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A CONCEPTUAL DESIGN PROGRAM FOR EDUCATIONAL PURPOSES

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Abstract

A description is given of a helicopter conceptual design course. The design is primarily concerned with the performance of the helicopter, and does not consider stability effects. The design process is enhanced through the extensive use of computer programs.

Introduction

The helicopter design process can be divided into five basic phases. The first phase is a background study of the historical data and the current trends in helicopter design. Second, a conceptual study is conducted using "rules of thumb" and experience to develop simple layouts. Third, preliminary designs are drawn which include volumetric sizing, airframe lines, mechanisms and structural concepts. Fourth, the design enters a "proposal status" in which subsystems are developed, structural sizing is refined and mockups are constructed. Fifth, the final details are completed.

In all of these phases, much use is made of "corporate knowledge". It is not by accident that one can easily recognize the manufacturer of most helicopters, for regardless of any advancing of the state of the art, much of any new design is predicated on previous work.

Traditionally, in the academic environment, design courses are presented in order to equip the student with the skills needed to meet the challenges in the real world of engineering. Engineering design courses are usually "capstone" courses, with the intent of pulling together material developed in other courses into a "user's" course. Several problems are inherent in design courses. Because of time limitations, very little, if any, new material can be introduced and the scope of the designs must be severely limited. This usually dictates that only the conceptual design phase may be considered.

A second problem exists in that the student does not have the benefit of "corporate knowledge". However, without some background information, the design processes could even take the entire collegiate time span, and as a result, some type of this information must be furnished to the student.

Furnishing background information is a syndrome of a third basic problem in educational design programs. Inasmuch as the student has never gone this way before, he must be guided along a productive path. This offers an extreme challenge for the instructor because there is a very thin line between providing a general procedural outline and furnishing a "fill in the blanks" course.

A final problem exists in that in addition to showing the student how a design process operates, a purpose of the course is to require the student to use his thought processes, particularly in making decisions. This dictates that the student must have opportunities to make selections, decisions and/or optimizations.

The Specification

In order to channel the efforts of all of the students in a somewhat similar direction, it is advantageous to present a specification sheet as a goal. Although multi-rotor helicopters are covered in the prerequisite Performance course, at the Naval Postgraduate School the designs are limited to single main rotor systems, primarily due to time restraints.

Three basic design groups have been established with each specification representing a different weight class of helicopter. Inasmuch as our students are military officers, these three classes represent utility (cum UH-1), observation (H-60A/B) and cargo (H-53) types of vehicles.

The design process is performed by teams of from two to four students each. In order to permit some degree of independent thought, each member of a team is encouraged to pursue some variations on the basic design that his team has produced. Rather than being a full-scale deviation, this work generally is focused on one or two factors.

The Specification is very abbreviated, as shown in Table I.

Although the details of the Specification are firm design goals, failure to meet the Specs should not necessarily reflect negatively on the students if they can properly justify the reasons for the deviations.

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TABLE I

SPECIFICATIONS

Design Group	I
Crew	2
Useful Load (lbs)	1,000
Hover IGE (ft)	11,000
Service Ceiling (ft)	14,500
V max* (kts)	120
V cruise* (kts)	105
Range max (nmi)	225
Gross Weight # (lbs)	11,000
Rotor Diameter# (ft)	54
Fuselage Length# (ft)	50

* 4,000 Ft Pressure Alt, OAT 95 deg F
\# Not-to-be-exceeded values

The Design Manual

A locally prepared Helicopter Design Manual[1] is given to the students at the beginning of the course. This manual supplements the instructor's lectures and provides for an orderly flow through the design process. The Table of Contents of this manual is shown in TABLE II.

TABLE II

HELICOPTER DESIGN MANUAL
Table of Contents

1. Introduction
2. Main Rotor Design
3. Preliminary Power Calculations
4. Tail Rotor Design
5. Power Calculation Refinements
6. Engine Selection
7. Range and Endurance Calculations
8. Miscellaneous Calculations
9. Final Compliance Checks

Each of these sections of the design manual will be discussed briefly.

