Environment of Design Requirements Input and Preliminary Sizing for Aircraft Conceptual Design

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Abstract: To supply a convenient and expandable tool to organize the design requirements of a new aircraft and estimate its basic design parameters during conceptual design, the Environment of Design Requirements Input and Preliminary Sizing (EDRIPS) was developed. In this environment, the performance requirements, mission profile and payloads could be inputted or selected respectively through user-friendly interfaces in a highly interactive way. Based on these requirements, it enables the designer to pick up a design point in the solution space through constraint analysis, and then conduct mission analysis either step by step or via auto iteration by using an improved method for estimating the takeoff weight. The implementation of each module and the methods utilized are described. A design example is finally presented and analyzed to validate the efficiency and reliability of applying EDRIPS to aircraft conceptual design.

Key words: aircraft design; design requirements; constraint analysis; mission analysis; computer aided design

用于飞机概念设计的设计要求输入和初步定参数环境. 刘 虎, 武 哲. 中国航空学报(英文版). 2003, 16(1): 15- 21.

摘 要: 为了在飞机概念设计过程中给新型号的设计要求组织和基本参数估算提供便捷且可扩展的工具而开发了设计要求与初步定参数环境(EDRIPS)。在这一环境中,设计者可以通过友好的用户界面交互地输入飞机的性能要求、构造任务剖面和选取有效载荷,然后以此为基础从约束分析所得的可行域中选取设计点,进而利用一种改进的估算飞机起飞重量的方法进行任务分析以得到飞机的基本设计参数。介绍了各模块的实现措施和所采用的方法。最后通过对一个设计实例的分析验证了EDRIPS应用于飞机概念设计的有效性和可靠性。

关键词: 飞机设计; 设计要求; 约束分析; 任务分析; 计算机辅助设计

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During the past two decades, computer aided design technique has played an important role in aircraft conceptual design. To any system for Computer Aided Aircraft Conceptual Design (CAACD), the handling of design requirements, which is the yardstick for a feasible design, is always an essential problem, for the items and data structures of inputted requirements should be propitious to subsequent preliminary sizing. Correspondingly, the part of preliminary sizing, which consists of constraint analysis and mission analysis, should enable the designer to get such basic design parameters as takeoff weight quickly, as well as to find out potential antinomies and inaccuracies in requirements. The Environment of Design Requirements Input and Preliminary Sizing (EDRIPS), which uses such current typical CAACD codes as AAA[1], ACSYNT[2], AeroDYNAMIC[3] and RDS[4,5] for reference, was just developed to supply an integrated environment that embraces both of the design requirements input module and preliminary sizing module. EDRIPS also offers an ex-

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pandable framework with friendly graphical user interface (GUI), so that it could not only fulfill the initial tasks of conceptual design conveniently, but also serve as the basis for further enhancement.

1 Basic Features and System Structure

At the beginning of aircraft design, the decision should be made that whether an absolutely novel design or a baseline one is required. One of the basic features of EDRIPS is setting two task modes to deal with them discriminatingly, which could improve the design efficiency by utilizing existent design information of baseline aircraft when baseline design is conducted.

Hierarchy of data precision is a distinct trait of engine, aerodynamic and weight fraction characteristics, which are the three kinds of primary data for sizing, with the proceeding of conceptual design. Take aerodynamic characteristics as example, statistical data for each category of aircraft, characteristics of baseline aircraft (if exists), computed characteristics for proposed configurations could be utilized at different stages of conceptual design. As for EDRIPS, the analysis is concentrated on the first stage approximation. However, it could be easily expanded to fulfill detailed sizing when more precise data are available due to the adoption of Object-Oriented Programming (OOP) technique with using C++ language, which also ensures the feasibility of contrasting the results of later performance analysis with well organized design requirements to evaluate a scheme.

The development environment of EDRIPS is PC platform and Windows operating system, which ensures that it could be accessed by more designers and be conveniently integrated into such available systems as RCSPlus[6].

Fig. 1 illustrates the system structure of EDRIPS. Task selection is dedicated to select the category of aircraft and distinguish design tasks. Performance requirements input, mission profile input and payload selection belong to the design requirements input module; sizing setting, constraint analysis and mission analysis are parts of the preliminary sizing module. Predefined data include the International Standard Atmosphere (ISA) characteristics and statistical data summarized from documents on conceptual design[7-9], while computed data are got from subsequential analysis and could only be studied from such aspects as data structures currently.

