Space tether technology and its application to air borne wind energy generation *

By

Hironori A. FUJII[1], Masahito HIRAKAWA[2], Mitsuyosi Tuchiya[2] and Kenji UCHIYAMA[2]

1. TMIT Research Center, 2-27-13, Asakusa, Taitoh, Tokyo 111-0032, JAPAN,
   e-mail: tmit@pa2.so-net.ne.jp, web: http://www013.upp.so-net.ne.jp/tmit/
2. Nihon University, College of Science and Technology, Department of Aerospace Engineering, JAPAN,
   e-mail: csms13106@g.nihon-u.ac.jp(Hirakawa),

Abstract

Tether technology is briefly introduced on space tether deployment. Two kinds of tether, thin tether and tape tether, are reviewed on their deployment mechanisms for the projects of YES2 (Young Engineers Satellite 2) and T-Rex (Tether Rocket experiment), and also deployment/retrieval mechanism of TSS (Tether Satellite System). Applications of tether technology are also introduced for airborne wind energy generation. Recent advances of the airborne wind energy generation are overviewed and classified for the schemes. Recent progress of a Japanese group on study of HSWG (High Sky Wind energy Generation) is introduced for both of the non-cross wind type and cross wind type. Tether technology has many advantages and also many disadvantages. This paper introduces as examples of application of tether technology with advantageous features as light in weight, strong against tension, compact and autonomous and avoiding its disadvantageous features as broken hazardous, slackness, and non-resistant to compression. This paper reports a study on the transfer of energy in a tethered airborne system as proposed by the Japanese high sky air borne study members.

宇宙テザー技術とその風力発電への応用

藤井裕矩 (TMIT 研究開発部)**,** 平川 雅人, 土屋光慶, 内山 賢治(日本大学理工学部)

概要

宇宙テザー技術としてテープ型テザーとひも型テザーの宇宙伸展にかかわるメカニズムを、合わせてひも型伸展・回収制御メカニズムの例を紹介する。また、最近の高空風力発電の動向をまとめ、さらに我が国のテザー技術を応用した高空の風を利用する風力発電手法として、定常飛行型と非定常飛行型の研究の紹介を行う.

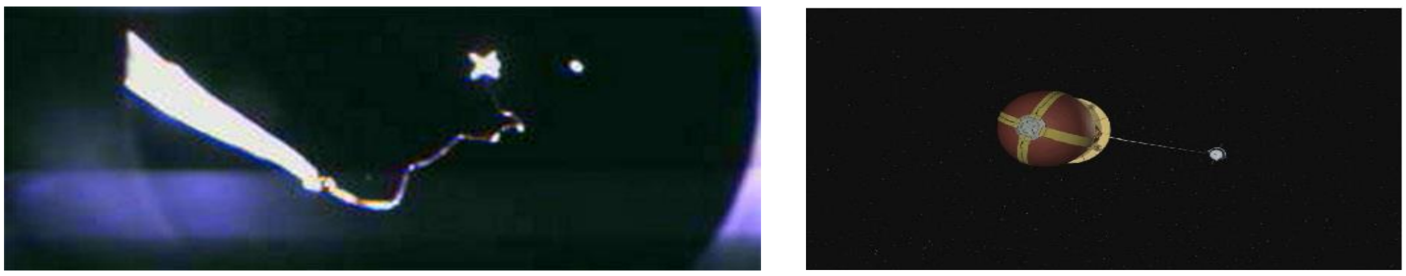


Fig.1 Tether deployed in space [left: tape tether (T-Rex), right: thin tether (YESII)]

1. Introduction

Tether technology is one of the advanced space technologies such as the inflatable technology[1)-5)]. Tether is useful for construction of space structures since of its light weight in long structures, compactness in fold, high strength in tension, and in particular needs little effort of human work.

