Overview of surfing aircraft vortices for energy

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Abstract. Surfing Aircraft Vortices for Energy (SAVE) refers to the behavior that an aircraft "rides" on the vortex of the front aircraft just like the formation flying of migratory birds and it can also provide guidance for the aircraft that is difficult to avoid entering the front vortex, reduce the incidence of flight accidents caused by the vortex, and improve the safe operation ability of civil aviation. The technology has the advantages of saving energy and increasing range, which is a hot issue in the field of aviation research. Firstly, this paper analyzes the main research contents, technological developments and applications in the field of SAVE at home and abroad. Then discusses the key technologies of SAVE such as aerodynamic principles, control of SAVE, safety guarantee, path planning, and related experimental verification technologies. Finally, the development and application trend of SAVE technology in military and civil aviation fields and its corresponding benefits brought by it will be pointed out.

1. Introduction
Aircraft vortex, also known as wake or eddy, is an aerodynamic phenomenon formed by the interaction of the tip vortex of an aircraft and the engine tail spray, as shown in Figure 1. Among them, the wingtip vortex is the determinant of aircraft vortex characteristics, which has the characteristics of backward and downward spiral extension [1-4]. For a long time, aircraft vortex is considered to be harmful, which is mainly reflected in "reducing lift and increasing drag" and affectes flight safety.

Is vortex only harmful? Can't the huge energy produced by vortex be used? The answer is clearly no. Scientists in the aviation field have found inspiration from the close formation flight of migratory birds. Migratory birds usually fly in oblique "human" or "one" formation for a long-distance, as shown in Figure 2 and Figure 3. In the formation, the strong head birds vibrate their wings and generate strong wingtip vortex at the rear. When the birds fly on both sides, as long as one wing extends into
the outside of the wingtip vortex in front of them, which is the place with the strongest up wash air flow, the energy of the wingtip vortex in front can be utilized so as to save physical strength in long-distance flight. Henri weimerskirch *, Julien Martin * and others had proved that this flying mode can save 11.4% - 14% energy through the formation flying experiment of pelicans [5]. The technology that the rear aircraft "rides" the vortex of the front aircraft to conduct the bionic close formation flying like a migratory bird is the Surfing Aircraft Vortices for Energy (SAVE). IMECE (Institution of Mechanical Engineers) calls SAVE one of the five popular Aviation Technologies [6], which can turn waste into treasure and has the advantages of energy saving, environmental protection, economy, etc.; it can reduce the aircraft spacing and improve the utilization efficiency of airspace resources, which is the ultimate solution to the tension of current airspace resource; it can also reduce the workload of controllers and improve the safe operation ability of civil aviation.

SAVE has great application prospects in both military and civil fields, and it is a hot research direction of aviation scholars. Although a large number of scientific research results have been achieved in recent years, there are no mature application cases around the world, so there is still a great research value and application development demand for it. In this paper, the research status, key technologies, development and application trends of aircraft SAVE and its benefits are summarized.

2. Research status at home and abroad

For a long time, aircraft vortex has been considered as an important factor affecting the flight safety of the rear aircraft, so focus of its research has been placed on the judgment of vortex dissipation. Once the vortex dissipation is confirmed, it is considered that the rear aircraft can take off or land, and the rear aircraft is absolutely not allowed to enter the vortex area of the front aircraft [7]. It is obvious that the recognition of vortex can not meet the flight requirements of SAVE. NASA (National Aeronautics and Space Administration of the United States) had done a lot of researches on the theory of vortex dissipation, large-eddy simulation method, ground effect and other aspects, trying to deduce the behavior characteristics of aircraft vortex by establishing a complex mathematical model [8-9]. Crow and others of Aerovironment companies had made a lot of observations and experiments on the formation and dissipation characteristics of vortex since the late 1970s, and put forward the famous crow instability theory [10-11]. Hough and Barrows and others studied the force distribution and calculation of vortex on the wing, modified and improved the strip theory, and proposed the vortex lattice method, which can be applied to theoretical analysis and calculation [12-13]. Greene of Langley Research Center put forward the far vortex dissipation model in 1986. He believed that the strength of the wingtip vortex would gradually weaken under the joint action of viscous resistance, atmospheric buoyancy and atmospheric turbulence, and replaced the vortex dissipation rate with the turbulent kinetic energy to describe the dissipation law of the vortex [14-16]. At the beginning of this century, DLR (Deutsches Zentrum für Luft- und Raumfahrt e.V.) and ONERA (Office National D’Etudes ET DE Recherches Aerospatiales) jointly carried out the collaborative research program (C.R.P.).This research project was devoted to the study of the physical mechanism and dynamic characteristics of vortex, the development of appropriate CFD wake research methods, and the
enhancement of wake test research capability. On the basis of summarizing the research results of many scholars, "C.R.P." divides aircraft vortex into four significant stages, as shown in Figure 4, which respectively are [17]:

1) The near-field vortex field (NWF), which is very close to the trailing edge of the aircraft wing, has a flow direction range of about the order of the mean aerodynamic chord (MAC). It is characterized by a vortex shear layer composed of highly concentrated vortices starting from the trailing edge of the wing, but the rotation speed is stable for a long time after rolling up, so SAVE is performed at this stage;

2) The extended near-wake field (ENWF), generally within 10 times the wing span, is mainly characterized by the roll-up and fusion of the wingtip vortex, and finally forms a pair of counter-rotating eddy;

3) The mid-wake field (MWF), which does not exceed 100 times the wing span, and the vortex in this area starts to move downward due to mutual induction, while showing certain instability;

4) The far-wake and dispersion field (FWDF), more than 100 times the wing span, exhibits unstable characteristics and eventually dissipates due to the mutual induction of wake vortices.

![Figure 4. Diagrammatic sketch of aircraft vortex development.](image)

For the research of formation flying, most of them focus on the analytical modeling of potential flow technique. Maskew used vortex lattice method to model in 1977 [18]. Blake and others used an improved horseshoe vortex model with a viscous vortex core in 1998 [19]. In 2005, Atilla, Sriram and others proposed a more complex modeling method, which can model the motion of the wingman of the rear aircraft in close formation flight, and its basis is still the improved horseshoe vortex model [20]. Dr. Fan qiongjian of Nanjing University of Aeronautics and Astronautics also proposed a model similar to Atilla et al [21]. In 2008, Bramesfeld and Maughmer applied computational fluid dynamics to study the aerodynamic performance of wing man in formation flight, and focused on the roll up of the front wing tip vortex, which indicated that the minimum induced drag could be obtained by the wingspan length with 10% lateral overlap of wing [22-23]. Since the mid-1990s, the U.S. military has funded close formation flight research. Through numerical simulation and wind tunnel test, the feasibility conclusion, risk assessment and formation parameter optimization of close formation flight are obtained [24-30]. In 2012, the U.S. Air Force conducted C-17 SAVE test at Edwards Air Force base [31].

For control research, one of the main applications of SAVE is aerial refueling. The United States and other countries have thoroughly mastered this technology and have put it into practice and have successively demonstrated great power in the 1982 British Arab Islands War, 2003 Iraq war, 2014 US F22 night attack Isis and other military operations [32]. There are few researches on SAVE control and practice in China, but due to the urgent needs of the military field, there are more researches on aerial refueling in China. At the military parade for the 90th anniversary of the founding of the People's Republic of China in 2019, China's H-6A tanker completed the feat of precision refueling for
the J-10B, marking that China has the actual combat capability of aerial refueling technology. Aerial refueling technology is an important application of SAVE. The success of aerial refueling technology will also promote the comprehensive development and application of SAVE in China.

In general, aviation powers such as the United States have conducted long-term systematic research on the generation, flow, evolution, and dissipation of aircraft vortices and the control technology of close formation flying based on SAVE. Abundant achievements have been made in flow mechanism, evolution prediction and flight control technology.

3. Key technologies of SAVE

3.1. Theory of vortex aerodynamics
The development of science and technology is inseparable from the support of theory. In order to better study SAVE, we need to explore the theory of aerodynamics in a deeper level. The stage motion equation of vortex, the motion law of vortex core and the shape characteristics of vortex in each stage (such as the formation, development and dissipation laws) are taken as the main research contents of vortex aerodynamics theory. Up to now, the classic vortex mathematical model is horseshoe eddy model and various models improved on this basis. According to the actual development, we need to further study the development and evolution law of vortex in different meteorological conditions and the combination of front and rear engines of various models. Based on the above researches, the aerodynamic coupling model of the rear engine in the front vortex, the mathematical models of up wash and side wash in each stage are established. These models are the basics for analyzing the control ability, safety and operation ability of the rear engine in the vortex.

3.2. Safety control technology
Safety control technology is the key to the success of SAVE. It mainly studies the safety judgment methods and control strategies when the rear aircraft "rides" on the front vortex. Two methods are used to judge whether the rear aircraft is safe or not: whether the maximum rolling moment is lower than the maximum acceptable rolling moment; whether the maximum slope angle is lower than the maximum acceptable slope angle. In the future, factors such as aircraft speed, altitude, atmospheric temperature, flight status and acceptable safety factor will be gradually integrated to build accurate safety margin model as the standard to judge whether the aircraft is safe or not. However, it is almost impossible to achieve such precise operation only by the pilot in a few seconds, so it requires the aircraft's autonomous control law as the support, which is designed from three angles of pitch, roll and yaw, including command branch, feedback branch and forward branch, mainly to achieve control stability enhancement, longitudinal relaxation and static stability, flight parameter boundary restriction, automatic deviation prevention and spin prevention and other functions provide a deep level guarantee for the realization of SAVE.