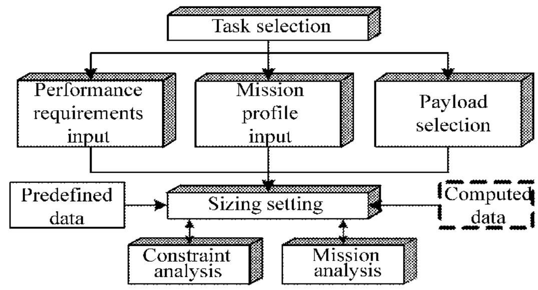

Fig. 1 System structure of EDRIPS

2 Design Requirements Input Module

2.1 Performance requirements input

Candidate requirements are classified into three groups: fundamental flight performances, such as maximum Mach number and maximum range; maneuver performances, such as sea level climb rate and load factor of sustained turn; structural and material requirements, such as maximum dynamic pressure and whether composite materials are used or not. The designer can select needed items and input associated data, while EDRIPS will judge which one should not function according to the category of current aircraft. For example, it will be no use if the load factor of instantaneous turn is given to an UAV.

2.2 Mission profile input

Because of the importance of the mission profile to sizing and trajectory analysis, there have been many researches on the methods for describing and utilizing it[10, 11]. In terms of the requests for the mission profile input method presented in Ref. [10], the expandability of profile definition and friendliness of GUI are two of the most outstanding ones. The former is ensured by using OOP technique in EDRIPS: each optional mission

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segment, *i.e.* takeoff, accelerated/decelerated climb/dive, cruise, horizontal acceleration/deceleration, combat turn, loiter, delivering expendables, descent and landing, is defined as an independent class that encapsulates all the associated specific data. By putting the basic information of each segment, such as its name and index in the list composed by segments belonging to the same kind, in a mission segments information list in succession, the whole profile could be built. Fig. 2 illustrates such data structures by taking cruise and descent segments as example.

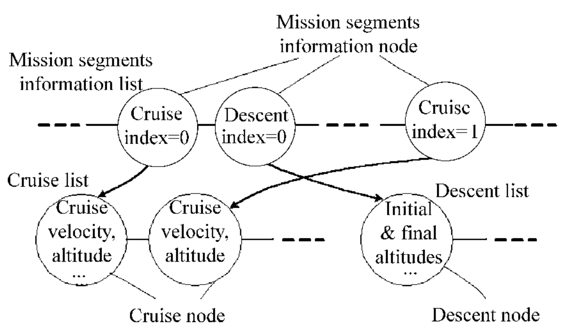

Fig. 2 Examples of data structures for mission profile

As to the friendliness of interface, the GUI as shown in Fig. 3 was devised for EDRIPS by using such systems as AeroDYNAMIC[3] and MPIS[10] for reference. The upper zone of the interface is to represent the mission profile by a set of independent bitmaps, which could supply visual feedback to the designer. Once a segment is selected by clicking the corresponding bitmap or has just been added, the associated data will be shown in the list box on the left of the interface. Then the designer could modify these data or even delete an existing segment.

In order to eliminate explicit mistakes of the inputted profile, an important measure adopted by EDRIPS is setting a plotting zone that takes range and altitude as abscissa and ordinate respectively. Once an operation has been accomplished, EDRIPS will adjust the range of coordinate axles according to the latest profile and plot its rough trajectory. Because only the abscissas of two adjacent segments are assumed to be continuous, if the altitude of any mission segment is unreasonable, the trajectory will be broken along the direction of ordinate, and the designer is thus notified to make some modification.

2.3 Payload selection

In EDRIPS, payloads are classified into four sorts, *i.e.*, persons, weapons, equipment and others; and each sort is subdivided into several more refined groups. For instance, guns, missiles and shells are subdivisions of weapons. All the available payloads are defined and initialized in a payload base firstly, and then invoked and displayed by EDRIPS. This indicates that the key element to payload selection is the developing of the payload base, while such operations as selecting, adjusting on interface are relatively conventional.

3 Preliminary Sizing Module

3.1 Sizing setting

Functions of this part include the following items: determine the usable hierarchy of data for sizing according to the design requirements and information of current aircraft and its baseline (if exists), and then feed back the information to the designer via GUI; enable the designer to change the category of engine to contrast the sizing results if its type has not been fixed; update the design information after sizing. It also serves as the joint between constraint analysis and mission analysis: the parameters of the design point, namely, sea level thrust loading T_{SL}/W_{TO} and takeoff wing loading W_{TO}/S, picked up through the former are transferred to the latter; the weight fraction characteristics calculated through the latter are passed back to the former to get more precise constraint boundaries.

