Review of tensairity and its applications in agricultural aviation

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Abstract: In recent years, the unmanned aerial vehicle (UAV) has undergone rapid development in field of agricultural plant protection; however, the payload and max-endurance are bottlenecks that limit its further development. Tensairity is a new structure consisting of a bag filled with low-pressure gas, an upper rigid rod and a lower flexible cable. It puts tension pressure on the whole structure through internal gas pressure, provides continuous support to the upper rigid rod, and that is to say, the tensairity improves the stability of the structure in some way. And also, tensairity is a self-supporting and self-balancing system, which means it is a simple, lightweight structure with small storage volume, strong bearing capacity, and low engineering cost. It also has the advantages of gasbag and BSS (beam string structure). The main objective of this research was to introduce the theoretical basis of tensairity and then discussed its development and applications. Moreover, the advantages and disadvantages of tensairity were summarized, and development prospects of tensairity in agricultural aviation were presented. At last, it can be concluded that tensairity has potentials in agricultural aviation. If tensairity is applied in agricultural UAVs, it will solve the two major problems of payload and max-endurance better, and help promoting the development of agricultural aviation technology in agricultural aviation administration and application. Also, it will help with meeting the aerial application requirements of high efficiency and maximal environmental protection. This research will provide a reference for improving working efficiency and economic benefits of UAVs in agricultural plant protection.

Keywords: tensairity, agricultural aviation, unmanned aerial vehicle (UAV), bionics, numerical simulation, payload
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1 Introduction

Tensairity is a new type of self-supporting, self-balancing structure system, and it has many interesting characteristics, such as a simple, lightweight structure, small storage volume, strong bearing capacity and low engineering cost, etc.[1,2] Agricultural aviation operation has the advantages of high efficiency, good quality, wide adaptability, low cost and strong ability to cope with unexpected disasters, which are more and more widely used by all sectors of society[3]. In 2014, the Central Committee of the Communist Party of China and

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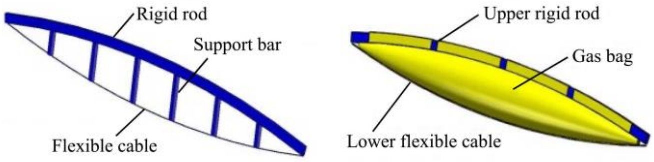
State Council made the decision to make "strengthening agricultural aviation construction" an important aim of future work in the No.1 Central Document. With the development of society and the introduction of advanced technology, aerial pesticide application technology has gradually become an important technology for enhancing the plant protection mechanization level in China[4]. According to the statistics, compared to the ground plant protection machine, the efficiency of agricultural plant protection UAVs is as high as eight times in low altitude spraying operations, the water-saving rate can reach 90% and pesticide-saving rate can reach 50% in the condition of low volume spraying[5]. Moreover, for the same operation area, the fuel consumption and power consumption of UAVs are lower than those of tractors and other agricultural machinery; and what is more, UAVs do not require a special airport and are flexible when landing in fields. Therefore, for plant protection, UAVs will be more and more widely used in agricultural plant protection.

However, due to the limitations of the current engine and battery technology, the payload of domestic agricultural plant protection UAVs is no more than 20 kg[6]. It is known that if the load is small and the max-endurance is short, there will be many times take-off and landing, which cannot meet the requirements of best operation efficiency and have a certain impact on the operation efficiency and economic benefit. The local standards of the Hunan Province "*Remote-control Plant Protection Machine in Super Low Altitude*" indicate that the capacity of plant protection UAVs should not be less than 10 L[7], which shows the demand of customers to increase the payload and max-endurance of plant protection UAVs and then improve the working efficiency. Therefore, increasing the payload and max-endurance are key technologies to further improve the rapid development of plant protection UAVs.

The main object of this paper was to introduce the theoretical basis, the development status and the applications of tensairity in China. The advantages and disadvantages of tensairity were also been summarized, in particular certain development prospects of tensairity in agricultural aviation.

2 Tensairity

The word "Tensairity" was proposed by Dr. Mauro Pedretti, an engineer of Airlight, Ltd. in 1982, it is a combination of tension, air and integrity, the word illustrates the composition and strength of the structure[8]. Compared to the traditional beam string structure (BSS) (Figure 1a), tensairity uses a bag filled with low-pressure gas to replace the support bar in the middle (Figure 1b)[9].

