# THE AIRCRAFT / PROPULSION INTEGRATED ASSESSMENT SYSTEM

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## Abstract

The Aircraft / Propulsion Integrated Assessment System is a computer aided assessment system that was developed for the conceptual and preliminary design phase of modern military aircraft. This system for various missions and technical development levels, enables to evaluate a wide range of combinations of aircraft configuration and engine (turbojet or turbofan) or to obtain the optimal solution with the numerical algorithm for multiobjective optimization with constraints.

A series of mission and aircraft / propulsion project, including the present aircraft modifi– cation and the future aircraft development has been studied. During optimization process, the best combinations of design parameters are selected. Note that the aircraft / propulsion system performance has been improved obviously.

In addition, to use this system does not require considerable input and user experience. The output is easy to understand too. An aircraft / propulsion project analysis using this system requires less than 1 minute of CPU time (IBM4341).

## Introduction

Overall raising the performance of modern military aircraft is required, to fit it to various flight mission and a wide range of work. Therefore, there is a qualitative change in aircraft / propulsion design, the integrated harmonization of aircraft and propulsion in aerodynamic performance, dimension and mass, should be sufficiently considered in design. In addition, aircraft and propulsion are high–technical products which have longer research lead time. In preliminary design phase, the determined optimal values of design parameters will have an effect on competitive ability of products in 5 to 10 years. For this reason, the aircraft / propulsion integrated system emerges at the moment. The paper introduces a rapid aircraft / propulsion integrated assessment method and software and some results which were obtained by using the method in aircraft / propulsion combination scheme demonstration and preliminary design.

## Assessment method

The aircraft / propulsion integrated assessment system consists of six modules (Fig.1), they are: geometry, aerodynamic performance, engine performance, mass properties, flight performance and optimization. User puts forward evaluating design requirements and missions of aircraft, i. e. flight profile and performance requirements, effective load and equipment mass, constrained conditions in performance, geometry and mass. Acorr–ding to these requirements, the design variables, constrained conditions and object function will be determined.

The available optimal variables of the assessment system are listed in figure 1. The nonoptimal variables will be taken as given quantities beforehand. Through operating the system, the aircraft / propulsion optimal combination scheme can be obtained according to the predetermined objective function and constrained conditions.

1. Geometry module

The geometry properties of aircraft, geometry dimensions of engine and the harmonic dimensions of aircraft and propulsion are computed according to the inputs of geometry parameters. The harmonic dimensions mainly consider the requirements of assembling propulsion, rationality of wing configuration, harmonic relations of wing to fuselage, fuel volume in wing and fuselage and so on. Geometry module may deal with normal and canard lay–out, wing plane shape, including rectangular and strake wing.

2. Aerodynamic performance module

Lift, zero–lift drag, induced drag and longitudinal moment performance can be calculated according to aircraft geometry property and given flight Mach number $Ma_\infty$, flight altitude H and flight angle of attack $\alpha$. The module can not only calculate the effect of trimming on aircraft lift and drag, but also provide lift and drag at a time when aircraft flies at low speed and puts flap and landing gear down as ground effect is considered. A rapid semi–empirical and semi–theoretical engineering evaluation method is employed to compute aerodynamic performance. We respectively examined the module for different aircraft configurations. The relative lift and drag errors of the aircraft is below 5%,some isolated relative errors are not more than 10% maximum at $0<Ma_\infty<3.0$ and at medium and small angle of attack. It is demonstrated that the accuracy of the method meets the requirements for the preliminary design. Fig.2 shows the results examined of zero–lift drag coefficient $C_{xo}$.

3. Engine performance module

A rapid calculation module of engine performance is selected in the assessment system. Engine performance,i.e.engine thrust and fuel mass flow, can be calculated according to engine cycle parameters (pressure ratios of compressor and fan, $\pi_{CD}$and $\pi_{FD}$; temperatures of burner and afterburner, $T_{3D}$and $T_{8D}$; bypass ratio $BR_D$), the schedule of engine control and various limited values (rotation speed, pressure, temperature and maximum mass flow of fuel) under any flight and engine conditions.

The model features that the general characteristic of components are established based on test statistical data. The simplified performance of components with main factors considered, but secondary factors neglected, will be obtained if design parameters of components are known.

