DEVELOPMENT OF ADAPTIVE ROOF STRUCTURE BY VARIABLE GEOMETRY TRUSS

Kohei KURITA*, Fumihiro INOUE*, Noriyuki FURUYA*
Takashi SHIOKAWA* and Michihiro NATORI**

**Technical Research Institute of Obayashi Corporation, Japan*
***Institute of Space and Astronomical Science, Japan*
E-mail;kurita@tri.obayashi.co.jp

Abstract: Moveable structure has been used for drawbridge and all-weather stadium with retractable roof. These structures move on the rail or turn around the hinge, and these behaviours are monotony and simplicity. However, near future, the shape of construction changes variously as harmonising with surroundings. In order to realize new constructions, we found VGT (Variable Geometry Truss) developed for foldable parabolic antennas of artificial satellites in space. In this study, the VGT structure was applied to the variable roofs of large hemisphere dome as ground construction. First, the roof design and motion was analyzed by computer simulation. Next, a reduced model of roof was made to investigate the structural characteristics and dynamic motion. As result of experiments for reduced model, the configuration of each roof was able to change smoothly from closing to opening, and also the roof was adept shape to any missions. Regardless of shape, the roof structure was confirmed to be dynamic stability.

Keywords: VGT, Adaptive Structure, Roof Structure, Shape Control, and Hemisphere Dome

1. INTRODUCTION

In recent years, the use to the construction diversified and the constructions equipped with the move function to the part of the structure have began to emerge [1]. The bridge to close and open in the traffic of the ship, the turning restaurant at the top of the building, the sliding roof at the dome stadium and etc., were the typical examples. These moving methods were those construction moved on the top of the rail and it was turned around the hinge. These behaviours were monotony and simplicity. Even if these moving functions were admitted, the change of structure itself could not be seen interestingly.

However, in the construction with a near future, it is possible to make a construction have a lively motion, flexibility and moreover intelligence. Especially, the structure changes into the shape harmonised with the environment around and the change of the shape realizes the more advanced function. In one of the mechanisms that make the more complicated movement possible, there is a variable geometry truss, what we called VGT [2] . VGT was originally developed as the actuator with structure at the spread-type universe construction in space, and that was equipped with the small motor to work various missions in the astrospace.

The purpose of this study is to apply to the ground construction by using VGT and it examines the development of the element technique and application possibility to the moveable construction.

In this paper, the basis characteristic of VGT, the analysis and simulation of VGT and application example to the actual construction are explained.

2. CHARACTERISTIC AND ANALYSIS OF VGT

2.1 Mechanism and characteristic of VGT

As shown in Figure 1, VGT is the truss, which is composed of elastic member and hinge. By controlling the length of the elastic member, it is possible to create various truss shapes. The example of the shape change that combined two dimensions VGT in series is shown in Figure 2. When stretching a elastic member of VGT every two, the truss beam changes into the shape as it moves solitude. And also, when stretching a marching elastic member together, the beam changes like a spring. Moreover, by choosing them optionally and controlling the

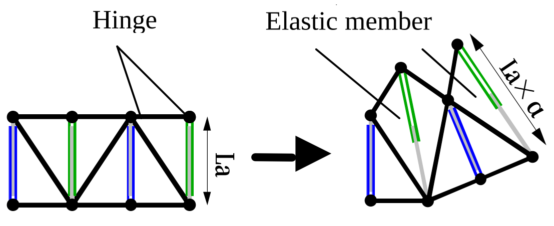


Figure 1. Basic mechanism of VGT

length of the elastic member, the truss beam changes into the intended shape.

The merits when applying VGT to the architecture construction are as follows;

(1) It is possible to create the various shapes which suited a purpose.
(2) It secures the strength of the construction because VGT forms always a truss.
(3) The simple structure including an elastic part
(4) The establishment of the technique of the elastic actuator
(5) The application to the spread and shrink type of construction method

On the other hand, to apply VGT as the ground construction because it is different from the use for the space structure, the influence of the self- weight and the earthquake power and so on must be estimated. Also, it is necessary to consider a cost and maintenance.

