32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

VALUE ANALYSIS AND RISK ASSESSMENT FOR MORPHING LEADING AND TRAILING EDGE FOR VARIABLE CAMBER WING

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Abstract

The value analysis and risk assessment for variable camber wing were studied in this paper. Firstly, a set of evaluation indexes system including variable camber system weight, maximum deflection angle, deformation accuracy, driving power, load-bearing capacity and other indicators were established. Then, three leading edges and three trailing edges were evaluated respectively. Finally, the key technologies of the leading and trailing edge variable camber wings are identified, and the technical risk assessment is carried out based on the technology readiness evaluation method.

Keywords: variable camber wing, evaluation index, value analysis, risk assessment

The variable camber wing is a form of the morphing aircraft. The aircraft with variable camber wing can change camber of the leading and trailing edges of the wing according to the flight conditions, so that the aircraft maintains the optimal aerodynamic efficiency during the entire flight phases, improves fuel economy and reduces aerodynamic noise[1-4]. As a new technology, the variable camber wing is still in the stage of conceptual design and technical verification. How to achieve smooth and continuous deformation while ensuring structural load-bearing capacity and reliability has become the biggest challenge. The value analysis and risk assessment for the variable camber wing aims to analyze the comprehensive benefits of the variable camber wing and grasp the technical risks, evaluate the feasibility and effectiveness of the current variable camber wing technical solution, promote the convergence of the variable camber wing technical solution and the maturity of key technologies, which provides a reference for further engineering applications.

1. Evaluation indexes for variable camber wing

Many different forms of technical solutions have been proposed for variable camber wing so far, including Mission Adaptive Wing (MAW) [5], Active Flexible Wing (AFW) [6], Smart Intelligent Aircraft Structures (SARISTU) [7], Adaptive Compliant Trailing Edge (ACTE) [8], Variable Camber Compliant Wing (VCCW) [4], etc. In order to evaluate the advantages and disadvantages of different variable camber wing solutions and the benefits compared with the traditional separated control surface wing, it is necessary to establish an evaluation index that can comprehensively and objectively reflect the function, performance and comprehensive benefits of the variable camber wing. According to the top-level design requirements of the aircraft, the design characteristics of the variable camber wing and the practical application requirements of the project, this study analyzed the influence of the variable camber wing on the aircraft performance, and formed an evaluation index system suitable for the comprehensive performance evaluation of the variable camber wing. The evaluation index system contains 16 evaluation indicators. Description of each indicator and evaluation basis is given in Table 1.

Table 1-Evaluation indexes of variable camber wing

No.	Index name	Indicator description	Simulation	Test
1	*Variable camber system weight	Total weight of variable camber structure and drive control system	★	★
2	*Maximum deflection angle	Maximum angle at which the leading and trailing edges can be deflected	★	★
3	*Deformation accuracy	Deviation between actual deformation and ideal shape	★	★
4	*Driving power	The total motor output power required to drive the normal operation of the variable camber system	★	★
5	*Bearing capacity	The ability of the structure not to fail under load	★	★
6	Material system and distribution	The materials and performance parameters used in the various structural parts		★
7	The process can be realized	The manufacturing process meets the design requirements		★
8	Assembly performance	Assemble each component of the front edge; assembly of the front edge system and the main wing box	★	★
9	Anti-bird-strike ability(only for the leading edge)	Anti-bird-strike ability of the front edge to resist bird-strike	★	
10	Anti-deicing (only for the leading edge)	Anti-deicing capability	★	
11	Response time	The time interval between the control command issued and the structural deformation response	★	★
12	Deformation rate	Average deflection angle per second	★	★
13	Number of deformation cycles	The maximum number of cycles of deformation		★
14	Aerodynamic performance	Lift, drag, lift-to-drag ratio, etc.	★	★
15	Noise	Noise reduction	★	★
16	Fuel consumption	Fuel consumption reduction in the whole journey		★