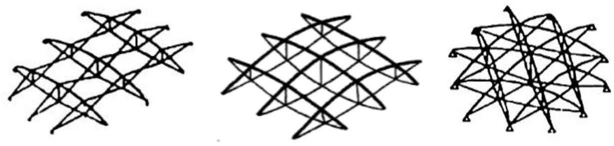


a. Traditional BSS b. Tensairity

Figure 1 Distinction between BSS and Tensairity

2.1 Beam string structure

Beam string structure (BSS) is a special type of cable arch structure that consists of an upper rigid rod, a lower flexible cable and the connection between them[10]. According to the stress and stress transmission system, BSS is divided into a plane BSS and spatial BSS; the plane BSS is divided into straight, arched and herringbone, according to the different rigid rod shapes[11]. The plane BSS is the basic unit of the space BSS, and the space BSS can be divided into one-directional BSS, two-directional BSS and multi-directional BSS[12] (Figure 2).



a. One-directional b. Two-directional c. Multi-directional

Figure 2 Space BSS

2.2 Envelope structure

The envelope structure is also an inflatable structure and has been used in many fields, e.g. tent room, hot air balloon, playground and aircraft. It is an important part of tensairity and can be made into different shapes according to the demands, such as an arch, spindle-shaped, spherical, square, and so on[13,14]. The main material of the inflatable gasbag is usually a high strength fiber fabric, which has better tensile strength and tear resistance under the condition of retaining air tightness. The tightness of the inflatable gasbag has a great influence on the safety of the structure, which can be improved by the following three aspects:

1) Using a continuous filling device, usually for inflatable structures on the ground, such as the National Aquatics Centre[15]. This is not appropriate for UAV operations in the field of agricultural aviation because the UAV will continue flies in the field, and the crop has a certain height, then the connection between UAV and the continuous filling device might receive great restraint.

2) Air tightness[16]. If the air tightness is not good, the gasbag cannot bear the force from the upper rigid rod and will have a great impact on the mechanical performance of the structure. Galliot and Luchsinger[17] pointed out that the coated fabric could be widely used in civil engineering, and PVC-coated polyester fabric could be easily folded and unfolded. Currently, PVC-coated polyester with a thickness of 0.1 mm is commonly used.

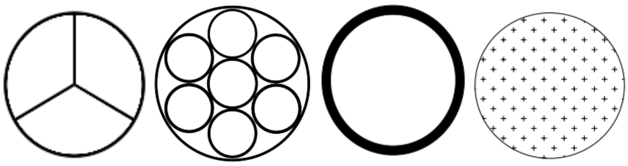


Figure 3 Different new gasbag cross-sections

3) Using a new type of inflatable gasbag[18]. The balloon in Figure 3a is divided into three space (two or more); the balloon in Figure 3b is a composite bag with new properties, as it has a physical or chemical reaction with a variety of materials, these two kinds of gasbag have been widely used in modern blimp gasbags; the gasbag in Figure 3c uses a new, high-strength fabric, the strength of which is up to 20 times higher than that of general architectural membrane materials; the interior of the gasbag in Figure 3d uses polyester foam to replace the air, improving the air tightness, and has been preliminary applied in the field of aviation and aerospace.

A simple model based on experimental observations of the yarn-parallel biaxial extension of PVC-coated polyester fabric cruciform specimens was proposed by Galliot and Luchsinger[19,20]. And as a result, compared to the standard orthotropic linear material model, in almost identical computation times, the model could significantly increase the accuracy of the finite element predictions.

2.3 Section summary

Tensairity is made up of an inflatable gasbag, an upper rigid rod and a lower flexible cable. It has the advantages of both inflatable balloon and BSS. For tensairity to be applied in the field of agricultural aviation, it requires the materials of the inflatable gasbag to obtain some characteristics, such as good air tightness, lightweight, waterproof design, and wind resistance, etc. Therefore, it is good choice to choose envelope materials filled with airship envelope materials and polyester foam to ensure the tightness of the gasbag, which, at the same time, can improve safety of the structure. The bottom chord is made of a steel wire rope, and the upper chord is made of carbon fiber tube. Carbon fiber material has the characteristics of lightweight, high strength, corrosion resistance and so on, and has been widely used in the manufacture of UAVs.

3 Researches on tensairity

3.1 Theoretical research

Based on the basic theory of tensairity, Roekens et al.[21,22] analyzed the contact stress between the gasbag and the upper and lower chord respectively, as well as the working principle of the various components, and obtained the theoretical value of cylindrical tensairity with an external load (Figure 4); Plagianakos et al.[23] conducted some compressive experiments. To estimate the potential of tensairity beams towards applications, including axial compressive loads, they made full-scale compression experiments on a simply supported spindle-shaped tensairity column. The column was subjected to axial compressive loading at various levels of internal air-pressure to quantify its effect on the structure; it was found that the axial stiffness of the column increases with air-pressure and eventually reached a balance. Displacements were measured in several positions along the span, whereas axial forces were experimentally determined via strain gauge measurements. Compared to finite element and analytical predictions, yielding good correlation for low air-pressure levels, while for higher ones, local imperfections led to significant deviations[24]. If tensairity is applied in UAVs, the pressure within the gasbag should be controlled to within a certain range until the axial stiffness of the spindle is sufficient.

