Preliminary Propulsion Performance Analysis for the Commercial Supersonic Transport

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ABSTRACT

With the development of supersonic aircraft and engine technologies, supersonic commercial aircraft is gaining more attention for its great advantage of time-saving. Consequently, several advanced supersonic commercial aircraft concepts are designed and demonstrated by aviation manufacturers. On the basis of those aircraft concepts, this paper focuses on the preliminary concept design without designed aircraft configuration. An estimation method is built to analyze and determine the design parameters during the aircraft concept preliminary design. According to the estimation results, the preliminarily designed propulsion system can meet the aircraft requirements.

Keywords Supersonic commercial aircraft, Adaptive cycle engine, Estimation method

1 INTRODUCTION

After Concorde was out of commission, there is no longer a supersonic plane for comercial operation in world commercial aviation market. However, supersonic commercial aircraft is still promising for its significant advantage of flight time, although it has a higher cost of research, manufacture, purchase and everyday operation. The development of supersonic commercial aircraft was never stopped in the past decades[1]. Especially, as the developments of engines for high supersonic flight, more different aircraft concepts came out.

Propulsion system is one of the most important factors for supersonic aircraft developments. Because of the limitation of gas turbine engines, the maximum flight Mach number of aircrafts with gas turbine engines should be designed below 3. Hence, the high Mach number supersonic aircraft concepts need advanced engine concepts, such as Turbine-Based Combined Cycle (TBCC)[2-7]. However, there are still several great design problems and challenges of those advanced engine concepts, such as supersonic combustion, mode transition, inlet and nozzle design, etc. Therefore, the studies before 2000 mainly focus on the supersonic aircraft concepts with gas turbine engines.

Aircraft configuration is another important factors for supersonic aircraft developments. While the cruise Mach number is above 3, the aircraft configuration is significantly different from those cruising below Mach 3, which is similar as Concorde's configuration. There are also several key technologies to develop such novel aircraft concepts. Considering both operating requirements and difficulties of research and development, a low supersonic aircraft, which cruises at a Mach number below 2.5 and is driven by gas turbine engines, is relatively easy to be achieved.

US started its Super-Sonic Transport (SST) research from 1970s[8]. After lots of studies, demonstrations and experiences, US accumulated a great amount of technologies for supersonic aircraft design. Furthermore, several studies on supersonic commercial aircraft concepts were launched from 1990s. NASA's Glenn Research Center[8] and Lewis Research Center[8] studied on both High-Speed Civil Transport (HSCT) and its candidate propulsion systems from 1993 to 1994. A Boeing HSCT configuration numbered 1080-924 and a McDonnell Douglas configuration numbered D-3235-2.4-7A, which are both 300-seat aircraft concepts, were designed in this project[8]. Meanwhile, six different candidate propulsion systems, including turbojet, turbine bypass engine, mixed flow turbofan, variable cycle engine, Flade engine, and the inverting flow valve engine, were compared to analyze the mission adaptabilities of such two aircraft concepts for a 5000 nautical mile, Mach 2.4 cruise design mission[8]. There was lots of design data used in the project, which are valuable for the following study. Furthermore, the conclusions of this study had great helps for the developments of supersonic commercial aircraft concepts with gas turbine engines.

From 2005, US started Supersonic Project for new researches and demonstrations on both supersonic aircraft concepts and their key technologies[9]. This project was divided to three stages named N+1, N+2, and N+3. N+1 project focused on supersonic business jet concepts for 4000 nautical mile, Mach 1.6-1.8 cruise design missions, and Gulfstream Aerospace, Supersonic Aerospace International etc. are responsible for this project[9]. N+2 and N+3 projects mainly studied on larger supersonic aircraft concepts for Mach 1.6-2.0 cruise design missions. These two projects are paralleling started by both Boeing and Lockheed Martin[9].

EU also had its own supersonic aircraft concepts with gas turbine engines, although EU focused on supersonic aircraft with TBCC from 2000[10-11]. A Super-Sonic Business Jet (SSBJ) concept was one of the demonstration concepts in EU's environmental friendly High Speed Aircraft (HISAC) project[11].

In order to decrease the cost and risk of supersonic aircraft concept developments, a low supersonic commercial aircraft concept with gas turbine engines, is chosen as a realizable concept for preliminary study in this paper.

2 MARKET REQUIREMENT

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EVALUATION

Although current aviation market is dominated by subsonic commercial aircraft, supersonic aircraft still takes advantage of time. Cruise Mach numbers of modern subsonic commercial aircrafts are usually less than 0.9. and cruise Mach numbers of advanced supersonic commercial aircrafts are expected to be more than 1.5. Therefore, at least 40% of cruise time is saved. Because cruise section is a main section of flight mission, cruise time decrease means saving of flight time. With the increase of flight range, the ranges of both climb and descent sections increase slightly, but the range of cruise section increases significantly. Hence, supersonic aircraft concept takes more significant advantage of flight time for long range mission.

However, there are also limitations of putting supersonic aircraft into commercial business. Firstly, engines using for supersonic aircrafts have lower bypass ratio to decrease drag force during supersonic flight. It leads to a relative higher level of mean exhausting velocity, which would cause increase of noise emission. Secondly, while engines are working at supersonic conditions, equivalent ratio for steady combustion and a relative higher level of turbine entry temperature both cause increase of NOx emission, which is harmful to atmosphere. Finally, a relative higher structure strength is necessary for supersonic flight, and would lead to increase of aircraft weight, which has a disadvantage of either take-off or landing distance.

Despite supersonic aircraft concept still has several operating limitations, the marked advantage of time-saving makes this concepts an alternative. With reasonable operating planning, supersonic commercial aircrafts would bring their time-saving superiority into full play.

Design of air route is an essential procedure for aircraft preliminary design. The design flight range has direct proportion to operating economical efficiency. However, a longer flight range needs more fuel, which would cause aircraft weight increase directly. It is unaffordable for both aircraft structure and airport runway construction. Therefore, a suitable design range should be chosen for increasing operating economical efficiency and satisfying weight limitation. In additional, because supersonic aircraft would create sonic booms during its supersonic flight, supersonic aircrafts are inadmissible to fly through the territorial air space of many states. In consideration of the limitations of air routes, only a few air routes through the Pacific Ocean, listed in Tab. 1, are treated as candidates in this study.