2. Variable camber wing leading and trailing edge design

The evaluation objects of this study are the 3 leading edge solutions with variable camber and 3 trailing edge solutions with variable camber designed by our team. The leading edge of variable camber solutions are: Variable camber Leading edge with variable thickness skin, variable camber leading edge with rigid mechanism, flexible mechanism variable camber leading edge; variable camber trailing edge solutions are: rigid-flexible coupling structure variable camber trailing edge, multi-section rotating variable camber trailing edge, and the eccentric beam drives the variable camber trailing edge. The implementation of each solution is as follows:

2.1 Variable camber leading edge solutions

(1) Variable camber Leading edge with variable thickness skin

The leading edge structure of the variable camber wing is decomposed into four parts: flexible skin, internal structure/mechanism, connection between internal structure/mechanism and the skin, and driver. According to the logical relationship, the design problem of the leading edge of the variable camber wing is decomposed. Iterative design is carried out by means of advanced optimization design technology and nonlinear simulation analysis to find the optimal skin stiffness distribution and the best topological form of the internal structure/mechanism. The solution is shown in Figure 1.

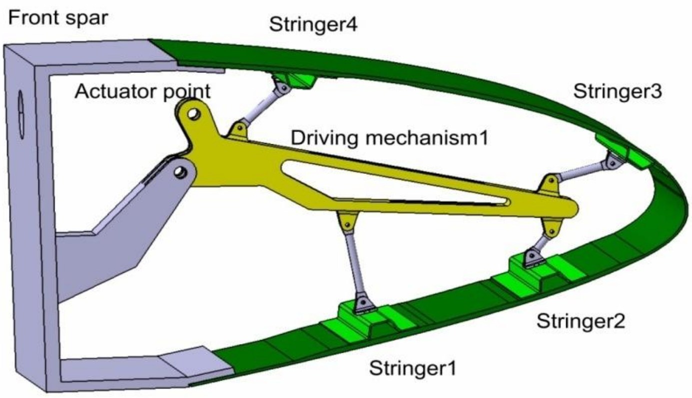

FIG. 1-Figure 1 The leading edge structure solution of the variable camber wing based on the linkage mechanism

(2) Variable camber leading edge with rigid mechanism

In order to make the wing meet the requirements of flexible deformation and load-bearing at the same time, a design of variable curvature leading edge based on a rigid five-bar mechanism is proposed. The leading edge skin adopts a method of curling a flat sheet material into an initial airfoil shape, which reduces difficulty in skin processing and manufacturing. The design method of the internal drive mechanism driven by a single motor improves the shape-keeping ability of the wing during deformation and reduces the weight of the whole machine. The solution is shown as in Fig. 2.

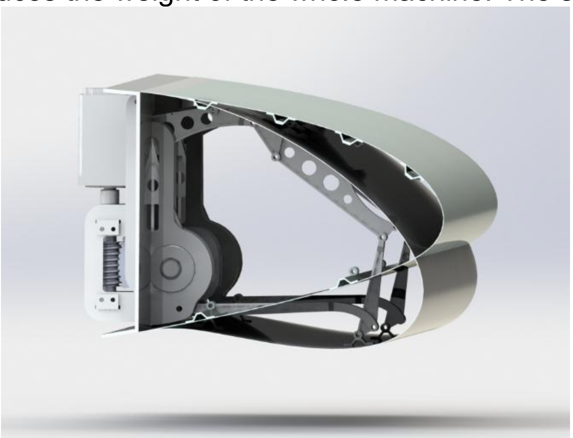

FIG. 2- Variable camber leading edge with rigid mechanism

(3) Flexible mechanism variable camber leading edge

The leading edge of the variable camber wing driven by the distributed flexible mechanism is used to obtain the distributed flexible mechanism that drives the skin deformation through the topology optimization algorithm, and the variable cross-sectional thickness skin is used to improve the deformation accuracy. The flexible structure at the joint of the driving mechanism and the skin is converted into rigid rods with concentrated flexibility hinges at both ends to improve the manufacturability of the flexible mechanism, while reducing friction and improving the fatigue resistance of the driving mechanism. The solution is shown as in Fig. 3.

