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Aerodynamics-based forward-swept wing structure optimization

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Abstract. This paper reviews and evaluates the most recent studies on forward-swept wing technology. A number of experimental plans and applications for forward-swept wing aircraft have been produced as a result of the study of forward-swept wings, the investigation of aerodynamic circumstances, and the creation of related designs. The related theories and exposed problems of the forward-swept wing aircraft, such as the problem of aeroelastic divergence, structural strength, and the descent of transonic flight state, are gradually solved. It will be demonstrated that forward-swept wing aircraft have outstanding aerodynamic performance in subsonic flight. In comparison to current aircraft, it may gain more controllability advantages, enhance low-speed controllability, increase aerodynamic efficiency in a variety of flying scenarios, decrease stall speed, making the aircraft less likely to enter the spiral state, and increase safety and dependability. The research in the field of forward swept wing will increase the possibility of successful development and practical use of forward swept wing aircraft.

Keywords: forward-swept wing, aeroelastic divergence, aerodynamic profile.

1. Introduction

The development of forward-swept wing aircraft began in the early 20th century. The first aircraft to use a forward-swept wing design was the Junkers J1 prototype, built in Germany in 1915. As in Figure 1 The 1930 s and 1940 s were the first stages of the development of forward swept wing aircraft. Belyaev was the project leader of the DB-LK project, which tested the forward-swept wing gliders BP-2 and BP-3 in 1934 and 1935. During the same period, a series of forward-swept wing aircraft such as PWS Z-17 appeared in Poland. The Cornelius XFG-1 military fuel supply towed glider is a forward-swept tailless design that was designed by the US. Meanwhile, in Germany, Hans Walker was working on the problem of swept-back wings at the near-sonic speeds that the new jet engines could achieve. He recognized that the forward-swept design offered many advantages over the then-developing swept-back design, while understanding the effects of aeroelastic buckling and yaw instability. In this context, the Y-prototype of the Ju 287 V1 was developed. In 1948, the Soviet Union created the Tsybin LL-3. The technical achievements of the forward-swept wing prototype have had a great impact on the Sukhoi SYB-A completed in 1982. When German research arrived in the United States after World War II, it provided valuable information on the development of the forward-swept wing of the United States. The relevant achievements of the United States during this period include the forward-swept variant of the North American P-51 Mustang, the Convair XB-53 supersonic bomber, the Douglas D-558-I and the Bell X-1 rocket plane. Related aerodynamic problems were found in related experiments and applications.

Serious structural problems were found in the forward-swept wing aircraft at that time, and this design required sufficient strength materials. When meeting the design scheme of the relevant structural strength, it is found that it is too heavy and not practical. As a result, the high-speed design of forward-swept wings was abandoned, and it was not until many years later that new structural materials were developed that the design was studied again.