Table 1 Alternative Air Routes of Supersonic Commercial Aircraft

Starting City	Ending City	Conventional Air Route Range (km)	Modified Air Route Range (km)
Beijing	Seattle	8910	11000
Beijing	San Francisco	9891	11900
Beijing	Los Angeles	10023	12000
Beijing	Honolulu	8135	9200
Shanghai	Sydney	7866	8000

In Tab. 1, the conventional air route range refers to the data from airline companies, and the modified one is estimated considering the range increase caused by keeping away from the lands. Based on those data, flight range for analysis is limited from 5000 km to 12000 km.

3 PRELIMINARY DESIGN

There are several indispensable conditions for detailed design and analysis of supersonic commercial aircraft concept, listed as follow.

Aircraft:

- Aerodynamical configuration parameters (including wing area, lift-drag performance, engine numbers, etc.);
- Weight parameters (including operating empty weight, commercial payload, fuel weight, etc.);
- Flight mission (including flight profile, flight tactics, etc.).

Engine:

- Engine performance (including Mach number performance, altitude performance, throttle performance, etc.);
- Propulsion system design (including performance of both inlet and nozzle flow path, etc.).

Because there is no existing supersonic commercial aircraft which could be considered as a referenced one, the essential conditions listed above which have close relations with aircraft aerodynamic configuration, are unusable for such a preliminary concept design in this study. Consequently, a substitutional method is needed for preliminary study without those conditions.

An estimation method is established for preliminary concept design and qualitative analysis. Although the results of such a method cannot be treated as accurate ones, it is still helpful for study on tendencies of aircraft concept design aims caused by various combinations of design parameters.

AIRCRAFT WEIGHT APPROXIMATION

Before evaluating the weight of aircraft concept which could finish the design flight range, it is necessary to get aircraft weight approximation without detailed aircraft configuration. In order to get the approximation, several assumptions, listed as follow, are needed:

- Usually, aircraft cruising at a higher Mach number needs a higher structure weight to bear greater aerodynamic loads caused by flight velocity. Because the aircraft concept considered in this study has a cruise Mach number less than 2.5, it is ignored that the design cruise Mach number would influence the Operating Empty Weight (OEW).
- Maximum Take-Off Gross Weight (MTOGW) is sum of OEW,

Maximum Fuel Weight (MFW) and commercial payload, which is in direct proportion to the number of passengers (PAX).
- OEW is only affected by the MFW and PAX.
- When either MFW or PAX increases, OEW increases.

Hence, a simple polynomial of OEW, showed as formula (1), is used to estimating the aircraft weight.

$$W_{OE} = a_0 + a_1 PAX + a_2 W_{MF} \quad (1)$$

Weight parameters of several different supersonic aircraft concepts, as shown in Tab. 2, are used to get the weight approximation. Those coefficients in formula (1) could be calculated by Least Square Method.

Table 2 Weight parameters of super-sonic commercial aircraft[2-3,8-9]

Aircraft Concept	PAX	MFW (t)	OEW (t)
N+2 M1.6 (30)	30	38.271	40.093
N+2 M1.6 (100)	100	61.294	61.380
M3 (250)	250	175.043	123.822
M4 (250)	250	229.015	138.678
HSCT MFTF5093	300	166.477	124.141
HSCT VCE701510	300	170.562	123.918
HSCT F193	300	177.083	132.940

Because formula (1) is not accurate enough to reflect actual relations among OEW, MFW and PAX, some corrections of formula (1) considers necessary. In fact, the change of OEW caused by the increase of either PAX or MFW, is not constant. In other words, the a_1 and a_2 in formula (1) couldn't be considered as constant. In this study, the PAX of aircraft is limited to 300, and the change of a_1 is ignored. In the condition without considering the aerodynamic design of aircraft, while the PAX is constant, the change of OEW becomes less as the increase of MFW. Because the increase of MFW simply enlarges both the volume and the weight of fuel tank, which have slight influence to the configuration weight of aircraft. Meanwhile, the change of OEW also becomes less as the increase of MFW while the PAX increases, because the PAX increase makes the aircraft bigger so that the aircraft needs a less increase of fuel tank weight for the same fuel raise. As a result, a modified polynomial is gotten as shown in formula (2).

$$W_{OE} = 26913.718 + 120.739PAX - 6.0546\frac{W_{MF}}{PAX} + 2.063\frac{W_{MF}}{\log_{10} W_{MF}} \quad (2)$$

If the PAX and MFW are known, the OEW and MTOGW can both be calculated.

AIRCRAFT WEIGHT EVALUATION

Usually, the value of MFW can't be determined directly, but has close relation with MTOGW and the range of flight. Therefore, an algorithm of flight profile is necessary for determining MFW. While using the algorithm, a guess value of MFW is sent to the calculation codes, and will be modified until the value of MFW calculated by the codes ultimately approximates the guess one. In this case, a simple estimate method of flight seems more convenient and efficient than a detailed calculation method.

A simple method is built for estimating the whole flight course mainly including climb, cruise and descent. Before the establishment of the method, several prerequisites are supposed as follow.

Cruise:
- The cruise altitude will increase as the aircraft flies with a constant Power Lever Angel (PLA), and the change of altitude is proportional to the range of cruise.
- Aircraft weight with half fuel is used as a mean value for estimation.
- Lift-drag ratio (L/D) of aircraft is a given value referring to technical level of aircraft design while the cruise Mach number is constant.
- Specific fuel consumption (sfc) of propulsion systems is also a given value referring to technical level of aero-engine design when the cruise Mach number is given.
- The range, altitude and Mach number of cruise are variable to analyze how those parameters affect MTOGW.

Climb:
- The climb rate of aircraft is limited to 4.7 m/s.
- The Mach number change per kilometer is constant.
- The fuel consumption in same range change of climb course is proportional to that of cruise course.