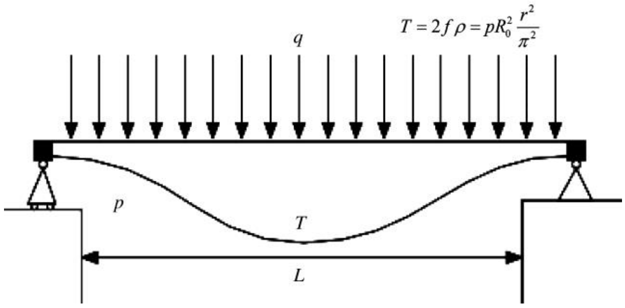
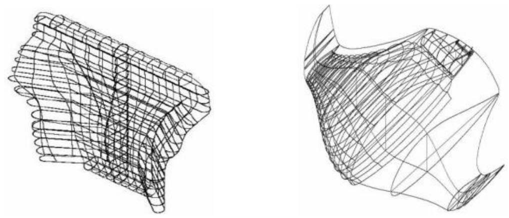


Figure 4 Force analysis of Tensairity

3.2 Numerical simulation

Pedretti established an ANSYS simulation model to realize the numerical solution of the tensairity[25]. According to the analysis results, the shape of the tensairity had an effect on static force behavior. Based on the experiments, two main conclusions could be made: one conclusion was that tensairity had obvious advantages in a large span structure compared with the traditional structure; the other one was that tensairity in different shapes had different performances, and the overall performance of the spindle-shaped was relatively the best[26]. Cao et al.[27] developed a fine model of spindle-shaped tensairity with ANSYS and analyzed the structure from the lofting state, i.e., the initial state, to the whole process of the loading state, with two concentrated loads applied in the middle of the structure span. The deformation of the whole structure and the distribution of internal forces of the structure were analyzed. Through a simulation test, he determined the effects of parameters on the mechanical behavior of the whole structure, such as the pressure, the shape and cross-section of an upper rigid rod, the stiffness of the gasbag material and so on. Moreover, he summed up the optimum range of each parameter, providing an effective theoretical basis for future research[28]. Luchsinger et al.[29,30] also developed ANSYS models for a tensairity shaped spindle and simulated the law in which the displacement of tension compression members and force change in the middle of the loaded beam.

Prospective concepts have been applied to the advanced network technology in the complex shape of inflatable structures[31]. To obtain the desired shape, the inflated volume is divided into chambers by webs. Via appropriate design of the number and form of the webs, the shape of the inflated structure can be produced. And, it is very accurate, as was proved by Stingray (Figure 5), where the maximum deviation of an inflated body was less than 1 cm from the calculated design with dimensions of more than 10 m.



a. The Inflated Back Cushion b. The Inflated Airplane Stingray

Figure 5 Complex Pneumatic Forms using Web Technology

3.3 Bionics of tensairity

Spatz et al.[32] found that the green tissue of plants was stabilized by the turgor; the cell pressure in plants was at 5-10 bar, which was remarkably high. *Equisetum giganteum* widely known by us is an example of a turgor-stabilized system, its height is approximately 3 m, and its center diameter is approximately 11.5 cm (Figure 6). Based on the experimental observations, it was shown that when the turgor pressure decreasing, the structural Young's modulus in the tangential direction of *E. giganteum* decreased, and thus the bending stiffness of the plant decreased as well. The cross section of the *E. giganteum* stem reveals that a thin outer ring of fibrous mechanical tissue (dark outer ring with wedge-shaped ridges at its inner surface) is stabilized by an inner layer of pressurized parenchymatous tissue. Pressure-induced stability has also been found in worms, starfish feet and sharks[33]. However, all biological systems use liquid as the compression medium, while tensairity uses gas as the compression medium. From the perspective of bionics, tensairity is feasible; it will improve the overall structural stiffness and strength.

