Development of an Advanced Rotorcraft Preliminary Design Framework

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Abstract

Various modules are generally combined with one another in order to perform rotorcraft preliminary design and its optimization. At the stage of the preliminary design, analysis fidelity is less important than the rapid assessment of a design is. Most of the previous researchers attempted to implement sophisticated applications in order to increase the fidelity of analysis, but the present paper focuses on a rapid assessment while keeping the similar level of fidelity. Each small-sized module will be controlled by an externally-operated global optimization module. Results from each module are automatically handled from one discipline to another which reduces the amount of computational effort and time greatly when compared with manual execution. Automatically handled process decreases computational cycle and time by factor of approximately two. Previous researchers and the rotorcraft industries developed their own integrated analysis for rotorcraft design task, such as HESCOMP, VASCOMP, and RWSIZE. When a specific mission profile is given to these programs, those will estimate the aircraft size, performance, rotor performance, component weight, and other aspects. Such results can become good sources for the supplemental analysis in terms of stability, handling qualities, and cost. If the results do not satisfy the stability criteria or other constraints, additional sizing processes may be used to re-evaluate rotorcraft size based on the result from stability analysis. Trade-off study can be conducted by connecting disciplines, and it is an important advantage in a preliminary design study. In this paper among the existing rotorcraft design programs, an adequate program is selected for a baseline of the design framework, and modularization strategy will be applied and further improvements for each module be pursued.

Key words : Rotorcraft, Design optimization, Modularization, Preliminary design

Introduction

In the preliminary design stage of the rotorcraft, knowledge regarding many different disciplines is generally required to estimate the performance, size, weight of the many different subsystems installed in the vehicle. In the past, a few preliminary design computer programs have been developed, especially in the rotorcraft industries [1-3]. However,

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those are far from a user−friendly computer program, and based on the resulting database composed of the old fleets of the rotorcrafts, because the computer programs themselves are now old−dated. Currently, it is observed that few brand new versions of the rotorcraft preliminary design program [4−5] are being developed and operated in industries and research institutes throughout the world. However, still those computer programs are not commercial products and thus have a quite limited availability. Thus, in this paper, an updating effort on such an old version of the rotorcraft preliminary design program is pursued.

Modularization Strategy

The preliminary design program used in this paper as a baseline should be maintained in terms of its generality and flexibility. It is also important to make it easy to implement and use. Among the existing rotorcraft design programs, HESCOMP is selected as a baseline for the present design framework since it estimates all the details of helicopter design parameters accurately, and it provides many different types of the helicopter configurations. However it is in a form of a single−unit source program with quite a few subroutines, and each of which is composed of a few thousands' lines. Such configuration in the program size makes it difficult for a user to understand and improve it. Thus, a separation, or a modularization strategy which are presented in Ref. [6] is selected and attempted in this paper. The modularized program will be composed of six specifically divided modules such as size trend module, aerodynamic module, engine sizing module, weight trend module, mission performance module, and an additional trim module.

A computational object considered in this paper is a single rotor helicopter with 4 blades, no wings, and no auxiliary propulsion. However various configurations of the rotorcraft, such as tandem, compound, and tiltrotor aircrafts, will be added into the present program. The target preliminary design program is composed of six specifically divided modules listed below and a trim module will be added later. Each module will be connected by either Model Center [8] or MATLAB Optimization Toolbox [9] for an additional optimization process. Figure 1 shows modularization and each module in the upgraded framework.

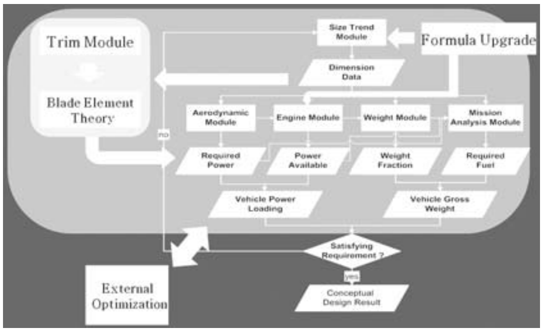

Fig. 1. Modularization and the modules in the framework

2.1 Size trend module

This module determines the trends of the rotorcraft geometric dimensions as the weight of the aircraft changes throughout the iterative sizing loop. At first, dimensions of the main rotor are estimated and then major fuselage dimensions of the helicopter are determined by the empirical formulas in the program. And it decides the size of the tail rotor to counteract the torque generated by the main rotor. And the other dimensions are also estimated. Modularization of this module is conducted. And some of the empirical formulas used in this module are updated by the brand new formulas which are introduced in Ref. [7]. Update of this module will be explained in the later section.