Descent:
- The descend rate of aircraft is limited to 3.3 m/s.
- The Mach number change per kilometer is constant.
- The fuel consumption of descent course is proportional to that of climb course.
- There is still 15% fuel in the plane for reserve mission after landing.

It should be noted that the climb rate is chosen according to the data in Ref. 8, and the descend rate is determined by the scaling relation between it and the climb rate.

On the basis of those supposing conditions listed above, the estimation method can be described as illustrated in Figure 1.

Using this method, the range of each part of flight course is arranged with the constraints of both climb rate and descend rate before the iterative computation of aircraft weight parameters. While the convergence condition of the iterative computation is achieved, it means the amount of fuel is suitable for finishing the whole flight. In summary, once the PAX and design flight range of aircraft is determined, an available design could be calculated by the method.

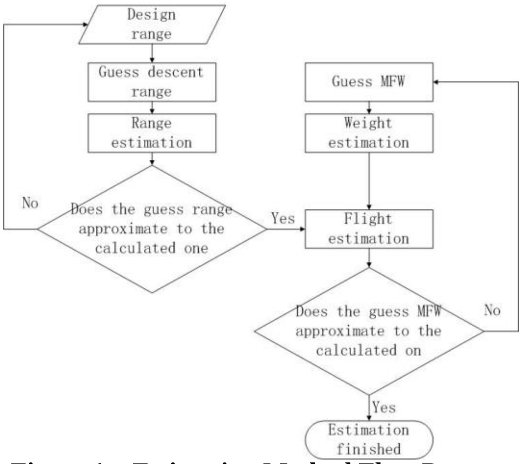


Figure 1 Estimation Method Flow Process Diagram

SENSITIVITY ANALYSIS

It is necessary to find out whether the simplification, caused by using estimation method, affects the dependability and usability of calculation results. There are three estimation parameters, which are fuel consumption ratio in the same range change between climb course and cruise course (SFCR) , fuel consumption ratio between climb course and descent course (FCR), and reserve fuel ratio (RFR), used with preceding values in the estimation method. Definitions of SFCR, FCR and RFR are listed as follow.

$$SFCR = \frac{\Delta W_{F,climb}/range_{climb}}{\Delta W_{F,cruise}/range_{cruise}} \quad (4)$$

$$FCR = \frac{\Delta W_{F,descent}}{\Delta W_{F,climb}} \quad (5)$$

$$RCR = \frac{W_{F,reserve}}{W_{MF}} \quad (6)$$

These three parameters affect the amount of fuel in each course of flight, which has a direct influence on MTOGW. Often, the values of those three parameters are diverse for different aircraft configurations and flight designs. In other words, set values of those parameters couldn’t satisfy all the conditions. As a consequence, it is necessary to make sensitivity analysis to those three parameters.

After demonstration of method adaptability, a preliminary aircraft concept could be designed by determining design parameters. The flight design parameters in the estimation method include PAX, flight range, cruise altitude and cruise Mach number. The aircraft configuration is designed in accordance with the requirements of all those parameters. PAX and flight range are crucial for economical efficiency of flight. Within the constraints of aircraft design technical level and the requirements of commercial aviation market, PAX and flight range should be carefully chosen in order to maximize the operating profits. Meanwhile, altitude and Mach number of cruise are important for aerodynamic design of aircraft configuration. Usually, the lift-drag ratio of aircraft in cruise condition is designed at a superior level, in order to minimize the fuel consumption during cruise course by decrease aircraft drag. Hence, those four parameters should be determined by sensitivity analysis before the detailed study on propulsion system.

While the preliminary concept is designed, it is time to analyze both the key design index of aircraft, cruise lift-drag ratio, and the key design index of engine, cruise specific fuel consumption. During flight design parameters analysis, the cruise parameters, including the cruise L/D of aircraft and cruise sfc of propulsion system, are set by referring to present technical level of aircraft and aero-engine in different flight conditions. Considering the commercial plane is designed for the future, state-of-the-art design of both aircraft and engine should be used to make further efforts to decrease the MTOGW and improve economical efficiency. A sensitivity analysis of both cruise L/D and cruise sfc is needed to ultimately decide the design requirements for both aircraft and engine.

4 CONCEPT DEMONSTRATION

After MTOGW of a set-range supersonic concept is preliminarily determined, the design level of aircraft lift-drag ratio is chosen, as well as the requirements of take-off thrust and cruise specific fuel consumption of propulsion system could also be decided.

A detailed flight computation method is established to analyze the mission adaptability of designed engine concept.

The determination of available design only means one of the computation conditions for flight detailed simulation is prepared. However, there are still several essential conditions needed to be confirmed for the detailed simulation, including lifting surface area of aircraft, lift-drag performance of aircraft, flight profile of aircraft design mission, engine amount and engine performance. All of those computation conditions can only be decided after the altitude and Mach number of cruise are determined, because supersonic commercial aircrafts designed for different cruise conditions have various aerodynamic configurations and need different designed engines.

A computation code is established for the flight detailed simulation of supersonic commercial aircraft. All those calculation conditions mentioned above are ultimately inputted into the code to get the calculated value of flight range.

5 PROPULSION SYSTEM

Propulsion system of the super-sonic commercial aircraft has many design challenges because the plane has extremely great gross weight and cruises at both high altitude and high Mach number. While the aircraft is cruising, although the operating condition of engines is far away from the design point, it is still necessary for satisfying flight range requirement that the engines keep a low level of specific fuel consumption. A novel engine concept is considered because conventionally-designed mixed-flow turbofans have several disadvantages of reconciling both subsonic and supersonic performance[12-14].

ADAPTIVE CYCLE ENGINE CONCEPT

Adaptive Cycle Engine (ACE) concept used in this study, as illustrated in Figure 2, has an extremely sophisticated fan system and a conventional gas generator. The fan system has several variable area structures which can be adjusted to modify the engine bypass ratio and pressure ratio distribution of compression components. As demonstrated in Ref. 14, ACE has features as follow: a convertible fan system adapted to have a variable fan pressure ratio while an air flow into the convertible fan system remains substantially constant; and an adaptive core having a compressor capable of maintaining a substantially constant core pressure ratio while a core airflow flow rate is varied.