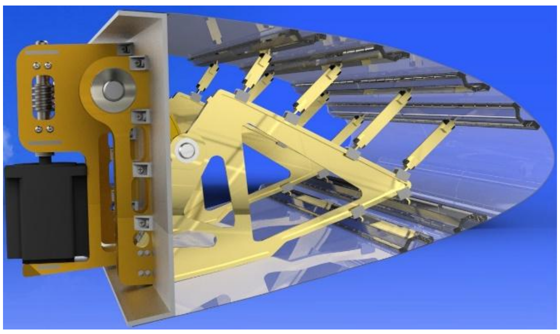

FIG. 3-Flexible mechanism variable camber leading edge solution

2.2 Variable camber trailing edge solutions

(1) Rigid-flexible coupling variable camber trailing edge

Using the design idea of rigid-flexible coupling, a design method of watts six-bar mechanism to achieve three "knuckles" rigid drive and distributed compliant mechanism to achieve wing deformation is designed. It effectively solves the current problems in the deformation of the wing, that is, the skin of the rigid mechanism is prone to buckling and is not smooth and the deformation is limited. Although the skin of the compliant mechanism is smooth, the load is small, and it is difficult to meet the dual optimization of deformation and load. The solution is shown as in Fig. 4.

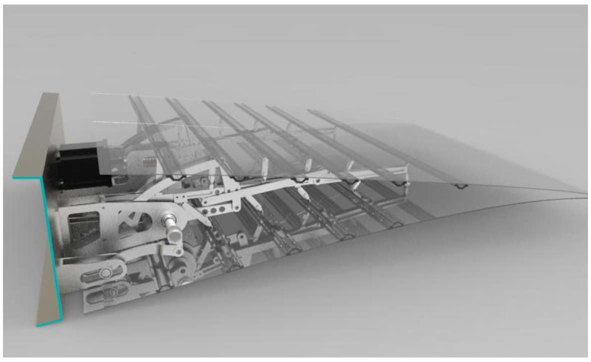

FIG. 4-Rigid-flexible coupling variable camber trailing edge scheme

(2) Multi-section rotating variable camber trailing edge

With reference to the initial airfoil and target deformation, a variable structure based on a multi-section rotating mechanism is used to modify the traditional wing trailing edge ribs that originally have load-bearing capacity, so that they can be used as a driving device to achieve upward or downward deflection. That is, the structural load-bearing capacity and the deformation driving capacity are integrated to form a variable camber rib structure. By arranging multiple variable camber ribs along the span on the trailing edge of the wing, when the variable camber rib is driven, the trailing edge is deflected upward or downward as a whole; and when the drive mechanism is locked, each variable camber rib is not Deformation occurs, and the trailing edge remains stable under aerodynamic loads. At the same time, the variable camber rib drive systems are independent of each other. If coordinated and synchronized control, the overall deformation of the trailing edge can be realized, and if the differential control is used, the twist of the wing can be realized. The solution is shown as in Fig. 5.

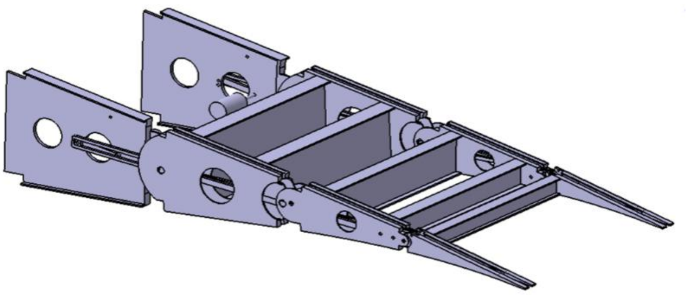

FIG. 5-Multi-section rotating variable camber trailing edge solution

(3) Variable camber trailing edge driven by eccentric beam

The structure of the variable camber trailing edge based on the eccentric beam/curved disc is shown in Figure 6. The entire structure includes upper and lower aluminum alloy skins, eccentric drive systems, wingtip sliders, upper and lower skin connecting rods, long trusses, and rear beams. The driving system consists of a curved eccentric beam and a curved disc fixed on it. The eccentric beam is rotated by the input torque and drives the curved disc to move downwards, thereby driving the lower skin to deflect downward; through the upper and lower skins The connecting rods and the wingtip sliders transmit the driving load to the upper skin and then the lower skin is deflected downwardly to realize the deflection and deformation of the trailing edge.