3.3. Adaptive path planning
Adaptive path planning technology is the premise of the successful implementation of SAVE, which refers to the real-time autonomous navigation path planning technology of the rear aircraft. SAVE needs to be carried out in the near-field vortex, and then needs to exit the whole vortex area through the MWF and FWDF. The flow of adaptive path planning technology is shown in Figure 5, including:

1) Navigation environment modeling: Environment modeling is the first step of path planning. The purpose is to establish an environment model which is convenient for computer to use in path planning. It is based on the former 3D mathematical model of aircraft vortex, combined with the flight performance parameters of airliner, to carry out the research of navigation physical environment and path parameter mapping method.

2) Path searching: In this stage, on the basis of the navigation environment model, the corresponding algorithm is applied to find the flight paths. The flight paths should meet the corresponding search performance constraints, which meet the above safety judgment basis. Firstly,
the front vortex is divided into several space grids, and the grid is encoded with constraint value; then, the flyable path is searched by combining the improved genetic algorithm.

3) Path smoothing: There are multiple flight paths found by path searching, and further processing and smoothing are needed to find the best flight path. The basis of path smoothing is flight control characteristics and smooth constraint model. The smooth constraint condition is the minimum roll risk.

4) Iterative searching: When the airliner flies in a grid according to the optimal flight path after smoothing, the iterative planning of navigation path will be carried out in the new position, which is the iterative process of adaptive real-time path search and smoothing, so as to determine the new optimal flight path under the current environmental conditions. This is repeated until the aircraft exits the vortex area completely.

3.4. Test verification technologies
Flight simulation tests and wind tunnel experiments are important steps for the safe and successful application of SAVE. The flight simulation test is to implant vortex models under various aircraft types and environmental conditions into the simulator, so that the pilot can better summarize the operation experience and skills of SAVE, and improve precise control capabilities; Wind tunnel test is to place the simulator in the wind tunnel and simulate the situation that the rear aircraft is in different front aircraft vortex, so as to explore the degree of energy saving and drag reduction brought by the rear engine using the front aircraft vortex in theory. Brown, William, Bangash and Ayumu Inasawa and others had proved through wind tunnel experiments that the lift-drag ratio of wingman in close formation flight can be increased by more than 50%, and the induced drag can be reduced by more than 25% [33-35]; in 2002 and 2008, Hummel and Ray respectively confirmed the effect of increasing lift and reducing drag of close formation flight through actual flight experiments [36], providing a very powerful basis for the energy-saving and consumption reducing effect of SAVE.

4. Development and application trends and benefits
Only put the theory and technology into practical application, find out the shortcomings and improve it can promote the development. In 2012, NASA’s compilation report on the research results of SAVE pointed out that the economic and environmental benefits of it applied to fighter, military transport aircraft, civil cargo aircraft to civil airliner were successively enhanced [18,37-38]. The most mature application of SAVE, aerial refueling, is the first to be launched in the fighter and military fields. It can expand the combat range of military aircraft, improve combat efficiency, and promote the rapid development of national defense forces. Coming to a vast market, the close integration of SAVE and UAV freight formation will greatly improve its transportation efficiency and bring higher economic benefits; Airbus believes that in the second half of the 21st century, it will be feasible for the airliner to fly in formation like a bird on busy routes [39]. When the airliner is inevitably to enter the front aircraft vortex, the pilot will use the SAVE to conduct timely and reasonable operation, which will reduce the occurrence of accidents; SAVE, as one of the five major technologies in the future, if the airliner applies it into the ocean formation flight, it can solve the problems such as the current airspace congestion and the heavy workload of controllers, so as to improve the flight operation efficiency, ensure safety and save energy.

5. Conclusion
This paper summarizes the research status of the new technology of SAVE at home and abroad, and analyzes the key technologies needed by SAVE combined with its application in military and civil
fields. As a research hot spot in the field of aviation in recent years and even in the future, SAVE will be widely used in the fields of aerial refueling, safety control of aircraft encountering vortex, ocean close formation flight and UAV freight formation. Its successful application will be conducive to improving the safe operation capacity of civil aviation, reducing unit energy consumption, promoting economic and environmental benefits, so it has broad application prospects.

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