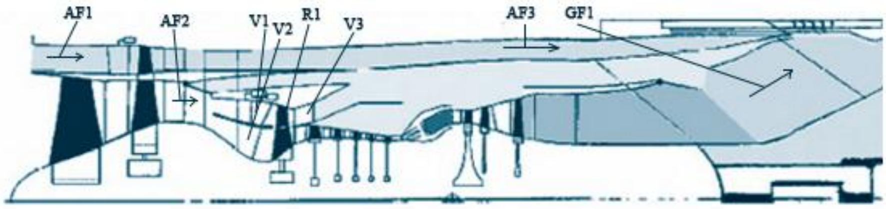


Figure 2 Adaptive Cycle Engine Configuration

It is a great challenge that design cycle parameters of engine should be selected with taking account of great thrust at take-off, low specific fuel consumption at cruise and low noise emission at taxi, take-off and landing. Especially, under the limitations of material, a low total pressure ratio at sea-level steady condition and a low throttle ratio should be chosen for decreasing turbine entry temperature at supersonic cruise.

OPERATING MODES OF ACE CONCEPT

ACE concept has many variable area geometries so that several different operating modes are derived by different combinations of variable area structures. Similar as the Flade® engine concept designed with Core Drive Fan Stage (CDFS), the ACE concept has four main operating modes.

a. Turbojet Mode (M1)

ACE working at the turbojet mode (M1) has the relatively lowest total bypass ratio because only the bypass downstream guide vane stage V3 (Fig. 2) and core flow path allow air to flow through. When ACE is operating at this mode, it considers a turbojet with intermediate bleeding. The working air is mostly burnt in the combustion chamber, so that the engine has high exhausting velocity and great specific thrust. Like turbojet, ACE working at this mode is suitable for supersonic flight, but has disadvantages of both thrust and specific fuel consumption at subsonic flight.

b. Main Engine Mode (M2)

ACE working at the main engine mode (M2) is similar as the Double Bypass Engine (DBE) concept which is applied in the design of GE's F-120 engine. The engine is working as a mixed-flow turbofan as the flow path AF1 (Fig. 2) is closed by turning down its inlet guide vane stage. ACE working at this mode sacrifices part specific thrust for decreasing the specific fuel consumption, and has advantages over ACE working at turbojet mode (M1) at subsonic flight.

c. Separated-flow Turbofan Mode (M13)

ACE working at the separated-flow turbofan mode (M13) makes air flow AF2 (Fig. 2) all flow through inlet guide vane stage V1 and V2 (Fig. 2) to be compressed by aft fan stage R1 (Fig. 2). While engine is operating at this mode, air flow AF3 (Fig. 2) and gas flow GF1 (Fig. 2) are exhausted without mixing, as the exhausting flow of separated-flow turbofan. Because the air flow with both low temperature and low velocity envelops the hot gas flow from inner nozzle and mixes in it, ACE works at a relatively low emission level of perceived noise of exhausting gas.

d. Normal Mode (M3)

ACE working at normal mode (M3) has the relatively highest total bypass ratio and allows more air flows into it to generate thrust. Consequently, ACE working at this mode takes advantage of thrust though it needs relatively more fuel. Furthermore, because of the existing air flow AF3 (Fig. 2), perceived noise of exhausting gas is lower than that of either turbojet mode or main engine mode.

All the four modes mentioned above can be treated as different adjusting results of fan system in ACE concept. The modes are just divided for convenience of establishing the simulation model and analyzing both engine performance and control schedule.

ENGINE SIMULATION

A simulation code of the ACE concept, which uses the component-level model of engine illustrated in Fig. 3, is established to calculate and analyze engine performance.

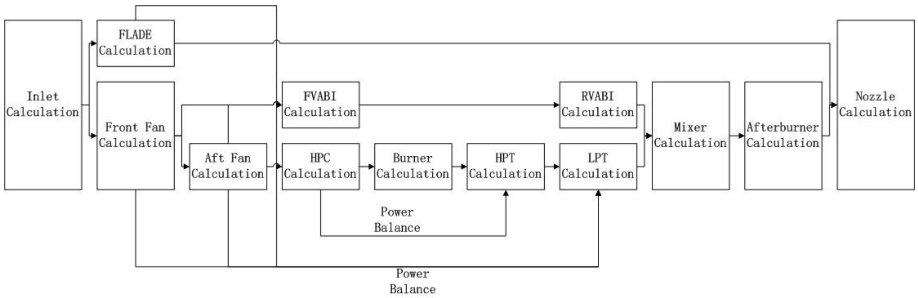


Figure 3 Component-Level Model of ACE Concept

Design cycle parameters are selected according to both aircraft requirements and technical level constraints. According to preliminary design results of aircraft concept, propulsion system has requirements of take-off dry thrust and cruise specific fuel consumption. Therefore, a medium bypass ratio should be chosen in order to maintain both core inlet diameter and cruise specific fuel consumption at a lower level. Meanwhile, considering the material limitation of strength and temperature, lower design pressure ratio and lower throttle ratio should both be chosen in order to avoid either rotation excursion or temperature excursion while engine is working at a higher Mach number.

The engine performances of four different modes are computed by the code to demonstrate engine mission adaptability for the design flight of aircraft concept.

6 RESULT AND ANALYSIS

All the results of preliminary design would be shown and analyzed in detail as following.

ESTIMATION METHOD DEMONSTRATION

In order to testify whether the estimation method is reasonable for preliminarily evaluating aircraft concept, two examples of existing aircraft concept are calculated by the estimation method. Table 3 lists the comparison results of those two computation examples.

Table 3 Examples Comparisons for Demonstrating Estimation Method

Aircraft	Referenced MTOGW	Calculated MTOGW	MTOGW Error	Referenced Fuel Efficiency FoM	Calculated Fuel Efficiency FoM	Fuel Efficiency FoM Error
Concorde	182 t	182.007 t	+0.0038%	7.347	7.310	-0.5036%
Boeing HSCT	355 t	362.976 t	+2.2468%	15.874	14.067	-11.3834%

Although the estimation results have errors with the referenced one, the results are still reasonable and usable for preliminary design. As a consequence, the estimation method is demonstrated usable for preliminary design of supersonic aircraft concept.

