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STUDY ON WING STRUCTURAL LAYOUT DECISION SUPPORT SYSTEM

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Abstract

This paper presents the results of a research and development study on the Wing Structural Layout Decision Support System (WSLDSS) for fighters. The wing structural layout design is an ill-structured problem that has to consider masses of quantitative and qualitative factors, and cannot be effectively solved only by algorithm-based methods. It is a complex decision making process in which expert experience and knowledge play a most important role. So we introduce decision theory and methods into structural layout design, and consider it from the angle of decision-making rather than only optimization for lightening weight. The scope of this study work, the solving strategy for wing structural layout decision, as well as corresponding technological measures adopted are presented. Integrating the technique of Expert System and that of Decision Support System, the structure framework of WSLDSS was proposed and the prototype system is being developed.

I Introduction

Minimizing the structural weight subject to satisfying design requirements is an eternal objective of aircraft structural design. The structural weight coefficient of the next-generation fighters will descend to 28 percent from current 31 percent. Optimizing dimensional parameters of structural elements and optimizing structural layout are two main means to lightening structural weight, while the later always results in greater benefit of weight reduction and will become the main approach to lightening weight. However, at present only can most optimization design methods consider dimensional optimization of elements for given structural layout. The potential of layout optimization has not been exerted. At conceptual design stage, the structural layout determination for new aircraft mainly relies on experience and prototype aircraft as reference, giving priority to qualitative analysis, with preliminary quantitative computation as assistance. Diverse layout types can not be roundly and quantitatively analyzed and compared. Layout optimization is a topic received increasing attention, and full-blown application software has not yet been developed.

On the other hand, in order to improve the design quality, cut down the life cycle cost and shorten the development period, the Current Engineering (CE) methodology[1] is accented to be applied in modern aircraft developments. CE requires that at initial design stage, the factors influencing aircraft performance, reliability, maintainability, economy and etc. in all successive processes, i.e., structural design, fabrication, operation and logistics, should be considered, and problems coming from these successive stages should be eliminated at the initial design stage as far as possible. For structural design engineers, CE requires them to actively take part in conceptual design activities, synthetically consider such requirements as aerodynamic performance, shape dimensions, positional arrangement, strength, stiffness, weight, reliability, maintainability and so on, present reasonable structural layout schemes and round, accurate analysis as well as evaluation information in time, coordinate with designers from other specialties, determine optimum layout scheme, in the mean time accomplish preliminary structural design of main elements. However, the realization of CE needs a sort of perfect design support tools and an integrated computer environment.

In this paper, the wing structural layout design of fighter is studied. The factors influencing wing structural layout are investigated systematically. Because structural layout is an ill-structured problem requiring expert experience and knowledge, and may not be effectively solved only by algorithm-based or process-based methods, so we introduce decision-making theory and methods into this problem. We consider the wing structural layout design in the view of not only optimization but decision-making, and the strategies and methods of wing structural layout decision are elaborated. Integrating the techniques of Expert System (ES) and Decision Support System (DSS), the knowledge-based Wing Structural Layout Decision Support System (WSLDSS) is developed.

The objectives of this study are as following:

- Developing a perfect system of evaluation indices and synthetic evaluation methods for wing structural layout decision-making.
- Inquiring the feasible analysis, optimization and decision strategies and methods suitable for different stages of wing structural layout decision problem.
- Defining the feasible architecture of WSLDSS.

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Exploiting existing structural analysis tools, developing intelligent WSLDSS prototype capable of providing a sort of preliminary analysis, optimization and decision support tools for wing structural layout design of fighters.

II Review of Relevant Researches

Since the advent of the computer, continuous attempts have been made to automate engineering design tasks and develop computer-aided tools to assist with their performance. A very significant level of progress has occurred in the last two decades in developing computer-aided design tools for aircraft structure analysis and synthesis, such as finite element analysis and structural optimization programs and techniques. These tools are basically algorithmic or procedural in nature that perform a given, repetitive function and tackle well-structured engineering problem following a predetermined procedure. The process of engineering design involves a number of steps that cannot be easily broken down into algorithms or procedures. Many researchers have studied the non-algorithmic nature of design process. In these studies, researchers have focused on issues such as: the design process; how designers think; whether design can be fully automated. Clearly engineering design is an ill-structured problem, requiring judgement, creativity, cultural conditioning, heuristic reasoning and the manipulation of large amounts of relevant and partially relevant data from which complex inferences must be derived[2].