Tether can be divided into two types, one thin round cross-section tether and the other thin-tape (flat) tether. Project YES2 (Young Engineers Satellite 2) has deployed successfully thin tether for the length 31.7km in space in 2007[6),7)]. Tape tether has difficulty in space deployment, i.e., autonomous deployment, but project T-Rex (Tether Rocket experiment) has successfully deployed bare electodynamic tape tether for the length 132.6m in space in 2010[8)]. Both projects are the world records in space deployment of thin and tape tethers and thin tether deployed for 31.7km is known as the longest space structure ever man made in space.

The bare electrodynamic tape tether is called “super tether” because it is enhanced small debris survival against hits by abundant[9)] and it is also “a bare electric tether” several times superior in the electrodynamic performance[10)] in comparison with the round-cross-section of same section area. The super tether is expected to be employed in such future space mission as debris mitigation plan, BETS project in ESA[11)-15)], and in NASA[1)] and also tape tethered space elevator[16)]. Space tether technology is now in progress for the application to future mission plans including debris mitigation and space structure construction.

While these space tether projects, some members of space tethers also are studying air borne wind energy generation to apply their experiences in space tether projects. Recent airborne wind energy generation employs tether technology to bring mechanical

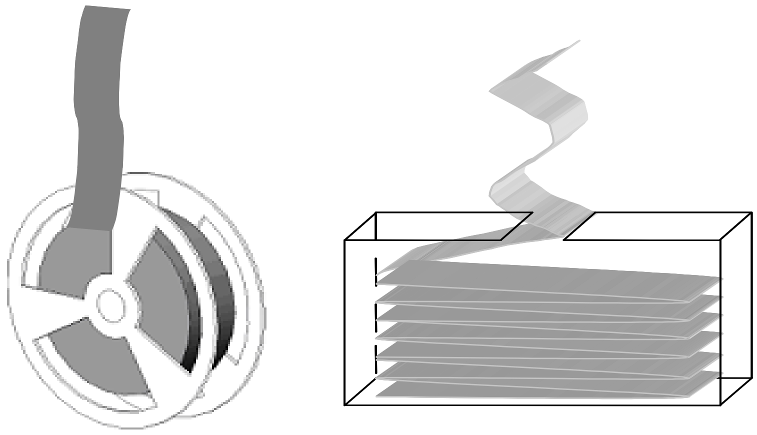


Fig.2 a reel system (left) and Inverse Origami method (right)

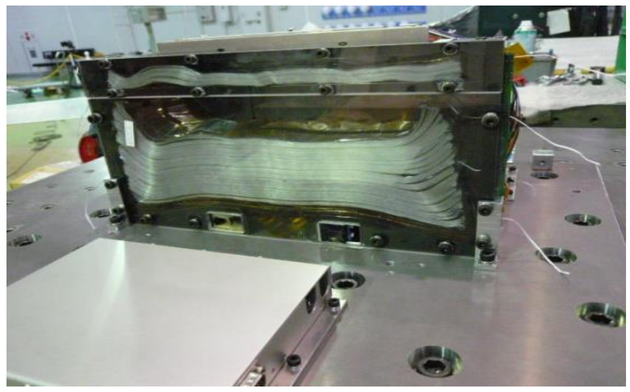


Fig.3 T-Rex tape tether box

or electric energy obtained in high sky to the ground[17]. This paper is devoted to report the deployment mechanism of space tether and the recent advances in air borne wind energy generation.

2. Tether deployment system in space (Project YES2, T-Rex and TSS)

Even widely used in our life on the earth not only in space, tether is generally wounded around reel and deployed along the rotation of the reel due to pulling force on tether. The reel system is very sensitive to the adjustment of the tether deployment speed with the rotation speed of a dram (Fig.2 left). Tether may be severed if the tether deployment speed exceeds the reel rotation speed and on the other hand tether may be jammed if the reel rotation speed exceeds the tether deployment speed. This difficulty of the tether deployment is possible to cause the failure of space tether deployment[18].