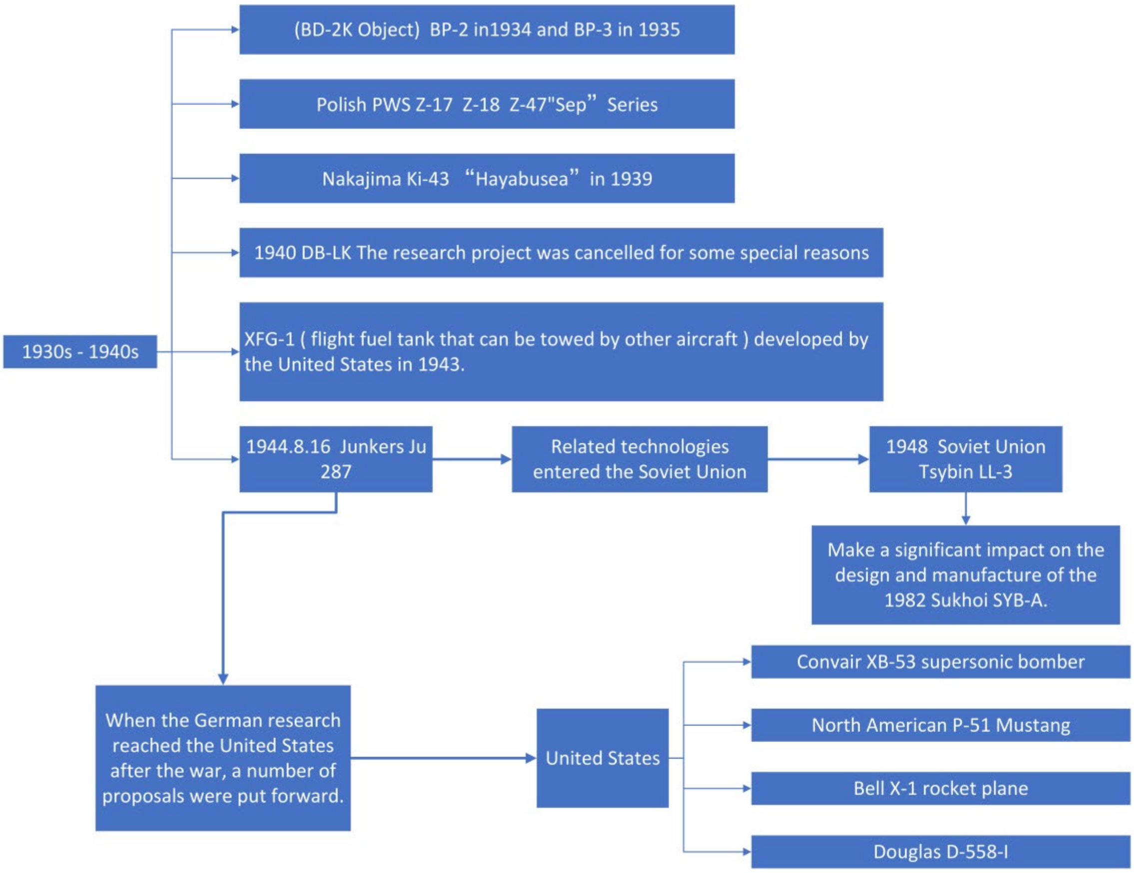

Figure 1. Research results of forward-swept wing from 1930s to 1940s.

After this period of time, related designs evolved. The large angle sweep required for high-speed flight remained impractical for many years. After decades of technological development, until the 1980s, the development of FSW has made significant progress.

In the 1980s as figure 2, NASA and the US Air Force began designing new FSW aircraft. X-29 is the most prominent example. The X-29 has a canard wing and a high degree of forward-swept wing design. The purpose of these designs is to provide more maneuverability and stability for the aircraft. The X-29 achieves good maneuverability at a large angle of attack, and it can maintain a controllable state at an angle of attack of 67°.

In 1997, Sukhoi launched a prototype of the Su-47 fighter at the Paris Air Show. This is another representative of the forward-swept wing aircraft. In the late 21st century, Russia developed the KB SAT SR-10 single-engine forward-swept wing trainer prototype. It flew for the first time in 2015 and is a mature and reliable aircraft [1].

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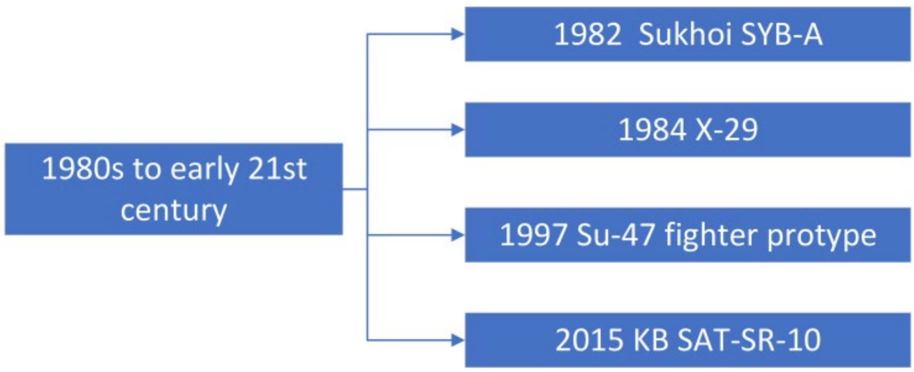

Figure 2. The development of forward-swept wing of the 20th century to the beginning of the 21st century.