2.2 Shape analysis of VGT structure

In the shape analysis of the construction used VGT, the direct kinematics analysis which fixes a shape by giving the elastic length of VGT and inverse kinematics analysis which fixes the elastic length of VGT by giving a shape are used generally. The former, the shape is solved by kinematics analysis, the latter, it is difficult to set the shape uniquely because shape itself becomes very high redundancy structure.

(1) Direct kinematics analysis

The composition unit of two dimensions VGT and the whole structure are shown in Figure 3. Each unit of VGT is composed of two sets of fixed member and elastic actuators. Then, the whole structure can replace robot manipulator combined the fixed member 1 serially. The tip part of x, y coordinates of the structure combined with n (n > 2) sets of VGT is shown in equation (1)and (2) by using each hinge angle q_j.

$$q_{x,n} = l_0 \cdot \sum_{k=0}^{n} \cos\left(\sum_{j=0}^{k} q_j\right) \qquad (1)$$

$$q_{y,n} = l_0 \cdot \sum_{k=0}^{n} \sin\left(\sum_{j=0}^{k} q_j\right) \qquad (2)$$

The length of the elastic actuator is easily found in giving q and the shape of structure can be uniquely fixed.

(2) Inverse kinematics analysis

It is quite difficult to control the elastic length of each VGT to change to the shape of intended structure. When thinking of the temporal change of the whole structure, equation (3) is obtained.

$$\dot{\boldsymbol{q}} = \boldsymbol{J}(q) \cdot \dot{q} \qquad (3)$$

where, $\boldsymbol{J}$ shows Jacobean Matrix (2 × n).