Performance of four different kinds of engines has been calculated to check the reliability and generality. The results are shown in fig.3 and 4. As indicated by the results, under many common practice flight conditions, the mean square root error of the above–mentioned calculations is 2.6% for thrust and 2.9% for fuel mass flow. The model can be correctly used to calculate engine performance of many kinds of engines and any value of design variables. It especially fits to use in the period of aircraft and engine conceptual demonstration for aircraft / propulsion integrated design, as the inputs of component characteristics are not required.

The effect of inlet and nozzle jet losses after assembling is considered in available thrust.

4. Mass properties module

The module can be used to calculate the structure mass of aircraft components if aircraft dimension and engine cycle parameters are known. A semi–empiricale engineering calculation method is employed, of which the coefficients can be modified and examined for various types of aircraft. The relative error of calculation results meet the requirements of the preliminary design.

5. Flight performance module

Flight performance is one of main foundations evaluating combat ability of aircraft. The calculations of flight performance can be determined according to flight profile which is fixed by design flight mission and selected object parameters and constrained conditions. In order to meet the needs for scheme demonstration in fighter development, subprograms are made in accordance with basic flight performance of aircraft in the assessment system, so that it can be used for calculation of different flight mission. It can be used not only to calculate distance of take–off, maximum horizontal speed, practical ceiling, operation radius, range, normal maneuver (rate of climb,horizontal acceleration time, practical stable turning load),supersonic maneuver, but also to perform quantitative evaluation and integrated assessment as well. The subprograms also can be coupled on the basis of flight profile required. Using the system, the flight performances of some present aircraft have been calculated, compared with data provided by the industry, the integrated error of calculation is less than 5%.

6. Optimization module

The optimization design method of seeking optimal parameters of aircraft / propulsion system is diversified. Method can be selected depending on the assessment system property. The assessment system is a big system of aircraft / propulsion integrated, and optimal performances in many ways are required. It belongs to constrained multi–object optimization problem.

The gross mass or main improved performance indexes that need to be improved, such as range, normal load, specific excess power, can all be selected as objective parameters.

In the assessment system, the evaluation function method is used to get multi–objective decision. The optimal resolution of the evaluation function which can be acted as a final solution of multi–objective optimization, is resolved by single–objective optimization method.

For the single–objective problem, direct search method such as pattern search method is adopted for the assessment system. The constrained optimization problem in which penalty function method is adopted, will be transformed to unconstrained optimization problem.

## Constraint and parameter analysis

Parameter analysis studied the effect of design variables on object parameters, while constraint analysis researches feasible region of design variables in which constrained conditions are satisfied. Constraint analysis and parameter analysis can point out whether feasible region which satisfies all constraints exists within the scope of design variables,and examine rationality of constrained indexes. Meanwhile they can quantitatively evaluate abjustable values of objective parameters in the feasible region.

It is obvious that by using the system, we can perform constraint analysis and parameter analysis for aircraft / propulsion integrated scheme. Their results are shown in fig.5, 6,7.

Fig.5 is a constrained boundary chart which can calculate design parameters wing load ($p_o$) and take–off thrust / weight ($\bar{P}$) assuming constraint dimensionless geometry variables, engine cycle parameters and air mass flow. From fig.5, it can be seen that there is a less feasible region if engine and aircraft geometry remain unchanged. It is apparent that there is little room for improvement.

Fig.6 shows the effect of aircraft design variables, wing aspect ratio ($A_w$) and take–off thrust / weight ($\bar{P}$) on range and constraints boundary. Fig.7 gives the effect of engine design variables, pressure ratio of compressor ($\pi_{CD}$) and turbine entrance temperature ($T_{3D}$) on range and constraints boundary. As shown in fig.6, under unchanged engine conditions increasing fuel mass makes thrust / weight decrease, and the range obviously increases. As shown in fig. 7, under unchanged aircraft configuration, increasing pressure ratio of compressor ($\pi_{CD}$) and decreasing temperature at turbine entrance ($T_{3D}$) can obviously augment the range, as it makes engine specific fuel consumption decrease. In short, increasing fuel mass and decreasing specific fuel consumption are main factors affecting adjustable value of range.