Although structural optimization techniques are applied extensively in aircraft design realm, general structural optimizations deal only with dimensional parameters of elements as design variables, e.g., the characteristic dimensions of finite elements. While structural layout defined by topology and shape parameters such as the arrangement and number of spars and ribs, is given at one time of optimization. Apparently, to make further improvement on structural design quality and structural weight reduction, it is insufficient to barely optimize dimensional parameters of elements and necessary to exert the potentiality of layout optimization to the full. Research of layout optimization has received high attention. For example, some effective algorithms have been developed for the topology optimization of the truss structures. Since the complexity of aircraft structure, structural layout optimization problems can not be validly solved by one or several kinds of numerical optimization methods. Furthermore, layout design is not merely a lightening optimization problem, but need consider diverse kinds of other quantitative and qualitative factors, such as aerodynamic performance, position arrangement, structural strength, stiffness, damage tolerance, safety, reliability, maintainability and all. How to allow for so many different requirements to obtain a satisfactory layout scheme, is the difficult point of layout design, in which expert experience and knowledge play an important role. The design process is the very process of analysis, judgement and decision applying these experience and knowledge, which calls for considering layout design problem afresh from the angle of decision-making.

With the growth of concepts and techniques in Artificial Intelligence (AI) and significant improvements in hardware architecture and speed, the development of intelligent software for engineering design is receiving increasing attention. Among the AI applications in engineering design, the technology of ES is most promising and successful so far. An ES (often referred as to a knowledge-base system), can capture human expertise and serve as an expert in solving engineering design problems. Such a software would perform judgement tasks (inferencing in complex environment) at the level of expert consultants integrating expertise of many different experts required for design process. The emerging technology of AI, in particular ES, along with traditional CAD programs, offers a feasible approach to layout design. As of today, tentative work of developing layout design expert system has been undertaken[3].

Layout design is a topic studied by many experts in the world, till now has not been solved effectively. On the whole, in aircraft design area, practicable layout design techniques and tools have not come to maturity.

III Scope of study work

The scope of work for this study consists of the following main issues:

1. Investigation of the factors influencing structural layout decision

Investigating and summarizing the varied influencing factors that have to be considered in layout design, e.g., aerodynamic shape and aerodynamic performance, structural weight, strength and stiffness, internal space utilization, positional arrangement (such as big opening placement, integral fuel tank placement and concentrated force impact location), harmony with fuselage structure, arrangements of flap and aileron, fatigue, damage tolerance and reliability requirements, material selection, manufacturing and maintenance requirements. Roundly investigating the relationships among these factors as well as working manners in which they act on wing structural layout.

2. Structural layout optimization strategies

Structural layout is defined by topology and shape variables. Generally wing shape (defined by area, aspect ratio, taper ratio, sweepback, and so on) is not altered largely once determined at the conceptual design stage, so structural layout optimization mainly deals with topology variables. Structural type, such as mass boom type, box beam type, multi-spar type or mixed type, is a kind of topology variable too.

Obviously, in the mean time of layout optimization, dimensions optimization of main elements should be conducted, which confirms to CE methodology, i.e., at as early design stage as possible detailed design of main elements should be determined.

Study on structural layout optimization strategies comprises the following 3 levels:

(a) Structural type optimization strategy

(b) Preliminary layout optimization strategy only dealing with locations and dimensions of main loading elements for determined structural type

(c) On the basis of (b), detailed layout optimization strategy on second thoughts about other loading elements

3. Rapid analysis techniques and tools

Structure analysis is the foundation of structure optimization, while the analysis precision will significantly affect the quality of optimization. Structure analysis techniques and tools are essential for layout synthesis too. However, since at the phase of layout design the structural details are not determined yet, sophisticated analysis techniques and tools will be inapplicable. This calls for developing rapid, simplified analysis techniques and tools yet with needed accuracy suited to layout design. Such techniques and tools include strength analysis, stiffness analysis, fatigue and damage tolerance analyses, reliability analysis, etc. , that possess different analytical depths so as to befit the various stages with the evolution of layout design.