Tape tether employed in T-Rex project is folded in a box through Z-holding system, or the Inverse Origami method (Fig.2 right). The tether deployment speed is controlled passively by the friction force at the exit of the tether box (Fig.3). The dram reel type deployment requires precise control of tether tension with respect to the angular momentum of the reel dram. The inverse ORIGAMI method has no rotating element and so no significant phenomena as slackness of tether invoked by the difference in the speed of reel dram rotation and tether deployment. The method has high reliability characteristics for deployment. Precise estimation of the tether deployment phenomena is however necessary in order to deploy tether for a prescribed length in deployment. Thin tether employed in YES" project is wounded in a canister and deployed along the radical direction without rotating the roll (Fig.4). The deployment of tether is controlled passively with employment of the barber pole brake system. It should be noted that the both successful space tether deployment systems are autonomous passively controlled systems.

The TSS project (Tethered Satellite System) is processed by human operation and was controlled actively employing the control system and level winder (Fig.5) [19]. The control was not only the tether deployment as were in YES2 and T-Rex but also the retrieval of tether using the level winder. The TSS project had conducted two space experiments but could not obtain results satisfactory including the loss of the tethered satellite in space. The reason of the difficulty includes very low tension of space tether and it may be necessary to employ a new kind of tether tension sensor[20] and very delicate roller system for the deployment/retrieval of space tether.

Fig4. YES2 tether deployer

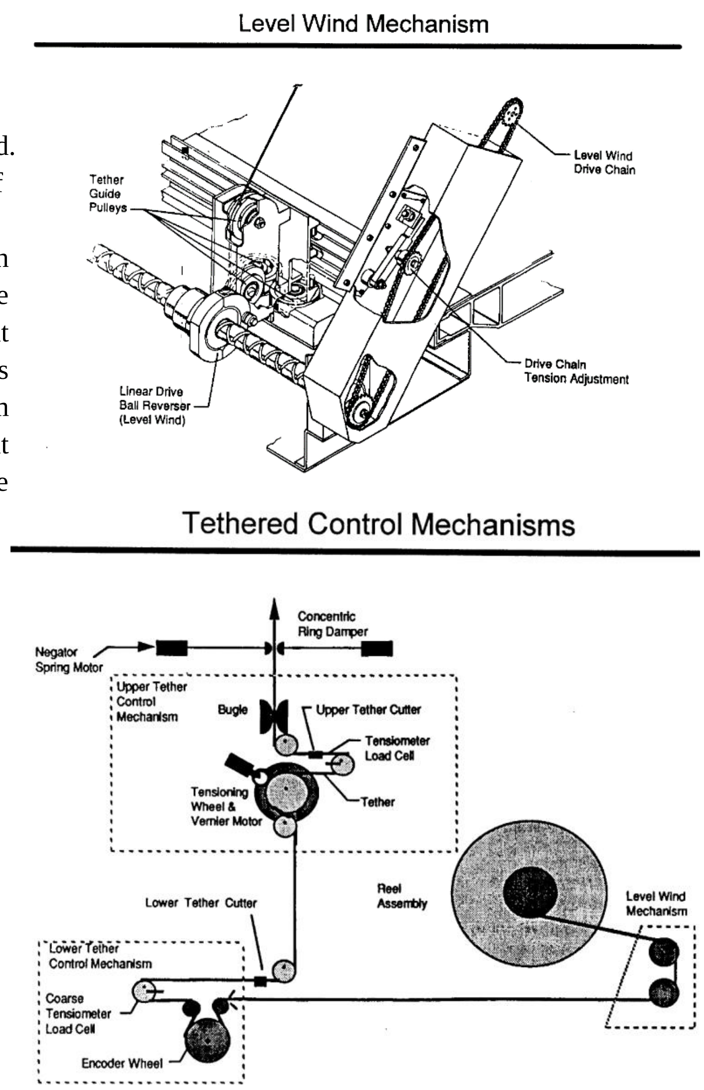
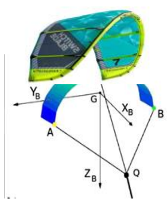


Fig.5 Tether control mechanics (above) and level wind mechanism (below) employed in TSS project