## Aircraft design variables optimization

Since there is a variety of aircraft design or improvement design mission, the premise conditions of optimization are different. There are a lot of constraints and limit conditions. Using the assessment system we can accomplish optimization and analysis in different conditions.

For multi–objective problem, the assessment system uses evaluation function method to optimize. Since aircraft has different improvement requirements for performance, it must have a relevant different evaluation function expression.

Table 1 lists three kinds of evaluation function expressions which correspond to aircraft performance improvement and ″linear weighted sum method″ integrated.

| item / number | aircraft performance improvement requirements | evaluation function expressions |
|---|---|---|
| I | increasing range | [L] / L |
| II | improving subsonic maneuver at low and medium altitude | $[SEP_5] / SEP_5 + [n_{y_5}] / n_{y_5}$ |
| III | improving maneuver increasing range | $[SEP_5] / SEP_5 + [n_{y_5}] / n_{y_5} + 0.5\,[L] / L$ |

* $SEP_5$, $n_{y_5}$ —separately specific excess power and turn normal load at H = 5 km, $Ma_\infty = 0.9$

* L —range

* $[SEP_5]$ , $[n_{y_5}]$ , [L] —given constrained values.

Table 1

The assessment system can be used to optimize aircraft design variables in given engine condition, and to search available technical measure of some aircraft in increasing range. In optimization, we still use the original engine. Fuselage lengthening is allowed but not fuselage widened, 18 constrained conditions are included. Optimization calculation results are shown in table 2.

Scheme A is obtained by optimization assuming constant fuel mass. The range of scheme A increases by 3.84%. The results show that the effectiveness of increasing range is not so obvious of decreasing wing area ($S_w$) which can decrease drag, and of increasing wing aspect ($A_w$) which can increase lift / drag ratio, both make fuel consumption decrease. Scheme B allows to longthen fuselage and increase fuel mass. The length fuselage will be restricted by the ratio of fuselage to wing span . As indicated by the calculation results, range will increase 25% if fuel mass increase 21% .

## Aircraft / Propulsion system design variables integrated optimization

Optimal combination of modern advanced aircraft with propulsion is required. The system may be used to perform integrated design of aircraft / turbojet and aircraft / turbofan system, to explore direction and way of improvement of aircraft / propulsion system performance. Calculation results show in table 2.

As indicated by the results, different requirements of improvement will lead aircraft and engine to a different direction of development.

If increasing range is required, the range of scheme C which is obtained from aircraft / turbojet system integrated design is 10.5% longer than the range of scheme A which is obtained from aircraft design variable optimization. $\pi_{CD}$ augmentation which needs to engine fuel specific consumption decrease is a main reason. Mean–while, in order to guarantee take–off and basic combat requirements, wing area and thickness ratio, wing leading edge sweep were adjusted. Obviously, compared with scheme C which results from aircraft / turbojet system integrated design, range of scheme E which is obtained from aircraft / turbofan system integrated design is 36.4% longer than that of scheme C. It shows that as compared with turbojet, the economic performance of turbofan is better. We can still raise the economic performance if bypass ratio of engine is further increased. Medium bypass ratio is required as it must consider the limit of climb time constrained condition in scheme E. As compared with scheme D which is from aircraft / turbojet system integrated design, $SEP_5$and $n_{y_5}$ of scheme F which is from aircraft / turbofan system integrated design increase by 6.9% and 2.8% respectively, if improvement of low and medium altitude performance is required. It is obvious that mainly relies on decrease of bypass ratio and suitable change of aircraft configuration. Increase of wing area can raise $n_{y_5}$ .

Optimal scheme G is obtained if improvement maneuver and range at low / medium altitude are both required.