A simplified history of the evolution of the forward-swept wing is shown in figure 3.

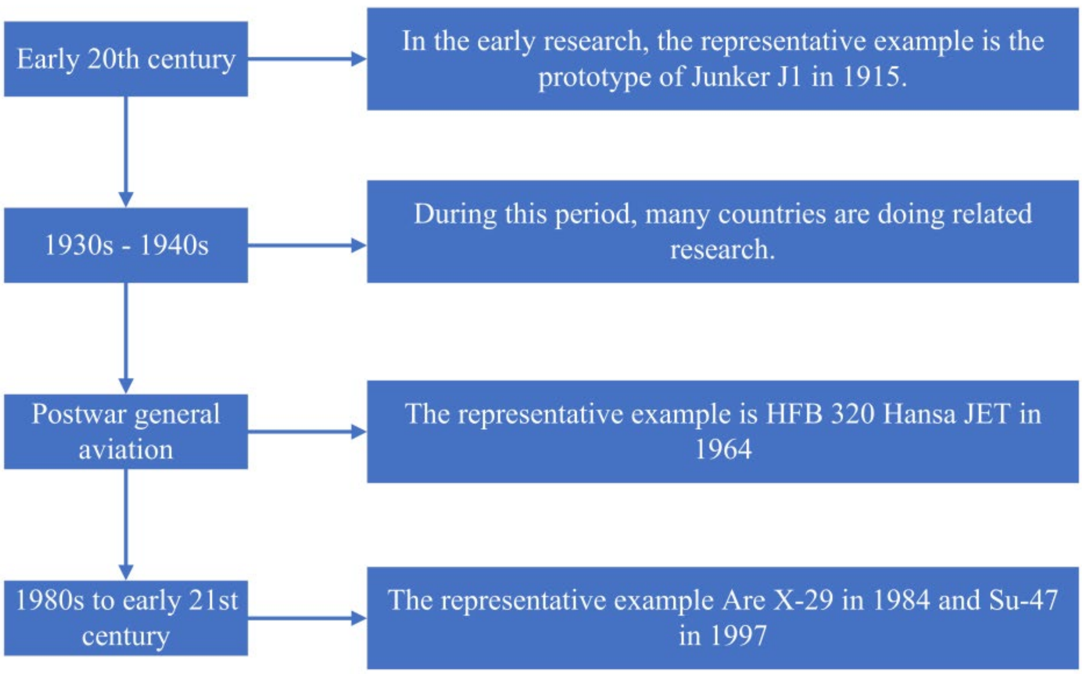

Figure 3. Development timeline and technology development path.

2. Recent progress

With the continuous development of technology, research in the field of materials science and related fluids continues to emerge, and various experimental schemes and various applications of forward-swept wing aircraft have been developed. The related theory and the problems exposed in the forward-swept wing aircraft, such as the problem of aeroelastic divergence, the problem of structural strength, and the decline of transonic flight state are gradually being solved. The research in the field of forward-swept wing will increase the possibility of successful development and practical use of forward-swept wing aircraft. The structural advantages of the forward swept wing include better connection between the wing and the fuselage and reasonable distribution of pressure between the wing and the forward landing wing.

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The maneuverability advantage is that the forward-swept aircraft can fly at subsonic speed and has very good aerodynamic performance, which greatly improves its maneuverability in the pitch direction. Take-off and landing advantages because forward-swept aircraft have more lift and 30 % more payload than backward-swept aircraft with the same wing area. This paper's research topic focuses on forward-swept wing technology and its potential benefits for aircraft design. The forward-swept wing technology can offer advantages such as reducing the wing size, face resistance, and structural weight of the aircraft. It can also decrease the aircraft's drag, increase the subsonic range, and improve the low-speed maneuverability of the aircraft, resulting in shorter take-off and landing glide distances. Furthermore, the controllability advantage can enhance the aircraft's controllability at low speed and improve the aerodynamic efficiency under all flight conditions. It can also reduce the stall speed, prevent the aircraft from entering the spiral, and ensure safer and more reliable operation.