2.2 Aerodynamic module

This module calculates the required power of a rotorcraft which already acquires certain dimensions estimated through the size trend module. In the original version of HESCOMP, the required power is determined by using the momentum theory. However, it is believed that the momentum theory is not accurate enough to meet the current preliminary design requirement. Therefore it is replaced by the blade element theory.

2.3 Engine sizing module

This module estimates the numerical value of the scaling factors; namely, the maximum static thrust or power. Engine sizing requirements for helicopters are generally set by takeoff conditions or forward flight conditions. There are two ways provided to operate calculation within this module. One is to use "rubberized" primary engines. The other is application of the fixed size engine whose detailed data are provided by a user. The update of the old-dated engine library included in the original program is conducted by using the collected data of current engines.

2.4 Weight trends module

The weight trend module estimates the weights for the propulsion system, the structures system, and the flight control system. The helicopter gross weight consists of payload, fuel, and empty weight. This module conducts iterative calculations considering an effect of variation in gross weight and required power.

2.5 Mission performance module

This module monitors the flow during calculation of the mission performance data and calculates the total fuel required at the final stage of the mission. The overall sizing process is shown in Fig. 1. It is composed of the vehicle power loading calculation and the vehicle gross weight calculation part. This approach is relatively easy to understand the overall process.

Upgrade of the Modules

3.1 Size trend module

As mentioned previously, the sizing module is executed based upon the database consist of the old fleets of the rotorcrafts. This is due to that the original version of HESCOMP is quite old-dated. In this paper, the sizing module update is conducted by adopting new empirical formulas presented in Ref. [7]. But there are only a few formulas available. Many empirical formulas are presented in Ref. [7], but some of them are not applicable to the present update of the relevant module because the module does not use directly support the parameters used in the formulas. Then, there are only a few formulas which are applicable to the present update of the module. During the present update effort, the number of the formulas which are directly applicable to the present update is found to be two. Those are the empirical formula between the ratio of main rotor diameter to tail rotor diameter and disk loading, and the one to determine the fuselage length.

Table 1 shows the comparison regarding the rotorcraft subsystem sizing result between the presently upgraded sizing trend module and the original version of HESCOMP. The original output data calculated from HESCOMP are compared with results obtained by the updated empirical formulas. Among the formulas used by the original version of HESCOMP, design parameters such as the ratio of main rotor diameter to tail rotor diameter

Table 1. Comparison between the original HESCOMP and the updated program

	Variables	Original outputs	Updated outputs	Deviation (%)
Tail rotor	Diameter	12.9	11.6	10.8
	Net disk loading(lb/ft^2)	18.2	22.9	25.8
	Thrust coefficient/solidity	0.08	0.1	25.0
Vertical tail	Aspect ratio	0.763	0.608	20.3
	Area(ft^2)	59.8	61	2.0
	Span(ft)	6.8	6.1	10.3
	Mean chord(ft)	8.9	10	12.4
Primary engine nacelle	length(ft)	6.4	6.5	1.6
	Wetted area(ft^2)	80.5	81.4	1.1

and the fuselage length, are updated in the present improvement. Even though only two formulas are currently modified, difference between the results of the original HESCOMP and those from the updated size trend module become considerable. At the present stage, it is difficult to prove completely that the update of the formulas is valid. It is because both the updated module is not executed completely through a full iteration and an external optimization is not conducted yet. However, it is expected that the modified version will exhibit more accuracy when more data included in the modern rotorcrafts are extracted and applied in the modification.