| item / scheme | optimal parameters | | | | | | | | performance | | | Ordimal in table 1 | kinds of engine | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\bar{P}$ | $p_o$ | $A_w$ | $\bar{C}_w$ | $\Lambda_{LE}$ | $\pi_{CD}$ | $T_{3D}$ | $BR_D$ | L | $SEP_5$ | $n_{y_5}$ | | | |
| | | kg / m | | | deg | | K | | km | m / s | | | | |
| A | 0.8455 | 334.3 | 3.0 | 0.047 | 57 | | | | 1342 | 135.9 | 6.06 | I | turbojet | fuel mass fixed |
| B | 0.8138 | 364 | 2.224 | 0.0575 | 52.5 | | | | 1614 | 133.4 | 5.38 | I | turbojet | longthen fuselage in allowable range |
| C | 0.9729 | 329.4 | 3.0 | 0.0485 | 50 | 17 | 1504 | | 1482 | 160.38 | 6.57 | I | turbojet | fuel mass fixed |
| D | 1.0333 | 294.5 | 2.854 | 0.053 | 51.5 | 14.5 | 1600 | | 1384 | 170.14 | 7.0 | II | turbojet | $T_{8D}=2000K$ |
| E | 0.9832 | 317.3 | 3.0 | 0.047 | 50 | 32 | | 0.47 | 2022 | 161.24 | 6.7 | I | turbofan | fuel mass fixed |
| F | 1.0530 | 282.1 | 2.524 | 0.053 | 55 | 20 | | 0.29 | 1783 | 172.3 | 6.89 | II | turbofan | $T_{3D}=1600K$ |
| G | 1.0448 | 276.0 | 2.464 | 0.053 | 55 | 20 | | 0.38 | 1823 | 171.05 | 6.89 | III | tuebofan | $T_{8D}=2000K$ |

table 2 Some kinds of optimal results

## Conclusions

Aircraft / propulsion integrated assessment method and software provided in the research considered the affect of aircraft main design parameters and engine cycle variable on aerodynamic performance, engine performance, mass and dimension of aircraft and engine and flight performance. In addition, couple relationship of aircraft / propulsion system in performance, geometry, dimension and mass are also included. As indicated by preliminary use, in preliminary design phase the aircraft and / or engine design scheme can be optimized according to given flight mission, tactical and technical requirements. It can be applied to the modification design of existing aircraft and engines,to select optimal one from existing engines in aircraft design,to analyze parameters of aircraft as well as that of engines when developing new type of aircraft to optimize aircraft / propulsion design parameters and to assess flight performance of new type aircraft.

Calculation results are reasonable. It took CPU time not more than 1 minute to assess an aircraft / propulsion scheme on IBM4341. Calculation speed and accuracy will completely satisfy aircraft / propulsion system scheme demonstration and preliminary design phase requirements. It is a very useful assessment tool with a wide application and development prospect.

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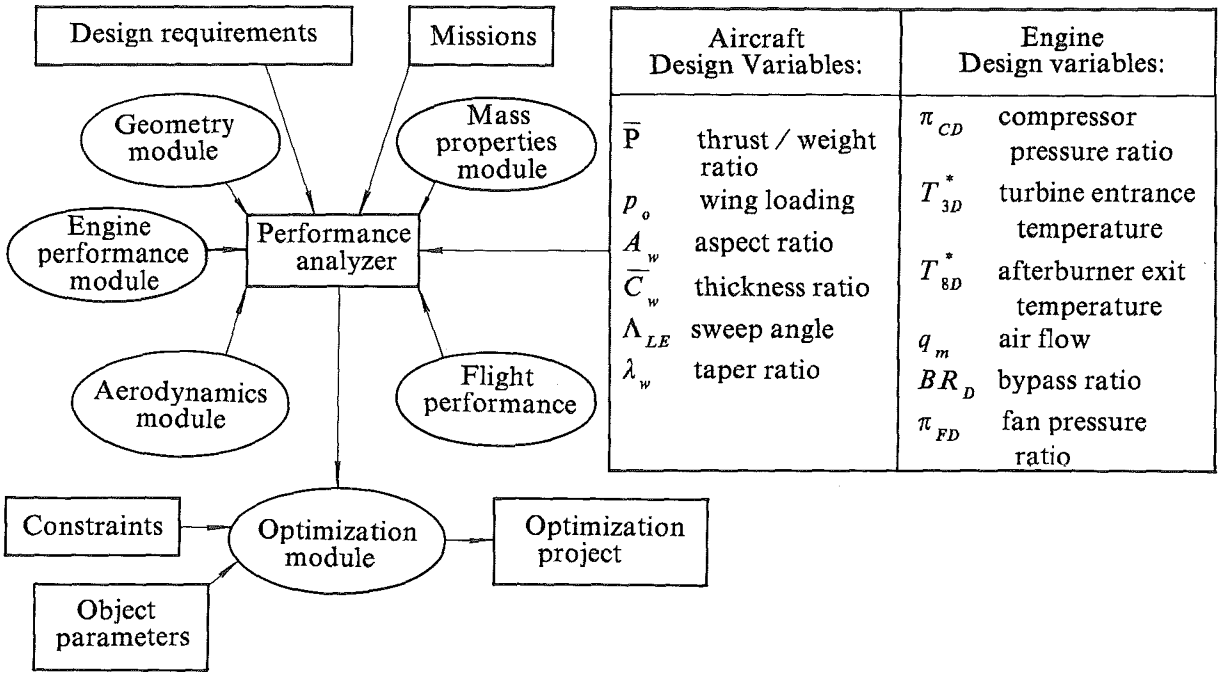