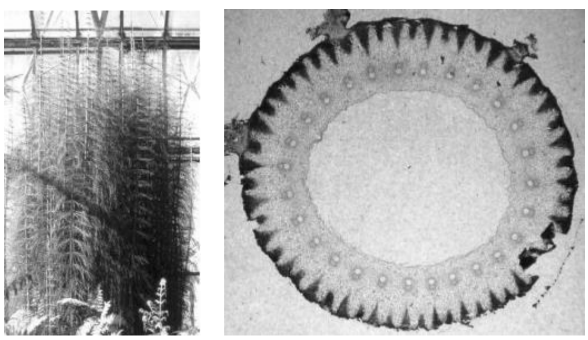


Figure 6 Turgor-Stabilized plant

Rampf et al.[34] inspired by the rapid self-sealing processes in plants and proposed a new self-repairing membrane for inflatable lightweight structures, such as rubber boats and tensairity. Thin, soft cellular polyurethane foam coating is applied on the inside of a fabric substrate, which closes any fissure if the membrane is punctured by a spike. Experimental tests were carried out using a purposefully built setup by measuring the air mass flow through a leak in a damaged membrane sample[35]. It was shown that the weight per unit area of the self-repairing foam, as well as the curing of two PU-foam components under an overpressure, influenced the repair efficiency. Curing the foam under overpressure affects the relative density and the microstructure of the foam coatings. Maximal median repair efficiencies of 0.999 were obtained at 1 bar overpressure[36]. These results suggest that the bio-inspired technique has the potential to extend the functional integrity of injured inflatable structures dramatically. The self-repair foam has good repair ability, even damages from crash events due to gas out of control can be avoided if is applied in UAVs.

3.4 Recent research development of tensairity

Wever and Plagianakos[37] addressed the effect of fabric webs inside the membrane hull on the static response of spindle-shaped tensairity columns to axial compression. Two full-scale spindle-shaped columns were fabricated and tested, one with webs and one without. The columns were subjected to axial compressive loading for various levels of internal air pressure to quantify its effect on the global structural response. It was found that the stiffness and the load bearing capacity for both columns increased with the increasing of air pressure. The experimental results also revealed the benefits of including fabric webs in the spindle configuration in terms of axial stiffness and buckling load. Luchsinger et al.[38,39] carried out some experiments to study the load carrying capacity of asymmetric tensairity and compared it with the finite element analysis. Under a uniformly distributed load, they proposed an analytical model based on the coupled double differential equations. They also proposed the stiffness action form of the tensairity through the comparison of the non-symmetric axis beam and cylindrical beam load deflectioncharacteristics.

Soo[40] conducted some researched on the relationship between the pressure and structural properties of tensairity and made a large number of samples in the experiments under different pressure conditions to prove that air tension may adjust the beam system. They formulated an effective analysis method[40]. Maurer and Konyukhov[41] conducted finite element analysis with multi-chamber tensairity full of liquid or gas. The test results showed that compared to the beam filled with gas, the stiffness of a multi-room filled with liquid was better. Galliot et al.[42,43] proposed two new designs for spindle-shaped tensairity girders with a reinforced coupling between the chords. The first one used a continuous coated-fabric web and the second one used a discrete reinforcement composed of 23 steel wire ropes to facilitate the load transfer between the chords. Both girders were studied experimentally and numerically and were compared to the original design. The results showed that the behavior of the tensairity girders was significantly improved by the integration of reinforcement for all tested load configurations. Under homogeneous distributed load at 25 kPa, the coupling increases the stiffness and the ultimate load.

In 2013, the load-bearing behavior of a symmetric spindle-shaped tensairity girder with a 5 m span and thin chords was studied experimentally, numerically, and analytically by Luchsinger[44]. The influence of the air pressure on the load-deflection behavior was investigated for a homogeneous distributed load, asymmetric distributed load, and central local load. A M-shaped deflection with two maxima at approximately one-quarter and three-quarters of the span was obtained for homogeneous distributed loads whose distributions were not linearly dependent on the applied load. The slope of the load-deflection curve, as well as the maximal load increases with increasing air pressure, demonstrated the stabilizing role of the inflated hull.

3.5 Section summary

Tensairity has many characteristics, such as a simple, lightweight, small storage volume, strong bearing capacity, and low engineering cost. It has great development prospects if applied to UAVs. However, in practice, there are many problems to be solved. Luchsinger et al. provided a theoretical basis and reference for its application in UAVs in many ways, such as mechanics analysis, numerical simulation and research on bionics. For example, most tensairity are used in large span objects listed above, it is imperative to adjust its parameters for its application in UAVs. Moreover, Cao summarized the optimal range of each parameter by conducting simulation research on tensairity and provided a valid theoretical basis for future research. If the new self-repairing film presented by Rampf et al.[34] applied in UAVs as capsule materials, it can avoid the plane from getting out of control due to the breakage of air bag and even can avoid air crash and other events. Therefore, it can improve tensairity based on the theoretical basics of our predecessors and apply it to UAVs, on one hand, to reduce the weight of the body, and on the other hand, to increase the burden quantity of the aircraft. Moreover, it can improve the work efficiency and promote development of agricultural plant protection UAV.

