Space Elevator and Its Research and Development at Present

Yoshiki Yamagiwa
Graduate School of Engineering, Shizuoka University
tmyyama@ipc.shizuoka.ac.jp

Key Words: Space Elevator, Space Transportation

Abstract: A space elevator is an ultimate transportation system access to space. Such a system is just a product of imagination until some decades ago. But recent advances in technology including the invention of new materials such as carbon nanotube make space elevator possible to realize, and academic researches and developments become active in USA, Japan and European countries in recent ten years. There are many technological problems should be overcome at present, but the increase and the cooperation of researchers and engineers to cope with space elevator and the continuous studies of space elevator will accelerate the realization of space elevator in near future..

1. Introduction

A space elevator is the ultimate space transportation system from the earth to space, because this system can bring the low cost and safe transportation method with low impact on environment and human body compared with the existing chemical propulsion. This system was just a product of imagination in the past, but the invention of new materials like carbon nanotubes and technological developments during a several decades make such a system possible and the studies about space elevator become active at present. This paper presents the overview of space elevator concept, its research history and the present state of research and developments

2. Concept of Space Elevator

A space elevator constructs on the equator and consists of a cable between the ground and the station, an anchor station which gives a tension to the cable, and a climber which transports the payload from the earth to space or from space to the earth by going up and down on the cable (Fig.1). The cable length is to be about 100,000 km although its length depends on the mass of anchor station, because the center of the system mass of space elevator should be on the geosynchronous earth orbit (GEO) for standing the system still to the earth's ground. The cable mass can be reduced by designing that its cross section is changed as the stress is constant through the cable. To construct the space elevator, the material which have more than 50GPa tensile strength is required to construct 100,000km cable, but such a material is not exist at present. However the possibility to complete the space elevator is rose by the invention of carbon nanotube[1)] which has the maximum strength of 150GPa about 20 years ago.

The fact that the space elevator requires 100,000km cable

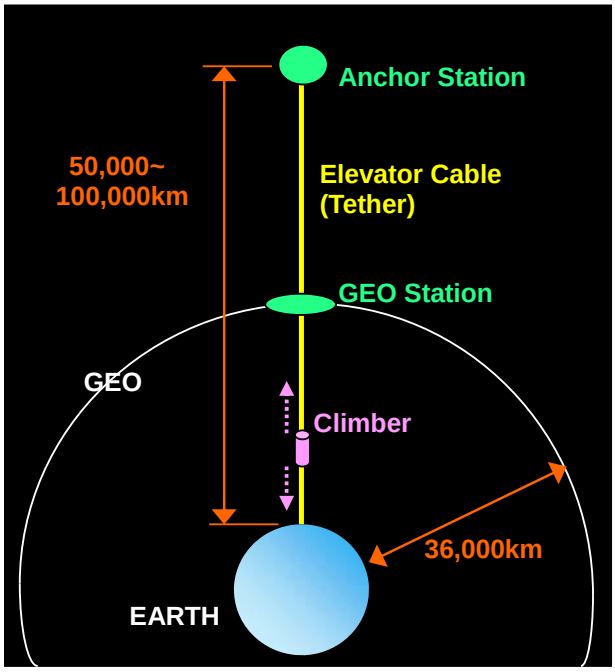


Fig.1 Conceptual figure of space elevator.

makes its construction difficult, but inversely, this length brings very attractive merit as space transportation system. At the altitude lower than GEO, the object on the cable has the lower orbital energy than the energy that is necessary to keep its orbit (aka. has the lower velocity than the orbital velocity that is necessary to keep its orbit), and fall to the earth if the object is separated from the cable. On the other hand, at the altitude higher than GEO, the object on the cable has the higher orbital energy than the energy that is necessary to keep its orbit (aka. has the high velocity than the orbital velocity that is necessary to keep its orbit), and can be sent to the moon or another planets by its velocity increment when the object is separated from the cable. For example, the object can be sent to the Moon by the

separation at the altitude of 46,000km, can be sent to Mars by the separation at the altitude of 57,000km, and can be sent to Asteroid belt and Jupiter by the separation at the altitude of 96,000km (Fig.2). That is to say, the space elevator is an evolutional space transportation system which brings easy transportation not only between the earth to orbit but also between the earth to another planets and satellites in the solar system, and the expansion of the region of mankind activities.