3.2 Engine sizing module

The engine library of the original program is also based on the old fleets of the rotorcraft engines. As mentioned previously, there are two ways provided to operate calculation within this module. In this paper, the engine library update is conducted in case of using rubberized primary engines. The basic cycle performance data of the original program consists of tabulated values of four variables such as power, fuel flow, gas generator shaft rpm, and power turbine shaft rpm. These tables are functions of Mach number and turbine inlet temperature. Therefore the transformation of the data to fit into the format of the original program is required.

Various helicopter engines can be classified by their generation such as the 1st, 2nd and 3rd. Each updated engine library which corresponds to the format of the original one are established in this paper.

Especially, verification of the established 2nd generation engine library is conducted using the data of UH−60 helicopter. Table 2 shows the comparison between the presently upgraded engine sizing module and the original version of HESCOMP. The gross weight converged by the original program is compared to those from the updated program. As a result, the improved deviation is less than those from the original one. Therefore the accuracy of the gross weight estimation of a rotorcraft is a little bit improved with regard to the engine library update. The verifications of the other generation engine libraries are being conducted.

Table 2. Effect of the engine library update

	Gross weight of UH−60	Original deviation	*Improved deviation*
Gross weight	17,431 lb	17,102 lb (1.8%)	17,380 lb (0.2%)

External optimization

4. 1. Phoenix Integration Model Center

Any general multidisciplinary design optimization (MDO) program may add a strong capability for the present design and optimization effort in rotorcrafts. To add MDO capability, a commercial optimization software, Phoenix Integration Model Center will be used in this paper. Model Center allows link among sub−divided modules so that a large system such as a rotorcraft, which involves inherently multiple disciplines, can be solved by an optimization method. Also, Model Center interconnects input and output variables using text file formats and even helps to convert units among modules and other addable applications. For consistency of the units between various disciplines, such characteristics may manage time−consuming jobs easily in various engineering analysis.

For the present rotorcraft design, a sizing module performs initial sizing based on the input data with a given mission profile. Then, a weight module is executed with inputs which are obtained from the sizing discipline. At this moment, Model Center keeps track of the constraints and requirements in order to satisfy all the requirements. Since it takes a lot of time for conducting iteration and interpolation tasks within Model Center, a small−sized sizing module may provide a great advantage in reducing the computation time compared to using a heavy application such as HESCOMP or VASCOMP, which are the typical helicopter or tiltrotor aircraft design programs developed by Boeing Helicopter Company. Various modules such as sizing, weight, engine, performance, trim, and stability will be interconnected by one optimization tool within Model Center, and the present framework is expected to perform effectively and efficiently in terms of the computational cost and time.

4. 2. MATLAB Optimization Toolbox

An alternative plan to conduct an additional optimization effort is required since Model Center is rather expensive to be used in this paper. MATLAB Optimization Toolbox also provides an environment to integrate several computational modules and conducts an optimization. The relevant MALTAB Toolbox provides quite a few routines to conduct many different types of optimization. Among those design optimization routines, “fmincon” is used in this paper, which conducts a constrained minimization function, integration, and optimization process.

During its first step, an application of the additional optimization program to original version of HESCOMP is tested. One possible example of the resulting design optimization framework which minimizes the rotorcraft gross weight is presented in Figure 4. And Table 3 indicates the selected design variables and those bounds. Currently the design variables are related to main rotor and tail rotor only, but the number of design variables will be increased in the future. Figure 5 shows the result from external design optimization of the example case. The objective function, vehicle gross weight, is converged within 10 iterations.