3.2 Constraint analysis

Ten kinds of constraints, such as takeoff ground roll length, maximum Mach number, cruise Mach numbers, and load factor of sustained turn can be handled in EDRIPS now. When the mission analysis interface (Fig. 4) is initialized, the data for each constraint item will be checked for usability based on the design requirements of the current aircraft: If usable, the corresponding

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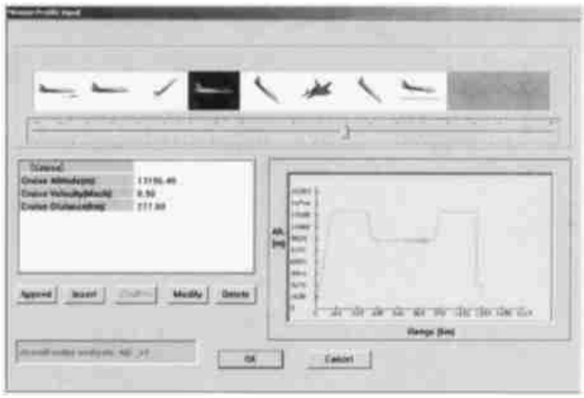

Fig. 3 Interface of mission profile input

boundary could be computed[9, 12] and the designer could control whether to display it or not; if unusable, EDRIPS will show prompts through the interface or pop-up dialogs. The designer could use his mouse to pick up a feasible design point in the solution space formed by different boundaries and view the values of T_{SL}/W_{TO} and W_{TO}/S of it in real time. As an assistant measure to make the selection more reasonable, the design points of existent aircraft that belong to the same category with the current design could be displayed in the constraint diagram as references.

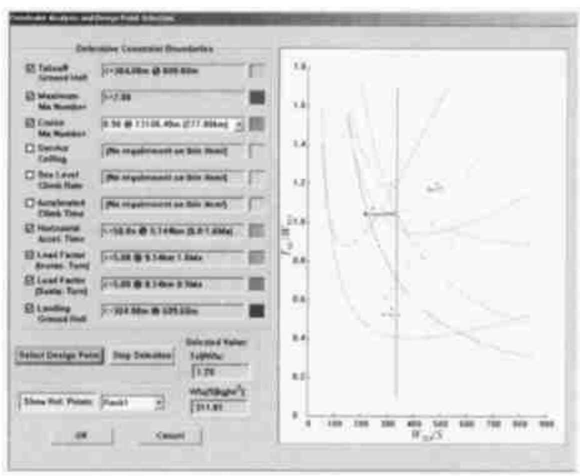

Fig. 4 Interface of constraint analysis

3.3 Mission analysis

The takeoff weight W_{TO}, sea level statistic thrust of engine T_{SL} and wing area S are the basic design parameters of an aircraft and objectives of mission analysis, in which the estimation of W_{TO} is the key problem. When W_{TO} is calculated, T_{SL} and S could be easily got by using T_{SL}/W_{TO} and W_{TO}/S selected in the constraint analysis.

The basic equation for estimating W_{TO} is[9]

$$W_{TO} = W_F + W_E + W_P \tag{1}$$

where W_F is the fuel weight, W_E the empty weight, and W_P the payload weight. Both W_F and W_E are related to W_{TO}, so utilizing Eq.(1) to conduct analysis is an iterative process and the designer should input a guessed takeoff weight $W_{TOguess}$ via interface firstly. W_P consists of the weight delivered during flight W_{PE} and the weight of fixed payload W_{PF}, and its value is determined by payload selection[13] and will not change during sizing.

W_F could be calculated through analyzing the weight fraction characteristics of each segment in the mission profile, which includes mission segment weight fraction Π and instantaneous weight fraction β that could be expressed as functions of propulsion characteristics and each segment's parameters[9]. To analyze those segments that deliver no expendables, the methods depicted in Ref. [9] are cited with modifications, *e.g.*, the minimum time-to-climb path in it will not be utilized in EDRIPS until further performance analysis is fulfilled.

If delivery of expendables is contained in the mission profile, the current methodologies for estimating W_F are basically considering solely the weight loss for the fuel consumed at first, and then modifying the result according to the delivered weight[7-9]. In order to avoid breaking the profile into several fractions, even if there exist several scattered segments for delivering expendables, the meaning of Π is expanded in EDRIPS, *i.e.*, the equations for calculating Π and β of the segment for delivering expendables (assumed to be segment 'i') are modified as follows

$$\Pi_i = \frac{W_{if}}{W_{ii}} = \frac{W_{ii} - W_{idelivered}}{W_{ii}} = 1 - \frac{W_{idelivered}}{\beta_{i-1} W_{TOguess}} \tag{2}$$

$$\beta_i = \beta_{i-1}\Pi_i \tag{3}$$

where W_{if}, W_{ii}, $W_{idelivered}$ and β_{i-1} are the final and initial weights of this segment, the delivered weight and β of the previous segment, respectively.

