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Conceptual Design of High Speed Supersonic Aircraft: A brief review on SR-71 (Blackbird) Aircraft

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Abstract. The paper presents the conceptual design of high-speed supersonic aircraft. The study focuses on SR-71 (Blackbird) aircraft. The input to the conceptual design is a mission profile. Mission profile is a flight profile of the aircraft defined by the customer. This paper gives the SR-71 aircraft mission profile specified by US air force. Mission profile helps in defining the attributes the aircraft such as wing profile, vertical tail configuration, propulsion system, etc. Wing profile and vertical tail configurations have direct impact on lift, drag, stability, performance and maneuverability of the aircraft. A propulsion system directly influences the performance of the aircraft. By combining the wing profile and the propulsion system, two important parameters, known as wing loading and thrust to weight ratio can be calculated. In this work, conceptual design procedure given by D. P. Raymer (AIAA Educational Series) is applied to calculate wing loading and thrust to weight ratio. The calculated values are compared against the actual values of the SR-71 aircraft. Results indicates that the values are in agreement with the trend of developments in aviation.

INTRODUCTION

Aircraft design is a unique discipline of aeronautical engineering. It stands alone in comparison to its counterparts such as aerodynamics, structures, controls and propulsion. As an aircraft designer, one requires knowledge in all these areas; however, they are not required to apply in detailed manner. It is an intellectual engineering process of creating on paper (or a computer) a flying machine to meet certain specifications according to the requirements established by potential user or perceived by the manufacturer [1, 2].

There are three phases of aircraft design process, namely conceptual design, preliminary design and the detail design phases. The conceptual design of an aircraft includes a conceptual sketch and calculations of performance parameters. These parameters can confirm whether stated requirements from the customer can be fulfilled or not. A preliminary design focuses on different trades of the aircraft such as structures, landing gears, control systems, etc. The detail design phase begins with fabrication of aircraft parts. If realized in detail design phase that earlier perceived idea of a part of an aircraft is not up to required performance or not economical. That part is redesigned and its impact is reflected throughout the design. Therefore, designing an aircraft with many new features is challenging and has a greater risk of failure. A think through conceptual design can help in reducing this risk [1, 2].

Conceptual design process is a long iterative process in which specifications are selected, verified, modified and again verified for their fitness in a particular design. Actually, there is a 'design wheel', which circles around the

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whole process. In this process, new concepts are developed to meet the requirements. In addition, new design analysis helps in employing new concepts. It is not a hit and trial method. It has a particular sequence and whole design process is carried out in stages. In each stage, different aspects are brought into consideration. Main components of 'design wheel' are given in FIGURE 1.

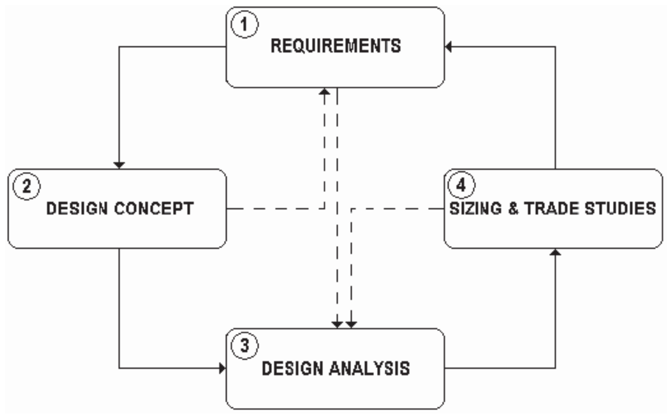

FIGURE 1*:* Design Wheel for Aircraft Design [1, 2]

Presented study focuses on conceptual design of SR-71 (Blackbird). SR-71 remained in use by United States for surveillance purpose against USSR (former name of Russia) during cold-war period from 1960-90 [3]. Its presence was undetected until it was opened to public in 1992 [4, 5]. Three views of SR-71 are shown in FIGURE 2.