3. <u>Air borne Wind Power Generation</u>

It is necessary for any windmill is to place it at the place where wind blows strong and steady. Japanese members for study on "High Wind Energy Generation" are now working on an air born wind energy generation technology to utilize wind power over the boundary layer of the ground, or canopy. Tether technology is applied to place a windmill at the high sky and transfer energy obtained in the high sky to the ground. The air borne wind generation technology in the world has been developed actively from the era 2000[17]. Examples are shown in Table 1 and include 1) Airship type to buoyant windmill employing Helium gas (Altaeras, for an example), 2) Kite type to fly by kite (Enerkite Project, for an example), 3) Glider type to fly a glider in eight figure (Ampyx Power, for an example), and 4) Aircraft type to fly in circle a propeller aircraft (Makani Power, for an example).

Table 1 Examples of airborne wind energy generation schemes

	１． Tethered kite (HSWG, Japan)[21] Wind energy at high altitude (constant but changeable) is transferred effectively to the ground through a tether system. A windmill on a kite employs the straight wind turbine which utilizes wind energy along the full span of the blades in comparison with the propeller type. Heavy generator is placed on the ground to reduce the mass of the kite. Flight of the kite is steady level flight and the flight control is simple.
	２． Tethered glider (Ampyx Power: Netherland, DUT) A glider tethered to a generator on the ground is used as an element of the windmill blade and the airspeed is enhanced through eight figure flight. The cable has high tension and the strength is necessary. The electricity is obtained intermittently and records 10kW for 10 hours in two days. The 5.5 m prototypes serve to demonstrate the principle of a fully automatic operation (power generation →land→launch→power generation), as well as to raise technology readiness level for the certifiable commercial system prototype AP-3 (200 kW) and the to-be certified commercial version AP-4 (2 MW) concept.
	３． Balloon (Altaeros：USA, MIT） The Altaeros Buoyant Airborne Turbine holds the potential to deliver cheap renewable energy to rural, island, and offshore sites that face high electricity costs. Founded in 2010 by MIT and Harvard alumni with a background in aerospace, energy, and industrial gases, Altaeros launched its first functional prototype in 2012 and is now working to develop the first commercial scale one. Altaeros Energies, located in Somerville, MA, is a founding member of Greentown Labs, the largest cleantech focused incubator in the United States. Altaeros closed a US$7 Million Series A investment from SoftBank Corporation in November, 2014.
	４． Paraglider (Enerkite: Europe, Germany) The first prototype of an EK200 unit with 100 kW is supposed to be brought to pilot operation. For the generation of an adequate basis for permissions EnerKite is on the course of standardization of the risk assessment and performance estimation. Theoretical models will be validated by use of the results of the 30 kW demonstrator platform, which soon will be fitted with the first system for autonomous launch and landing of semi-rigid wings.
	５． Surf Kite (Universidad Carlos III de Madrid: Spain） Kites can produce electrical energy by implementing a "yo-yo" maneuver, which is based on a periodic cycle made up of two phases. During the reel-out phase, the strong traction force in the tether of the kite, generated by the kite flying in a crosswind maneuver, is used to produce electrical energy by spinning a generator at ground. The tether is winched in, and the kite flies back during the reel-in phase. A simulator of the power kite, which includes bridle and tether control, is constructed to find optimal control laws to maximize the generated power and the stability of the kite.
	６． Unmanned aircraft (Makani Power: USA) An energy kite (600 kW energy kite, present 20kW) comprises a high aspect ratio carbon fiber wing with eight onboard rotors, each of which is used both for generation and for launching and landing. Power is transmitted to and from the ground through a carbon fiber electromechanical tether, and enters the electrical grid through a perch and ground station that the kite rests on when not operating. Because of the robust, predictable nature of this architecture, the model will be able to operate fully autonomously with a small land footprint. Acquired by Google in 2013,