Introduction

Here are discussed the design objectives, the design phases, the assumptions and the applicability.

The goal of the design is to optimize the mission effectiveness of the system. There are two groups of factors which determine the mission effectiveness of the system:

1. Operational Factors
    a. Overall performance
    b. Mission Readiness
        (1) Availability
        (2) Reliability
        (3) Maintainability
    c. Survivability
2. Economic Factors
    a. Life-cycle costs
        (1) R & D
        (2) Initial investment
        (3) Annual operating costs
        (4) Maintenance costs
        (5) Salvage value

Inasmuch as neither the time or the desired scope of the course will permit any in-depth evaluation of the above factors (other than the overall performance), the exercise of these factors is performed only in the engine selection process.

The listing of these factors gives a clue as to one type of extra, individual effort that a member of a design team may exert. Because the students are exhorted to draw on other courses, some students have opted to perform a survivability analysis on their design using knowledge drawn from the Naval Postgraduate School's strong and unique course in Aircraft Combat Survivability.

The design phases have previously been discussed, and in this section of the manual they are listed so that the student is aware that, although typical of an actual design process, what is to be accomplished is but one small part of the whole.

To speed the design process, many assumptions are made and these are mentioned as they occur.

Main Rotor Design

Inasmuch as sizing of the helicopter is extremely dependent on the weight of the vehicle, initial estimates and later refinements[2] of the Manufacturer's Empty Weight and the Gross Weight are required. There is nothing in the academic background of the students that prepares them for this task and, as a result, they must rely on historical data. In preparing these data, care must be exercised so as not to have too many data points! This sounds as though it is contrary to all rules of mathematics, statistics and even common sense, but due to the rapid changes in the state-of-the-art of helicopter construction during the recent past, if older helicopters are included in the data bank for weight estimations, for example, there is a danger of incorrectly skewing the data.

The first perturbation of maximum rotor Tip Velocity is based on a need to maintain subsonic conditions at the tip, and this figure, together with a rotor size that will satisfy both the specification limits and the limiting values of Disc Loading, determine the desired Rotational Velocity.

The maximum advance ratio is used as an input to an historical limit of Blade Loading to determine the solidity of the rotor system.

The number of main rotor blades is a function of rotor radius (as it affects solidity) vibration and weight. And with the radius of the blades already determined, from the solidity, one can now obtain a value for the initial blade chord. For this first perturbation, it is usually desirable to consider only a rectangular planform, although other shapes may be considered in later calculations.

The selection of an airfoil section for the main rotor blades is based on the following criteria:

1. High stall angle of attack to avoid stall on the retreating side.
2. High lift curve slope to minimize operation at high angles of attack.
3. High maximum lift coefficient to provide the necessary lift.
4. High drag divergence Mach number to avoid compressibility effects on the advancing side.
5. Low drag at combinations of angles of attack and Mach numbers representing conditions at hover and cruise.
6. Low pitching moments to avoid control loads and excessive twisting of the blades.

Historically the NACA 0012 airfoil and its derivatives have been used most often. The primary source for selecting an airfoil section is "Theory of Wing Sections" , or a small shopping list of candidate airfoils may be furnished.

Preliminary Power Calculations

The first power calculations are for the power required to hover out-of-ground effect (OGE) at standard sea level. Inasmuch as power is a variable in the weight estimation formulae, the power that has just been determined, together with the first-cut values of rotor sizing, is now used to refine the weight estimate, and the revised weight is, in turn, used to make a second evaluation of the power required to hover OGE.

Historically, a Figure of Merit of 0.75 is considered optimum. This figure will be approximated if the induced power is between 70 and 80 percent of the total power at hover. If the Figure of Merit is too high, the power required will be too high at hover. If the Figure of Merit is too low, even though the hover power may be low, any decrease in power required with forward flight will be minimized, and, in fact, the power required in forward flight may even exceed that for hover.