The research in forward-swept wing technology mainly focuses on the following aspects as figure 4: Firstly, in aerodynamics and fluid mechanics, the research aims to optimize the aerodynamic shape of the forward-swept wing to achieve better flight performance in each flight stage. Based on the research results of aerodynamics, forward-swept wing aircraft is improved, and its various dynamic layouts are explored. The problem of aeroelasticity is also explored, and solutions to aeroelastic divergence are proposed. Secondly, designing and manufacturing aircraft for different industries, such as transport aircraft, business aircraft, and trainer aircraft, to accumulate data and promote the evolution of forward-swept wing technology. Finally, based on the current development of material science, new materials are utilized to optimize the forward-swept wing scheme, making it lighter, and with better structural strength. This approach aims to resolve the issue of increasing the structural weight to increase the critical speed, which forms a vicious cycle until the wing breaks. Using new composite materials and developing new aerodynamic shapes will enable the designed forward-swept wing aircraft to meet the needs of different industries better.

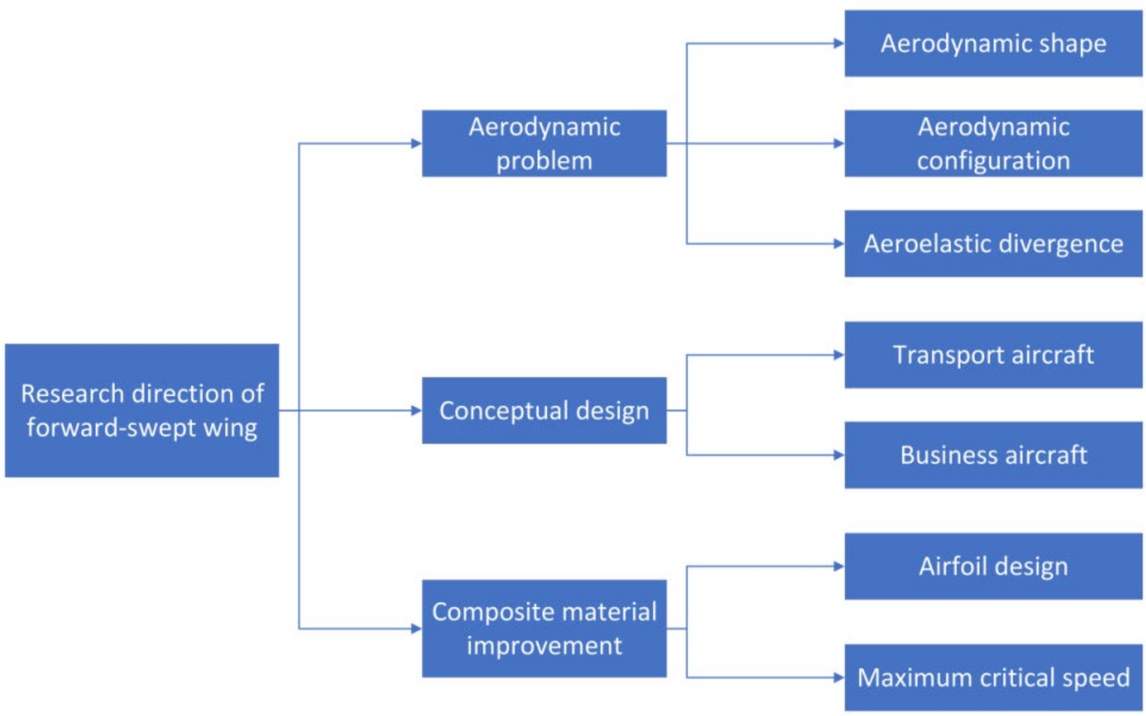

Figure 4. Main research directions of forward-swept wing.

3. Analysis of mainstream research directions

In this chapter, several mainstream research directions will be specifically analyzed and their research results and future applications will be explored.