There now are a lot of schemes for the application in the world and can be summarized as shown in Appendix1. The schemes are divided into a) non-cross wind and b) cross wind. The non-cross wind scheme is to place a windmill just on high sky and the windmill in a steady state in high sky. On the other hand, in the cross wind scheme the windmill flies in high sky through such closed trajectories as a circle or an eight-figure in order to enhance the wind velocity more than the steady wind velocity. Then the windmill of the cross-wind scheme is in non-steady state in high sky. The cross-wind type is supposed to be able to attain high electric power as megawatts and now prevails in almost of the airborne wind energy generation teams. The schemes are also classified into “fly-gen” to equip a generator on the flying windmill and “ground-gen” to place a generator on the ground. The fly-gen transfers electric energy obtained in high sky through electrodynamic tether to the ground. The ground-gen transfers kinetic energy obtained in high sky to the generator placed on the ground through no-electrodynamic tether and the electric power is obtained on the ground.

It is necessary to 1) place the windmill stable on the high sky, and 2) transfer the energy obtained by the windmill to the ground without loss. This air borne wind energy generation is able to apply such high-performance technologies as light-weight, small-size, low cost, and automation which have advanced radically in every field in accordance with the development in IT (Information Technology).

Two kinds of airborne wind energy generation systems are introduced in the following sections.

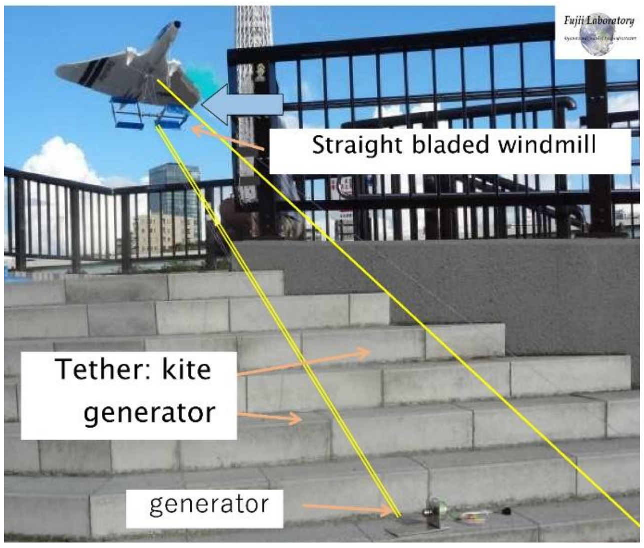


Fig.6 Concept sketch of tethered system (HSWGJapan)

3.1 Tethered airborne wind energy generation: Non-cross wind system

Figure 6 shows the concept of a tethered airborne system of Japanese group HSWG (High Sky Wind power Generation)[21]. A straight blade windmill is supported in its rotation axis horizontally under a kite and connected through tether to a generator placed on the ground. Employment of the straight blade windmill affords the present system much effective aerodynamic characteristics over the straight blade and low noise characteristics. Wind energy at high altitude (constant but changeable) is transferred effectively to the ground through a tether system. A windmill on a kite employs the straight wind turbine which utilizes wind energy along the full span of the blades in comparison with the propeller type. Heavy generator is placed on the ground to reduce the mass of the kite. Flight of the kite is steady level flight and the flight control is simple.

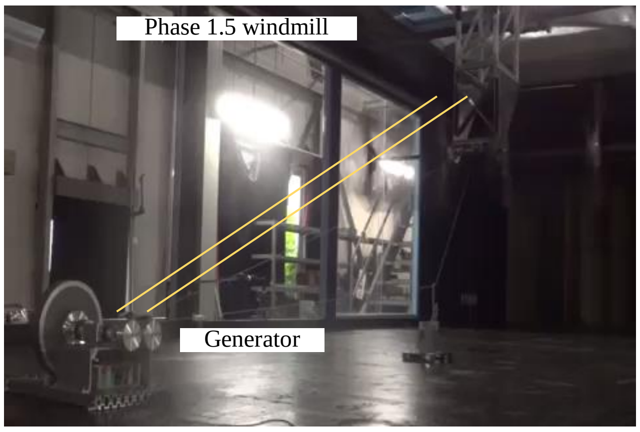


Fig.7 Tethered system of phase 1.5 set up (HSWGJapan)

The concept is demonstrated for phase 1.5 (0.2kW class) in the 3.6m×2m boundary layer wind tunnel of Kyusyu University. It is concluded by the experimental study that the flexibility of tether has much influence on the performance of the electricity generation.

