APPLICATION OF ADAPTIVE STRUCTURE AND CONTROL BY VARIABLE GEOMETRY TRUSS

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Abstract

Attractive structures equipped with movable functions have been constructed in several places. Typical examples are drawbridges, large all-weather stadiums and revolving stages. These structures move on rails or turn around a hinge. However, these behaviors are monotonous and simple. In the near future, structural shapes may change more flexibly to harmonize with their surroundings and to follow to environments. In order to realize such future structures, we focus on the Variable Geometry Truss (VGT) developed as parabolic antennas in space. The VGT is an adaptive structure with intelligent controller and with smart and sustainable elements. In this study, the VGT structure has been applied to the roofs of domes as ground construction. Each roof shape was changed variably, and the design and motion were analyzed by computer simulation. A scale model of a dome was made to investigate the structural characteristics and dynamic motion of the roof. From experiments on this model, the configuration of the roof was able to change smoothly from closing to opening, and also the roof shape was controlled automatically according to the environments.

Keywords: VGT, Adaptive Structure, Roof Structure, Shape Control, Hemisphere Dome, Numerical Simulation, Dynamics

1. Introduction

Recent years have seen the emergence of interesting structures with moving functions in several places [1]. Bridges that open when ships pass underneath, revolving restaurants at the tops of buildings, sliding roofs on dome stadiums, etc., are typical examples. However, the moving functions have so far been achieved only by rolling on rails and turning around hinges. There has been no structural shape change, and the movements have not been flexible and uniform.

However, with future structures, it may be possible to produce a lively motion, freedom and moreover intelligence. In particular, they will respond to voice commands with instant and adaptive shape change harmonising with their environment. One mechanism that enables more complicated movement is the Variable Geometry Truss, or VGT [2]. This was originally developed as an actuator for a spread-type universe construction in space, and it is equipped with a small motor to work various missions. The VGT is considered to be an extremely convenient structural tool.

The purpose of this study was to apply this technology of the VGT to ground construction and to examine the development of the element technique and its applicability to moveable structures and smart and sustainable structures. This paper explains the basic characteristics of the VGT structure, applied to both cantilever-type and arch-type structures. Furthermore, a scale model comprised of changeable roofs was tested in several structural configurations and environment conditions

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2. Characteristic and Analysis of VGT Structure

2.1 Mechanism and advantages of VGT

The VGT is a truss structure composed of elastic members, fixed members and hinges. By controlling the length of the elastic member, it is possible to create various truss shapes. An example of a shape change that combines two-dimensional VGTs in series is shown in Figure 1 (a). When stretching the elastic members at same time, the structure changes like a spring stretching (b). When changing the alternate elastic member of VGT, the truss structure changes into the shape as it draw a circle (c). Moreover, by choosing them optionally and controlling the length of the elastic member, the truss beam changes into the intended shape (d).

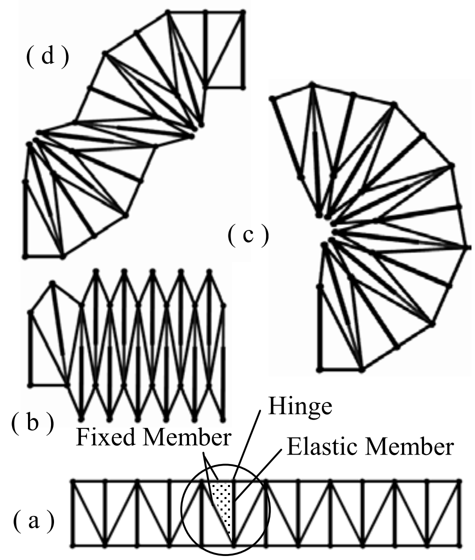


Figure 1 Shape Change of VGT Structure

Advantages in applying VGT to architectural structures are as follows:

1. It is possible to create various shapes according to the purpose and environments.
2. The structure's strength is ensured because the VGT always forms a truss.
3. The VGT unit is a simple structure including an elastic part.
4. A hydraulic cylinder or electric cylinder can be used for the elastic member.
5. The VGT can be applied to spread- and shrink-type structures.

When the VGT structure is applied on the ground, the self-weight and the earthquake power and so on must be estimated in construction, because this is different from the situation in space. Further, it is necessary to consider cost and maintenance.