Fig.1 Diagrammatic sketch of the Aircraft / propulsion integrated system

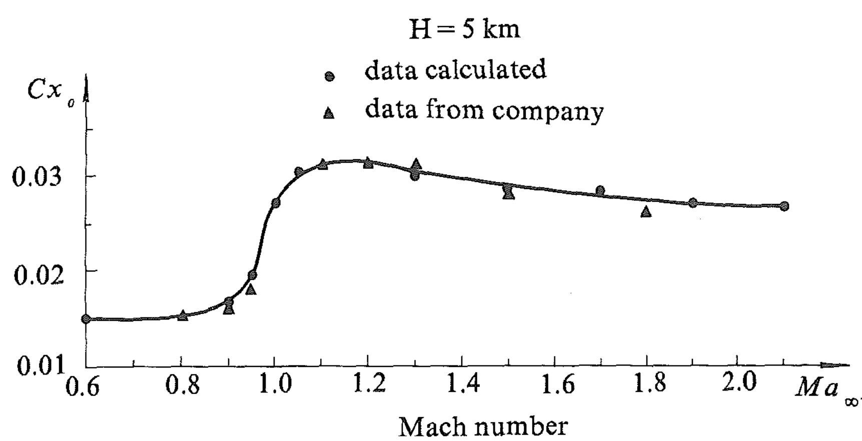



Fig.2 Zero–lift drag coefficient