The efficiency of energy transfer through tether is proven to be high[22], however, energy loss exists at the pulleys of windmill axis and also of the generator axis. The design at the pulleys is revised to increase friction coefficient at the pulley by increase of the contact length of tether around the pulley. Energy translation through tether affect critically on the power generation and tether tension control is critical technology. The tether technology developed for space tether will be employed for the present system in order to control precisely small tension of tether[20].

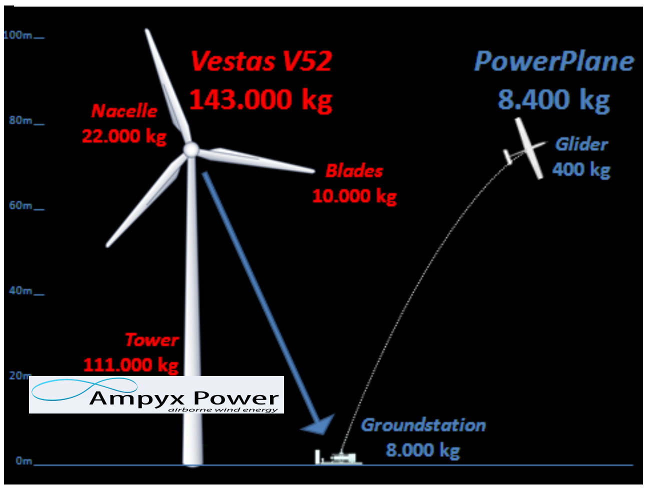


Fig.8 Cross wind power generation (AmpyxPower)

3.2 Tethered airborne wind energy generation: Cross wind system

The concept of the cross wind airborne wind energy generation is presented in Fig.8 [23]. The large windmill as usual one on ground construction is shown for comparison at the left of figure. Most of the wind energy in the large windmill is produced by at the tip of the wind turbine blade. In the cross-wind concept a tethered glider flies in a closed loop, circle or eight-figure, in the same manner as the tip of the large windmill. The glider can produce electrical energy by implementing a "yo-yo" maneuver, which is based on a periodic cycle made up of two phases. During the reel-out phase, the strong traction force in the tether of the kite, generated by the kite flying in a crosswind maneuver, is used to produce electrical energy by spinning a generator at ground. The tether is winched in, and the kite flies back during the reel-in phase. A simulator of the power kite, which includes bridle and tether control, is constructed to find optimal control laws to maximize the generated power and the stability of the kite. It is evident that the tethered glider or kite is able to produce almost same amount of electricity with the large windmill but the system is simple, small, and cost effective. A preliminary step of the cross wind airborne wind power generator is under study by the Japanese HSWG group and a model of an aircraft is tested in the

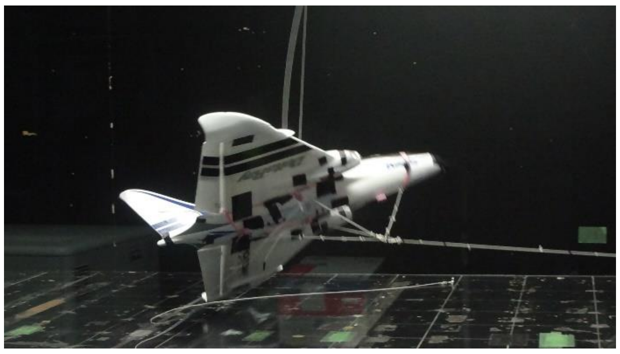


Fig.9 Wind tunnel test of a tethered aircraft (HSWGJapan)

2.3m×1.8m Turbulent Atmospheric Boundary Layer Wind Tunnel at the Tokyo Polytechnic University (Fig.9).