3.1. Conceptual design of special aerodynamic configuration of forward-swept wing aircraft

3.1.1. Business aircraft. This research uses a new design method, Aircraft design workflow, in RCE [2]. At the 2020 European Aerospace Congress, a team set up an aircraft design environment called MICADO in this research direction, which integrates the aircraft's overall design remotely into the component environment RCE and is used for TA and BWB configurations on the DLR. At the same time, the system also has the function of experimental design (DOE) and post-processing. Different configurations in the system can also be changed according to special design requirements. The purpose of the project to improve the adaptability of the system, the standard data exchange format will be used to implement the general parametric aircraft configuration scheme (CPACS) to ensure that all the communication between the modules involved is a consistent aircraft model. This design environment allows web-based design methods to link tools in different fields to meet more design needs [2].

MICADO (A aircraft design environment) [3] is applied to analyze the SBFSW and FSW-BJ configuration of DLR. The main disciplines in conceptual aircraft design are represented by loosely coupled modules that make up MICADO. The MICADO workflow [4] is used to evaluate unconventional aircraft, and an additional model used in [5] to calculate the configuration quality of unconventional wings is introduced.

In this design environment as figure 5, a variety of forward-swept wing variants are designed and studied. The forward-swept wing (FSW) in these designs can achieve NLF at high Reynolds's numbers [6]. Three FSW variants considering different NLF degree assumptions were proposed to explore how to use such techniques on business jets. In these designs, carbon fiber reinforced polymer (CFRP) will be selected as the material for the forward-swept wing.

Figure 5. Three FSW design solutions [2].

The configuration of different FSW design schemes is shown in Table 1.

Table 1. Different settings for the three FSW design options.

Type	Status of NLF	Details
NLF-FSW	a permanent NLF at the upper and lower wing side	50% of the local chord is NLF.
TF-FSW	a permanent NLF at the upper and lower wing side	50% of the local chord is NLF. and carries additional fuel to fulfill the design mission.
KR-FSW	NLF just on the side of the upper wing	The Kruger flap will be used as a high lift and shielding device as in [7].

This study is based on data from the CERAS CSR-01 database opened by the Aachen University of Technology [8] and uses it as a commonly used general reference configuration. Verification and calibration are carried out with the support of ONERA and DLR tools. By using the identical top-level aircraft criteria as CSR01, ONERA shows that the MYSTIC tool can replicate those results (TLAR) [9]. MICADO and RCE workflows were used to recalculate this reference configuration for unconventional forward-swept wing design successfully. In order to make the results more accurate, and taking into account the impact of advanced technology, DLR used the ' EIS2035 reference '. It utilizes the fuselage technology and engine listed in [10] for use in 2035. The thrust-weight ratio and wing load are also optimized.

There is another special FSW design in this research field as figure 6. The design of the SBFSW (Strut braced forward swept wing) is intended to achieve NLF in the upper part of the main wing. The design of the strut part reduces the mass penalty of the forward-swept wing. At the same time, the contribution of the design to lift can reduce the main wing'ar. The results of Reference [7] are used for the wing design. Therefore, -18 ° leading edge sweep combined with Kruger flap is selected as the high lift and shielding device. A high-lift device identical to the advanced reference is used at the trailing edge. Some designs use the 36 m wingspan constraint in Reference [11]. The influence of this constraint is evaluated, and the parameters are studied.

The SBFSW configuration has great advantages, but it also causes the problem of complex engine integration. Some adjustments and modifications have been made to this problem. Two variants of different engine configurations are considered in the scheme: rear fuselage (SBFSW-RE) and wing mounted engine (SBFSW-WE). The wing load, thrust-weight ratio, lift distribution and strut size were optimized in the design. For FSW-BJ, simultaneous use of NLF and FSW reduces high lift performance.

Figure 6. Two SBFSW design solutions [2].

This special design partly improves some of the shortcomings of the forward-swept wing scheme, but it also brings new challenges and difficulties. In this design, the position of the engine has a great influence on the geometry of the environmental strut. The increase in strut size reduces the longitudinal stability, which results in the entire wing moving backwards to maintain the specified static margin. The area of the horizontal stabilizer needs to be increased to produce higher mass and resistance. The purpose of the engine placed under the wing is to achieve a balanced mass distribution to reduce the negative impact. However, these schemes have not considered the influence of wing wake on engine performance, nor the anti-interference ability of the engine installed between the wing and the strut [2].