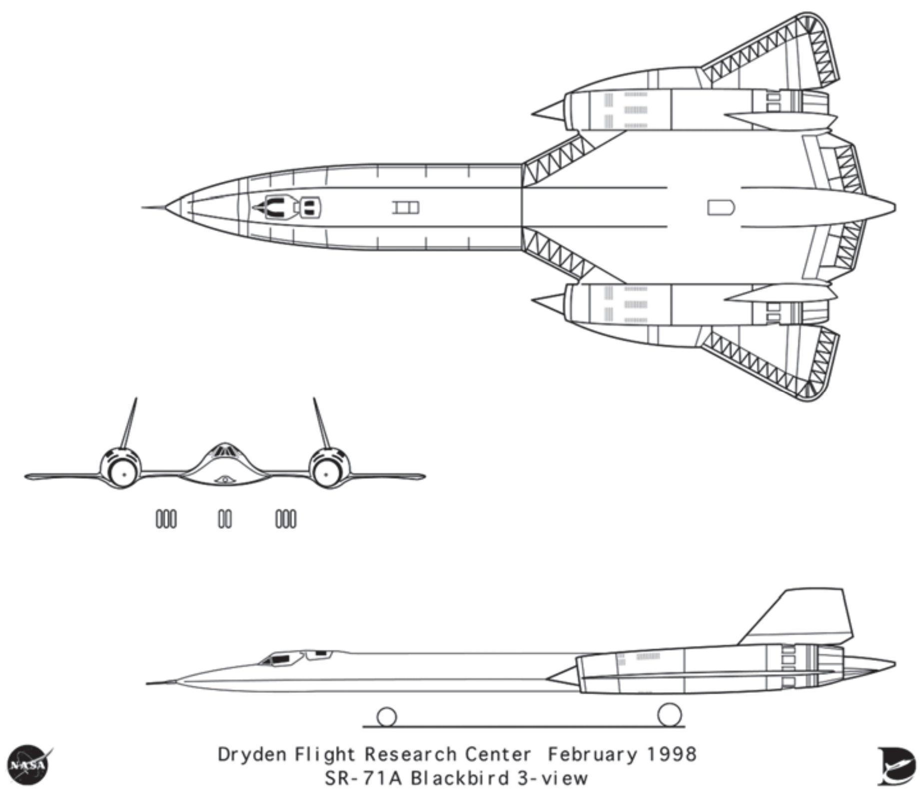

FIGURE 2: SR-71A top, side and front view (courtesy of www.sr-71.org [6])

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METHODOLOGY

Conceptual design process starts with a rough sketch of an aircraft. This gives a very crude idea of under design aircraft. It is called ‘back of napkin sketch’ of the aircraft. This sketch may include approximate wing geometry, location of engines, payload, crew station(s), landing gear locations, etc. After the rough sketch, weight estimation is carried out. This is followed by wing geometry selection including the calculation of other parameters of the aircraft such as wing loading, thrust to weight ratio, etc. Then an initial sizing is carried out. This is followed by an iterative process, which results in the final values of performance parameters of the aircraft.

Mission Profile

To initiate the design process, mission profile is required. Mission profile gives a typical mission, which the aircraft requires to perform. Mission profile decides the type aircraft and plays a major role in sizing and configuration of the aircraft. The mission profile of SR-71 is shown in FIGURE 3.