4. Conclusion

Tether technology is briefly introduced for space tether deployment. Two kinds of tether, thin tether and tape tether, are review on their deployment mechanisms. Applications of tether technology are also introduced for airborne wind energy generation. Recent advances of the airborne wind energy generation are overviewed and classified for the system. Recent progress of the Japanese HSWG (High Sky Wind energy Generation) is introduced for both of the non-cross wind type and cross wind type. Tether technology has many advantages and also many disadvantages. Tether technology is expected to play important roles also in future employing its advantageous features as light in weight, strong against tension, compact and autonomous and avoiding its disadvantageous features as broken hazardous, slackness, and non-resistant to compression.

Acknowledgement

This work was supported by JSPS Grant-in-Aid for Scientific Research (C) Grant Number 26420817.

References

1) Johnson, L., Khazanov, G., Gilchrist, B., Hoyt,R., Stone,N., Lee, D., and Elder, C., “Space Tethers”, Journal of Space Technology and Science (JSTS), Vol.26 No.1 (2012), pp.2-13.
2) Fujii,H.A, and Watanabe, T., "Historic Lessons Learned from Space Tethers and Solution -From GEMINI11 To Space Elevator-," Proceedings of 64st International Astronautical Congress, IAC-13.D1.5, 1x16777, September 2013, Beijing, China.
3) Space tether missions – Wikipedia, the free encyclopedia.
4) Tethered Satellite System contingency Investigation Board Final Report, NASA-TM-108704.
5) NASA (1967). Gemini XII Program Mission Report, Manned Spacecraft Center, Houston, USA, January 1967.
6) Kruijff, M., Tethers in Space, Ph.D Thesis, Technical University of Delft, 2011.
7) Fujii,H., Kruijff,M., van der Heide,E.J., Watanabe,T., and Ockel,W., “The Second Young Engineers' Satellite: Innovative Technology Through Education,” Tansactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan, Vol. 8 (2010) No. ists27, pp.Tb_11-Tb_17.
8) Fujii, H.A., Watanabe, T., Sahara, H., Kojima, H., Takehara, H., Yamagiwa, Y., Sasaki, S., Abe, T., Tanaka, K., Oyama, K-I, Johnson, L., Khazanov, G.V. Sanmartin, J.R., Charro, M., Kruijff, M., van der Heide, E.J., Rubin, B., Garcia de Quiros, F.J., Trivailo, P.M., and Williams, P., “Space Demonstration of Bare Electrodynamic Tape-Tether Technology on the Sounding Rocket S520-25,” AIAA-2011-6503, AIAA Guidance, Navigation and Control Conference, Portland, OR, August 2011.
9) Shaker Bayajid Khan and Juan R. Sunmartin, “Analysis of tape tether survival in LEO against orbital debris,” Advances in Space Research, Volume 53, Issue 9, 1 May 2014, Pages 1370–1376.
10) Van Noord, J., West, B., Gilchrist, B., "Electrodynamic tape tether performance with varying tether widths at low Earth altitudes" AIAA-2001-1141, Aerospace Sciences Meeting and Exhibit, 39th, Reno, NV, Jan. 8-11, 2001.
11) J.R. Sanmartin, A. Sanchez-Torres, S.B. Khan, G. Sanchez-Arriaga, M. Charro, “Optimum sizing of bare-tape tethers for de-orbiting satellites at end of mission,” Advances in Space Research 56 (2015) 1485–1492.