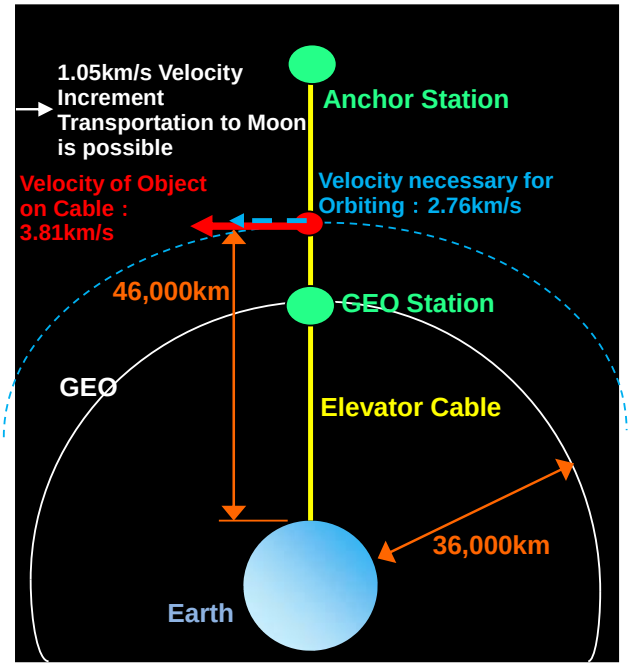


Fig.2 Transportation to Moon by using space elevator.

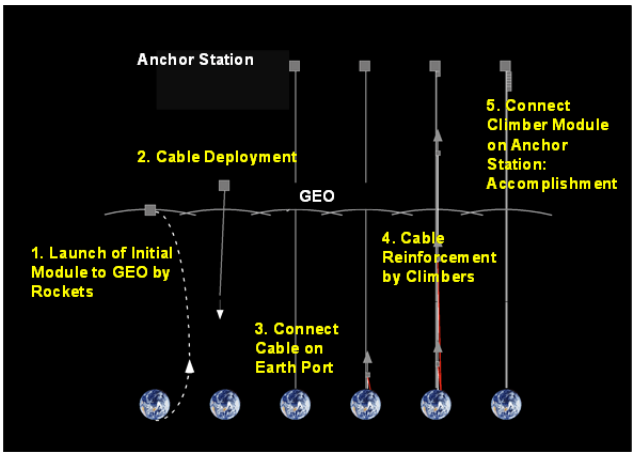


Fig.3 Steps of space elevator construction.

The construction of space elevator generally takes following steps (Fig.3)[2]; the first step; launch of initial module to GEO by rockets, second step; deploy initial cable from the station, third step; connect the cable on the earth port, forth step; strengthen the cable and the anchor station by transporting cable and station module by the climbers along the cable, final step; completion of construction and start of normal operation. The concrete form of space elevator system is not fixed at present, but the idea proposed by Obayashi Co. (Fig.4)[3] is presented here as an example for understanding space elevator scale. The final system can be constructed by the cable of about 7,000t total mass with the configuration of 50mm maximum width (at GEO) and 1.4mm thickness if the carbon nanotube is used. The final climber is 100t total mass (70t for payload) and the normal transportation velocity is assumed 200km/h. The final mass of anchor station is about 6,500t. The floating structure on the sea is used as connection system of the cable to the earth, and the seawater is used as ballast to adjust the cable tension (Fig.5). Some stations such as GEO station, LEO station, etc., will be built along the cable. As the energy supply, the solar power is used for stations, and the wireless energy supply system from stations or from the ground is used for climber because the energy supply by wired system or by batteries is difficult to equip on the climber as the climber is moving and is required extreme lightweight.