The rotor geometry is adjusted in an attempt to obtain an optimum Figure of Merit, new hover power is determined and gross weight is adjusted in accordance with these changes. The weight-power values are iterated until the steps converge satisfactorily (say less than 10% difference between steps).

The power required to hover in-ground-effect (IGE) is now calculated (involving only a change in induced power).

The power required in forward flight may now be determined up to the specification value of maximum velocity. The power required at maximum velocity is compared with the power required at hover to ascertain if any adjustment of the power inputs to the weight estimations need be made.

Although the partial equations for power required may be combined, it is wise to list separately the components, e.g., induced, profile and parasite, for each total. This provides an insight as to the relative needs of the helicopter, i.e., weight (induced power), rotor torque (profile power) or fuselage drag (parasite power).

Tail Rotor Design

The sizing of the tail rotor is similar to the procedure used for the main rotor, but less sensitive to parameter variation. Without an offset of the tail rotor axis, the lever arm of the tail rotor, with respect to the main rotor, is the sum of the two radii plus one-half foot.

The tail rotor power required to balance the main rotor torque is calculated for velocities from hover to maximum velocity and added to the main rotor power to determine total power required.

As a baseline, any effects of a vertical stabilizer on tail rotor power may be ignored. It is of interest to note, however, that some military helicopters have a specification requiring a capability for a roll-on landing without a tail rotor. Programs have been design for the design and evaluation of a vertical stabilizer that will provide this function.[3] This program uses DATCOM information [4], thereby requiring the students to make use of information learned in another course.

Inasmuch as the entire design process is one of trade-offs, the design of a vertical stabilizer offers interesting opportunities. A properly designed vertical stabilizer may reduce the total rotorpower enough at maximum velocity that the design will meet the specification with smaller engines. On the other hand, the increased drag and weight of this structure, may tip the scales in the other direction.

Power Calculation Refinements

"Worst case" power required, usually OGE at standard sea level or at specification density altitude, must be calculated and corrections made for compressibility effects and retreating blade stall effects. Those not too familiar with helicopter performance are amazed to learn that high speed effects, i.e., advancing blade Mach effects, and low speed effects, i.e., retreating blade stall, both occur at high values of forward flight.

All of the power requirements up to this point are in terms of Rotor Shaft Horsepower (RSHP), which must be converted to Engine Shaft Horsepower (ESHP) before engine selection can proceed. The assumed conversion factors that may be used include:

1. Ten horsepower for accessories
2. Three percent transmission losses.
3. Ten percent losses in SHP for multiple engine installation

Engine Selection

Engine selection may be either by designing a "rubber engine" to fit the needs or by selecting from a shopping list of "existing" engines. The latter method is preferred because it is more closely attune with actual design practices.[5]

The size of the engine(s) selected is a function of the maximum ESHP required, while the number of engines is dependent on safety, survivability and reliability. The criteria for the type of engine to be selected are weight, life-cycle costs, availability, reliability, maintainability and, of course, perormance.

Engine selection offers the student designer the best opportunity to make (and justify) value judgments. Not only is the student required to select engines that will provide the required performance, but they are required to justify the selection on basis of life-cycle cost, maintainability, availability and reliability.

Once engine selection has been completed, the engine performance parameters, such as fuel flow rates, can be determined.

Range and Endurance Calculations

The velocity for maximum endurance and for maximum range may be determined graphically from a plot of power required versus velocity, or may be determined algebraically. From the power required at these two velocity points and from the fuel flow rates previously determined, one may calculate fuel requirements. A scenario for maximum range flight might be such as:

1. Warm-up and take-off
   a. Three minutes of fuel at Normal Rated Power (NRP)
2. Cruise at specification velocity
   a. Power for maximum range
3. Approach and landing
   a. Three minutes at NRP.
4. Reserve fuel
   a. Fifteen minutes at maximum endurance velocity.

The amount of fuel required for the range problem may exceed the amount of fuel originally computed in the weight calculations. If so, the weights must be recalculated, as must all of the power required functions.It is obvious that this would require almost an additional complete trip through the design process.

Miscellaneous Calculations

Final calculations include the determination of best rate-of-climb, and service and hover ceilings.