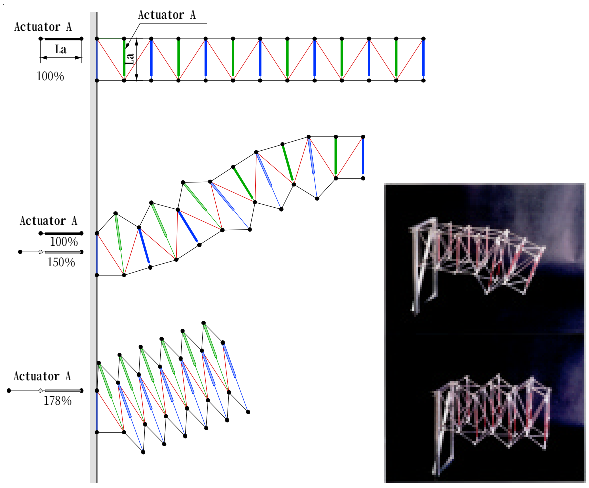


Figure 2. Shape change of truss beam by VGT

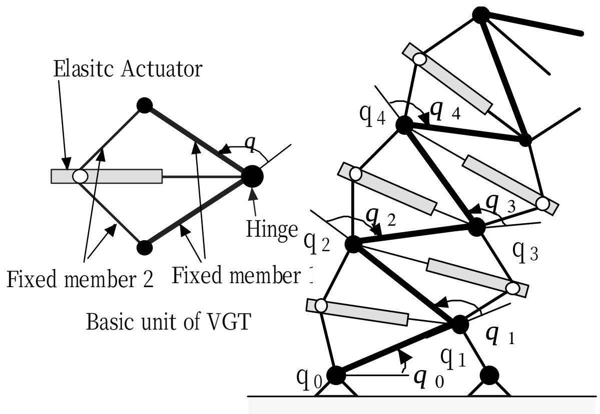


Figure 3. Two dimensions VGT unit and the whole structure

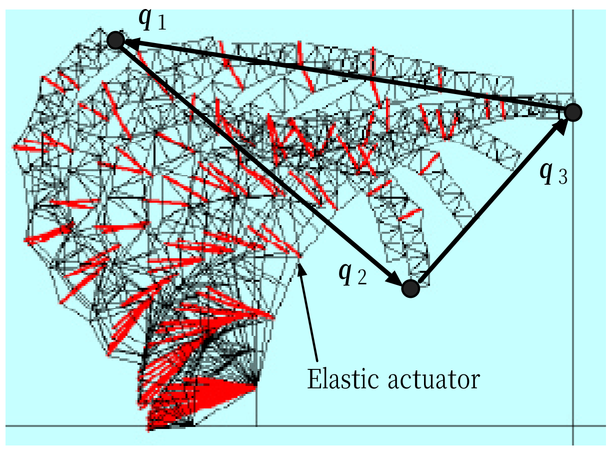


Figure 4. Shape change of the beam solved by inverse kinematics analysis

$$\boldsymbol{J}(q) = \frac{\partial \boldsymbol{q}}{\partial q} = \begin{bmatrix} \frac{\partial q_x}{\partial q_1} & \frac{\partial q_x}{\partial q_2} & \cdots & \frac{\partial q_x}{\partial q_n} \\ \frac{\partial q_y}{\partial q_1} & \frac{\partial q_y}{\partial q_2} & \cdots & \frac{\partial q_y}{\partial q_n} \end{bmatrix} \qquad (4)$$

An inverse matrix isn't necessary decided because $\boldsymbol{J}$ is not a regular system in n≠2. Here, it finds q by the numerical simulation from $\boldsymbol{q}$ using the pseudoinvesre matrix $\boldsymbol{J}^{\#} = \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{J}\ \boldsymbol{J}^{\mathrm{T}})^{-1}$ of $\boldsymbol{J}$.

The example of the shape change of the structure solved by inverse kinematics analysis is shown in Figure 4. By specifying a tip position, the length of each elastic actuator is found and the shape of structure can fix at any time. As a result, the optimal and rational shape design moving structure is accompanied and its shape control become possible.

2.3 Dynamic analysis of VGT structure

To actually design the structure using VGT, in addition to the kinematics analysis, the motin dynamic analysis which is the external force acting on the structure and the torque power for the shape change of the structure must be examined. In the study of analysis, the models replacing VGT with multi-joint manipulator and with one-dimensional tree shape structure was proposed [3]. Using Kane' method [4], the final forming dynamical equation is indicated as showing (5).

$$M\ddot{\boldsymbol{q}} + \boldsymbol{h}(q, \dot{q}) + \boldsymbol{c}(q) = \tau \qquad (5)$$

where M is inertia matrix, $\boldsymbol{h}(q, q)$ is vector of centrifugal force and Coriolis force, $\boldsymbol{c}(q)$ is vector of external for as gravity and t is vector of driving torque. Solving the equation (5), the motion of the whole structure can be described.

2.4 Application example of VGT

VGT can be used for the stress control of the structure in addition to the shape control. Thus, its application range is estimated to be wide. Following example applying VGT is indicated.

(1) The shape control of skeleton structure inducting Chapter 3.
(2) The actuator controlled the stress and vibration of structure.
(3) The facility equipment and temporary structure including moving part: The example of shapes changeable gondola accompanying with building wall (Figure 5).
(4) The moveable monument made a structure.

3. REDUCED MODEL EXPRTIMENT OF FLEXIBLE STRUCTURE BY VGT

To get the basis data to manufacture the construction using VGT, we tried to apply to the hemisphere-shape dome, what we called "Flowering

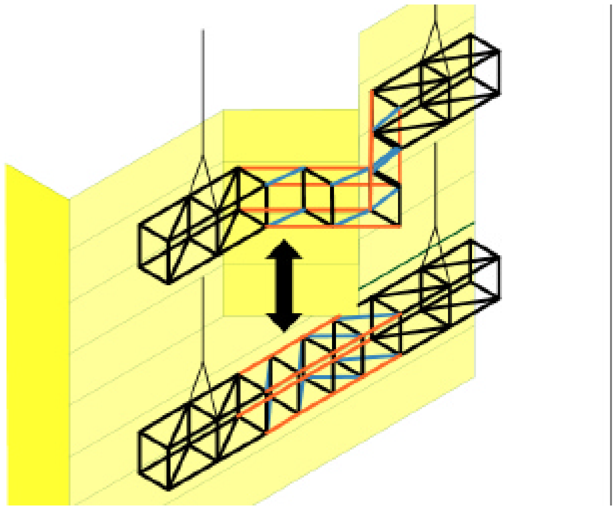


Figure 5. The example of shape changeable gondola

Dome" showing in Figure 6, which the roofs opened as floral and each roof could change into the optional shape. By manufacturing a reduction model actually here, a design technique included the structure, finishing material and its motion control was established.