FIG. 6- Variable camber trailing edge driven by eccentric beam

3. Value analysis and evaluation of variable camber wing

Taking the leading edges of the three variable camber wings and the trailing edges of the three variable camber wings as objects respectively, the comprehensive benefit evaluation of the variable camber wing is carried out. The evaluation process is divided into two stages: the performance evaluation of the alternative solution and the benefit evaluation of the winning solution.

3.1 Performance evaluation of alternatives

The first stage is the performance evaluation of the alternatives, which mainly compares the leading edge solution and the trailing edge solution, and selects the best solution based on the data of design and simulation analysis.

In the stage of performance evaluation of the alternatives, five indicators including the weight of the variable camber system, the maximum deflection angle, the deformation accuracy, the driving power, and the bearing capacity are more important. At the same time, the material system and distribution, process achievable, assembly performance, bird strike resistance (only for the leading edge) Deicing prevention (only for the leading edge), response time, deformation rate, number of deformation cycles are taken into consideration.

The performance evaluation of alternatives is carried out by means of expert scoring. In view of the indicators above, the evaluation experts score 1-3 points for the three leading edge options and the three trailing edge options respectively, of which 1 is the worst and 3 is the best. The total score of each indicator is the score of the solution. Invite seven experts to conduct a review, and the solution with more expert support is the final preferred one.

The 7 experts cover the main professions of variable camber wing design. They are:

Expert1: Overall aerodynamic design;

Expert2: Intelligent Morphing Aircraft design;

Expert3: Overall aerodynamic design;

Expert4: Non-linear aeroelastic analysis, design of deformable wings and morphing aircraft;

Expert5: morphing aircraft design;

Expert6: Mechanical design and manufacturing, control system design;

Expert7: Structural optimization design, structural stability analysis.

The principle of evaluation and selection of alternatives is "individual elimination and gradual convergence". To this end, two rounds of evaluation process have been conducted. The variable camber Leading edge with variable thickness skin and the rigid-flexible coupling structure variable camber trailing edge become the superior solutions respectively.

The expert scoring results are shown in Table 2 and Table 3.

Table 2-Statistics of the scoring results of the leading edge

Scoring by experts	Variable camber Leading edge with variable thickness	variable camber leading edge with rigid mechanism	Flexible mechanism variable camber leading edge

	skin		
Expert1	11	12	10
Expert2	20	19	19
Expert3	20	17	18
Expert4	18	20	15
Expert5	18	16	14
Expert6	20	16	21
Expert7	21	14	19
Votes	4	2	1

Table 3- Statistics of the scoring results of the trailing edge

Scoring by experts	Multi-section rotation variable camber trailing edge	Variable camber trailing edge driven by eccentric beam	Rigid-flexible coupling structure variable camber trailing edge
Expert1	16	10	12
Expert2	15	14	17
Expert3	12	11	19
Expert4	18	10	13
Expert5	11	11	12
Expert6	19	9	17
Expert7	15	11	24
Votes	3	0	4

3.2 Benefit evaluation of the winning solution

The second stage is the benefit evaluation of the winning solution, which evaluates the comprehensive benefits of the best solution selected in the first stage. Therefore, three indicators including aerodynamic performance, noise, and fuel consumption in the evaluation index system are included in the investigation. The evaluation at this stage is based on the real test data obtained from the ground function test, strength verification and wind tunnel test of the principle prototype developed according to the winning solution. Through comparison with the benchmark model, we can know the comprehensive income of variable camber wing compared with the traditional wing.

Evaluation result shows that the aircraft with variable camber wings has reduced noise and fuel consumption and improved aerodynamic performance compared with traditional aircraft with discrete control surface wings.

4. Risk assessment of variable camber wing

Although the continuous smooth camber wing plays an important role in improving aircraft fuel efficiency and reducing noise, there are still many challenges in shifting from technical research to engineering application, due to the high complexity and difficulty of variable camber wing which covers aerodynamic analysis, structural design, new materials, drive control and other disciplines [9]. Carrying out the risk assessment of the variable camber wing is of great significance for understanding the technical status, grasping the technical risks, and supporting the decision-making.