2.2 Shape analysis of VGT structure

In the shape analysis of a VGT structure, direct kinematics and inverse kinematics analyses are generally used. For the former, the shape is solved by kinematics analysis, and for the latter; numerical analysis is needed because the shape creates very highly redundant structure.

2.2.1 Direct kinematics analysis

The composition units of the two-dimensional VGTs and the whole structure are shown in Figure 2. Each VGT unit is composed of two sets of fixed member and elastic actuators. Then, the whole of the structure can replace a robot manipulator combing fixed members 2 in series. The tip of the x, y co-ordinates of the structure combined with n (n > 2) VGT sets is shown in equations (1) and (2) by using each hinge angle θj.

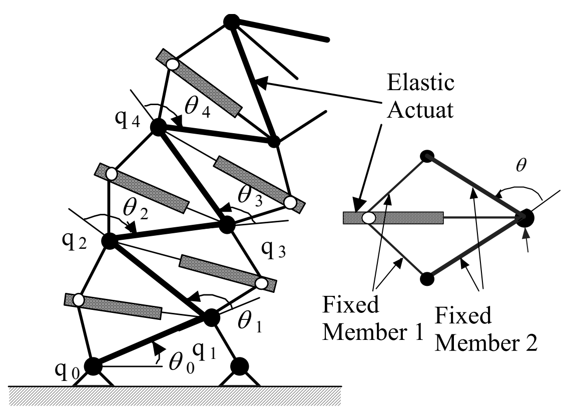


Figure 2 Two-dimensional VGT Unit and structure

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

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

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

2.2.2 Inverse Kinematics Analysis

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

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

Where, $\boldsymbol{J}$ shows Jacobean Matrix (2 × n). In this case, an inverse matrix isn't necessarily decided because $\boldsymbol{J}$ is not a regular system in n≠2. Here, it finds $\boldsymbol{\theta}$ by numerical simulation from $\boldsymbol{q}$ using the pseudoinvesre matrix $J^{\#}$ shown by equation (4)

$$J^{\#} = J^{T}\left(J \cdot J^{T}\right)^{-1} \qquad (4)$$

2.3 Dynamic Analysis of VGT Structure

To actually design a structure using VGTs, a motion dynamic analysis must be carried out. This is the external force acting on the structure and the torque power for its shape change. In the analysis, a model replacing the VGT with a multi-joint manipulator and with a one-dimensional tree shape structure was proposed. Using Kane's method [3] and Lagrange's method, the final dynamical equation is as showing the equation (5).

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

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

2.4 Typical Structure Using Two-dimensional VGT

We focus on the two basic structures applying the VGT structure.

2.4.1 Cantilever Structure

Cantilever structure is supported at a single position and, a top of the structure is unrestrained from external force. The movement of the structure is thought to be that of a multi-joint robot arm. Figure 3 shows the shape change of the structure solved by inverse kinematics. Specifying a top position moving as vector $\boldsymbol{q}$, the length of each elastic member is found from equation (3) and the shape of the structure can be fixed at any time. It is easy to create

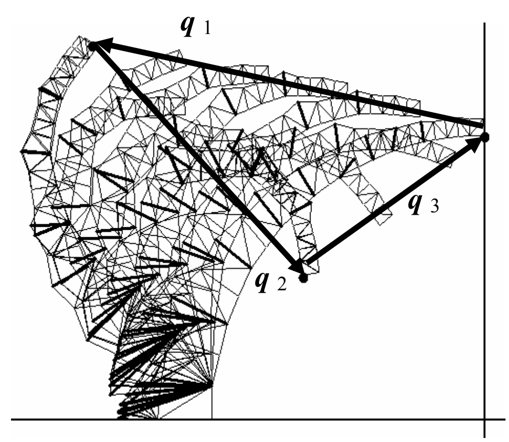


Figure 3 Shape Change of Cantilever Structure

several shapes.

2.4.2 Arch Structure

In the arch structure, the two tips of the structure are supported at each hinge. It is very difficult to determine the shape of the structure because these tips are absolutely suited at the hinge position. Figure 4 shows the shape variations of the arch structure like a big wave with the lengths of upper side members fixed. In this case, by slightly changing the length of a lower side member near the tip, the lengths of the lower side members are respectively analyzed by numerical simulation to correspond to the end of the structure in the hinge position. Using inverse analysis, a very flexible movement can be expressed.