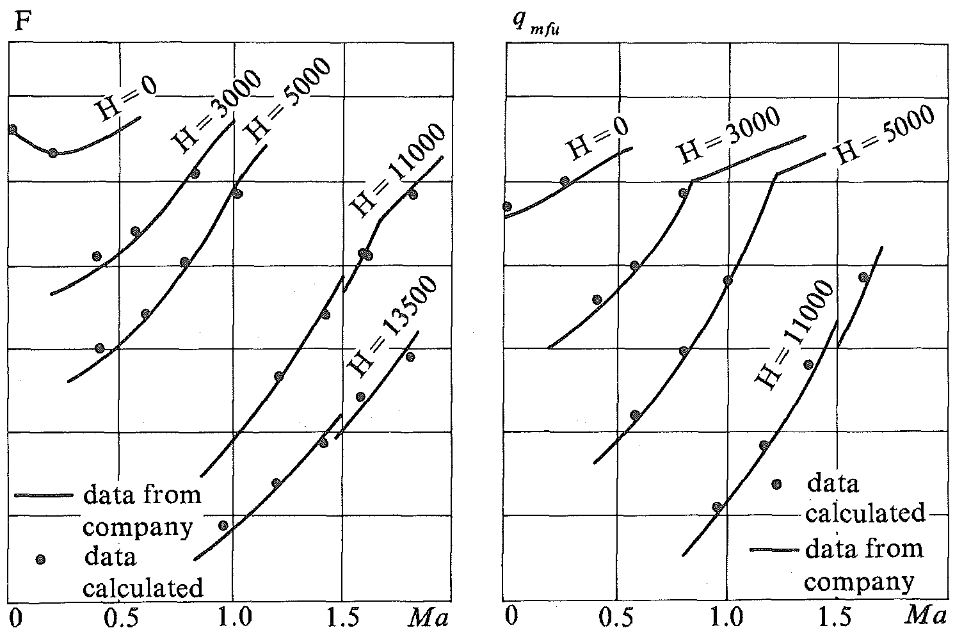



Fig.3 The turbojet performance with secondary augmentation

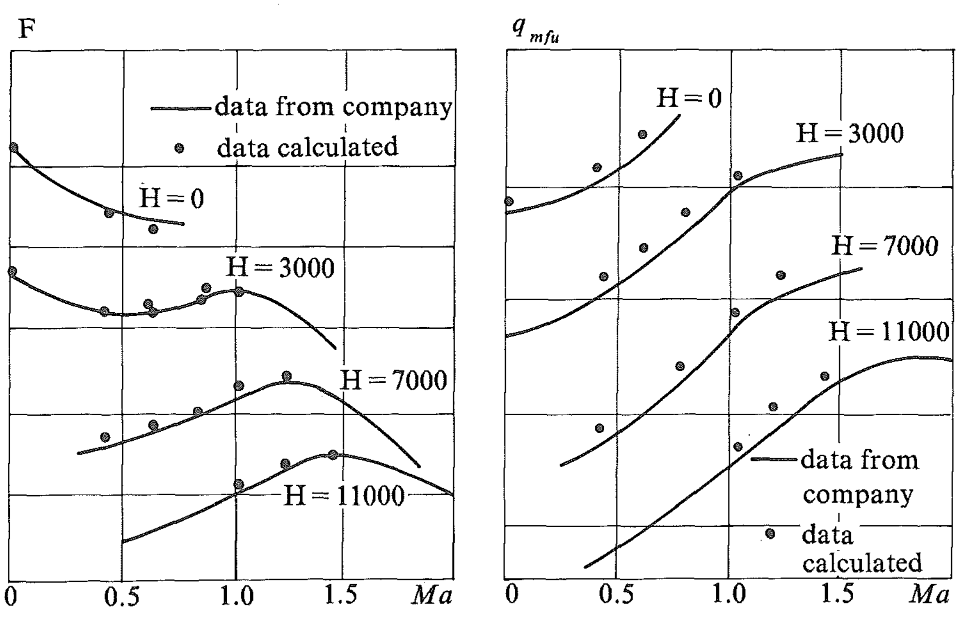
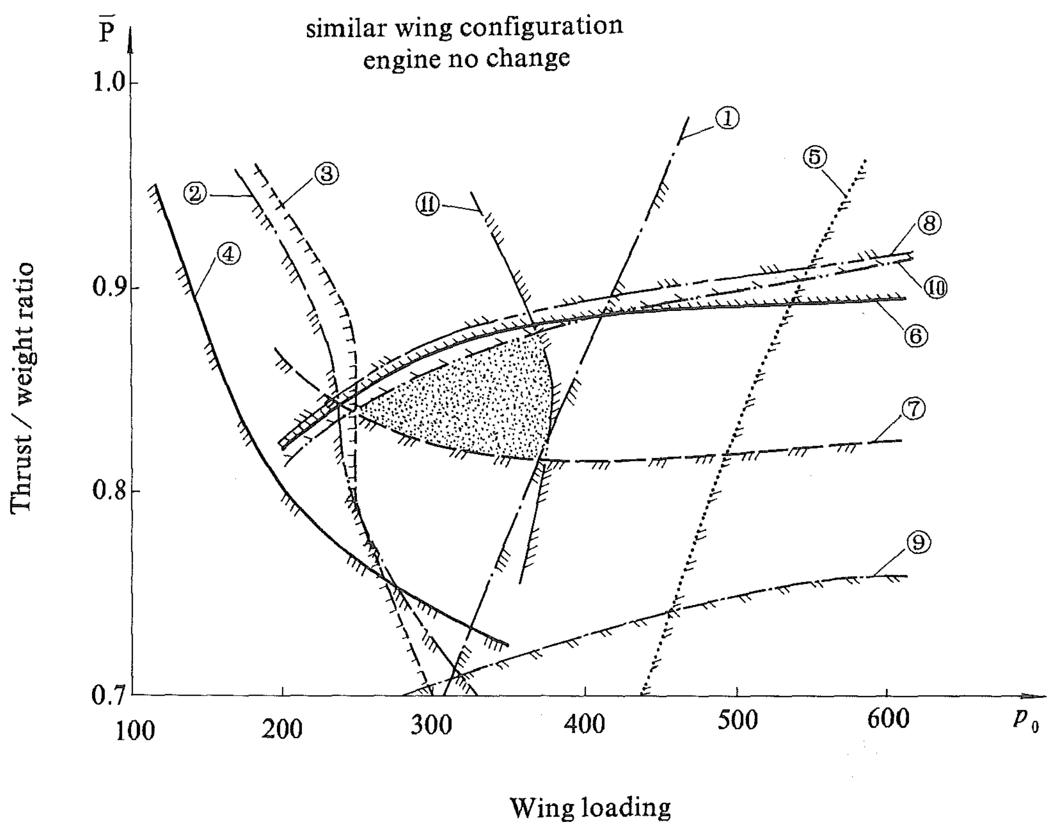