3.1 Simulation of roof shape

The roof was composed of the partial roof of 10 sheets of sectors. VGT actuators were set in serial at the main truss of each partial roof. To describe the roof shape and driving range of actuator, the numerical simulation of the roof was carried out by the advanced method of 2.2 and its result was indicated in a computer graphic. The shape change of from opening to shutting of roof in Flowering Dome is shown in Figure 7. From the simulation, the various roof shapes became able to be created in controlling the elastic length of each VGT.

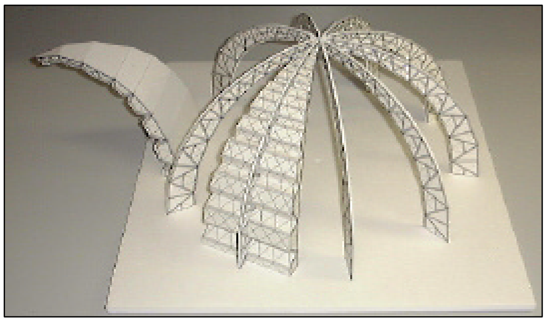


Figure 6. Model of "Flowering Dome"

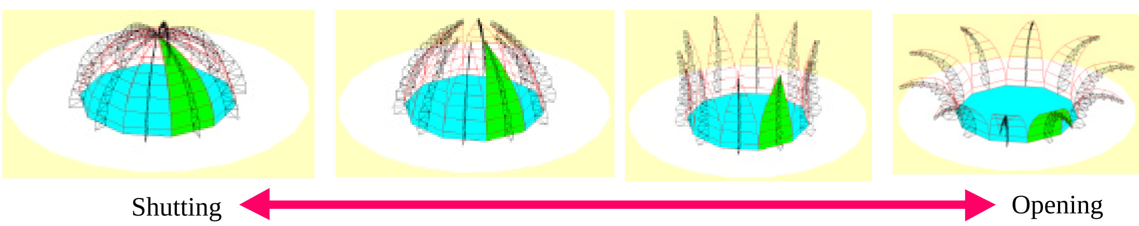


Figure 7. Simulation of the opening and shutting of roof in flowering dome

3.2 Basic characteristic of VGT

The structure of roof was composed of between the moved part containing VGT actuator and the fixed part of installing the finishing material, and two parts were arranged mutually. In the composition of the VGT, the pier type and the chord type are considered as Figure 8. The former used the elastic members for the pier parts. The latter used the elastic members for the chord parts. The characteristics of each VGT type was examined by FEM analysis from following items; (1) Stiffness of roof, (2) Precision of control (3) Power of elastic actuator. In elastic member in the analysis, oil compression, stroke length and the direction of the load were considered. The characteristic of hydraulic actuator and standard steel is indicated in Figure 9.

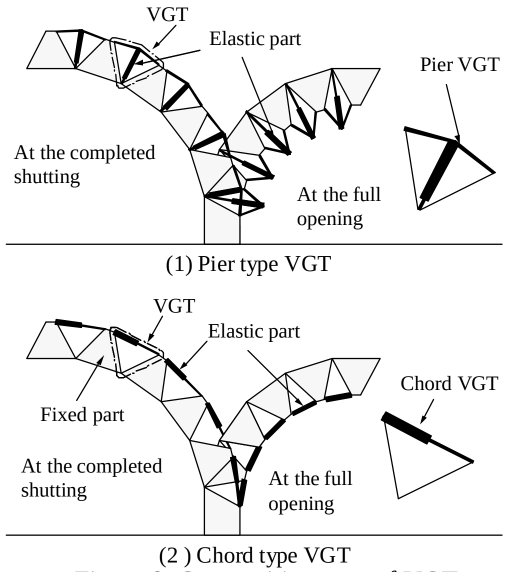


Figure 8. Composition type of VGT

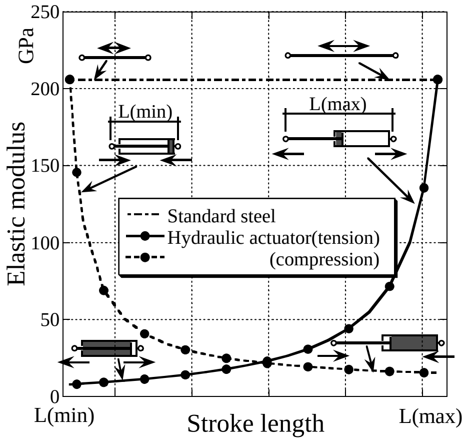


Figure 9. Characteristics of hydraulic actuator

(1) Stiffness of roof:

When the roof was moved from shutting to opening, the stiffness of tip displacement is shown in Figure 10. When using standard steel for the elastic member, the stiffness of both the pier type and the chord type were equal approximately, but the stiffness of the pier type became low approaching a full opening. On the other hand, considering the charctistics of the actuator, the pier type showed larger stiffness than chord type at a complete shutting.

(2) Precision of control:

Because a few errors were contained in the control length of the elastic actuator, in case of the roof of the cantilever, the accumulation error occurred in the position of the tip. Relation between the roof shape and the quantity of accumulated error at the tip is shown in Figure 11. The quantity of the chord type error was constant approximately regardless of the shape change. However, the quantity of pier type error was very small at a complete shutting.

(3) Power of elastic actuator:

When changing a roof to all the shapes under self-weight, the relation between the range of the axis power of the most lowly elastic part and the control angle *q* is shown in Figure 12. The large tension acted on the pier type of elastic actuator as the roof moves to the full opening, whereas the compression power acted on the chord type. The most lowly actuator needs more large operating power than the axis power range shown in the Figure12. Therefore, the chord type actuator was smaller than the pier type.

From these results, the composition of VGT was decided to use the pier type VGT which was superior about the characteristic of stiffness and

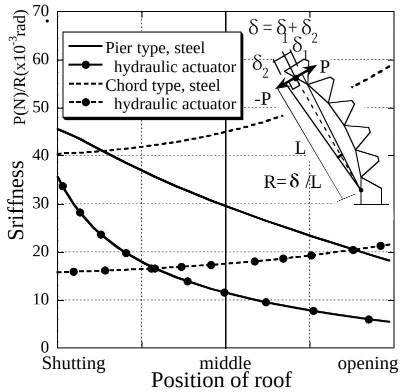


Figure 10. Comparison of stiffness of roof

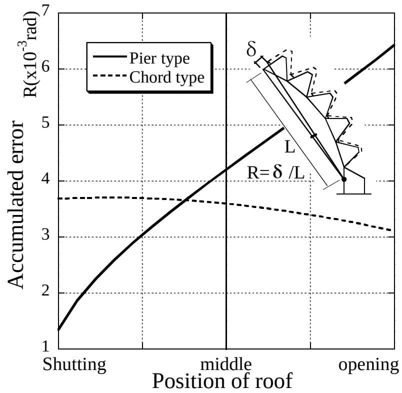


Figure 11. Comparison of precision of control

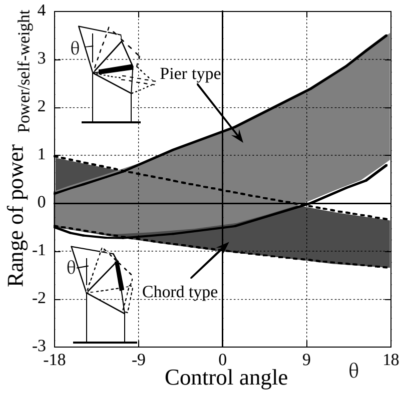


Figure12.Comparison of actuator power

control at the completed shutting. In this study, VGT actuator was decided to select hydraulic pressure actuator because it could make high output power easily.

3.3 Manifesting of the reduced model

(1) Roof structure:

The composition of the partial roof to use for Flowering dome is shown in Figure 13. Five sets of pier type VGT were arranged in serial on the center of each partial roof. The solid truss was installed on either side of VGT and the roof surface was formed. The side truss was installed through the hinge outside the solid truss and each solid truss was joined continually. The acrylic board, which was a finishing material, was fixed on the underside of the solid truss. When the roof was closed, the end of the roof on both sides overlapped and the water cut off.

(2) Composition of VGT:

The detailed composition of VGT is shown in Figure 14. VGT was composed of the fixed truss set the solid truss, hydraulic actuator as the pier type and the chord member. As for the hydraulic actuator, the standard device was improved, and the isolated device was originally developed by integrating the cylinder, the pump and the oil tank. To get the elastic ratio of VGT widely, the trunnion type of hinge, which set at the middle position of elastic part, was adopted.