4. Structural layout decision support technologies

Structural layout involves multi-objectives and has to allow for masses of qualitative and quantitative factors. It is a complex decision making process necessitating expert experience, judgment and inference. Structural layout decision support indicates that through providing data, information, models, knowledge and methods relevant to layout decision problem, aiding designers to conduct decision analysis, design and evaluate feasible layout schemes, select optimal or satisfactory scheme, as well as modify or improve scheme.

Study on layout decision support technologies includes the following several items:

(a) Identifying data and information needed by layout decision, including data and information produced by model and knowledge processing, qualitative and quantitative information, graphic information, and so forth

(b) Determining the major factors layout decision must consider, possible decision objectives along with relations among these objectives, and forms of decision problem

(c) Establishing indices systems for layout scheme evaluation and comprehensive evaluation methods

(d) Modeling layout decision process, offering a sort of normalized decision making techniques, including single and multiple objectives decisions. For example, endowing each index or objective with a weighted coefficient so as to grade various layout schemes, thereby obtaining ordering of alternative schemes

Generally only can layout optimization deal with single index, e.g., structural weight, also quantitative factors. However layout decision support technologies can deal with multiple quantitative and qualitative indices, thus can synthetically balance alternative schemes. For example, making a trade-off among optimal layouts of different structural types allowing for many indices besides weight.

5. Framework design of WSLDSS and the prototype system development

Defining the feasible architecture and basic framework of WSLDSS, presenting representation, management, usage and integration schemes of data, models, knowledge, methods and graphs, determining design schemes of data base, model base, knowledge base, approach base, graph base as well as their respective management systems, preliminarily building each base and framework architecture of overall system. System design should characterize flexibility and keep open, with modularization structure, so as to facilitate system development, management, maintenance, modification , expansion , and interface to other systems and software.

Structural layout expert subsystem is the kernel subsystem of WSLDSS. This subsystem is used to assist users to form reasonable layout scheme, recommend appropriate analysis tools, organize analysis flow, propose appropriate optimization and decision-making methods, as well as answer user's questions. It is able to learn by itself, update and enrich its knowledge base along with running of the system. The development of this subsystem is the key of the overall system development.

IV Solving strategy for wing structural layout decision

We divide wing structural layout decision problem into the following 3 stages:

Stage I: Preliminary selection of structural types

There are three basic types of primary wing structure, i.e., mass boom type, box beam type, and multi-spar type. In mass boom structures, the flanges of one or two spars take the normal forces resulting from bending, while the torsional load is carried by either the spar webs (differential bending) or the combination of the spars and skin covers (shear). Box beam structures incorporate skin panels, which are stressed not only to take shear forces, but also the end load due to bending. Multi-spar structures are used on very thin wings, where skin cover carries torsional load and most of normal stresses resulting from bending.

At this stage, the factors influencing the selection of wing structural type are considered comprehensively. Experience shows that the main constraints for wing design are:

1) Stability of wing box, in particular buckling of skins
2) Static aeroelastic requirements
3) Fatigue and damage tolerance

For most of the wing, experience shows that the skin buckling is the most important design constraint. According to the above experience, when selecting wing structure type, the influencing factor that should be primarily considered is the stability of wing box. This constraint determines that whether a large percentage of the wing bending should be carried by the spars, or whether the skins should be utilized to a large extent. Besides stability, other factors such as aeroelastic requirements, fatigue and damage tolerance, landing-gear attachment and retraction, power plant, ailerons, flaps, and a host of others, are also considered synthetically. Various structural types are analyzed and compared, finally one or varied kinds of appropriate structural types, along with the arrangement and number of main loading elements such as spars and ribs, are recommended. At this stage, shallow rapid structure analysis techniques will be utilized.