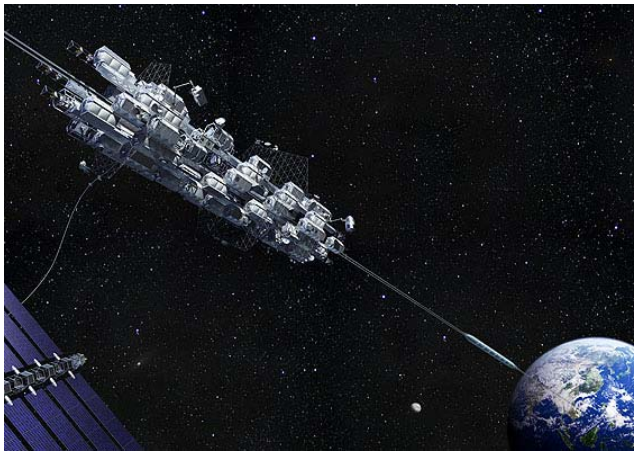


Fig.4 Conceptual figure of space elevator by Obayashi, Co.[3]

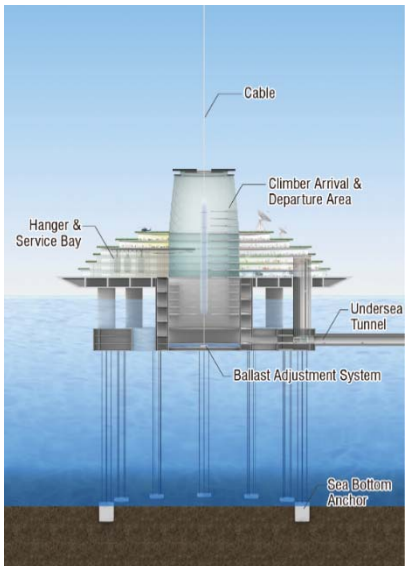


Fig.5 Conceptual figure of earth port by Obayashi Co.[3]

3. History of Space Elevator

The first idea of space elevator itself was proposed by Tsiolkovsky[4] who was the father of rockets, but, the idea of space elevator, in which the cable was deployed from the space station and connected to the earth and was the basis of many research of space elevator today, was proposed by Artsutanov[5] in 1960. In 1975, Pearson academically examined the realization of space elevator at that time[6]. In 1979, Arthur C. Clarke published the science fiction masterpiece "The Fountains of Paradise"[7] in which the construction and operation methods of space elevator were detail described by using the forefront technologies at that time, and extended the existence of space elevator widely to public. Anyway, until that time, the space elevator is just an impracticable idea, but the invention of carbon nanotube, which is the lightweight high-strength material corresponded to "Whisker" called in "the Fountain of Paradise" , changed that situation, and the realization of space elevator became to have an air of authenticity. Triggered by this invention, NASA hold the workshop of space elevator, then Edwards in Los-Alamos Research Center performed detail study about space elevator granted by NASA in 2000[8]. After Edwards's study, the regular academic studies shown later are continuously performed for the main elements of space elevator; cable dynamics, climber mechanism, etc.

Other than individual researches, the activities by organized committee were also began from 10 years ago. The Spaceward Foundation was established in 2003 and held space elevator challenge games called "Power Beaming" and "Strong Tether" which prize money from 2005 to 2009, and the Space Elevator Conference sponsored by International Space Elevator Consortium (ISEC) was also started from 2008 in USA. In Japan, Japan Space Elevator Association (JSEA) was established in 2009, and the space elevator challenge and Space Elevator Conference are held every year by JSEA from 2009. In 2012, Obayashi Co. announced their space elevator plan, and the space elevator study committee in the Japan Society for Aeronautical and Space Sciences was started from 2013. The detail of the space elevator challenge is shown in next chapter. In Europe, European Spaceward Association (ESA) was established in 2007, and held the international conference of space elevator, but, it is discontinued at present. Meanwhile, the European Space Elevator Challenge was began from 2012 at Technische Universität München. There are also some activities of international cooperation of study to realize the space elevator, for example, International Academy of Astronautics(IAA) established the permanent study committee of space elevator in 2014.