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Based on such modification, the final weight at the end of a mission is

$$W_{land} = \beta_{land} W_{TO} \quad (4)$$

where β_{land} is the instantaneous weight fraction of the landing segment.

Thus the fuel weight decreased during flight

$$W_{Fused} = W_{TO} - W_{land} - W_{PE} = (1 - \beta_{land}) W_{TO} - W_{PE} \quad (5)$$

and then

$$W_F = \gamma W_{Fused} \quad (6)$$

where γ is determined by the reserved fuel for mission. Moreover, to the potential air fueling segment, this strategy also functions, once the increased fuel is counted into W_{PE} as negative expendables.

At this stage of design, W_E is estimated based on statistic relationship between W_E and W_{TO} of existent aircraft, and a general format of estimation could be summarized from Refs. [7–9] as

$$W_E = \lambda(\varphi W_{TO}^p + \zeta) \quad (7)$$

where λ reflects the effect of weight saving caused by using composite materials, φ is a combined factor determined by the category of aircraft and design parameters, while both of p and ζ are determined by the category of aircraft. It should be noted that in the methods introduced in Ref. [7] and Ref. [9] (the latter one is adopted by EDRIPS), φ is also determined by the category of aircraft solely and ζ equals zero.

Substituting Eqs. (5–7) into Eq. (1) provides

$$W_{TO} = \lambda\varphi W_{TO}^p + \gamma(1 - \beta_{land}) W_{TO} + W_P + \zeta \quad (8)$$

Under the mode of 'step by step' supplied by EDRIPS, $W_{TOcalculated}$ got by substituting $W_{TOguess}$ into the right hand side of Eq. (8) is just the final result. This mode could help the designer, especially those who are still under learning to comprehend the practical meaning of the takeoff weight. However, an evident error always exists between $W_{TOguess}$ and $W_{TOcalculated}$ here, so the 'auto iteration' mode must be utilized to get such a result that could satisfy the given relative error.

When no segment for delivering expendables exists, β_{land} is a constant, and Eq. (8) can be written as

$$W_{TO} = A W_{TO}^p + B W_{TO} + C \quad (9)$$

where $A = \lambda\varphi$, $B = \gamma(1 - \beta_{land})$ and $C = W_P + \zeta$ all of which could be treated as constants for a specific aircraft if its design parameters are not changed during iteration. Then a function could be defined according to Eq. (9) as

$$f(W_{TO}) = A W_{TO}^p + (1 - B) W_{TO} + C \quad (10)$$

Its first derivative with respect to W_{TO} gives

$$f'(W_{TO}) = A W_{TO}^{p-1} + (1 - B) \quad (11)$$

Thus by comparing the recursive rule

$$W_{TO_k} = W_{TO_{k-1}} - \frac{f(W_{TO_{k-1}})}{f'(W_{TO_{k-1}})} \qquad k = 1, 2, \cdots \quad (12)$$

based on Newton-Raphson theorem[14] with the widely used

$$W_{TO_k} = W_{TO_{k-1}} - q(W_{TO_{k-1}} - W_{TO_k}) \qquad k = 1, 2, \cdots \quad (13)$$

(q is an amending factor), it is seen that the former could get an convergent root far more rapidly than the latter at the least cost of computation complexity, and its range of feasible $W_{TOguess}$ that makes the iteration converge is also much broader than that of the latter.

If there exists a segment for delivering expendables, it could be deduced from Eqs. (2) and (3) that β_{land} is not only related to propulsion characteristics and each segment's parameters, but also has complex non-linear relations with $W_{TOguess}$, so Eq. (11) is untenable strictly. However, for the variation of the values of β_{land} is not drastic during iteration, Eq. (11) can still be utilized approximately although a new value of β_{land} must be calculated by analyzing the profile again for each step of iteration. Under this condition, it is found through enlightenment of previous experience[8] and test in EDRIPS that if the result from Eq. (12) is amended following Eq. (13) with q equal to 0.75 or so, the most rapid convergent speed will be achieved. On the contrary, the iteration sequence converges more rapidly with no amendment, namely $q = 1$, if

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β_{land} is a constant.