Tensairity is feasible in theory test and also has certain structural advantages. However, we may face a large number of problems to solve in actual applications. In this paper, we introduced the application situation of tensairity in aviation and architectural engineering, as well as in other aspects, and clarified its advantages.

4 Applications of tensairity

4.1 Application of tensairity in architectural engineering

In 2003, the first patent of tensairity was applied in the field of civil engineering[45]. The bridge span was 8 m and the maximum carrying capacity was up to 3.5 t (Figure 7)[46,47].

Figure 7 Tensairity footbridge with 8 m span

In 2003, during the Bridge Design Competition in London Leamouth, someone presented the idea of applying elongated tensairity to a pedestrian bridge and made it a translucent form (Figure 8)[48,49]. In 2004, the world's first tensairity parking lot was built in Montreux, Swiss (Figure 9)[50]. The parking lot is composed of 12 tensairity; the biggest span is 28 m and the construction area of the parking lot is 1700 m^2.

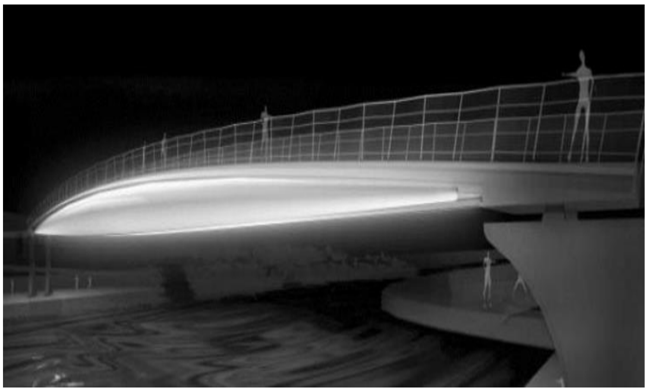


Figure 8 Tensairity footbridge with 72 m span

Figure 9 Swiss parking lot

In 2005, the “Skier” bridge was built in French Alps (Figure 10)[51]. The bridge span is 52 m. Two tensairity were put side-by-side, one with rigid wood material and the other with steel strands. According to the test results and calculation, the ratio maximum load and its own bearing weight reached as high as 10. The project reflected that the tensairity had good application prospects in large span and heavy load structures[52].

Figure 10 French Alps “Skier” bridge

Crettol et al.[53] studied the structural behavior of a tensairity arch with 10 m span for temporary tent structures. Results show that the arch could sustain a homogeneous load of 35 kN (Figure 11).

Figure11 Tensairity-Arch

4.2 Application of tensairity in aircraft

In May 1998, the Prospective Concepts company made public their manned pneumatic aircraft Stingray and Pneuwing[31]. Stingray was a successful demonstration of new forms and possibilities of pneumatic structures. A wing span of 13 m and a length of 9.4 m made it an area of 70 m^2, and its total volume is 68 m^3, including gas (Figure 12).

Figure 12 Inflated airplane stingray

Stingray is a hybrid of an aircraft and an airship. This flying wing could take off at a speed of 47 km/h and reach a maximum speed of 130 km/h with its two 47 kW engines. The maximal take-off weight was 840 kg, of which the membrane made up 80 kg. The overpressure in the membrane varied between 20-50 mbar, with higher pressure in the outer and thinner part of the wing. The pressure was maintained by two 80 w fans (The airship was a few mbar, and the tires had high pressure of more than 2 bar).

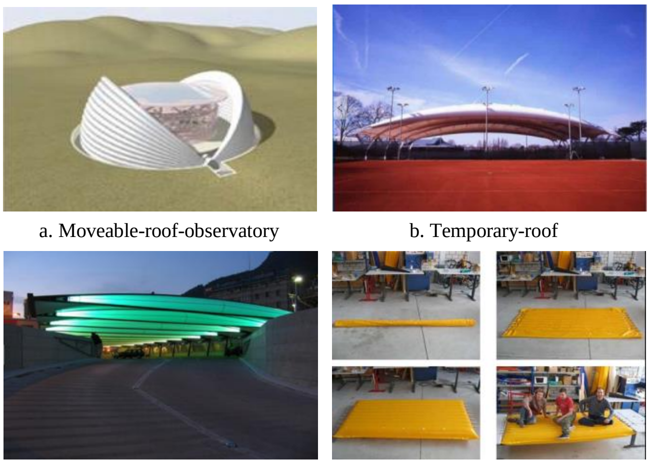
The airplane Pneuwing has a pneumatic wing and a conventional metal fuselage (Figure 13)[54]. Compared to the stingray, it requires an overpressure of 700 mbar to maintain stability because its aspect ratio is much higher and the thickness of the wing has reduced considerably. As discussed, a high slender inflatable beam requires higher pressure to maintain stability. In other words, the quality of membrane material needs to be improved and the cost increases. Therefore, the application of slender air-supported structures such as beams in agricultural aviation is somewhat limited[55].