(3) Control system:

The stroke sensor and the hydraulic pressure power (head side and rod side) installing inside each actuator were measured at any time, and they were controlled by the integrated management system. In the software of the management system, LabVIEW which as general type control tool was developed, and various control programs, which was manual control, automatic control and optimal control by inverse analysis, was tried to apply to the VGT structure. The control panel is shown in Figure 15.

(4) Manufacturing and operating condition:

The whole structure of model roof is shown in Figure 16. The main specification of structure and the hydraulic actuator are respectively shown in Table 1 and Table 2. The model was reduced about 1 / 6 scale of the actual structure and two

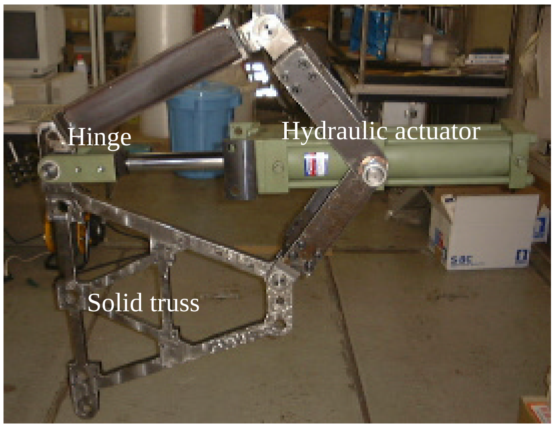


Figure 14. Composition of VGT actuator

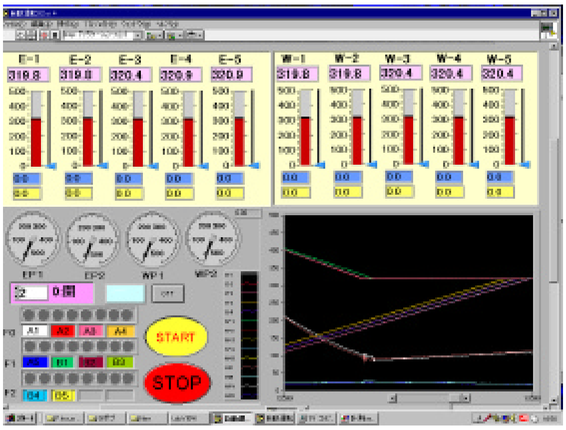


Figure 15. Operating panel of control system

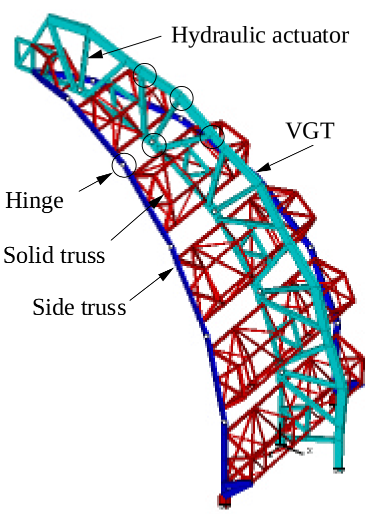


Figure 13. Composition of the roof structure installed VGT

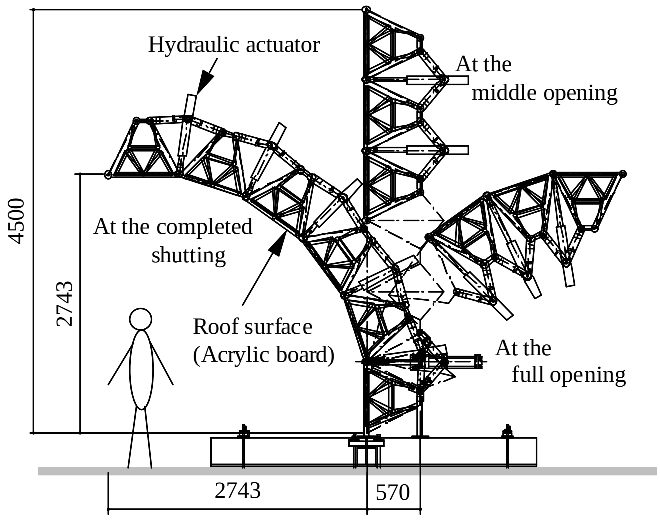
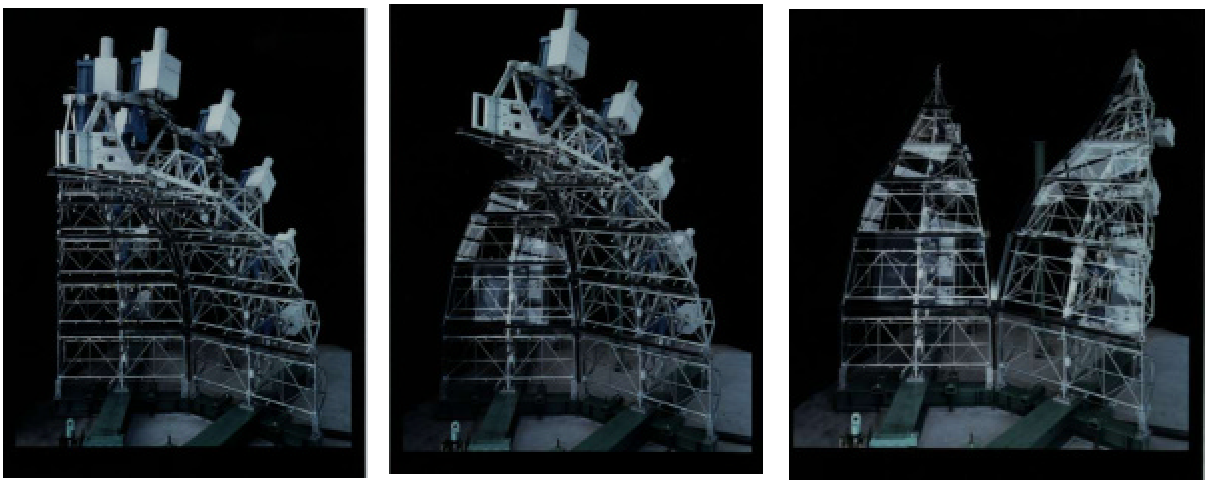


Figure 16. The whole structure of model roof



(1) Completed shutting (2) One of roof is shutting and the other is opening (3) Moving the roofs to several shape

Figure 17. Operating Condition of the mode of Flowering Dome

sheets of the roof divided into 10 sheets were manufactured. The operating conditions of moving model roof of a completed Flowering Dome are shown in Figure 17. The movement of the roof was smooth and it took about 3 minuets to move the roof from the shutting to the full opening. Controlling the stroke of actuator, variable structure roof could be made at one's desire. Further, the positioning precision of the tip of each roof was good at the shutting and it got enough precision to overlap the end of each roof.