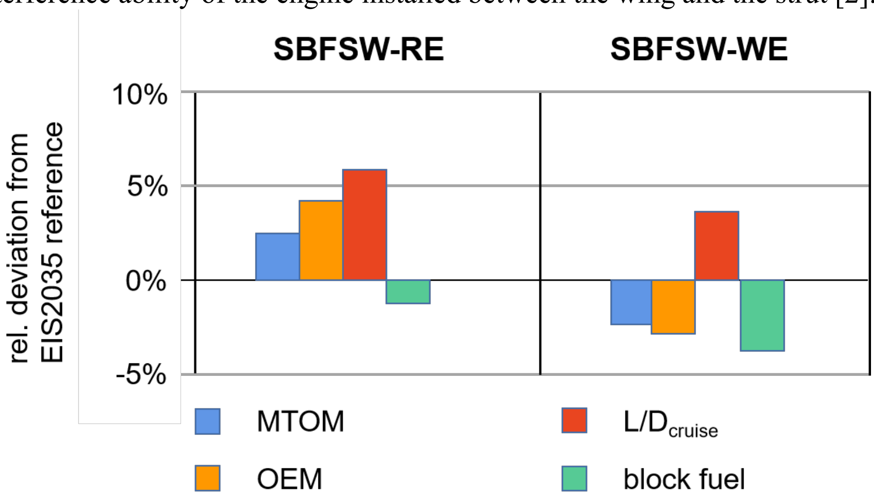

Figure 7. Data comparison of two SBFSW design options.

From the conclusion of figure 7, it can be concluded that these designs have improved the performance of the aircraft. The improved aspect ratio based on NLF is the main reason for these improvements. The SBFSW-WE configuration also shows potential mass savings. The effects of aircraft-level NLF and disturbance resistance have been evaluated in parameter studies [2].

3.1.2. Transport aircraft. From 2014 to 2017, the German Aerospace Center DLR conducted an internal project called TuLam (Laminated Technology). The existing research mainly focuses on the aerodynamic design of forward swept wing in cruise flight. In the process of project implementation, two technical routes of Natural Laminar Flow and Hybrid Laminar Flow Control were adopted. NLF technology is used to create a mid- and short-range transport aircraft with forward-swept laminar wing. To assess the overall fuel saving potential of the wing, the CSR-01 configuration (basically a redesign of the Airbus A320-200) is employed as a benchmark.

After exploration, the aerodynamic design concluded that natural laminar flow is also feasible at a design Mach number Ma = 0.78. The off-design operating condition is Ma = 0.80. The aerodynamic design came to the conclusion that natural laminar flow is also possible at a design Mach number Ma = 0.78 after extensive research. Ma = 0.80 is the off-design operating condition [7].

3.2. Aeroelasticity

A configuration with aeroelastic twist divergence under dynamic pressure is the forward swept wing (FSW). The aeroelastic torsional divergence problem is caused by the fact that the Aerodynamic Centre (AC) is always in front of the center of stiffness of the structure, resulting in head-on torsion of the forward-swept wing vehicle. This phenomenon will increase the local angle of attack (AOA), resulting in more lift and aeroelastic torsional deformation problems in general. This change will continue to occur during the flight phase and eventually lead to structural failure due to uncontrollable aerodynamic forces. The application of FSW in commercial aircraft is severely constrained by this phenomena.

Traditionally, this issue has been solved by making the wing construction more rigid. However, this approach would increase the weight of the structure significantly. A current solution is to use advanced composite cutting technology to mitigate torsional phenomena in the FSW, which increases the rate of torsional dispersion and does not add much structural weight. It has been successfully applied to the X-29 Forward Swept Prototype. The composite cutting technique uses isotropic structural behavior to strengthen the local directional stiffness of the structure, allowing this problem to be solved [1].