Stage II: Preliminary layout optimization

The layouts of main structural elements for each kind of structural type recommended at stage I are optimized, where the basic design variables are the arrangement, number and dimensions of spars and ribs, the thickness of covers, as well as material types, the objective function is structural weight. The positionai and sectional parameters along with structural weights of these elements can be obtained after optimization.

At this stage, appropriate utilization of engineering experience may reduce the complexity of optimization problem. For example, for multi-spar wing, the total weight of substructure elements equals to the total weight of the vertical elements, therefore only comparative skin cover analysis should be performed. The complexity of the skin cover layout optimization in multi-spar wing can be reduced significantly by exploiting the following knowledge of failure modes:

1) There are 2 modes of failure: overall buckling of the stiffened skin as a wide beam, and local buckling.
2) At the optimum design conditions, the effect of interaction between the modes is negligible.

The failure modes or design criteria are: panei buckling, stiffener crippling, material strength and allowable stress for tension (fatigue and damage tolerance criterion).

Once preliminary layout optimizations of main elements are accomplished, then the optimal layouts corresponding to various structural types are evaluated synthetically according to such indices as weight, strength, stiffness, space utilization, economy, harmonies among different components, and so on. Based on the evaluation, the decisions on adopting which kind of structure type and the relevant optimum layout are made. If only one kind of structure type is recommended at stage I, then the decisions would not be needed. At this stage, deep rapid structure analysis technique will be applied.

Stage III: Detailed layout optimization

For the determined structural type and preliminary optimal layout from stage II, the detailed layout design is optimized, including further layout optimization of main elements on the basis of stage II, and structural optimizations of less important elements comprising positional parameters. The characters of strength, stiffness, fatigue, damage tolerance, reliability and others of the overall wing structure are analyzed more accurately. Next conduct further evaluation on the optimum results, discover problems and improve the design. At this stage, deeper rapid structure analysis techniques would be utilized, for example, stiffening panel analysis technique.

Clearly at all stages, there are both optimization problems and decision problems.

V Technological measures

Structural layout decision problem is of great hardship and comprehensiveness. To solve it successfully, varied kinds of methods and technological measures must be adopted.

1. Integrating ES technique and DSS technique

A typical ES consists of knowledge base, inference machine and dynamic data base, primarily employing non-quantified logic sentences to represent knowledge, and using the mode of automatic reasoning to solve problems. ES adapts to qualitative analysis and reasoning. While DSS is generally made up of user interface, data base, model base, data base management system and model base management system, mainly employing quantitative methods, i.e., data and models, to assist ill-structured problem solving through human-machine interaction[4]. DSS is used to facilitate the structuring of a decision so that analytic tools, possibly several in combination, can be used in generating solutions, facilitate the use of the analytical tools that have been brought together through a structuring process, and facilitate the manipulation, retrieve, and display of data.

The difficult point of layout design is how to make synthetic decision, which requires decision theory and DSS technique be applied. At the same time, layout design also incorporates analysis, reasoning and judgement based on experience and knowledge, programming this process must draw support from ES technique. Structural layout design involves not only reasoning based on knowledge, but also calculation based on data and models. Thus, we combine the techniques of ES with DSS to develop WSLDSS so that their respective advantages can be exerted.

2. Utilizing diverse kinds of optimization methods

Preliminary selection of structural type is handled by structural layout expert subsystem. The layout optimization methods themselves only cope with other topology and dimensional variables for given structural type. Layout optimization is a compound optimization problem containing discrete and continuous variables. It is essential for various stages and various requirements to adopt different optimization methods. Besides considering regular Mathematical Programming and Optimality Criteria methods, several other approaches[5] appear promising to layout optimization are also investigated. These are:

1) Genetic Algorithm (GA)

GA has recently emerged as a powerful and robust approach for finding a global optimal solution of discrete optimization problems. Initialization/selection, mutation and crossover constitute the salient features of this algorithm. GA has remarkable advantage over conventional algorithms. It expresses design variable by a certain length of coding, operates the coding rather than the variable itself when optimization is conducted, thus can conveniently handle discrete variables. The value information of objective functions in stead of derivatives is needed for determining the searching direction, which makes it especially suitable for the cases like aircraft structure analysis where no analytic expressions exist.