(5) Verification experiment:

As the reduction model was completed, in future, following verifications of VGT are carried out, and then the basis data to the actual flexible structure is intended to obtain.

- The structural and dynamic verification experiment on the model roof contained VGT.
- The verification experiment on the finishing method followed flexible structure.
- The verification experiment on motion dynamic control and its system for the roof shape.

4. CONCLUSION

As one of the mechanisms that make a flexible structure possible, variable geometry truss VGT was explained. VGT is the structure, which is equipped with the actuator, and can create the various shapes freely contriving its arrangement and control. The application device used VGT is though to be a very wide and deep. In here, we proposed the example of flexible structure applying VGT. Manufacturing the reduced model of Flowering Dome, the efficiency and the characteristic of VGT could be grasped at the several points. In future, moreover detailed characteristic of VGT structure is understood and the actual development is expected to carry out.

Table 1. Specification of roof structure (one roof)

Size	4.5m(L)×1,78m(W) ×0.57(H)
Material	SS400
Hinge material	S45C
Roof material	Acrylic board
Self-weigh	1.1 ton (including actuator)

Table 2. Specification of Actuator

Power	Compression; 56 kN Tension; 45 kN
Pressure range	Max. 7 MPa
Stroke length	450 mm (Elastic ratio; 1.88)
Elastic velocity	1.7 mm/s, 2.1 mm/s
Self-weight	100 kg (Pump and oil tank)

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