This research carried out research on the framework of technical risk assessment models from three aspects: technical risk identification, risk rating, and risk response. And then, proposed a technical risk assessment method for variable camber wings based on technical readiness.

In terms of risk identification, it uses technology breakdown structure(TBS) traversal analysis as a means and key technology elements (CTEs) as a characterization method; in terms of risk grading, it builds a mapping relationship between technology readiness levels (TRL) and technology risk levels as a measure of technology risk Tools; in terms of risk response, it develops a technology maturity plan (TMP) as a means to promote technology maturity and reduce technology risks. Figure 7 shows the process of technology risk assessment method based on technology readiness.

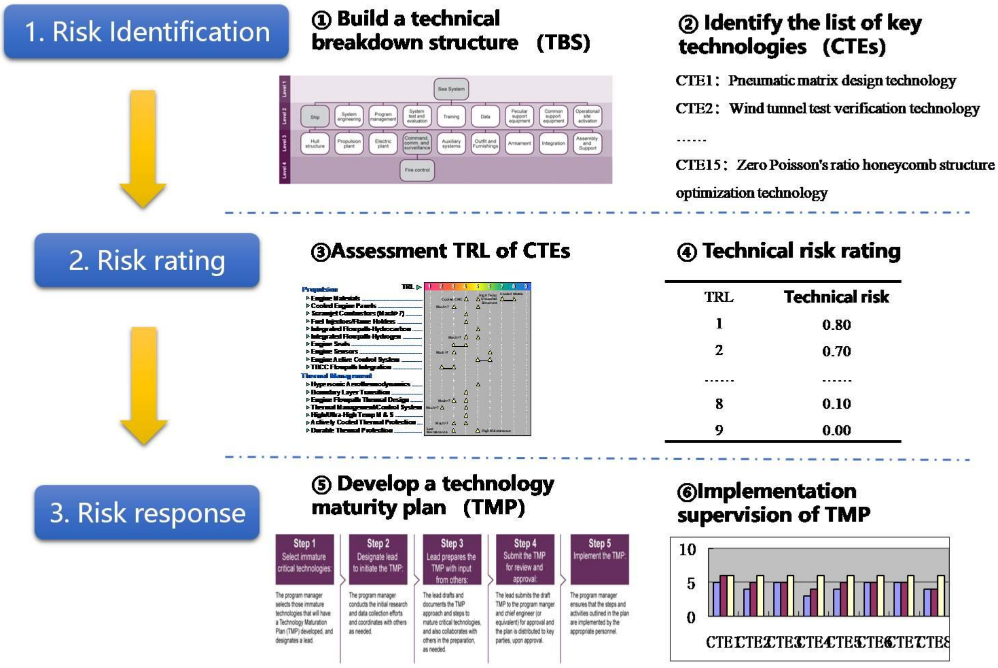

FIG. 7-Risk assessment process and method based on technology readiness

4.1 Risk identification

Taking the variable camber wing mentioned in this article as the object, a technical breakdown structure (TBS) is constructed, which is divided into 4 layers. The first layer is the variable camber wing; the second layer includes 7 items: variable camber wing aerodynamic technology, leading edge with variable thickness skin, leading edge of rigid mechanism, leading edge of flexible mechanism, rear edge of rigid-flexible coupling, rear edge of multi-section rotation, and rear edge of eccentric drive; the third layer includes 21 items: pneumatic design technology, variable stiffness composite flexible skin Technology, drive mechanism technology, drive control system development, etc; the fourth layer includes 44 items: variable bending shape parameterization technology, flexible skin material technology, variable stiffness composite skin structure optimization design technology, variable stiffness composite material manufacturing technology, etc. There are 72 technical units in total. TBS forms a technology set covering variable camber wings. Each technology unit has a clear and detailed description, including connotation scope, technology carrier, verification environment, functional performance requirements, etc.