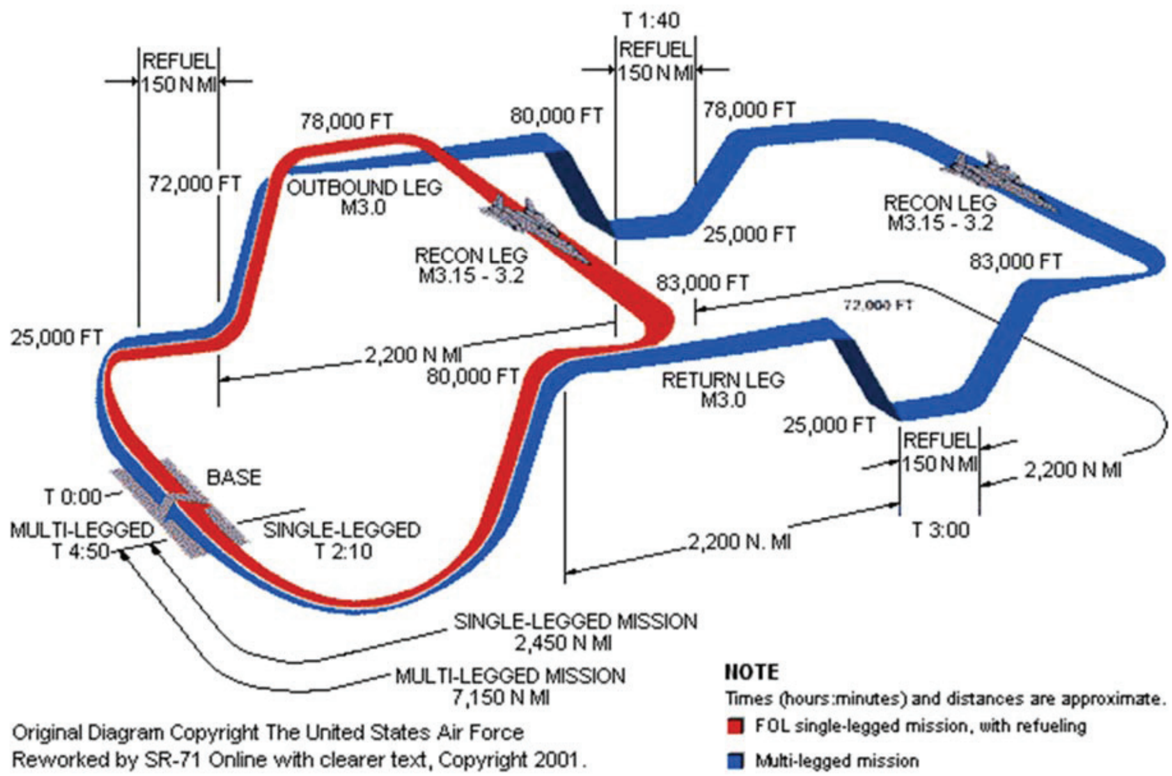

FIGURE 3: Single and multi-legged mission profiles of SR-71 (Blackbird) aircraft; distances are in nautical miles (N MI), altitudes are in feet (FT), time (T) is in hours and Mach number is indicated with (M) (courtesy of www.sr-71.org [6]).

Single legged mission has a range of 2450 nautical miles and time of flight of 2 hours and 10 minutes. First leg after the takeoff is refueling leg, which takes place at an altitude of 25000 feet for a distance of 150 nautical miles followed by outbound leg cruising at Mach 3 at an altitude of 78000 feet. Reconnaissance leg is followed shortly after the flight at 80000 feet at Mach 3.15 to 3.2. The return leg is dropping down from altitude of 80000 feet and landing. The complete single leg mission is shown in FIGURE 3 (red color).

Multi legged mission has a range of 7150 nautical miles and time of flight is 4 hours and 50 minutes. First leg after the takeoff is refueling leg, which takes place at an altitude of 25000 feet for a distance of 150 nautical miles followed by outbound leg cruising at Mach 3 at an altitude of 80000 feet for a distance of 2200 nautical miles. The refueling leg follows after. The reconnaissance leg is varied out at 83000 feet at Mach 3.15-3.2 for a distance of 2200 nautical miles. The third time refueling happens after the reconnaissance leg and aircraft returns to cruise at

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80000 feet at Mach 3. The multi legged mission ends after diving from 80000 feet and landing. The complete multi legged mission is shown in FIGURE 3 (blue color).

SR-71A mission profile is special in the sense that it requires atleast once and maximum up to three times refueling for its operation. In addition to that the altitudes and speeds are so high that it is closer to the space missions than any other aircraft. NASA used SR-71 in 1990s for experimental flights [7]. Only one aircraft has been built closer in performance to SR-71, which is the commercial supersonic jet Concorde [8, 9].

Wing Planform and Vertical Tail Configuration

Wing has a major role in a flight of an aircraft. Its layout directly affects the lift, drag, performance and maneuverability characteristics. Therefore, it is necessary to select parameters defining wing, horizontal and vertical tails in a conceptual design. These parameters are aerofoil shape, sweep angle, aspect ratio, dihedral angle, twist, wing incidence angle, wing vertical location, wing tips geometry, etc.

The design of a supersonic airplane is essentially the design of two different airplanes combined into one. The airplane must be optimized for its supersonic mission and it must be capable of flying in subsonic regime especially for take-off and landing. Therefore, some attention must be given for obtaining satisfactory low speed characteristics. In essence, a supersonic airplane is designed for double duty having reasonable flight characteristics at both subsonic and supersonic speeds.

Wing geometry (planform) is important as it influences the aerodynamics of the aircraft significantly. It may also equip essential components of the aircraft such as propulsion system, fuel tanks, etc. Some important parameters of wing are span, sweep, taper ratio, aspect ratio, wing location (vertically), wing dihedral, twist, wing incidence, etc.