ESTIMATION RESULT AND ANALYSIS

The estimation method is used to calculate MTOGW and fuel efficiency FoM owing to different combinations of design parameters of both aircraft and flight. Comparison and analysis of those results are helpful for the final design of aircraft concept and its flight profile.

a. Estimation Parameters

Figure 3 and 4 illustrate how SFCR and FCR influence the MTOGW and fuel efficiency FoM of a 300-passenger commercial aircraft concept. While SFCR increases, MTOGW has a significant increase and the fuel efficiency FoM decreases rapidly. Especially, when SFCR is more than 4, the MTOGW would be more than 750 t, which is further beyond the acceptable range of MTOGW in current technical level, and fuel efficiency FoM is less than 8, which is less than 1/3 of subsonic aircraft fuel efficiency FoM. The changes of both MTOGW and fuel efficiency FoM caused by FCR increase are similar as those caused by SFCR increase. As a consequence, these two estimation parameters, SFCR and FCR, should be designed carefully during the estimation in order to ensure the estimated results reliable and usable.

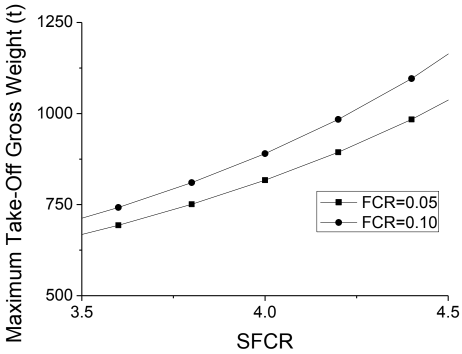


Figure 3 MTOGW vs. SFCR and FCR

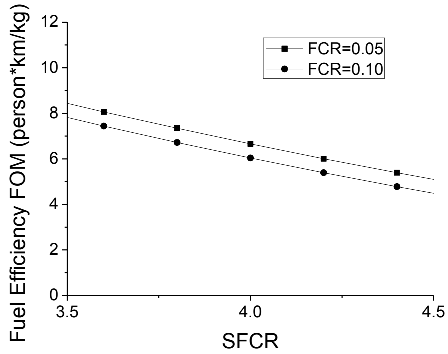


Figure 4 Fuel Efficiency FoM vs. SFCR and FCR

Figure 5 and 6 show how RFR influences the MTOGW and fuel efficiency FoM of a 300-passenger commercial aircraft concept. When the amount of reserve fuel increases, MTOGW has a sharp increase and fuel efficiency FoM decreases rapidly. Therefore, decrease of reserve fuel with satisfying the fuel requirement of reserve mission is helpful for lighten the aircraft and improve the economical efficiency.

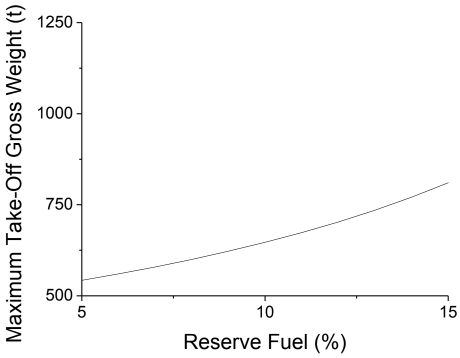


Figure 5 MTOGW vs. RFR

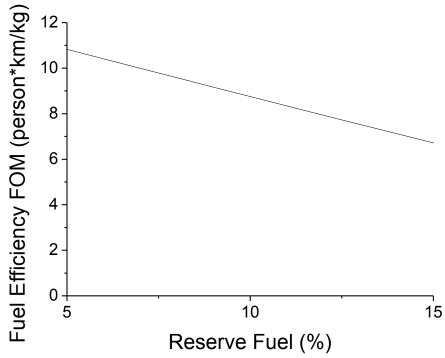


Figure 6 Fuel Efficiency FoM vs. RFR

Although these three estimation parameters all have significant influences to both MTOGW and fuel efficiency FoM, those values can only vary within smaller ranges. Therefore, while these three parameters are set reliably, the uncertainties of these parameter have less effect on estimation results.

b. Flight Design Parameters Analysis

Fig. 7 and 8 shows how PAX influences MTOGW and fuel efficiency FoM. While PAX increases, both MTOGW and fuel efficiency FoM increase markedly. Despite great advantage of fuel efficiency FoM, a 300-seat concept is considered as an uncompetitive one because of its unacceptable MTOGW. Meanwhile, a 50-seat concept is also rejected for its under fuel efficiency FoM. Therefore, a 100-seat concept considers an alternative for its lower MTOGW and acceptable fuel efficiency FoM.

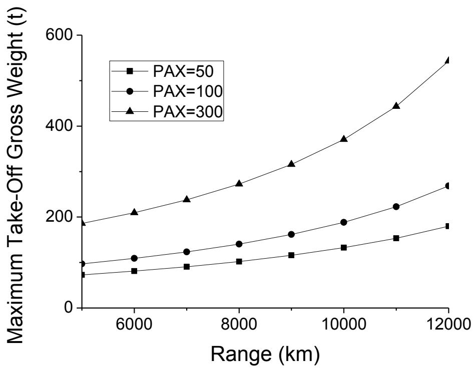


Figure 7 MTOGW vs. Range

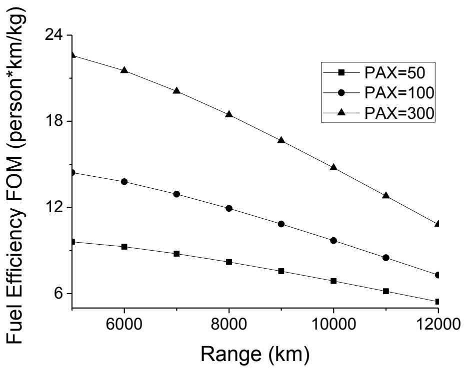
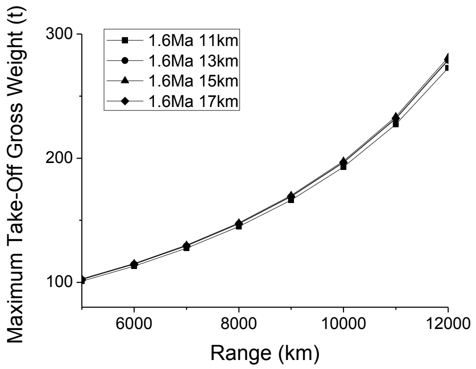