Table 4-Technical breakdown structure of variable camber wing

level	Decomposition unit	level	Decomposition unit
1	Aerodynamic technology of variable camber wing	4.2	Leading edge flexible drive mechanism
1.1	Aerodynamic design technology	4.3	Variable camber leading edge drive-transmission and control technology
1.2	Aerodynamic analysis and verification technology	5	Rigid-flexible coupling trailing edge
1.3	Pneumatic profit evaluation technology	5.1	Rigid-flexible coupling deformation drive technology with variable camber trailing edge
2	Variable curvature leading edge based on variable stiffness	5.2	Flexible hinge technology with variable camber trailing edge

	composite skin		
2.1	Variable stiffness composite flexible skin technology	5.3	Variable camber trailing edge drive-transmission and control technology
2.2	Driving mechanism technology based on open chain mechanism	6	Multi-section turning trailing edge
2.3	Drive control system	6.1	Multi-section rotating and variable camber trailing edge structure technology
3	Rigid multi-link mechanism driven leading edge	6.2	Flexible skeleton deformation skinning technology
3.1	Leading edge skin design technology	6.3	Drive control system
3.2	Leading edge rigid multi-link deformation drive mechanism technology	7	Variable camber trailing edge based on eccentric beam/curved disc
3.3	Leading edge drive-transmission, control and test system design	7.1	Eccentric drive design technology integrating drive and load
4	Variable camber wing leading edge based on flexible mechanism	7.2	Upper and lower skin connection technology
4.1	Bending Forming Technology of Variable Section Thickness Skin	7.3	Variable camber trailing edge based on eccentric beam-substrate-zero Poisson's ratio honeycomb

TBS is a systematic review of the overall technical plan of the variable camber wing from a technical perspective. It is usually necessary to identify all the technologies that support the overall technical plan, and define the connotation and scope of each technology, as well as the logical relationship between each technology.

According to the principle of importance and novelty shown in table 5, the constructed TBS is traversed to determine whether the technology is a candidate for CTE. Only technologies that meet both importance and novelty can be judged as CTE candidates [10].

Table 5-List of questions to identify key technical elements

Classification	Question list
Novelty (Probability)	● Is this technology new (for example, next-generation technology)? ● Is the technology applied in a novel way? ● Has the technology improved? ● Is the technology expected to exceed its original design intent or proven capabilities in performance? ● Is the technology being used in a specific or different system architecture or operating environment (relative to the initial expectations or design)? ● Is the technology likely to have potential adverse effects on the system it will interface with?
Importance (Consequence)	● Does the definition of requirements for this technology contain uncertainty? ● Does technology directly affect functional requirements? ● Could the cognitive limitations of the technology have a significant impact on cost (for example, overspending) or affordability? ● Is it possible that the cognitive limitations of the technology will significantly affect the progress (for example, not ready for embedding when needed)? ● Is it possible that the cognitive limitations of the technology significantly affect performance?

Through the traversal analysis, the CTEs list of the variable camber wing is shown in Table 6.

Table 6-List of key technical elements of variable camber wing

No.	CTEs
1	Pneumatic matrix design technology
2	Wind tunnel test verification technology
3	Pneumatic profit evaluation technology
4	Optimal design technology of variable stiffness composite skin structure
5	Driving mechanism technology based on open chain mechanism
6	Leading edge rigid multi-link deformation drive mechanism technology
7	Bending Forming Technology of Variable Section Thickness Skin
8	Topology optimization technology of distributed flexible mechanism
9	Concentrated flexibility hinge technology
10	Variable camber trailing edge open chain "three-knuckle" skin drive technology
11	Flexible hinge technology with variable camber trailing edge
12	Multi-section rotating variable camber wing rib driving mechanism
13	Flexible hinge technology with variable camber trailing edge
14	Multi-agency coordinated control technology
15	Zero Poisson's ratio honeycomb structure optimization technology

4.2 Risk rating

Generally, we describe risks from two dimensions: the probability of the occurrence of the risk and the degree of impact after the occurrence of the risk, and the risk matrix is formed as shown in Figure 9 [11].