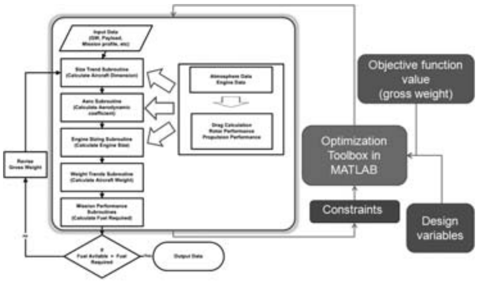

Fig. 4. Optimization framework to minimize the gross weight

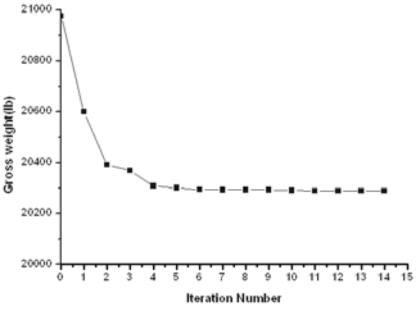

Fig. 5. Result from design optimization of the example case

Table 3. Selected design variables

	Design variables	Lower bound	Upper bound
1	Gross weight (lb)	15000	25000
2	Disk loading	5	12
3	MR built−in twist (º)	−15	0
4	Rotor blade thickness/chord at 75% radius (%)	5	15
5	MR tip speed (ft/sec)	680	725
6	TR built−in twist (º)	−7	0
7	Tail rotor tip speed (ft/sec)	680	725
8	Gap between MR and TR disk (ft)	0.5	1
9	TR solidity	0.1	0.3

Conclusion

In order to develop a brand new multidisciplinary optimization framework for rotorcraft preliminary design, the relevant work scope and requirements are investigated and established. Among the existing rotorcraft design programs, HESCOMP is selected for a further improvement and its modularization has been pursued. Also, a few new modules for the present design framework, such as blade element rotor aerodynamics and trim analysis, are being developed. Empirical formulas are updated using new ones based on modern rotorcraft database. Among several modularized modules, size trend module and engine sizing module are updated and validated in this paper. A size trend module uses simple but upgraded empirical formulas introduced in Ref. [7]. The results from the presently upgraded sizing trend module are compared with those from the original version of HESCOMP. The results show quite a few amount of difference. Therefore the update of the empirical formulas has a significant influence on the numerical results. At the present stage, it is difficult to prove completely that the update of the formulas is valid. It is because both the updated module is not executed completely through a full iteration and an external optimization is not conducted yet. But when more data included in the modern rotorcrafts are extracted and applied in the modification, much more reliable result will be expected. The engine library included in the original program is substituted by the updated engine libraries classified by their generation. As a result, the accuracy of the gross weight estimation is a bit improved. An external design optimization routine is also developed and validated. Those design optimization process will be applied to the finally updated program. When those updating efforts are applied to the program, the program will be able to design modern rotorcrafts accurately.

Acknowledgments

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References

1. Davis, S. J., Rosenstein, H., Stanzione, K. A., and Wisniewski, J.S., “User’s Manual for HESCOMP: The Helicopter Sizing and Performance Computer program”, Prepared by the Boeing Vertol Company, 1979.
2. Schoen, A. H., Rosenstein, H., Stanzione, K. A., and Wisniewski, J. S., “User's Manual for VASCOMP II, The V/STOL Aircraft Sizing and Performance Computer Program”, Prepared by the Boeing Vertol Company, D8-0375, 3rd revision, 1980.
3. Hansen, A.C. and Layton, D.M., “An Analysis of Three Approaches to The Helicopter Preliminary Design Problem”, Naval Postgraduate School, California, March 1984.
4. Yeo, H. and Johnson, W., “Aeromechanics Analysis of a Heavy Lift Slowed-Rotor Compound Helicopter”, *Journal of Aircraft*, Vo. 44, No. 2, March-April, 2007, pp. 501-508.
5. Hirsh, J. E., Wilkerson J.B., and Narducci, R.P., “An Integrated Approach to Rotorcraft Conceptual Design”, 45th AIAA Aerospace Sciences Meeting and Exhibit, 8 - 11, Reno, Nevada, January, 2007.
6. Lim, J. and Shin, S-J., “Modularization and Formula Upgrade for a Rotorcraft Preliminary Design Framework”, 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials, Palm Springs, May4-7, 2009.
7. Kim, J. and Oh, W., “A Study of Rotorcraft Initial Design Using Statistics”, International Forum on Rotorcraft Multidisciplinary Technology, Seoul, Korea, 15-17 October, 2007.
8. Anonymous, “Model Center User Guide and Programmers’ Reference, Version 3.1”, Phoenix Integration, Inc., 2001.
9. Anonymous, “Matlab Optimization Toolbox Reference Version 2”, MathWorks, Inc., 2001.