Figure 8 Fuel Efficiency FOM vs. Range

Fig. 9 shows how cruise altitude, cruise Mach number and flight range influence MTOGW of a 100-seat commercial aircraft concept. When flight range increases, MTOGW has a notable increase, and rises more rapidly with the increase of flight range. However, while both cruise Mach number and flight range are constant, cruise altitude only slightly influences MTOGW. With increase of cruise Mach number, the MTOGW differences of concepts with various cruise altitudes become a little more significant. Meanwhile, when both cruise altitude and flight range are constant, cruise Mach number also slightly influences MTOGW.



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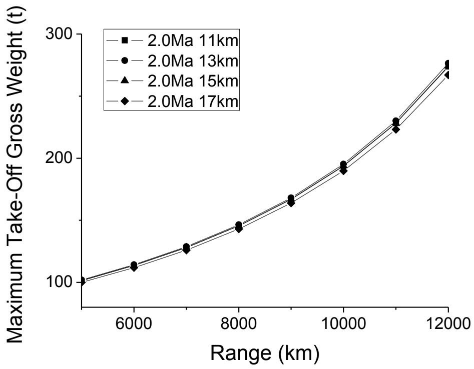

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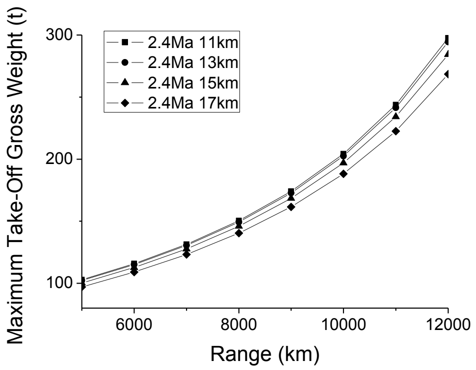

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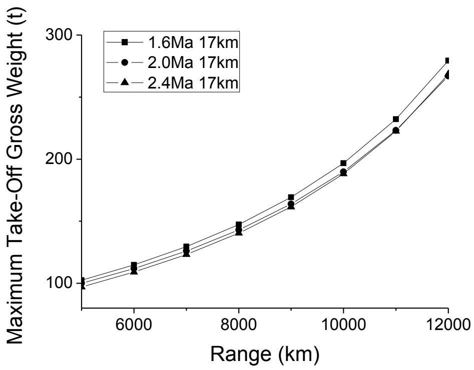
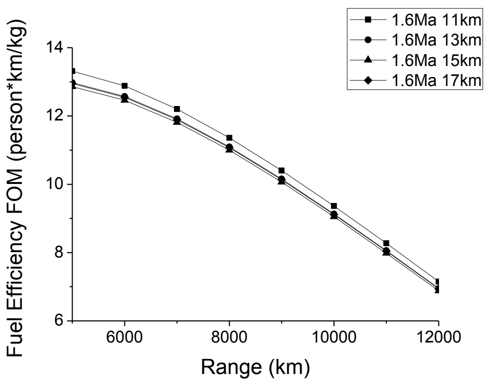


(d)

Figure 9 MTOGW Comparison of Various Flight Design Parameters

Fig. 10 shows how cruise altitude, cruise Mach number and flight range influence fuel efficiency FoM of a 100-seat commercial aircraft concept. Similar as the conclusion mentioned above, there are also slight differences among the fuel efficiency FoM of aircrafts cruising at various altitudes and Mach numbers, and the design flight range is still the main factor affecting fuel efficiency FoM.



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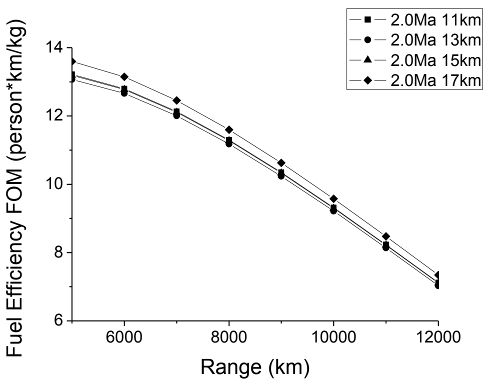

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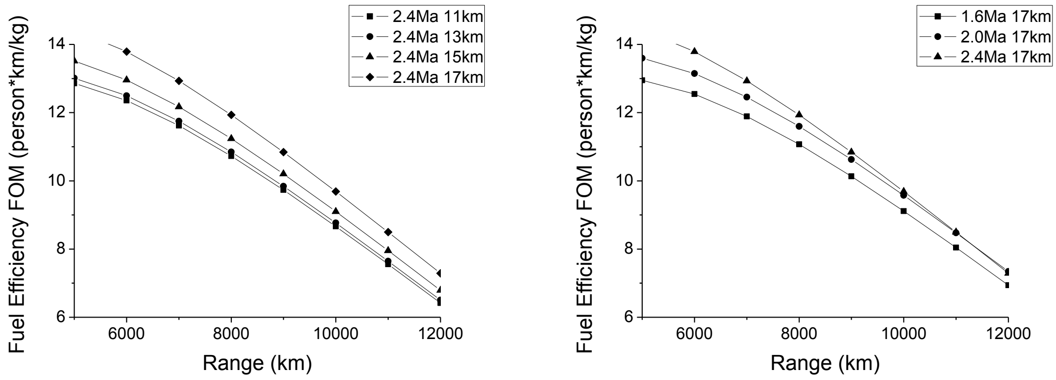


(c) (d)

Figure 10 Fuel Efficiency FoM Comparison of Various Flight Design Parameters

Fig. 11 shows how flight range and cruise Mach number influence flight time of a 100-seat commercial aircraft concept. While flight range increases, flight time almost increases linearly. Meanwhile, when cruise Mach number increases, flight time has a remarkable saving. With the increase of flight range, the flight time differences caused by various cruise Mach numbers become more significant, because of the range increase of cruise section.