Figure 13 Inflated Wing Pneuwing

In 2014, Suñol et al.[56,57] attempted to apply tensairity to a large lighter-than-air (LTA) airship. Large volumes imply high loads, and, lightweight is a major requirement for this type of vehicle. The justification of the feasibility of applying tensairity components in airships is discussed based on two criteria: One is the justification of the need of a lightweight structure and studying the principal characteristics of the existing types of LTA vehicle structures; the other one is a preliminary technical analysis, which aims to clarify whether the load bearing behavior of airships is suited for the application of tensairity concept. Moreover, airships have to withstand high bending moments; and tensairity structures are appropriate for withstanding such loads. Of course, more researches, designs, tests, analysis and optimizations are needed to design an airship with tensairity[58].

4.3 Other applications of tensairity

Tensairity has been applied in Various fields temporarily or permanently[59]. For example, the moveable roof observatory in Figure 14a, the temporary roof in Figure 14b, the permanent roof Montreux in Figure 14c, and the tensairity mattress in Figure 14d.



a. Moveable-roof-observatory b. Temporary-roof

c. Permant-roof-montreux d. Tensairity-mattress

Figure 14 Applications of Tensairity

Luchsinger and Braeker[60] inspired by pressure driven locomotion in nature, and presented a novel pneumatic actuator concept. Based on the principle of tensairity, the actuator consists of a conical inflated hull and a compression and a tension element that are tightly connected to the hull. The flexible compression and tension elements are stabilized by internal air pressure. Acting against gravity, a first proof of concept demonstrator weighing only 300 g was able to lift a weight of 25 N (2551 g) and a distance of almost 70 cm with an internal air pressure of only 20 kPa. The efficiency of the actuator was studied and optimized. Possible applications of the new actuator concept are seen in locomotion (Figure 15).

Figure 15 Tensairity-Actuator

In 2010, the concept of web-tensairity was further developed into curved girders to build wings with dihedral, sweep and twist by Breuer et al.[61]. A comparison between a curved and a straight web-tensairity girder proved that with the same dimensions and internal pressure, their load deflection behavior was very similar and superior to a curved and straight air-beam. After many flight tests and optimizations, a kite proto-type with a span of almost 8 m and a projected area of 11 m^2, which could fly stably along a single line, was established (Figure 16).

Figure 16 A tensairity kite in testing

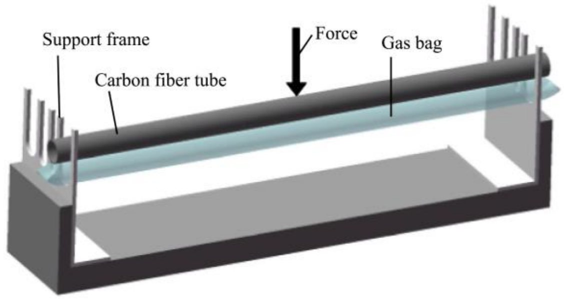
The tensairity kite performed better than commercially available kite. It is expected that there is still a large potential to further enhance the performance of the tensairity kite via an improved tailoring of the wing, including its aerodynamic and structural performance, light quality, impact resistance, small storage capacity, etc. This is not only meaningful for kite applications but also has far-reaching significance for UAVs, glider planes and ultra-light UAVs[62].

Maffei et al.[63] proposed to consider the advantages of the use of an innovative structure, such as the concept of tensairity. At the same time, they looked for new materials, techniques and methods, combined with their technology and methods to innovate the new lightweight structure and apply them in natural disasters and other emergencies. And De Leat et al.[64] also studied about the behavior of inflatable and tensairity arches.

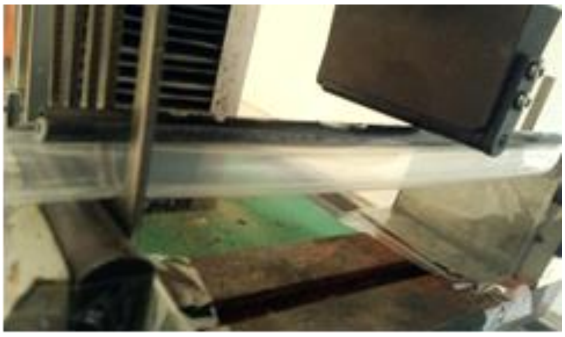
4.4 Preliminary test of tensairity used for spraying UAV