2) Neural Network (NN)

NN has come to maturity stage and been extensively applied in many areas. It can deal with manifold factors when applied to structural layout optimization, give a successful layout scheme satisfying given design requirements through the learning of the network. Simulated Annealing (SA) is another effective algorithm for discrete optimization problems. Applying the combination of NN and SA to layout optimization can find the global optimal solution.

3) Nonlinear Branch and Boundary (NLBB)

As the name implies, NLBB combines the essences of nonlinear continuous optimization and the branch and boundary algorithm of integer programming, which presents a reasonable engineering approach for discrete optimization.

4) Sequential Linear Discrete Programming (SLDP)

SLDP is based upon sensitivity analysis, approximation concept, binary representation of design variables, and binary/integer programming. It has been applied successfully to materials optimization problem of composites. The primary advantage of this approach lies in its simplicity and CPU efficiency, but it usually converges to a local optimum.

5)Fuzzy optimization methods

This species of methods can handle optimization problem containing qualitative parameters. Structural layout design involves lots of qualitative parameters, these qualitative parameters need be quantified so that they can be operated with quantitative parameters. The theory and methods of the fuzzy mathematics will be used for the quantification of qualitative parameters.

3. Developing the prototype system by stepwise extension

Corresponding to the above 3 stages of layout decision, the prototype system development is divided into 3 steps too. As an emphasis, the task of the first step is to preliminarily set up structural layout expert subsystem, that can basically assist the performance of preliminary selection of structure types. The tasks of the later 2 steps, are to encircle the structural layout expert subsystem, gradually augment every base of the system, add and improve such functions as structural analysis, layout optimization, synthetic evaluation and decision-making. The second step system is required to have the initial function assisting the preliminary layout optimization, while the third step system has the demonstrating ability of assisting the detailed layout optimization.

VI Structural framework of WSLDSS

The structural framework of WSLDSS proposed is as shown in figure 1. This figure shows the essential building blocks of the overall system. In the actual system development, the system will be enhanced by display facilities, graphics, report generation, error-checking, knowledge acquisition facility, and explanation facility. The system design is highly modular. As new knowledge, model, method, data or graph become available, or radical changes occur in the design paradigm, the individual building blocks can be modified or replaced without affecting the other pieces of the software significantly.

Knowledge base (KB) consists of varied kinds of knowledge, including expertise relevant to wing structural layout design, heuristics pertinent to the expert reasoning and problem solving, knowledge of selecting optimization methods and decision-making methods, knowledge of decision process management and scheduling , and knowledge of system control and conflict resolution, and so on. Model base (MB) stores structure analysis models and decision models of layout design. Approach base (AB) is made up of optimization methods and decision-making methods, as well as numerical methods often used such as extrapolating and fitting methods. Data base (DB) stores general facts, original data and computing solutions (including mediate solutions). Graph base (GB) consists of diagrammatic sketches of wing structural layouts and relevant parameters of existing fighters, drawing tools, and graphs produced in the course of design. Base management system is responsible for management and maintenance of corresponding base, such as adding, deletion, update, or usage. The integration core of these five bases is knowledge base subsystem, that is, structural layout expert subsystem, constituted by knowledge base and its management system as well as inference machine. This subsystem is also responsive for controlling and scheduling overall system. Through the base management systems, knowledge in KB can access data in DB and graphs in GB, or activate models in MB and methods in AB. The knowledge base subsystems also can link models and methods to organize data flow required.

There are various ways through which representing human designers' expertise and incorporating it into KB. Knowledge representation schemes include formal logic, semantic nets, production systems and frames[6]. Each one of the representations has its own strong points and limitations. In WSLDSS, data, model, method and graph are treated as special kinds of knowledge. We introduce a multilevel knowledge representation scheme into WSLDSS, and categorize all knowledge into three levels.

The first level knowledge is that about knowledge management, scheduling, and control, by which the system can implement interacting with users, recognizing layout decision situations and goals, scheduling appropriate qualitative reasoning and quantitative computing knowledge, monitoring and controlling the decision process. This kind of knowledge is represented as a set of production rules because its main purpose is to generate a series of actions under some conditions.