Wingspan selection is one of the most basic decisions in a wing design. The span is sometimes constrained by hangar size, or operating facilities (aircraft carrier). It is not the deciding factor in this case, therefore, the use of the largest span consistent with structural dynamic constraints (flutter) would reduce the induced drag. However, as the span is increased, the wing structural weight also increases, which offsets the induced drag savings. The optimization is quite simple and one may stretch the span a great deal to reach an optimum value.

Wing sweep has direct impact on transonic wave drag. If chosen correctly, it provides higher coefficient of lift at the design Mach number without drag divergence. In other words, the sweep is useful in reducing the drag under transonic and supersonic conditions.

In SR-71 aircraft, wing sweep is 60^{o} (as shown in FIGURE 4(a)), which is optimum for supersonic flight however provides greater angle of attack during approach and relatively higher speed of landing. The thickness to chord ratio of a supersonic wing can be as low as possible (ideally a thin plate), however it is not possible in practice due to required structural strength.

Higher wing sweep angle has an impact on horizontal tail. Generally, higher sweep diminishes the idea of separate horizontal tail and brings in the possibility of merging horizontal tail with the wing providing a delta wing configuration. This configuration is seen in various aircrafts such as Concorde, Mirages, Typhon Eurofighter and reentry space vehicles [10]. In delta wing configuration, the control surfaces for pitch (elevator) and roll (ailerons) are usually combined together to create elevons.

The higher wing sweep has an impact on vertical tail and can be compensated by larger area. This can be achieved by twin tail combination, which doubles the area of a vertical tail. In addition to that vertical fins below the wing can be deployed in flight for extra yaw control on demand. In general, vertical tail not only have impact on yaw movements of aircraft but also on the rolling movement. In SR-71 aircraft, this impact is reduced by installing vertical tail tilted inwards as shown in the FIGURE 4(b).

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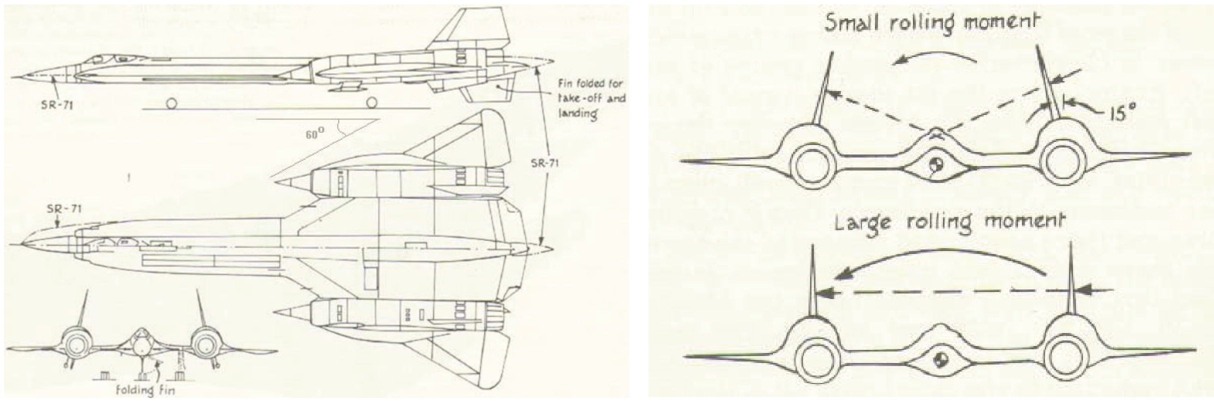

(a) (b)

FIGURE 4: (a) 60º wing sweep in SR-71 aircraft. (b)Tilt in the vertical tails of SR-71 aircraft to reduce the impact of vertical tail on rolling moment [11].

Propulsion System

A propulsion system is the source of power for an aircraft. It has direct influence on the flight and the performance parameters of an aircraft. Since SR-71A has a unique mission profile hence it is equipped with a special propulsion system known as “turbo ram jet” engine. Turbo ram engine is multi-stage engine having turbojet engine in the center and by pass routes for air to go into ramjet part. At low speeds all of the air is sucked by turbojet part for generation of thrust. But at high speeds due to ram effect, mass flow is so high that all cannot move through turbojet so it passes through ram jet part where combustion takes place and effective thrust is generated. At high speeds, inlet contribution to the thrust significantly increases which is the aerodynamic thrust and can be increased by careful inlet design. In essence turbo ram jet propulsion system is a mix of turbo jet and a ram jet engines working in conjunction with each other. Their combination provides an ability to provide the thrust in complete flight regime. The SR-71 propulsion system is equipped with two Pratt and Whitney J75 turbojet engines [12]. The operational figure of SR-71 propulsion system with turbojet engine in middle (gray), spike (green) and exhaust (red) is shown in FIGURE 5.