One of the solutions is to study the possibility and effectiveness of AAW applied to FSW by adding two control surfaces for static aeroelastic simulation as figure 8. For dynamic aeroelastic simulation, a more intricate FSW model with more control surfaces is developed. Future studies will build a system that integrates structural behavior, aerodynamics, and dynamic control of the flap and aileron. Then, the closed-loop control is added to establish the flight dynamics equation. On the basis of the previous scheme, the optimization strategy can also be introduced to strengthen the control and structural upgrading of the control surface to obtain better FSW torsion suppression effect [12].

Another application in the direction of composite materials as figure 9. Change the thickness and ply of the composite material to optimize the aeroelasticity. The results achieved in this direction. The best orientation and ply were obtained from the four basic ply. This outcome correctly extracts the two modal frequencies of the FSW before and after AT.. After the AT optimization process, the first-order modal frequency of FSW increased by 33.0%, and the second-order modal frequency increased by 37.9% [12].

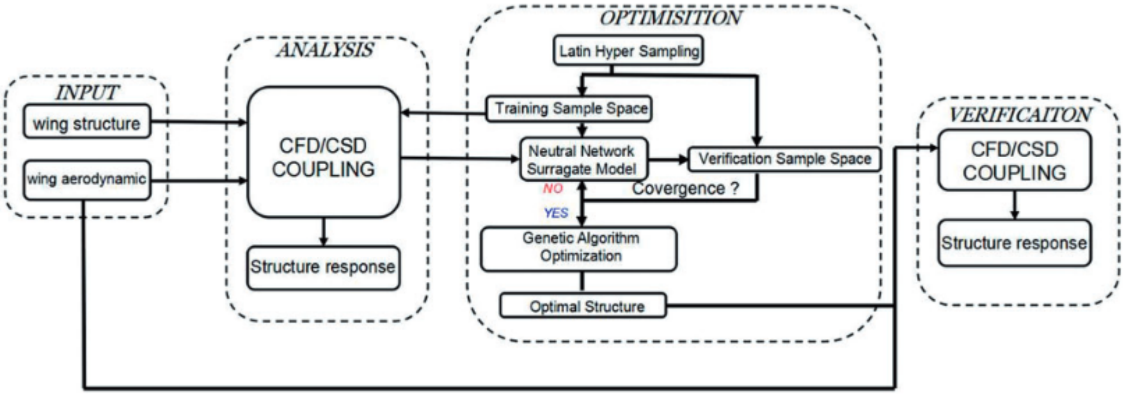

Figure 8. Aeroelastic tailoring optimization process [12].

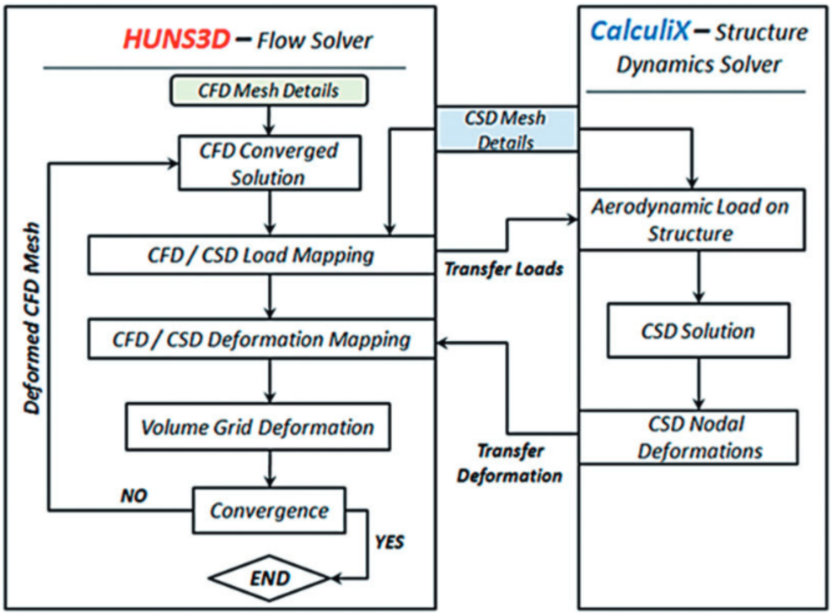

Figure 9. CFD/CSD coupling process for computational static aeroelastic [12].