Based on the development status of tensairity in domestic currently[65,66]. The students of South China Agricultural University simulated the shape of tensairity, pasted an appropriate size of the gasbag with carbon fiber tube, and made three point bending test with universal testing machine in school. Under the same experimental condition, mechanical contrast tests were also made. One is the carbon fiber tube and the other is carbon fiber tube with a gasbag, same force, same speed, and put pressure on the midpoint. At the same time, the specimen deformation and stress were input into a computer with the form of curve, and compared with the data. In order to ensure the reliability of the data, selecting three specifications of the carbon fiber tube to do the test, 18 mm×16 mm, 16 mm×14 mm, and

12 mm×10 mm, and all of which, thickness is 1 mm, length is 400 mm. The length of inflatable bag is 450 mm, diameter is 20 mm, and the gasbag was inflated with helium (Figure17).



a. Schematic diagram of the test device



b. Test scenario for the designed tensairity

Figure 17 Test of tensairity used for spraying UAV

Take 18 mm×16 mm carbon fiber tube experiments as an example, the experimental curves are shown in Figure 18.

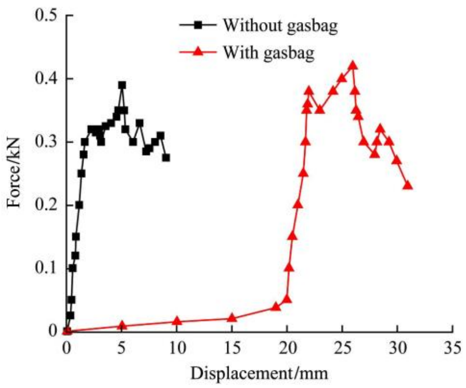


Figure 18 Comparison of experimental results

Through the analysis of experimental data, the following conclusions can be drawn:

(1) Compared to the ordinary carbon fiber tube, the maximum load of carbon fiber tube with a gasbag is larger (0.42 kN, 0.39 kN).

(2) Compared to the ordinary carbon fiber tube, when reaches the limit state, the structure with a gasbag can prolong the time of destruction, and mitigate the damage in some degree (152 s, 31 s).

5 Summary and prospect of tensairiry

5.1 Advantages of tensairity

Tensairity is combined with an inflatable gasbag structure and BSS; thus, it owns the advantages of the above two structures, and have been applied to planes or unmanned aircraft wings several times. Moreover, it also has many advantages, such as a lightweight design, small volume, easy installation, and applicability to large span structures.

(1) Compared with BSS, tensairity replaces the support rod with a balloon, improves the stability of the structure and increases the material utilization rate. At the same time, because the gas is very light, it can also reduce the weight of the structure to a great extent[67].

(2) Compared with traditional inflatable bags, tensairity adds an inflatable rigid and flexible bottom chord to inflatable balloon gasbags. Then, the inflatable bags can reach the same bearing under smaller internal pressure than that for BSS[68]. In other words, for the same slenderness ratio and bearing capacity, the air pressure in tensairity is 1/10-1/100 of the pressure in traditional inflated beams, reducing the requirements of the material performance of building inflatable gasbag membranes; thus, the cost of the structure is reduced[69].

(3) Tensairity is a type of self-supporting and self-balancing system, compared with other structures, it requires lower boundary constraints. Horizontal thrust of the upper rigid rod is borne by its flexible component, while the vertical force is the main form in the boundary constraint; both supports only withstand the vertical force, thus making design and production convenient.

(4) Tensairity can be designed with different shapes according to the demands, such as spindle-shaped, cylindrical shell, arch, etc., and it can achieve a variety of functions of the building and meet the requirements of aesthetics[70].

(5) Tensairity also has many advantages of inflatable structures, which is very convenient in production, transportation, construction and other aspects. The foldable tensairity can be made in future research (Figure 19). Moreover, tensairity has been applied to planes and unmanned aircraft wings several times and is suitable for agricultural aviation application[71].

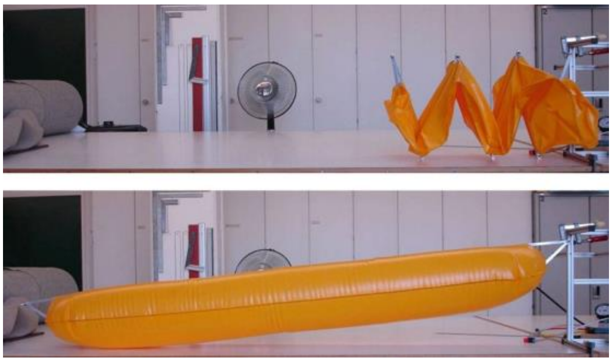


Figure 19 Foldable tensairity

5.2 Existing problems of tensairity in agricultural aviation

(1) Wind resistance

The weight of a plane is decreased if tensairity is applied, and the volume will increase slightly due to the gasbag; thus, the efficiency may be affected by the wind direction and wind speed in operation. Therefore, it will be one of the urgent problems in agriculture to improve the wind resistance performance and ensure the flight stability as much as possible.