In the consideration of MTOGW, fuel efficiency FoM, flight range, flight time and technical difficulties, a 100-seat aircraft concept cruising at 17 km and Mach 2.4, is demonstrated as an acceptable and realizable alternative design for a flight range of 12000 km.

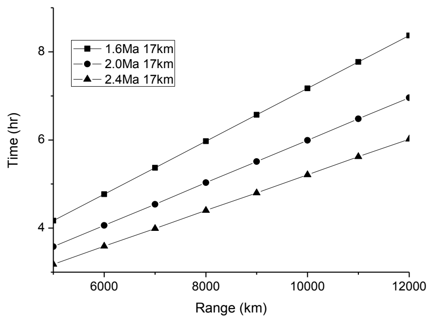


Figure 11 Flight Time Comparison of Various Flight Design Parameters

c. Cruise Parameters Analysis

Fig.12 and Fig. 13 shows how the cruise parameters affect MTOGW and fuel efficiency FoM. Those two figures considers helpful for preliminary concept design while the technical levels of both aircraft and engine are known. While cruise L/D increases, MTOGW decreases and fuel efficiency FoM increases. With the increase of cruise L/D, the decrease of MTOGW become less. Therefore, when the cruise L/D reaches an advanced technical level such as 10, there is less help for further improving cruise L/D. While cruise sfc decreases, MTOGW decreases and fuel efficiency FoM increases. With the decrease of cruise sfc, the decrease of MTOGW become less. Consequently, when the cruise sfc reaches an advanced technical level such as 1.2, it is less helpful for further reducing cruise sfc.

Hence, a cruise L/D nearby 9 and a cruise sfc nearby 1.2 is considered as realizable values within the state-of-the-art design.

CONCEPT DEMONSTRATION RESULTS AND ANALYSIS

After the preliminary aircraft concept has been designed, some detailed design parameters of both aircraft concept and engine concept are simply designed to demonstration whether such a aircraft concept could finish its design flight mission.

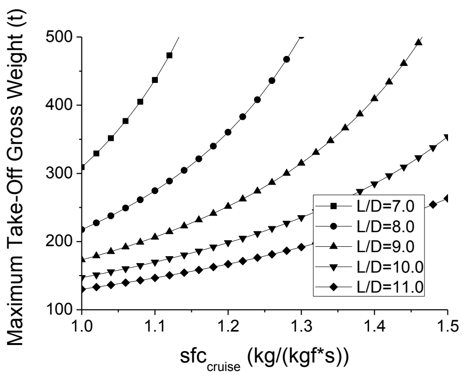


Figure 12 MTOGW vs. Cruise L/D and sfc

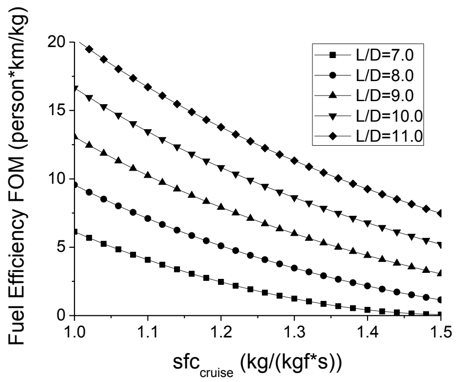


Figure 13 Fuel Efficiency FoM vs. Cruise L/D and sfc

a. Aircraft Design Result

According the preliminary decision of aircraft and its flight profile, design parameters of such an aircraft concept are determined with the consideration of slightly technical improvement of both aircraft and engine, as shown in Tab. 3.

Table 3 Main Design Parameters of Supersonic Commercial Aircraft Concept

Parameters	Value
MTOGW	220 t
OEW	82.767 t
MFW	127.433 t
PAX	100 persons
Wing Area	480 m^2
RFR	0.12
Amount of Engines	4

It is noted that the wing area of aircraft concept is selected referring to Boeing HSCT design in Ref. 8. Because of the lack of detailed configuration of aircraft concept, lift-drag performance of Boeing HSCT is used only for this preliminary study of the aircraft concept. The flight profile is simply designed as illustrated in Fig. 14.

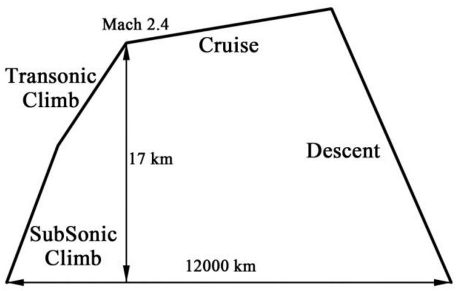


Figure 14 Flight Profile of Supersonic Commercial Aircraft Concept

b. Engine Design Result

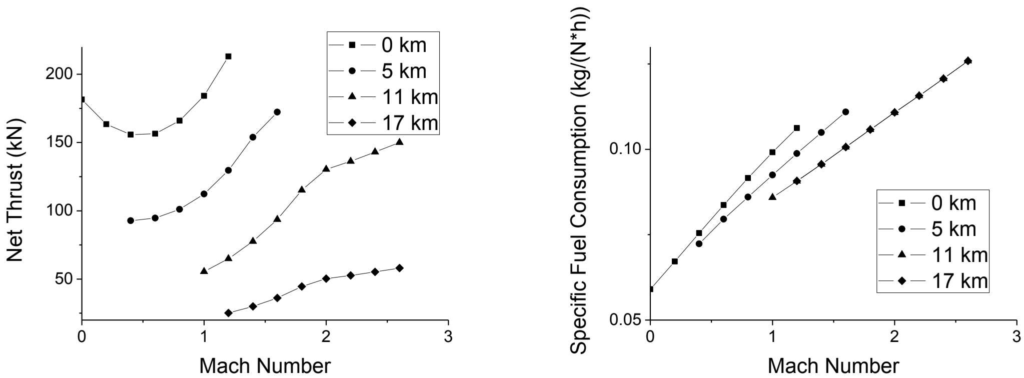
The aircraft concept is required to cruise at Mach 2.4, where has a significant pressure improvement cause by stagnation. Hence, lower total pressure ratio of engine concept should be chosen for maintain a suitable thermodynamical cycle pressure ratio at cruise condition. Meanwhile, in the constraints of material and operating life, turbine entry temperature of engine at cruise need be lower than 2000K. Therefore, the cycle parameters are selected as shown in Tab. 4.

