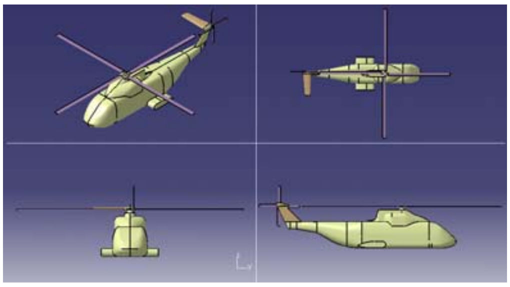

Figure 37 - VVIP Helicopter – CATIA Design View

Conclusions

As reviewed in the paper, the possibility of bringing together all aspects of aircraft design into one exercise is possible. Developing software enables the sophistication of the process to be very noteworthy. The linking in to a flight simulation package has enabled the realism of the final design to be assessed rigorously. The fidelity of the simulation for a very modest outlay has helped in the students' perception of the validity of their work.

The final product is not the aircraft but the graduate. They will always complain about the workload and the pressure of meeting deadlines, but they always comment favourably on the learning process. This is the important point; the final report is merely a mechanism for assessment.

The Future This paper has described a method of synthesizing the design process and producing a flying simulation at low cost. The latest developments in computer games technology have made the visual impression very sophisticated. What can now be envisaged is the use of these techniques in designing the aircraft within its operating environment. In this way, the design changes can be assessed by using the flying qualities of the aircraft and the effects of the environment. A particular example is the difficulties in operating a helicopter from the confines of a ship's flight deck. Early work on this problem is shown in Figure 38. Here a Bell 206 is being flown towards an aircraft carrier type ship. The simulation needs to involve the interaction of the rotor downwash with the ship airwake and vice versa. (This is an early version of the simulation package.)

In order to establish the ship airwake and its interaction with the helicopter, wind tunnel testing has taken place.

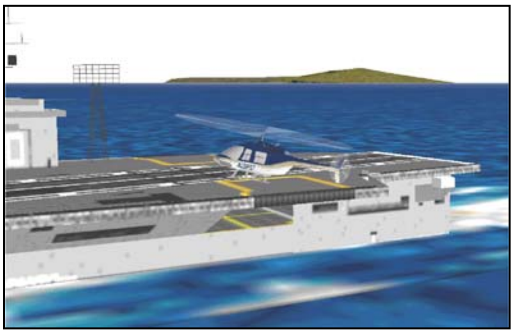

Figure 38 - Shipborne Helicopter Flight

Figure 39 shows a PIV test of a rotor /ship model combination in the wind tunnel.

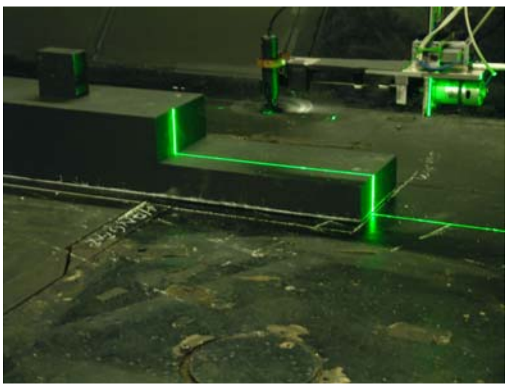

Figure 39 - PIV Rotor Ship Wind Tunnel Test Installation

Typical results of these tests show the flow patterns obtained down the central vertical plane of the flight deck.

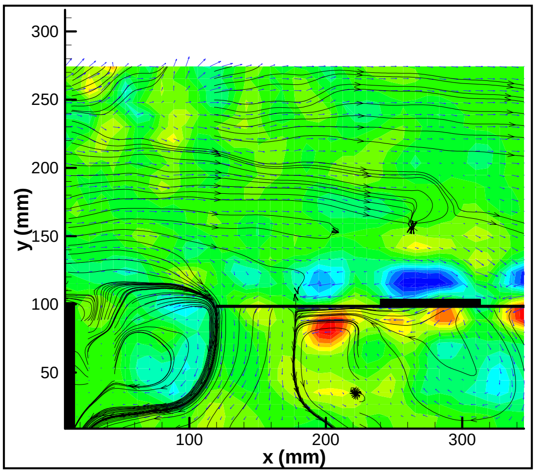

Figure 40 - Rotor Downwash / Ship Airwake Interaction

Figure 40 shows the recirculation at the front of the hangar face passing through the rotor. This situation is typical of the rotor just before touchdown on the deck.

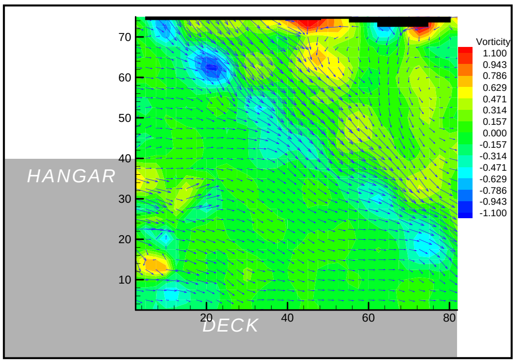

Figure 41 - Rotor Wake on Approach to Flight Deck

Figure 41 shows the PIV plot of the rotor vortex wake as the helicopter descends towards the flight deck. The forward edge of the wake is readily seen. The interaction with the flight deck is just commencing with vortices rolling along the deck surface towards the hangar and a gestating recirculating region forming at the foot of the hangar door.

The results of such tests can be used to model the atmospheric conditions around a ship's flight deck.

A suggestion for the incorporation into a flight simulation is shown in Figure 42.

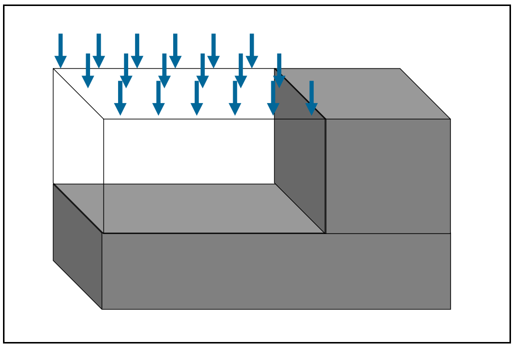

Figure 42 - Block Downflow Model

In this case, a 3D block is defined above the flight deck within which a downflow is invoked. This is a simplified model but can be extended to cater for more sophisticated results of wind tunnel tests. Indeed, the position of the aircraft above the flight deck is known to the simulation package and this can be interpreted to give the interaction between the rotor flow and the ship airwake. In this way the dynamic and aerodynamic situations of the helicopter and the ship can be linked via the simulation and any design changes – to both helicopter and/or ship – can be assessed in terms of the changing flight mechanics and handling qualities.

There is much to be achieved but the technology is there now – it requires effective application.

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