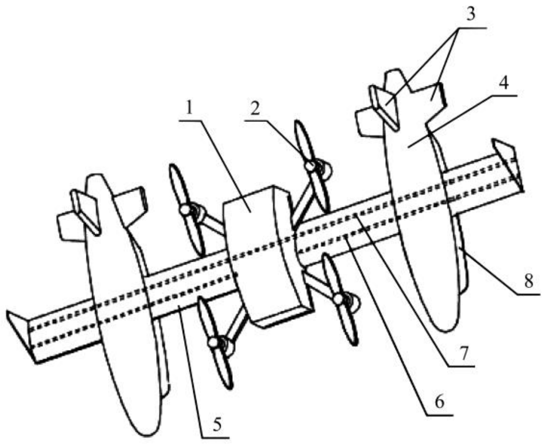
(2) Helium extraction and resource recycling

Tensairity is usually filled with hydrogen and helium to achieve lift in the application of agricultural aviation. At present, helium is mainly used because hydrogen is flammable with poor security. In practical application, it is imperative to compress the air to facilitate the lifting; however, helium extraction is difficult and costly. Therefore, how to recycle compressed helium in the bag is another problem in agricultural aviation for tensairity.

5.3 Consideration of tensairity applications in agricultural aviation

Compared to the traditional ground spraying and manned aircraft spraying, the UAV spraying has unique advantages[72], such as low altitude, flexible movement, 100% over target, no pilot at risk, accessing regardless of ground condition, zero soil compaction, and taking off and landing on the fields do not need special airports. However, there is no choice but to use high concentration and low volume pesticides in UAV spraying due to the limitation of payload and the max-endurance. The droplet size is relatively small and it will easily drift by natural wind before the droplet falling into the crop canopy. This phenomenon affects the effect of plant protection operation[73,74].

According to the advantages of tensairity and its application in aviation, a spraying UAV was proposed. Imagine that two gasbags are arranged on both sides of the spraying UAV airframe. During aircraft landing, the gasbags can act as landing gear (Figure 20). It also plays the role as a buffer and reduces the damages to UAV when a crash occurs. If the aircraft falls into the water accidentally, protected by gasbag, it can float on the water's surface. This will avoid damages from sinking into the water, and then improving the safety performance of the UAV. Moreover, the gasbag can prevent crosswind and reduce droplet drift to a certain extent, allowing for precise control of the deposition location and amount of droplet deposition.



Note: 1. UAV airframe 2. Rotor wing 3. Tailplane 4. Gasbag 5. Wing 6. The first connecting beam rotor wing 7. The second connecting beam rotor wing 8. Hump

Figure 20 A tensairity spraying UAV with functions of anti-crash and anti-droplet-drift

In addition, it also provides some additional lift when using a lighter than air gas, such as helium. Thereby, tensairity increases the ratio of the maximum load of the overall structure and the quality of spraying, as well as increases the lift time, to further improve the work efficiency[75,76].

6 Conclusions

Tensairity is an innovative inflatable membrane expansion structure, created by the addition of an upper rigid rod and a lower flexible cable; it improves the structure bearing capacity greatly, reduces the air pressure effectively to better solve the contradictions among the inflatable structure design of inflation pressure, strength of materials and bearing force, and opens up a new direction for the application of inflatable structures. This paper summarized the advantages and disadvantages of tensairity, showed its development potential, introduced the force mechanism and performance characteristics, and through the analysis of tensairity in the research progress and application situation, analyzed the feasibility and prospects in agricultural application of aviation and provided a certain reference to develop operation efficiency and better economic benefit of plant protection UAVs.

Researches should focus on the following aspects in the future:

(1) According to the curve of airship, yacht, and the biological of swordfish, shark and other bionics, four kinds of gasbags with different curves will be designed for the future research.

(2) Choose suitable materials, and make simulation and optimization with software “ANSYS”.

(3) Split, make patterns and make the four kinds of target models with software developed by Vsang Information Technology Co., Ltd.

(4) Make the gasbag with high frequency welding machine.

(5) Make wind tunnel test to measure the resistance of these three models and optimize the best appearance.

(6) According to the proportion, make an appropriate gasbag applied on the UAVs, and conduct field experiments to make contrast with the tradition UAVs.

(7) Consolidate test data and provide a reference for the future development of agricultural aviation.

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