Table 4 Main Design Parameters of ACE Concept

Parameters	Value
Total Air Flow Rate	346 kg/s
Total Bypass Ratio	2.0
Bypass Ratio without the Flade® Bypass	0.61
Pressure Ratio of Front Fan Stages	3.2
Pressure Ratio of Aft Fan Stage	1.4
Pressure Ratio of FLADE®	2.0
Turbine Entry Temperature	1740 K
Throttle Ratio	1.15

This design of engine concept is computed by the simulation code of ACE concept. Engine performances of both with and without afterburning at all four operating modes are calculated. Fig. 15 illustrates engine dry performance working at operating mode M3. The control law for this performance calculation is maintaining low-pressure spool rotation rate, in order to keep engine working at a higher thrust level. While flight Mach number is greater than 2, turbine entry temperature reaches the limitations, and the control law has to be changed to controlling constant turbine entry temperature. Hence, there is a significant deflection of the thrust curves upon Mach 2.

While aircraft is climbing with the tactics mentioned above, engine is demanded to afford the thrust for both climbing and accelerating. Therefore, engines should working at a higher thrust level of all the four modes. While the thrusts of different modes have only slight differences, specific fuel consumption would be compared to find out a lower one. The optimal operating mode for each climbing point is analyzed in Tab.5.



(a) (b)

Figure 15 ACE Performances of Various Altitudes and Mach Numbers at M3

Because of the selection of bypass ratio, engine working at either M1 or M2 has a remarkably lower total air flow rate. Further, engine thrusts of both M1 and M2 are significantly less than those of M13 and M3. Without the consideration of the limitation of climb rate in commercial aviation, both M1 and M2 are useless for climb.

Fig. 16 shows engine throttle performances of different operating modes at 17 km and Mach 2.4. The control law of throttle performance calculation is controlling the rotation rate change of low-pressure spool.

Table 5 Optimal Mode of Net Thrust During Climbing

Flight Altitude (km)	Flight Mach Number	Optimal Mode
3	0.6	M3
5	0.7	M3
7	0.8	M3
9	1.1	M3
11	1.5	M3
13	1.8	M3
15	2.1	M13
17	2.4	M13

The mode for cruise is decided by a combination of both thrust requirement and specific fuel consumption for cruise. Ultimately, operating mode M13 is chosen for its advantage of specific fuel consumption.

c. Preliminary Concept Design

The estimation of aircraft and the engine performances are prepared for the flight detailed computation, and are inputted into the established flight simulation code. Tab. 6 shows the calculation results of the simulation code.

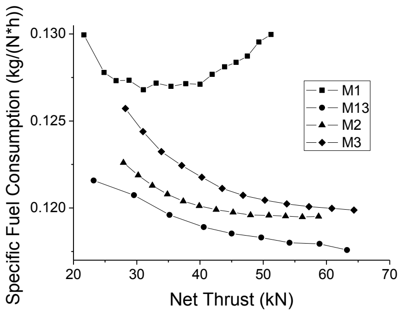


Figure 16 ACE Throttle Performance of Various Operating Modes

The ending flight range in Tab. 6 is less than the design flight range 12000 kilometers, and ending flight time is also less than the estimated value 6.02 hours. However, this design is acceptable as a preliminary concept design, although it still has some inaccurate supposes and algorithms.

Table 6 Flight Detailed Results

Course	Ending Altitude (km)	Ending Mach Number	Ending Flight Range (km)	Ending Flight Time (h)	Ending Aircraft Weight (t)
Climb	17	2.4	1340	0.77	181.021
Cruise	19.89	2.4	10178	4.24	111.640
Descent	0	0	11849	5.87	107.859

It is noted that the difference between the install and uninstall performances of engines, which would lead to at least 10% thrust loss at cruise, is not considered in this study. If the install performances are used in flight detailed computation, MTOGW of aircraft fitting the requirement of flight range will increase significantly.

7 CONCLUSION

This study concentrates on preliminary design of propulsion system for a supersonic commercial aircraft concept. Several estimation methods are studied and used to get aircraft concept design parameters and requirements for engines, without a designed aerodynamical configuration of aircraft concept. A flight simulation code and an ACE performance simulation code are established for demonstrating the preliminary concept design. There are some useful conclusions summarized after those research mentioned above.

Firstly, the estimation methods used in this study are demonstrated for preliminary design of a supersonic commercial aircraft concept with cruise Mach number less than 2.5, and the simulation codes of both flight and ACE are both usable for computing and checking mission adaptability of ACE. It is helpful for a further study on aircraft concepts and their propulsion systems.

Secondly, Within current technical level, it is demonstrated that a 100-seat supersonic commercial aircraft concept, cruising at 17 km and Mach 2.4, is analyzed and demonstrated realizable for 12000-kilometer flight range, which could satisfy the requirements of most air routes over Pacific Ocean. However, this concept is still potential by optimizing the design of both itself and its propulsion system.

Finally, ACE concept has well capabilities of both subsonic and supersonic flights, therefore it could be an alternative propulsion system for such a low-cruise-Mach-number supersonic commercial aircraft concept.

There are still several problems of ACE concept worthy of further studies.In some of calculation points, either corrected rotation rate of low pressure spool or turbine temperature reaches the limitations, and it is harmful to both performance and cycle life of engine. Consequently, rules of variable area modules for ACE concept are essential to get reasonable and reliable engine performances, and are worthy of further study on them.

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