4. Technological Subjects of Space Elevator and the State of Their Study

The realization of space elevator is theoretically obvious[9], but it is necessary to overcome many technological problems to construct the system. Follows are the major technological subjects and problems:

* Development of lightweight and high-strength cable
* Dynamical stabilization of the cable
* Development of low frictional wear and high efficiency climber
* Stabilization of the climber dynamics
* Stable energy supply method
* Development of efficient connection method of the cable to the ground (earth port)
* Development of protection method from strong wind
* Development of protection method from space debris
* Development of protection method from radiation
* Countermeasure to rain and lightning
* Legal problems (space law, aviation law, marine law, etc.)
* International Cooperation

Among them, the technological subjects and the present state of their study for the cable and climber, those are the main elements of space elevator, are shown below.

4.1 Technological subjects of the space elevator cable and the present state of the study

The realization of space elevator extremely depends on the development of lightweight and high-strength cable. The invention of carbon nanotube made a breakthrough, but the performance which is necessary to satisfy the space elevator requirement is not obtained at present because the research and development of carbon nanotube material is mainly focused on its electrical characters and the research focused on its usefulness to building material is not active at present. As the development focused on mechanical strength, Teijin Co. achieved 2GPa strength of cm scale CNT fiber[10], and we can expect the future development of their research.

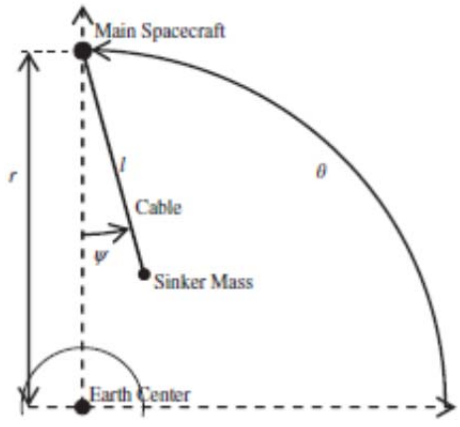


Fig.6 Analytical model of elevator-cable deployment model by Takeichi[12]

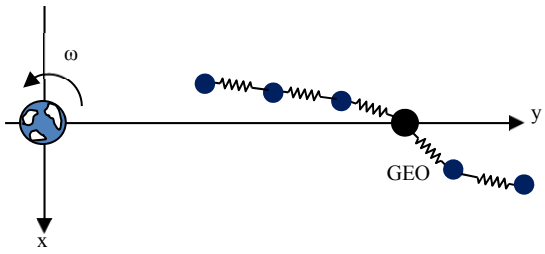


Fig.7 Analytical model of elevator-cable deployment model by Fujii[13)]

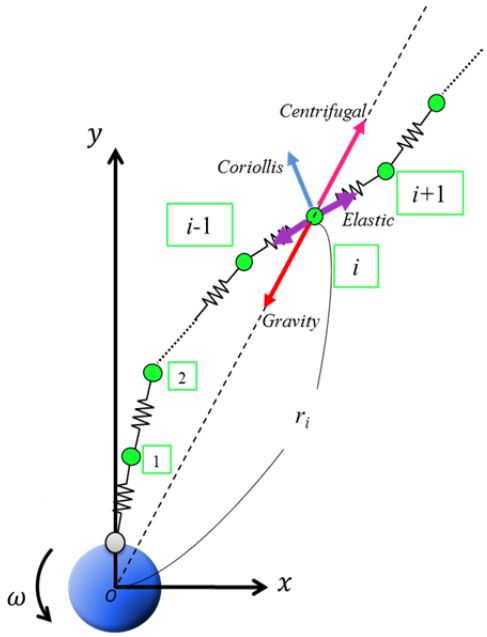


Fig.8 Analytical model of elevator cable dynamics model with climber motion by Yamagiwa, et. al.[18)]