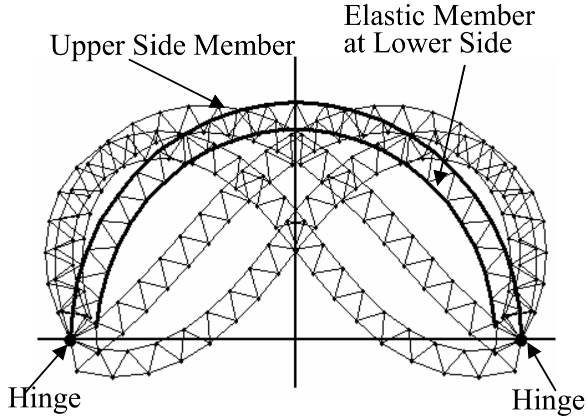


Figure 4 Shape Change of Arch Structure

As a result, the optimal and rational shape design of a moving structure is produced and it is possible to control its shape.

2.5 Application Example of VGT Structure

The VGT can be used for stress control of a structure in addition to shape control. Thus, it has a wide application. The following are some possible application examples:

1. Facility equipment and temporary structures with moving parts:
   Variable-shaped work gondolas for building walls, shown in Figure 5 and
   flexible roofs in music halls to suit stage contents.
2. Shape control of the structural dome described in Chapter 3 and the pavilion changing the roof shape according to inner environment conditions shown in Figure 6.
3. Artistic moveable monuments equipped with artificial intelligence harmonizing with the surrounding environment.
3. Actuators that control the stress and vibration of structure

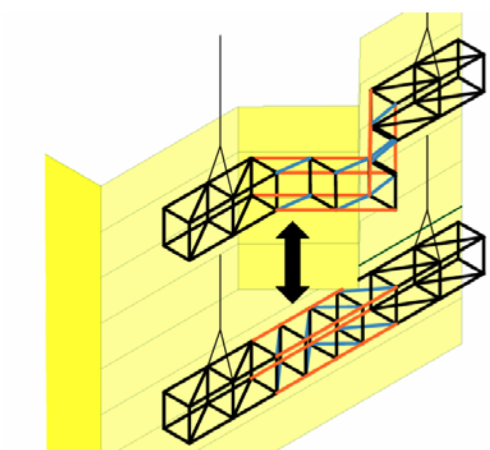


Figure 5 An Example of Shape of Changeable Work Gondola

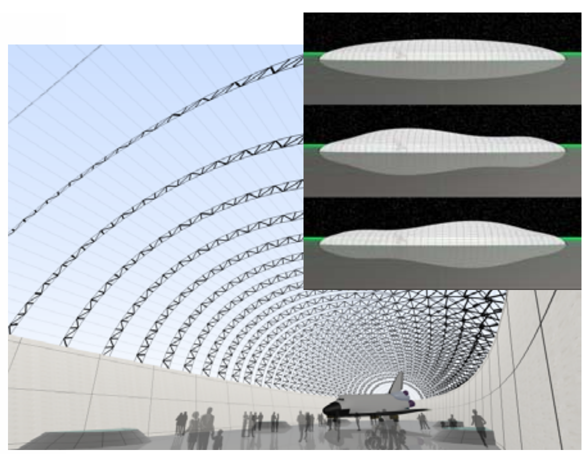


Figure 6 An Example of Large Pavilion Waving Several Shapes of Arch Roofs like a Life

3. Experiments and Verification of Adaptive Roofs Dome

To obtain basis data of the VGT structure for design and manufacture, we tried to apply it to a hemispherical dome. This was classified as a cantilever-type VGT. The roofs were opened in floral manner and each roof could change into an optional shape, what we call a "Flowering Dome" as shown in Figure 7. A scale model of an adaptive roof dome was made, and a design technique for the structure, finishing materials and motion control was tested.

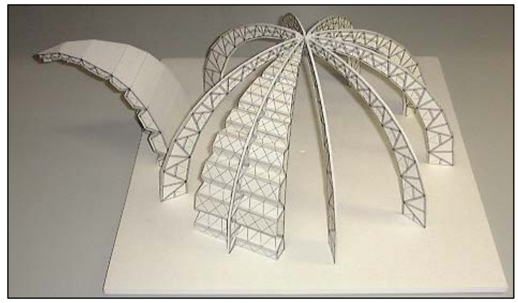


Figure 7 Model of Adaptive Roof Dome

3.1 Outline of Adaptive Roofs Dome

The doom was composed of a partial roof of 10 sectors. VGT actuators were set in series at the main truss of each partial roof. To describe the roof shape and driving range of the actuator, a motion simulation of the roof was carried out by the advanced method of 2.2 and the results were indicated by a computer graphic. The shape change of from opening to shutting of the roofs of the Flowering Dome is shown in Figure 8. From the simulation, various roof shapes could be created by controlling the elastic length of each VGT.