3.3. Basic airfoil

As the angle of the wing changes, the aspect ratio and the relative velocity of the cross-sectional wing relative to the incoming flow of a forward swept wing aircraft will change and this change will have a significant effect on the aerodynamic characteristics of the wing [13].

In this research area, the impact of the fundamental airfoil's inclination angle on the aerodynamic performance of the forward-swept wing is investigated.

Special morphing aircraft are capable of switching between common wing configurations like straight wings, forward-swept wings, and delta wings [14-15]. The aspect ratio of the wing and the relative thickness of the cross-section wing compared to the incoming flow will also alter proportionally with a change in the forward-swept angle, which has a significant effect on the aerodynamic performance of the forward-swept wing design [16]. Therefore, it is crucial to research how the fundamental airfoil inclination angle affects the forward-swept wing's aerodynamic performance during the deformation process [17-18].

Different oblique sweep angles will produce different aerodynamic performance of forward-swept wing. According to the change of cross section airfoil in the process of variant, it can be seen from the current research results.

1) The lift of the straight wing design is relatively high and has great aerodynamic efficiency when the fundamental airfoil inclination angle is 0°, however the issue of wing stall is evident. The stall angle of attack is greater in the version with forward-swept wings. The lift and drag decrease as the forward sweep angle rises, while the torque has a significant negative absolute value.

2) When the basic airfoil's inclination angle is 30°, the forward sweep angle's effect on the wing's aerodynamic performance is identical to that of the forward sweep angle when the inclination angle is 0°. The wing with a 30°inclination angle is superior than the wing with a 0°inclination angle in that it produces more lift and less drag.

3) The basic airfoil's tilt angle has a substantial impact on the wing's aerodynamic performance whether it is in a straight state or a forward-swept condition. When the basic airfoil sweeps forward by 30 degrees, the maximum lift coefficient rises by 20% and the drag coefficient falls by 37% when compared to the wing with the basic airfoil upright.

4) When the basic airfoil is slanted, the wing has higher lift and lower resistance, which means it has better aerodynamic performance, as seen from the aerodynamic performance of the straight wing and the forward-swept wing at different angles of attack.

Consequently, to design the wing as a variable forward-swept wing aircraft, the rib arrangement can serve as the foundation for airfoil tilt. In this instance, the wing's aerodynamic performance while deforming is superb. This also provides a feasible direction for future development.

3.4. Supersonic forward-swept wing

For practical usage of SuperSonic Transports (SSTs) it is essential to reduce both the aerodynamic drag and sonic boom during the supersonic cruise; many studies have aimed at reducing both simultaneously. In those studies, the delta wing and cranked arrow wing have often been used; however, the lift distribution along the body axis is concentrated in the rear of the airframe, making it especially difficult to reduce the aft boom. To solve this problem, Horinouchi suggested a variable forward wing aircraft, and demonstrated the possibility of achieving both sonic boom and drag reduction during the cruise, using both computational fluid dynamics (CFD) simulationsand wind tunnel tests. According to these numerical results, the maximal strength of the sonic boom for a forward swept wing (FSW) was determined to be ~4. 8 PLdB lower than that of a typical backward swept wing (BSW), while the aerodynamic drag was almost the same. Thus, an FSW is promising as a main wing of an SST, from the viewpoint of supersonic performance.

4. Conclusion

Forward-swept wing aircraft, from the early 20th century to the present, the relevant principles, design tools and design schemes are rapidly maturing. The new design scheme is being demonstrated, and the related design is also applied to the aircraft. The issues that previously surfaced on forward-swept airfoil aircraft are progressively being resolved as a result of ongoing technological advancements in the fields of materials science and related fluids. The research results of forward swept wing will be widely used in transportation, scientific research, material research and development. The excellent aerodynamic performance of forward-swept wing aircraft in subsonic flight will be demonstrated. Compared with the existing aircraft, it can obtain more controllability advantages, improve the controllability at low speeds, increased aerodynamic effectiveness in a variety of flight scenarios, reduce the stall speed, and ensure that the aircraft does not easily enter the spiral state, so that the aircraft is safer and more reliable.

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