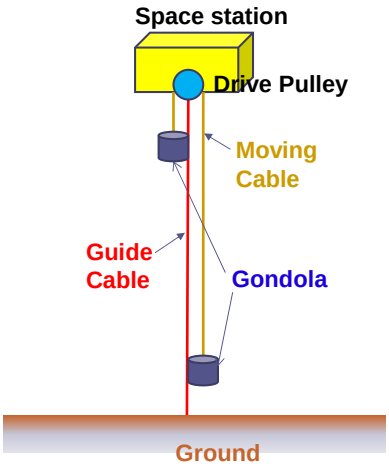
The understanding of cable dynamics is also important not only for the cable design itself but also for another elements of space elevator including the climber design, control of energy supply, etc. The dynamics of cable deployment at the beginning of space elevator construction, was studied by Lang, Takeichi, Fujii, etc. Lang[11)] and Takeichi[12)] analyzed the dynamics of two mass points of the anchor station and the cable tip (Fig.6) for the case proposed by Edwards in which the cable was deployed to Earth's direction and the anchor station rose it's altitude for keeping the center of gravity at GEO, and proposed the control method for stable deployment of the cable. Fujii[13)] analyzed the cable dynamics by using the multi mass point model (Fig.7) for the case in which cables was deployed to the Earth's direction and space direction simultaneously from the GEO station, and showed the dynamical deformation of the cable and the variation of cable stress distribution.

The cable dynamics after the completion of space elevator construction was studied by Lang, Williams , Cohen, Yamagiwa, etc. Cohen[14)] and Williams[15)] analyzed the cable dynamics when the climber goes up and down by regarding the cable as rigid body. Lang[16),17)] analyzed the cable dynamics with considering the strong wind effect in the atmosphere and the climber motion more detail by using the lamped mass model, in which the cable, anchor station and climber were considered as the segmented masses and connected masses by springs. Yamagiwa, et. al.[18)] also analyzed the cable dynamics with climber motion by using the lamped mass model (Fig.8) more detail, and showed that the cable swing motion can be depressed by the operation of two climbers rise and down the cable simultaneously. There still remains many evaluations to understand the cable dynamics more precisely because the dynamics of very long flexible cable is extremely complex, but the informations lead to design of space elevator are gradually obtained at present.

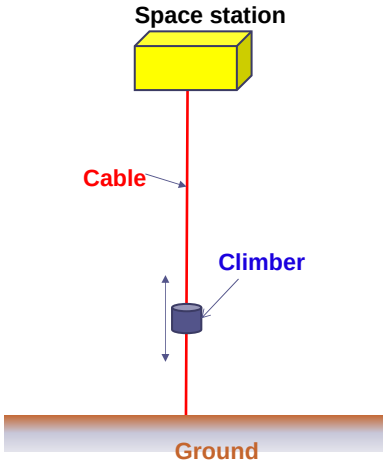
4.2 Technological subjects of the space elevator climber and the present state of the study

The advantage of space elevator is the easiness of transportation between the earth to space once the system is constructed, but it is necessary to make the multi-times round trip possible to decrease the transportation cost. For this requirement, the ability that the multi-times round trip of 100,000km passage with high efficiency and minimum maintenance is required for the climber which is the carrier of payload. There are many ideas of transportation methods, and it is considered that the best efficient method is the counterweight type (Fig.9 (a)) which is the transportation by two gondolas that connected each other by the cable through the anchor station, because this system can use the potential energy of one gondola to the ascent of another gondola. But, the investigation of such a system is insufficient now, and the many studies are assumed the self-propelled climber type (Fig.9 (b)) by using the friction between the rollers of the climber and the cable at present like the proposal by Edwards.

The design of climber is the trial and error stage at present, and the space elevator challenge by JSEA[19)] offers the nice opportunity to try the climber technology. The space elevator challenge is the game in which belt and rope tethers are floated by balloons and the climbers of participating teams are moved up and down along the tethers (Fig.10). The objective of space elevator challenge is to advancing the climber technology through competing climber's abilities such as ascent speed, control ability, safety mechanism, carrying ability, etc. and obtaining various data with climber motion. The altitude of the challenge began from 150m in 2009, and reached 1200m in 2013. In the space elevator challenge in 2013, 17 teams from universities, technical collages, and engineer groups participated. One engineer team achieved the world record of 1100m round trip (Fig.11), and the another team achieved the climbing speed of 60km/h. The climbers in the challenge is the miniature climber of about 10kg weight, so the knowledge obtained from



(a) Counterweight type



(b) self-propelled type

Fig.9 representative method of transportation by space elevator.