The second level knowledge is the set of qualitative knowledge composed of the experiences and skills of domain experts. This kind of knowledge is represented with the hybrid structure of frame and semantic net, indicating the knowledge nodes and their relationships respectively, by which the capability of representation can be enhanced effectively. In order to connect qualitative knowledge with quantitative ones such as model and method, a sort of frame Qual-Quan is introduced, whose slots are stored with the entries, parameters list, and results list of the relative quantitative algorithms. During reasoning, algorithms will be activated to work under the scheduling of the first level knowledge if the relative Qual-Quan frame is met.

The third level knowledge indicates data, models, method and graphs represented through the most befitting schemes respectively. They are transferred by the knowledge belongs to the first or the second level.

VII Conclusions

Structural layout design must synthetically consider multi-objectives and a host of quantitative and qualitative factors, requires expert experience, knowledge and reasoning. In this paper, the wing structural layout design of fighters is studied in the view of not only optimization but decision making. The solving strategy and technological approaches for wing structural layout decision are put forth. We combine the technique of ES with that of DSS, to design and develop the knowledge-based WSLDSS capable of providing structure analysis, optimization and decision support for wing structural layout design of fighters. The structure framework of WSLDSS was proposed and the prototype system is being developed. At present, the structural layout expert subsystem has been preliminarily set up. This research is ongoing and further developments are being carried out to develop a complete prototype system.

References

[1]Winner, R.I., et al., The Role of Concurrent Engineering in Weapon System Acquisition, IDA R-338, 1988.

[2]Vaish, A.K., Kamil, H., An Expert System for Structural Analysis and Design, Proceedings of 29th Structures, Structural Dynamics & Materials Conference, 1988, 1333-1338.

[3]He, L.S., Zeng, X.P., Application Researches on Expert System Used for Structural Layout Optimization of Wings, Acta Aeronautics et Astronautics Sinica, 12, 9(1991), A534-536.(in Chinese)

[4] Sprague, Jr., R.H., Carlson, E.D., Building Effective Decision Support Systems, Prentice-Hall, Englewood Cliffs, NJ, 1982.

[5] Kumar, V., Acikgoz, M., Cakal, H. and Ari, O., Multilevel Optimization with Multiple Objectives and Mixed Design Variables, AIAA-92-4757

[6] Dym, C.L. and Levitt, R.E., Knowledge-Based Systems in Engineering, McGraw Hill, NJ, 1990.

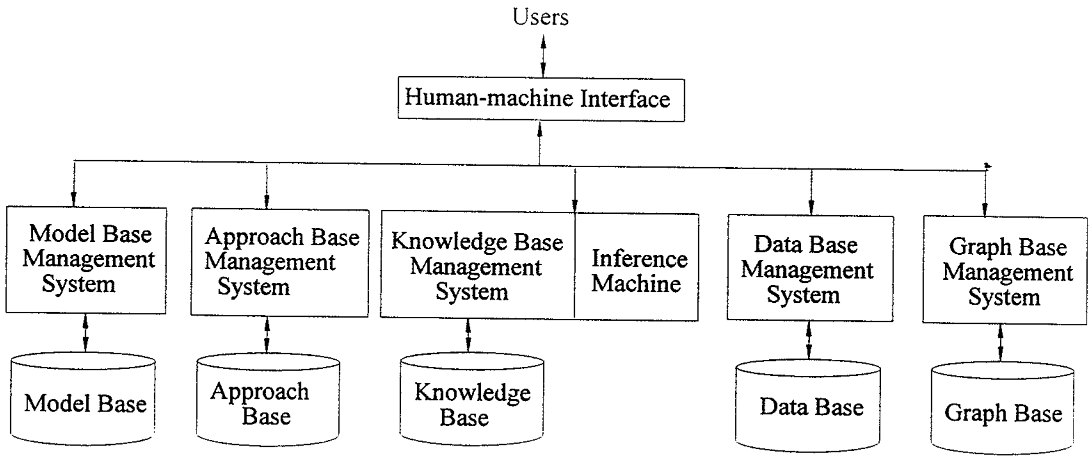

FIGURE 1 - Structural framework of WSLDSS