4 Program Validation

Due to the difficulty of accessing the data of real aircraft, EDRIPS was validated by testing such designs as introduced in Refs. [7-9], and the example of Air-to-Air Fighter (AAF) in Ref. [9] (renamed as AAF _v1 in EDRIPS) is presented here.

The performance requirements and payloads of AAF _v1 are absolutely the same as those of AAF, and several slight modifications are made on the mission profile, including omitting the segments of warm-up and takeoff rotation, setting two segments instead of one to deliver the three kinds of expendables, *etc*., but the total number of mission segments remains 20. Only about a single hour was used to accomplish these modifications and input all design requirements into EDRIPS. The final status of the mission profile of AAF _v1 are shown in Fig. 3 given earlier.

Fig. 4 above illustrates the initial constraint analysis for AAF _v1 in EDRIPS. The final solution space bounded by seven kinds of available constraints quite conforms to the result given in Ref. [9] and definitely contains the design point of AAF.

Because no numerical iteration is conducted in Ref. [9], the 'step by step' mode was firstly chosen to contrast the results (the fps units in Ref. [9] are conversed into mks units). The initial parameters are as follows

$$\left.\begin{array}{ll} T_{SL}/W_{TO}=1.2 & W_{TO}/S=312.48\text{kg/m}^2 \\ W_{TOguess}=11340\text{kg} & W_P=1205.04\text{kg} \end{array}\right\} \quad (14)$$

Finally, the estimated takeoff weight of AAF _v1 in EDRIPS equals 11776.60kg, which is 6.40% heavier than the value of AAF (11067.84kg).

As viewed from methods used for analysis, the error is mostly caused by three points except for the simplification of climb path mentioned above:

(1) The reserved fuel for mission is not considered in Ref. [9], while $\gamma=1.06$[8] in EDRIPS.

(2) Π is set to be 1 for both descent and landing in Ref. [9], while equals 0.990 and 0.995 respectively for fighter aircraft according to the statistic data[7,8] in EDRIPS. Moreover, a descent segment of AAF was turned to a decelerated dive of AAF _v1 for more precise calculation.

(3) Only horizontal acceleration is subdivided in Ref. [9] in practice, while all of climb, horizontal acceleration, cruise and loiter are refined based on preset minimum subdivision criteria in EDRIPS.

All these modifications will increase W_F and result W_{TO}. If they are not made, the relative error between W_{TO} of AAF _v1 and that of AAF will decline to 2.40%。What is more, due to the fact that no uniform methods exist for preliminary sizing, namely, the results in Ref. [9] should not be regarded as absolutely standard ones, EDRIPS could be deemed as reliable.

Under 'auto iteration', if the same initial parameters are used and the relative error allowance is 0.0000001, the results got by using different typical recursive rules (Table 1) indicate that such strategy for iteration as argued in Section 3.3, which is also the same as adopted in EDRIPS, is highly effective.

Table 1 Results from different typical recursive rules

Formulas Used	Total Iteration Steps	Result W_{TO}/kg
Eq. (12) and Eq. (13) ($q=0.75$)	6	14411.6529
Eq. (12)	16	14411.6527
Eq. (13) ($q=1$)	80	14411.6451
Eq. (13) ($q=0.5$)	165	14411.6447

5 Conclusions and Future Work

EDRIPS supplies a convenient and reliable tool to the design requirements input and preliminary sizing for aircraft conceptual design. It features its highly interactive and use-friendly environment on the one hand, and the improvements on analysis methods, such as the strategy for estimate takeoff weight, on the other hand, both of which improve the efficiency and quality of concep-

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tual design.

The emphases of future work should be placed on the following two aspects.

(1) Current EDRIPS is developed for the conceptual design of fighter aircraft, whose design requirements and analysis methods are the most complex ones. Although the expandability of its architecture has been validated by taking UAV into account during system design and programming, EDRIPS should be further extended to be applied to other categories of aircraft.

(2) Based on the basic design parameters of an aircraft estimated in EDRIPS, the designer could conduct design synthesis to determine its configuration and other detail parameters, and then realize the initial iteration of conceptual design after accomplishing a series of subsequent work, including geometric modeling, geometric characteristics analysis, aerodynamic analysis, performance analysis, comparing the results with design requirements and conducting modification[15]. Consequently, by taking such measures as researching on more convenient modeling methods, developing engine database and integrating available sophisticated analysis codes, EDRIPS should be ultimately enhanced to be an integrated system for CAACD and then be utilized to solve practical engineering problems.

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