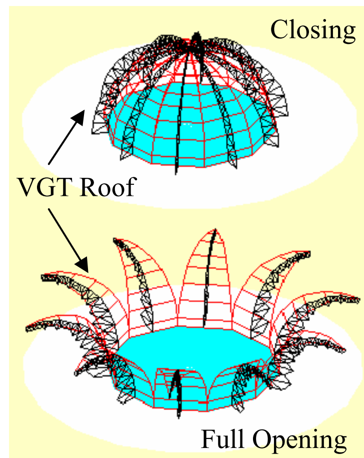
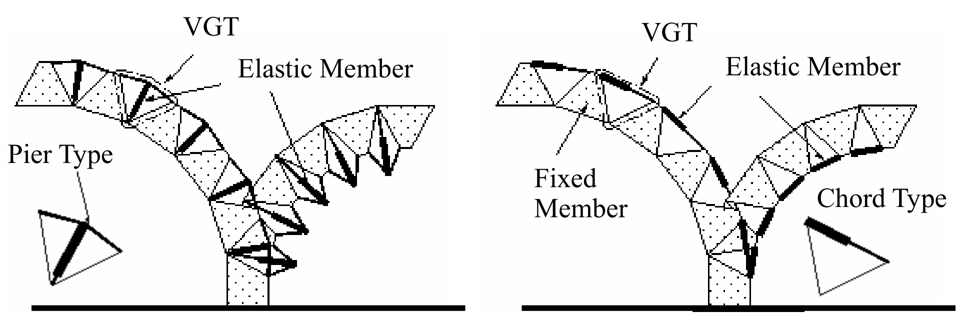


Figure 8 Computer Simulations of Adaptive Roof Dome

3.2 Static Characteristic of VGT Roof

The roof structure was composed between the moving parts containing the VGT actuator and the fixed part of the finishing materials, and these two parts were arranged mutually. The pier type and the chord type were considered for the VGT type, as shown Figure 9. The former used the elastic member for the pier parts. The roof opened by increasing the length of the elastic member. The latter used the elastic member for the chord parts. The roof was closed by increasing the length of elastic member. The characteristics of each VGT type were examined by static analysis of several items.



(1) VGT of Pier Type (2) VGT of Chord Type

Figure 9 Composition type of VGT

(1) Force of Elastic Member

When changing the roof to all the shapes under self-weight, the relation between the range of the axial force and the length of the elastic member is shown in Figure 10. A large tension force acted on the pier-type elastic member as the roof moved to full opening, whereas lower compression force acted on the chord-type member in the model roof. For full scale, we considered six times the model size for the "flowering doom", and the range of compression force was much larger. Thus, the force should not act on the elastic member because of the need to avoid elastic member buckling. Therefore, the pier type VGT was more suitable for the dome roof.

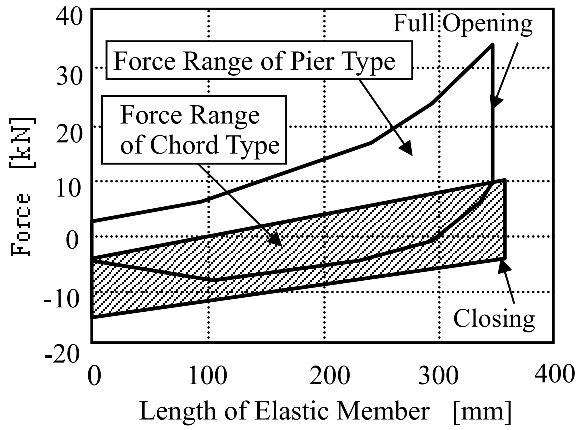


Figure 10 Comparison of Axial Force

(2) Stiffness of Roof and Precision of Control Length

When the roof was moved from closed to full open, the tip displacement stiffness was very important from the viewpoint of structural design. If the pier-type roof shape was similar to the chord-type roof shape, the pier-type stiffness increased with the roof opening and the chord-type stiffness was opposite. However, considering the characteristics of the hydraulic actuator, the pier-type stiffness was showed larger than the chord type at complete closure.