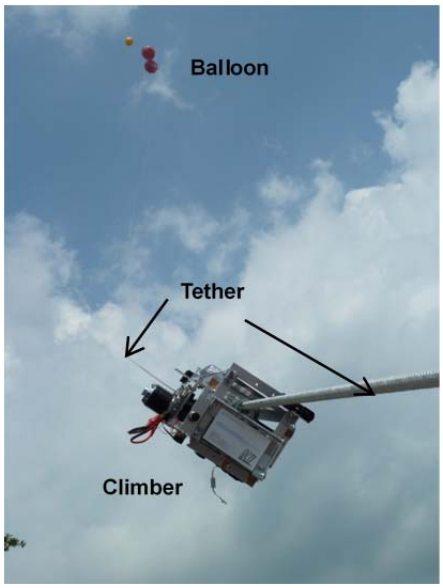


Fig.10 Space Elevator Challenge 2012 (Balloon altitude 700m, climbing moment of Sizuoka Univ.'s climber)

the challenge cannot applied to real climber directly, but the design guide lines, such as that the multi-roller design contacts with tether (Fig.12) is good for reducing frictional wear and the slender body design is suitable for reducing air drag, are gradually obtained at present. The space elevator challenge also offers the good practical opportunity of the engineering education for university and high school students.

Fig.11 Team Okuzawa's climber which achieved the world record of 1,100m round trip in space elevator challenge 2013. (Photograph offered by JSEA/Akiyama) [19)]

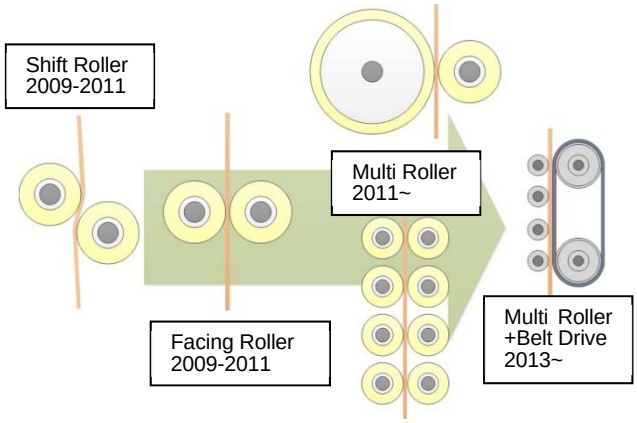


Fig.12 Variation of climber mechanism during space elevator challenge (Photograph offered by JSEA) [19)]

5. Summary

The human kind should not stay on the earth but needs to expand the range of their activity to space for surviving next century and beyond because many natural resources on the earth including energy resources will run out and cannot sustain human growth by the resources only on the earth if our population grows at present rate and the resources are consumed exponentially. The space elevator makes the constant transportation of payload from the earth to space and from space to the earth possible. Furthermore, the massive scale materials will be transported among the earth and planets if we also construct space elevators on another planets. Such a situation leads the social revolutions in which new space

industries and businesses that economically cannot expected by rockets only, such as the construction of space power plants, space hotels, space hospitals, transportation of natural resources from another planets, etc., are generated. That is to say, the space elevator brings new revolution of transportation method in future.

The technologies necessary to construct the space elevator relate the wide range of technological fields, and we should overcome many technological problems by gathering many engineers' and researchers' skills and knowledge in various fields At present, the research and development of space elevator is just begun, but the knowledge connected to realization of space elevator are gradually obtained, and the technological problems are not impossible to overcome. In addition, the technologies of space elevator is not only the special ones for space elevator development, but also can apply to the technologies necessary to the ground systems, for examples, the technology of ultra-light weight high-strength cable can apply to the materials of buildings and transportation machines, the technology of climber can apply to ropeways and cable cars and maintenance probes of elevators and towers, and the technology of wireless energy supply system can apply to the wireless energy supply system to cars, planes, and isolated areas, etc. Furthermore, the measure to space debris is the most important and inevitable subject for space development itself, and the protection from strong wind, lightning, rain, and radiation are the subject in various technological fields, so there is a possibility to overcome the technological problems in various another technological fields through space elevator development.