Fig.4 Performance of turbofan(*Spey*–MK–202) at maximum state




① distance of take–off run ② practical ceiling
③ maximum Mach member ④ specific excess power at 5 km high
⑤ normal load factor when turn at 5 km high ⑥ range
⑦ climb time ⑧ operation radius ⑨ upper boundary of fuel scale
⑩ lower bunodty of fuel scale ⑪ geometry constraints

Fig.5 The relations of aircraft main parameters and boundary of constraints

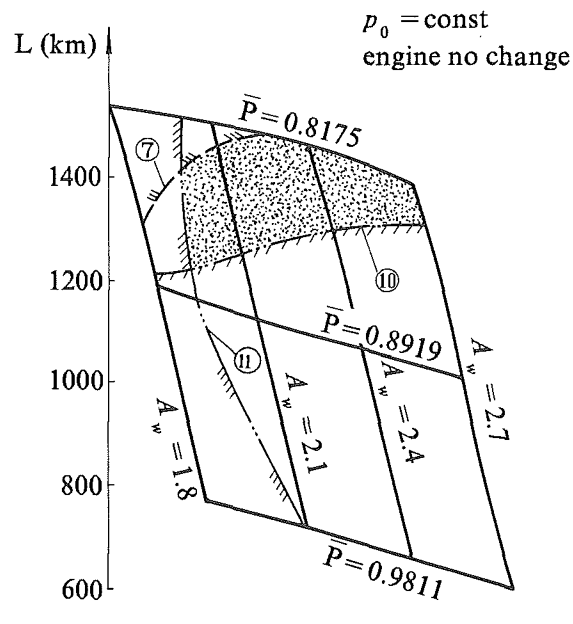



Fig.6 Relation between range and parameters L($\overline{P}$,$A_w$)

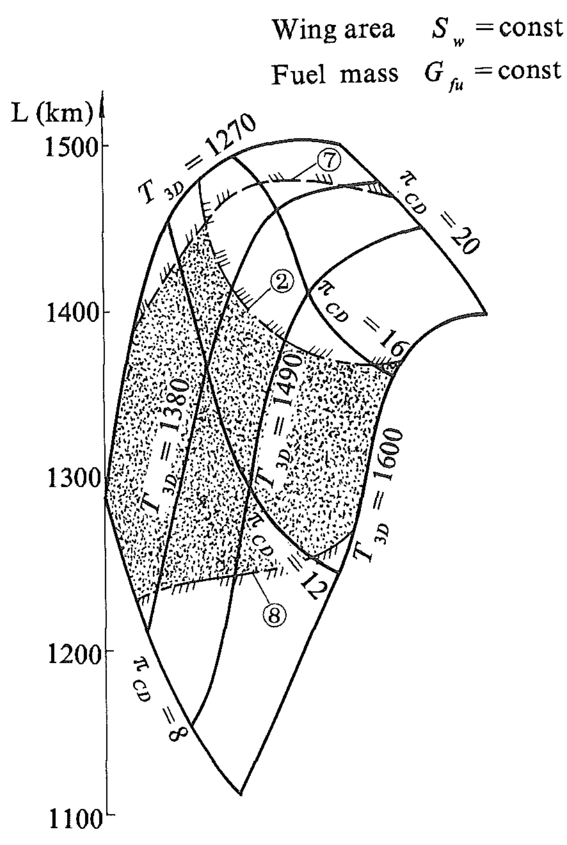



Fig.7 Relation between range and parameters L($\pi_{CD}$, $T_{3D}$)