A few errors occurred in the control length of the elastic actuator. For the roof, accumulation error occurred in the position of the tip. The chord-type error was approximately constant regardless of shape change. However, the pier-type error was very small at complete closure. This detail was shown in a previous report [4].

From these results, it was decided to use the pier-type VGT because it was superior in static characteristics at completed closure.

3.2 Dynamic Characteristic Acted on VGT Roof

As the roof rotated around the VGT hinge, the force and rotation moment, i.e., centrifugal force and Coriolis force acted on the whole roof. In particular, by increasing the length rate, a large dynamic force was activated near the base and the lower elastic member of the roof. In this analysis, an exclusive dynamic software was applied under several conditions with a model of an elastic member, as shown above Figure 11. This figure shows the force acting on the

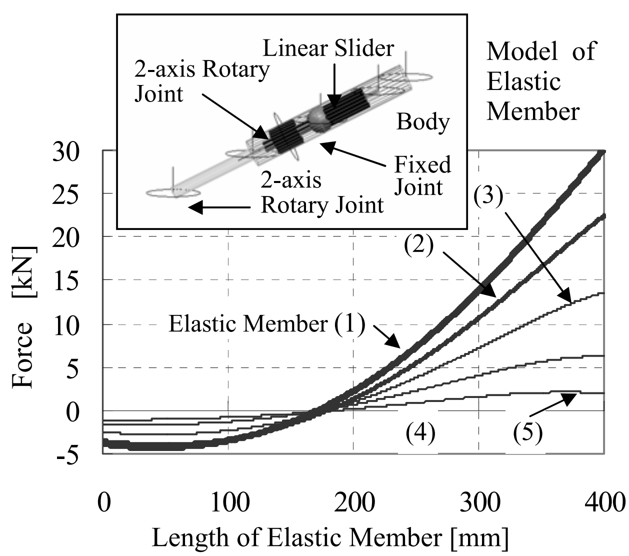


Figure 11 Dynamic Force Acted on Elastic Member

elastic member under a normal length rate of 5 mm/s. This force was equal to that of the static data, but the dynamic force was influenced near full opening. Figure 12 shows the force acting on the lower elastic member at several length rates. For length rates of 5 through 100 mm/s, the dynamic item wasn't considered. For length rates of more than 200 mm/s, a very heavy force was activated on the elastic member. At full scale, the dynamic force greatly increased. In this case, the elastic member as well as the material design was obliged to resume. Dynamic analysis is indispensable for solving these complicated movements of adaptive structures.

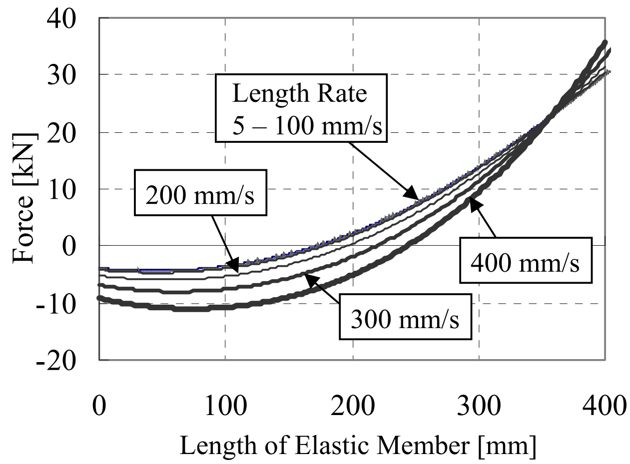


Figure 12 Forces to Length Rate of Elastic Member

3.3 Manufacture of a Reduced VGT Dome Model

The composition of the partial roof for the Flowering dome and the whole of the model roof are shown in Figure 13 and Figure 14 respectively. Five sets of pier-type VGT were arranged in series at the centre of each partial roof. A solid truss was installed on either side of the 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 continuously. The acrylic board, the 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 was waterproofed. The elastic member was comprised a hydraulic actuator, a trunnion-type special device equipped with a pump and an oil tank. The elastic length and the hydraulic pressure were measured by a stroke sensor and a pressure gage, and they were controlled by an integrated management system. The model was about 1 / 6 scale and two roof sheets divided into 10 sheets were manufactured.