Another interesting possibility has to do with landing gear. Normally, the design is conducted on the basis of a skid-type landing gear. The additon of a fixed, wheel gear system will probably add weight and drag and a retractable landing gear will require even more weight, but can result in a decrease in drag when the gear is retracted. The designer must now consider a cross-over point as to when, and if, the retractable landing gear becomes an asset rather than a liability. Because the benefits accrue at the higher airspeeds, typical mission profiles must be included in the specification to assist in such an evaluation.

Reports

In addition to a formal, written final report containing the intermediate calculations and rationalizations as well as the final results, each design group must make an oral presentation during the last week of the course. The oral report serves three basic purposes: first, it gives the students an opportunity to prepare and deliver a time-limited technical report, a function that they will find necessary in their post-schooling days. Secondly, this provides the other students an insight as to how others approached and solved the same type of problems. This immediate feedback, although somewhat obtuse, is an essential part of the academic process. Last of all, it provides the instructor with an overview of each design, and this facilitates his grading process.

Some intermediate reports are also required, although these may be more implicit than explicit. Formats are stipulated and forms are provided in the design manual for several of the intermediate steps such as initial power determinations and weight estimations in addition to a form for a final report summary. Even if the intermediate step forms are not collected, the instructor has the opportunity to see these data as he circulates among the design groups.

Computer Programs

The heart of this design course is a series of computer programs.[6] It has been mentioned that it is essential that the student have an understanding of the make-up of the component powers, weights, et cetera, but after the student has solved an equation two or three times, the point has been made, and summary information is all that is required.

The basic equations that are used in the design sequence have been developed in a prerequisite course "Helicopter Performance"[7]. These equations have been programmed in various formats and combinations on an HP-9830 desk top compter, an IBM Series 1 system, the

TRS-80 Model 1, the Apple II and the HP-41. The latter programs are currently the primary programs. These programs have been developed in an extensive subroutine format in order to permit facile changing of the programs. In addition to the subroutines, several of the programs have been duplicated in "stand alone" format. For example, density is computed from density altitude in a subroutine to be used in power determinations, while density may also be determined from pressure altitude and temperature for direct readout. There are currently nearly sixty (60) HP-41 programs in use.

The entire performance process has also been programmed on a main-frame computer (an IBM 3037) with the primary output a a printed plot of power required versus velocity with text on graphics. This program is generally too long and too complex for use in intermediate steps, but it provides an excellent summary for final and near-final results, e.g., total power required and main rotor only power required.

Sample Design

The following design sequence is presented without the supporting handouts in order to shorten this paper. It is meant only as an overall view of the design process.

Main Rotor Design

The Specification maximum Gross Weight (GW) (from Table I) is listed as 11,000 pounds. A graph of historical weight ratios indicates that the Manufacturer's Empty Weight (MEW) is approximately 60% of the Gross Weight thereby giving a first-cut MEW of 6,600 pounds. A rough estimate of GW is made at 80% of the Specification value to accommodate future growth. With a Disc Loading of 6.0, this GW gives a rotor radius of 21.6 feet.

Maximum Tip Velocity, for a Mach number of 0.65 at standard sea level conditions is approximately 725 feetper second. With a rotor radius of 21.6 feet/second, a rotational velocity of 35.6 radians/second is indicated. This is within usual bounds.

With a computed Coefficient of Thrust of 0.0059 and a maximum advance ratio (at maximum forward velocity) of 0.279, the solidity is obtained from a plot of advance ratio-blade loading limits as 0.0554. With four main rotor blades, this solidity indicated a blade chord of 0.94 feet and an Aspect Ratio of 22.98.

This ratio is outside the usual range of 15 to 20, so the rotational velocity was reduced to 31 radiansper second and the revised values obtained were: Coefficient of Thrust - 0.0070; Blade Loading - 0.1038,; blade chord - 1.144 feet; V(Tip) - 669.8 feet per second; solidity - 0.0674; and Aspect Ratio - 18.88.