As shown in FIGURE 5, SR-71 propulsion system is controlled by movement of spike, forward bypass doors, aft bypass doors, suck-in doors, tertiary doors and ejector flaps. At stationary and low speeds around Mach 0, the spike moves forward, forward bypass doors are open, aft bypass doors are closed, suck-in doors are opened to allow passage of maximum flow through and around the turbo jet engine with tertiary doors open and ejector flaps closed. At around Mach 0.5, the forward bypass doors and suck-in doors are closed. At around Mach 1.5, the forward bypass doors are opened to position the inlet shock wave with tertiary doors closed while ejector flaps begin to open. At around Mach 2.5, spike starts to retract, aft bypass doors are scheduled to open with ejector flaps keep opening. At maximum Mach of 3.2, spike is retracted, forward bypass doors are closed, aft bypass doors are opened and ejector flaps are opened to maximum. The idea behind these complex movements is to ensure sufficient thrust at a range of speed. In addition to that, propulsion system is also responsible to provide pressurized air for various onboard operations, such as thermal control in cockpit and equipment, pressurization, etc. [13].

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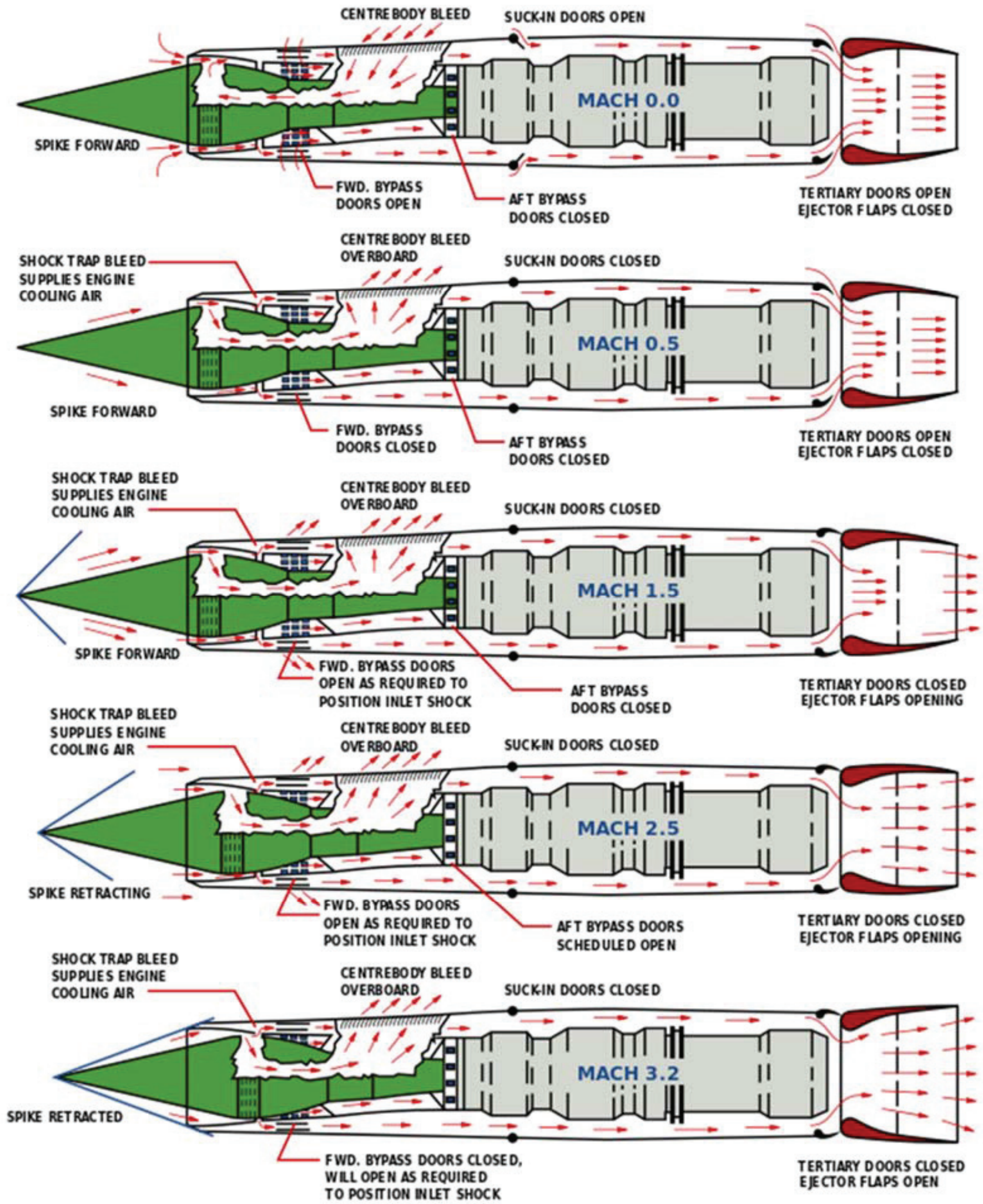