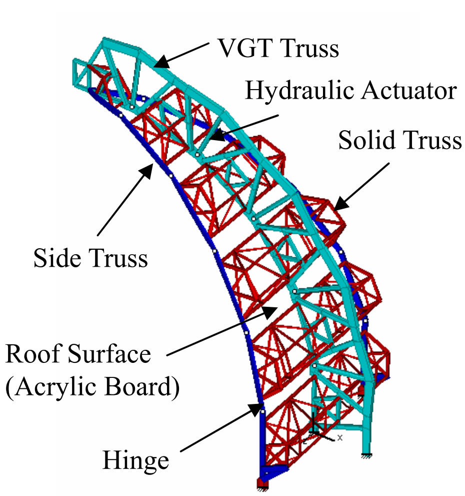


Figure 13 Roof Structure Installed VGT

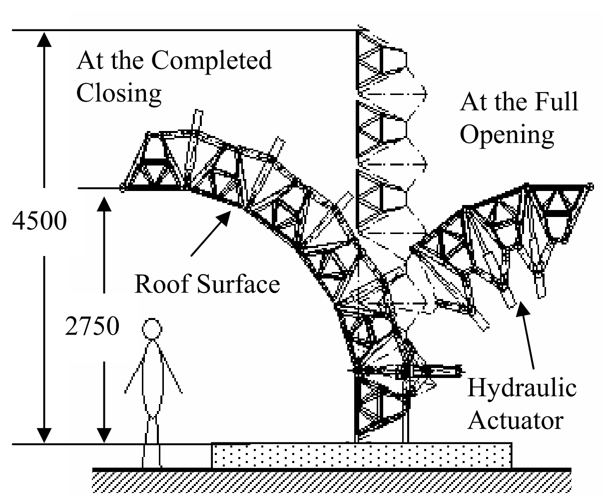
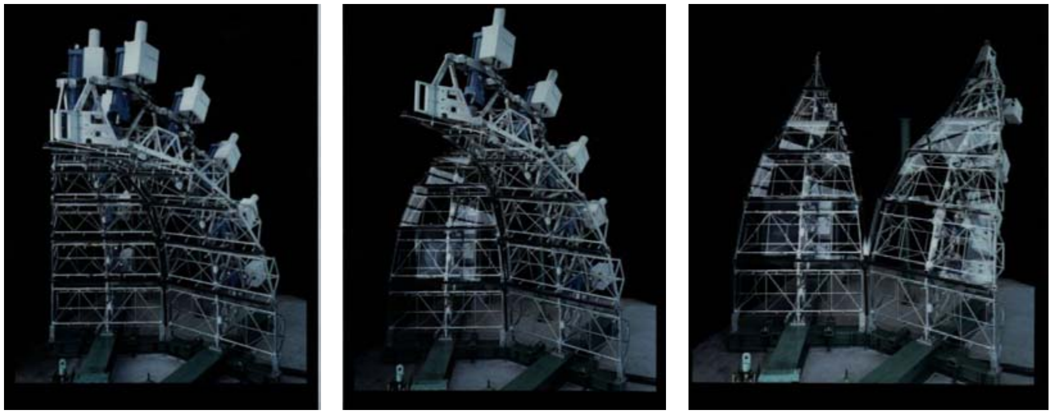


Figure 14 Schematic Structure of VGT Dome Model



(1) Completed Closing (2) One of Roof was Closing and the Other was Opening (3) Moving Roofs to Several Shape

Figure 15 Operation Condition of the Model of Flowering Dome

Figure 15 shows the operating conditions of the moving model roof of a completed Flowering Dome. The length rate of the elastic member was set constant at 5 mm/s. The roof's movement was smooth and it took about 3 minutes to move the roof from fully closed to fully open. The variable structure roof could be set as required by controlling the length of the elastic member. Furthermore, the positioning precision of the tip of each roof was good at closing and it was precise enough to overlap each roof. The scale model verified that the actual adaptive dome was possible.

4. Conclusion

The Variable Geometry Truss was developed to enable a flexible structure. It was equipped with flexible and intelligent functions, and various shapes could be created freely by contriving its arrangement and control. The structure was considered to have a very wide application included the smart and sustainable structure. This paper has proposed an example of an adaptive structure applying the VGT. The efficiency and the characteristics of the VGT could be grasped under the several conditions by a scale model of a Flowering Dome. In the future, more detailed characteristic of the VGT structure need to be understood and further development is expected.

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