The time the space elevator is not just a dream system has come at present. I wish the increase and the cooperation of researchers and engineers in various fields to cope with space elevator and the continuous studies of space elevator will accelerate the realization of space elevator in near future.

References

1) Iijima, S. : Helical microtubules of graphitic carbon, Nature, 354, pp56-58, 1991.K. E. Tsiolkovski: Grezi o zemle I nebe, izd-vo ANSSSR, 35, 1959.
2) Edwards,B. C. and Westling, E. A.: The Space Elevator: A Revolutionary Earth-To-Space Transportation System, 2003. B. C. Edwards, Huston, USA, 2003.
3) Obayashi Co. CSR Div. Ed.: Quarterly Obayashi, No. 53 (Special Issue: Tower), pp38-39, 2012. (in Japanese)
4) Tsiolkovski, K.E.: "Speculations About Earth and Sky and on Vesta,"Moscow, Izd-vo AN SSSR, 1959; Grezi o zemle i nebe (in Russian), Academy of Sciences, U.S.S.R., Moscow,
5) Artsutanov, Y.: original is in Russian, "V kosmos na elektrovoze" "Into the Cosmos With an Electric Locomotive," Komsomolskaya Pravda, July 31, 1960.
6) Pearson, J. : The orbital tower: A spacecraft launcher using the Earth's rotational energy, 2, 9-10, pp785-799, 1975.
7) Clarke, A. C., The Fountains of Paradise, Harcourt, Brace; Book Club Edition (BCE), 1979.
8) Edwards,B. C.; The Space Elevator, NIAC Phase II Final Report (http://www.niac.usra.edu/files/studies/final_report/521Edwards.pdf#search='The+Space+Elevator%2C+NIAC+Phase+II+Final+Report'), 2003.
9) Sato, M., Phsics of Space Elevator, Ohmsha, Tokyo, 2011. (in Japanese
10) De Volder, M. F. L., Twafick, S. H, Baughman, R. H. and Hart A. J. ; Carbon Nanotubes: Present and Future Commertial Applications, Science, No.339, pp.535-539, 2013.
11) Lang, D. D., Space Elevator Initial Construction Mission Overview, (http://www.keithcu.com/wiki/images/f/ff/Paper_Lang_GEO_Deploy.pdf)
12) Takechi, N., Geostationary Station keeping Control of a Space Elevator During Initial Cable Deployment, Acta Astronautica 70, pp.85-94, 2012.
13) Fijii, S., Yamagiwa, Y, Matsui, M., Otsuka, K. and Ishikawa. Y, Analysis of the Cable Dynamics at the Deployment of the Cable from GEO Station in Space Elevator Construction, Proceedings of Space Transportation Symposium 2013, STCP-2013-074, pp.1-4, 2014.
14) Cohen, S. S. and Misra, A. K., The Effect of Climber transit on the Space Elevator Dynamics, Acta Astronautica 64, pp.538-553, 2009.
15) Williams, P., Climber Motion Optimization for the Tethered Space Elevator, AIAA 2008-7383, pp.1-17, 2008.
16) Lang, D. D., Space Elevator Dynamic Response to In-Transit Climbers, 1st International Conference on Science, Engineering, and Habitation in Space, Albuquerque, NM, Space Engineering and Science Inst., Paper 10152148, 2006.
17) Lang, D. D., Approximating Aerodynamic Response of the Space Elevator to Lower Atmospheric Wind, (http://spaceelevatorwiki.com/wiki/images/8/8d/Paper_Lang_Aero.pdf)
18) Yamagiwa, Y., Doi, H., Oshuka, K. and Ishikawa, Y.; Cable Dynamics of Space Elevator with Considering Climber Motion, Journal of Space Technology and Science, 2014. (to be published)
19) Ohno, S., Roadmap of Space Elevator Development and Activities in JSEA, Proceedings of 16th Solar Power Satellite (SPS) Symposium, pp.1-5, 2013. (in Japanese)