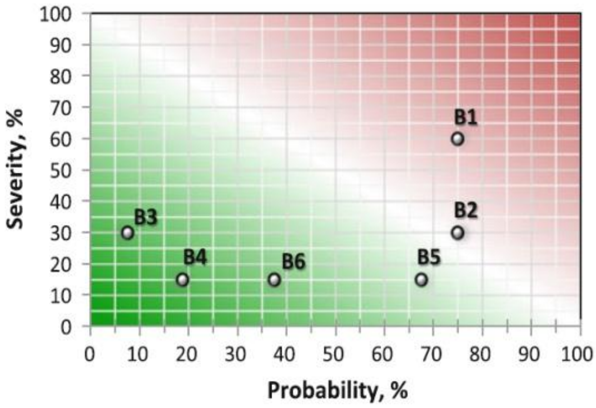

FIG. 8-The risk matrix

When determining the key technical elements, the novelty and importance of each technology are examined. Among them, novelty reflects the probability of risk occurrence. The more brand-new technology, the higher the probability of risk occurrence; the importance corresponds to the occurrence of risk. The more important the technology is for the schedule, cost, and performance of the system development, the more serious the impact after the risk occurs. The technological readiness level comprehensively reflects the state of the technology itself. The lower the technological maturity, the higher the technological risk. On the contrary, the lower the risk. The negative correlation between the technological readiness level and the technological risk level forms the risk of this article. The grading method is shown in Table 7.

Table 7-Correspondence between technology maturity level and technology risk

TRL	Technology risk
1	0.80
2	0.70
3	0.60

4	0.50
5	0.40
6	0.30
7	0.20
8	0.10
9	0.00

For the CTEs list identified in Table 5, the technology readiness evaluation criteria are used to evaluate the technology maturity level of each CTE item by item, and the technology readiness level (TRL) definition is used for preliminary judgment during the evaluation, and the detailed rules are used to determine the final level, and then the technical risk grade of each CTE is obtained according to the relationship between technical risk and technical readiness in Table 6. The technical risk level of variable camber wing is shown in Table 7.

Table 8-Technical maturity and technical risk level of variable camber wing

CTEs	Technology Readiness Level (TRL)	Technical risk level
CTE1: Pneumatic matrix design technology	3	0.60
CTE2: Wind tunnel test verification technology	4	0.50
CTE3: Pneumatic Profit Evaluation Technology	4	0.50
……	……	……
CTE15: Zero Poisson's ratio honeycomb structure optimization technology	3	0.60

4.3 Risk response

According to the current technology readiness level and target level of each CTE, use the technology maturity difficulty evaluation (AD2) [10] to clarify the scientific research activities required to upgrade the immature CTE to the desired technology readiness level, and formulate accordingly the scientific research work plan, including detailed test plans, precise costs and schedules, etc..The plan can be used for revising and refining the main project plan, to form a technology maturity plan (TMP) of key technologies.

Supervise the scientific research activities after the implementation of TMP, mainly monitoring whether various CTEs can reach the expected TRL before the specified time; whether the financial support required for the implementation of TMP is in place, especially for some newly discovered technological risks that require an appropriate increase in the development cycle and funding.

In addition, during the implementation of the TMP, it is also necessary to focus on whether the landmark work is carried out or whether the landmark results are obtained. Through the implementation of TMP, the technological maturity of immature key technologies is continuously updated, and the technological maturity is continuously promoted, thereby reducing technical risks and realizing risk supervision and response.

5. Conclusion

The smooth and continuous variable camber wing has become a current research hotspot due to its potential benefits in terms of improving aerodynamic efficiency, reducing noise and fuel consumption. As a new technology, the variable camber wing is still in the stage of program exploration and research. A variety of technical approaches have been put forward. The variable camber wing evaluation index proposed in this paper comprehensively reflects the comprehensive benefits of various variable camber wing solution in terms of function, performance, cost, etc., which is in line with the design characteristics and practical application requirements of variable camber wing, and can effectively evaluate the pros and cons of different solutions. The risk assessment method of variable camber wings based on the technological readiness provides support for the further development and application of variable camber wings, and is an important means to promote technological progress and ensure the effective use of resources.

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