12) Sanmartin, J.R., Charro, M., Chen,X., Lorenzini,E.C., Colombatti,G., Zanutto, D., Roussel, J-F., Sarrailh,P., John D. Williams, J.D., Xie,K., Metz,G.E., Carrasco, J.A., Garcia-de-Quiros, F., Olaf Kroemer,O., Rosta,R., van Zoest,T., Lasa, J., Jesús Marcos,J., , A Universal System to De-Orbit Satellite at End of Life,Journal of Space Technology and Science (JSTS), Vol.26 No.1 (2012), pp.21-32..
13) Fujii,H.A., Watanabe,T., and members from USA, Europe, Australia, and Japan, Deployment of Bare Electrodynamic Tape-Tether Technology on the Sounding Rocket S520-25, BETS Meeting in Madrid, Spain, 17 - 18 November 2011.
14) Fujii,H.A., Watanabe,T., and members from USA, Europe, Australia, and Japan, “Deployment Technology for 6km of Bare Electrodynamic Tape-Tether,” Final Manufacturing Review, DLR Institute of Space Systems Bremen, Germany, 29th – 30th of November 2012.
15) Watanabe, T., Sukegawa, M., Fujii, H. and Kojima, H., “Examination on 2-Dimensional Storage Method of Tape Tether and Analysis of the Deployment Behavior,” Transactions on Advanced Research IPSI Bgd Internet Research Society, July 2013 Vol. 9 No. 2 , pp18-22.
16) Swan,P., Raitt,D., Swan, C., Penny, R., Knapman, J., ed., *Space Elevators*, Virginia Edition Publishing, October 2013.
17) Ahrens, Uwe, Diehl, Moritz, Schmehl, Roland (Eds.), *Airborne Wind Energy,* Springer 2013.
18) http://projects.nrl.navy.mil/atex/ATEx.html
19) Stone, N. and Bonifazi, C., “The TSS-1R Mission: Overview and Scientific Context,” Geophysical Research Letters, Vol. 25, No. 4, pp. 409-412, 1998.
20) Hironori A. Fujii, Takeo Watanabe, and Tairo Kusagaya, “Tether Actuator to Control Vibration of Space Structures,” Acta Astronautica (2015), pp.55-63.
21) Fujii,H., Okubo,H., Arakawa,K., Kusagaya,T., Stroeks, R., Takahashi,Y., Endo,H., Watanabe,T., Maruyama,Y., Nakajima,T., Asou,T., and Seki,K., “Progress Report on Study of Air Borne Wind Energy (In Japanese),” Journal of Japan Wind Energy Association, Vol.39, No.4, pp.543-553, February 2016,
22) Fujii,H.A., Maruyama,Y., Motegi,Y., and Kida,K., “A Model Demonstration of Kite-Type Windmill,” International Conference and Exhibition, Grand Renewable Energy 2014, July 27-August 1, 2014, Tokyo Big Sight, Tokyo, Japan
23) Breukelman,P., Kruijff,M., Fujii,H.A., Maruyama,Y., “A New Wind-Power Generation Method Employed with High Altitude Wind,” International Conference and Exhibition, Grand Renewable Energy 2014, July 27-August 1, 2014, Tokyo Big Sight, Tokyo, Japan

Appendix1 Classification of airborne wind energy generation activities

- AWES
  - Cross Wind
    - Fly-Gen
      - ◎MakaniPower (CA, USA)
      - ◎Joby Energy (CA, USA)
    - Ground-Gen
      - Fixed Ground (Pumping system)
        - Kite power (TUD)
        - ◎AmpyxPower (NL)
        - ◎Kite Gen (Italy)
        - ◎Guangdong Tech. (China)
        - ◎Sky sale power (Germany)
        - Swiss kite power (Swiss) → Twing Tec
        - ◎Kite Gen (Italy)
        - Twing Tec (Swiss)
        - EnerKite (Germany)
        - e-Kite (NL)
        - Kitemill (Norway)
        - KU Leuven (Belgium)
        - Universidad Carlos III de Madrid (Spain)
        - ◎Kite energy (Italy)
        - ◎HSWG (JPN)
      - Moving ground
        - NTS (Germany)
        - KiteGen Research (Italy)
  - Non cross wind
    - Fly-Gen
      - Altaeros Energies (USA)
      - ◎Mnidea
    - Ground-Gen
      - HSWG (JPN)
      - LadderMill (TUDelft) → Kite power (TUD)

◎MW class