FIGURE 5: Propulsion system of SR-71 aircraft at various Mach numbers ([13])

Structural Loads

There are four major forces in an aircraft flight known as lift, weight, thrust and drag. These forces strain the aircraft structure hence in combination becomes structural loads. Structural load estimation is dependent on the combination of information from aerodynamic and propulsion analysis. In conceptual design, structural weight is estimated rather than calculated in actual.

SR-71 aircraft has an extreme high speed performance. Its structure not only needs to withstand pressure load but the thermal effects in conjunction with. At dynamic pressure of Mach 3.2, the temperature surrounding the aircraft may rise significantly. A structure of aluminum is not possible even if it could withstand such high pressures.

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Therefore, exotic materials of the time such as titanium alloys are used to build SR-71 aircraft structure [14].The SR-71 aircraft is shown in FIGURE 6.

FIGURE 6: SR-71 Aircraft in Flight

Wing Loading and Thrust to Weight Ratios

Wing loading and thrust to weight ratio are the two major parameters of an aircraft design. Optimization of these parameters is a major part of the conceptual design process. A simplified procedure based on empirical correlations given by [1, 2] is followed to find out wing loading and the thrust to weight ratios for different stages of the mission profile. Estimated values for various segments of flight are as shown in TABLE 1.

TABLE 1: Estimation of Wing Loading (Lbf/ft^2) and Thrust to Weight Ratios [1, 2, 15].

Flight Segment	Wing Loading (Lbf/ft^2)	Thrust to Weight Ratios
Take-off	133.8	0.6
Cruise	103.5	--
Max. Ceiling	120.0	--
Loiter	81.5	--
Landing	80.6	--
Thrust Matching	--	0.76
Historical	107.2	0.55
Average	104.2	0.64

The wing loading values ranging from minimum of 80.6 to 133.8 Lbf/ft^2 with an average of 104.2 Lbf/ft^2 for various flight segments. Similarly, the values of thrust to weight ratio varies between 0.55 to 0.76 with an average value of 0.64. These initial estimates are slightly different in comparison to the values of SR-71 aircraft, which has a wing loading and thrust to weight ratio of 84 lbf/ft^2 and 0.44 respectively. These differences are as expected, since [1, 2] is considering trend in development in aviation industry. Newer aircrafts are made of lighter materials and better performing propulsion systems. A comparison with [1, 2] is given in fig.7. The design and actual values are in the range of jet fighters and jet transport aircrafts.

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Table 5.1 Thrust-to-weight ratio (T/W)

Aircraft type	Typical installed T/W
Jet trainer	0.4
Jet fighter (dogfighter)	0.9
Jet fighter (other)	0.6
Military cargo/bomber	0.25
Jet transport	0.25

0.64 Design
0.44 Actual

Table 5.5 Wing loading

Historical trends	Typical takeoff W/S (lb/ft^2)
Sailplane	6
Homebuilt	11
General aviation—single engine	17
General aviation—twin engine	26
Twin turboprop	40
Jet trainer	50
Jet fighter	70
Jet transport/bomber	120

84 Actual
104 Design

FIGURE 7: Comparison of Thrust to Weight Ratio and Wing Loading (Lbf/ft^2) of design and actual values with historical trend [1, 2].

CONCLUSION

The conceptual design process helps in understanding the existing aircrafts and their variations. In addition, the process helps in following the trend of development in aircraft technologies. Conceptual design process given by [1, 2] is a step by step process and can be applied in the design of aircrafts of complex mission profile such as SR-71. The study predicts values of performance parameters such as thrust to weight ratio and wing loading in reasonable accuracy to the actual SR-71 aircraft. The difference indicates the trend in development of modern aircrafts, which are made of materials with higher strength to weight ratio and better performing propulsion systems.

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