Airfoil Section "A" from the proposed airfoils was chosen with a profile drag coefficient of 0.010 and a lift curve slope of 6.4458 per radian.

Preliminary Power Calculations

For these vehicle dimensions, the main rotor power required in hover is 744.48 HP, with 583.92 Hp for induced power and 160.56 HP for profile power. Using this power figure, additional Gross Weight estimates were made and new power requirements computed for each new weight. Rotor dimensions were adjusted to provide a Figure of Merit between 0.70 and 0.80 until on the fourth iteration, a Gross weight of 7579.43 pounds and a total main rotor power to hover OGE of 681.36 HP was obtained. Main rotor power requirements were then calculated up to maximum velocity

Tail Rotor Design

In a manner similar to that used for the main rotor, the tail rotor dimensions and power requirements were calculated so as to provide anti-torque reaction at all flying speeds. At standard sea level, the tail rotor power ranged from 46.64 HP at zero airspeed to a low of about 11 HP at 60 - 80 knots. At the Specification altitude, the tail rotor power ranged from 55.21 HP at zero velocity to a low of about 11 HP at about 80 knots. These powers were added to the main rotor power to obtain total power curves.

Power Calculation Refinements

Compressibility and blade stall corrections to the main rotor power were made at maximum velocity and the rotor shaft horsepower required to hover at the Specification hover ceiling was determined. The maximum power required (maximum velocity at sea level) of 766.8 HP was then used for the engine selection. This was converted to an Engine Shaft Horsepower of 876.5.

Engine Selection

It was decided (with supporting rationale) to use two engines and engines "B" from the shopping list were selected. This selction was based on an analytical examination of life-cycle costs, availability, reliability and maintainability as well as performamce. The actual weight of these engines was 8017.5 pounds, which was within 10% of the original estimate of 7579.4 pounds, so no further revisions in weight or power needed to be made. Fuel flow as a function of power was then obtained.

Range and Endurance Calculations

The velocity for maximum range (115

knots) was obtained graphically, as was the velocity for maximum endurance (65 knots). The fuel required for the maximum range scenario was calculated as 1,032 pounds. This is less that the 1,500 pounds of fuel carried, so no revision of the values need be made.

Miscellaneous Calculations

The extra fuel on-board would permit an extra 232.75 nautical miles of range for the maximum range problem.

At 120 knots it was determined that the Collective was set at 17.6 degrees, the Cyclic at -6.2 degrees and the maximum angle of attack on the retreating blade was 11.7 degrees (below the blade stall regime).

By an iterative process, the Best Rate of Climb was determined to be 3,656 feet per minute at a forward velocity of 58 knots.

Conclusions

A helicopter conceptual design program for a course of instruction can be devised that challenges the students, permits integration of material used in prerequisite courses and provides a series of realistic results without overtaxing either the abilities or the time of the students, and yet without spoon feeding the students.

The design process is open ended, thus permitting the ready addition or delection of material. The heart of the design sequence is user friendly computer programs.

References

1. Kee, Stephen G., Guide for Conceptual Helicopter Design, MS Thesis, Naval Postgraduate School, Monterey, CA 1983

2. Schwab, Rudolf T., Computer Program Analysis of Helicopter Weight Estimate Relationships Utilizing Parametric Equations, MB Thesis, Naval Postgraduate School, Monterey, CA 1983

3. Young, James E., Helicopter vertical Stabilizer Design Considerations, MS Thesis, Naval Postgraduate School, Monterey, CA, 1983

4. Ellison, D. E. and Mattan, L., USAF Stability and Control DATCOM, McDonnell Douglas Corp., Project No. 8279, Air Force Flight Dynamics Laboratory

5. Casey, Timothy J., Powerplant Selection for Conceptual Helicopter Design, MS Thesis, Naval Postgraduate School, 1983

6. Fardink, Paul J., Hand-Held Computer Programs for Preliminary Helicopter Design, MS Thesis, Naval Postgraduate School, 1982

7. Layton, Donald M., Helicopter Performance, Naval Postgraduate School, 1980