Improved Morphable Beam Device for Equipping Camera at Beam End

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To conduct remote inspection missions, the authors has proposed Morphable Beam Device (MBD) and developed an experimental device using a bendable beam without any articulated joints. In the device, a beam is deployed, enabling a wide range of shapes and lengths. In this paper, a prototype of an MBD is introduced and a beam shaping theory for two beam shaping mechanisms of slide and rotation types is discussed and verified with experiments.

Key Words: MBD, Beam, Visual Check, Camera

1. Introduction

In the case that a body or solar panel of a artificial satellite is damaged by collision with debris, it is difficult to identify the cause or problem using only internal information of a satellite such as current or voltage measurement. For a large space structure such as the International Space Station (ISS) visual checks can be made using the robot arm or extra vehicle activity by astronauts, but for many space structures in orbit such checks cannot be made because such systems necessitate large mass and high costs. Thus, a visual check system in low costs and small mass is desired. A visual check system which can be attached to a small satellite has been proposed by the authors and called the Morphable Beam Device (MBD)¹⁻⁵⁾.

The concept of the MBD is shown in Fig.1. The MBD is composed of a bendable beam which has no actuators and a device which controls the beam shape. This beam can be flexed easily and keep its shape like a desk lamp shown in Fig.2. By equipping the camera to the top of the beam and controlling the shape and length of the beam, the MBD can make a visual check of the satellite.

This characteristic of the MBD can realize to downsize the visual check system. For example, comparing with the case of using a robot arm, the MBD does need not an actuator inside of arm.

Fig. 1. A illustrative concept of MBD.

Fig. 2. A desk lamp beam has the similar features to the MBD beam.

A test model of the MBD has been developed to verify the

concept¹⁻⁵⁾ (Fig.3). The extension and shaping of the beam was tested using this model. In the next step, the prototype model of the MBD was developed to verify the storage, extension, shaping and control algorithm.

In this paper, the structure of the prototype model and a beam shaping theory are introduced and verified with experiments. A new structure for beam shaping is also proposed and compared with the existing structure.

Fig. 3. The test model (left) and prototype model (right) of MBD.

2. The Structure of the MBD Prototype Model

The structure of the prototype model⁵⁾ is shown in Fig.4. This consists of a storage, an extender and a shaper.

Fig. 4. MBD prototype model structure.

2.1 Storage structure

The storage structure stores the beam spirally and consists

of a bobbin and a guide structure as shown in Fig.5. The maximum length of beam is 5 m for storage. The bobbin is actuated by a stepping-motor.

Fig. 5. Storage structure.

2.2 Extender structure

The extender extends the beam from the storage to the shaper and consists of two gears. These two gears bite the beam as shown in Fig.6. To fit the tooth to the gear chase, the extender must get enough friction to extend the beam. The extender is driven by a stepping-motor.

Fig. 6. Structure of the extender.

2.3 Shaper structure

The shaper changes the beam shape which extends from the extender. This consists of a cross-roller-ring and a roller slide mechanism as shown in Fig.7. Each structure is actuated by a stepping-motor and the roller slide mechanism changes the rotation of the motor to a linear motion using a ball screw and a ball spline. The table adjunct to the roller slide mechanism has one hole. By sliding this hole to any point, the beam can be bent, whilst extended. As a result, the shape of beam can be changed.

Fig. 7. Shaper structure.

2.4 Beam structure

The beam of MBD consists of a spring and a wire as shown in Fig.8. The wire is twisted around the spring. By the friction between the wire and spring, the beam can keep the shape.

Fig. 8. Beam structure.

3. A Theory of Beam Shaping

A theory of beam shaping based on the shaper mechanism is explained with considering a model of the beam shaping. There are two types of the beam shaping. One is a roller slide mechanism as shown in the previous section and another one is a roller rotation mechanism which controls the beam shape by rotating two rollers as shown in section 3.2. For each beam shaping structure, the structure is modeled and the relation between input values and a beam curvature is obtained.

3.1 A roller slide mechanism for the beam shaping

3.1.1 The principle of the beam shaping

A side view of the shaper is shown in Fig.9. The shaper consists of an upper and a lower stage. The upper stage moves on the ball screw fixed to the lower part. The deformation volume of the beam is decided by the position relation between the hole of the upper stage with rollers and the hole of lower stage at the entry point of the shaper. As shown in Fig.10, by extending from the extender to the shaper and touching the roller, a curvature is induced on the beam. The beam curvature is 0 when the hole of the upper stage is in the center, and the curvature increases as the displacement of upper stage increases. This is the basic principle of the beam shaping of the MBD. However, the relationship between the displacement of the upper stage and the beam curvature is not linear, which means that it is difficult to control the beam shape.

Fig. 9. A side view of the shaper.

Fig. 10. A concept of the beam shaping.

3.1.2 Retro-bending phenomenon

The retro-bending phenomenon²⁻⁴⁾ was confirmed with both the test and the prototype models. Normally, the beam bends in the same direction as the upper stage displacement. The beam curvature increases as the displacement increases. When the upper stage reaches a certain point, the beam starts to bend in the opposite direction as shown in Fig.11. This phenomenon is called “retro-bending phenomenon” and should be discussed in the beam shaping theory.

Fig. 11. Beam shaping before and after the retro-bending phenomenon.

3.1.3 A gap model and a theory of beam shaping

A theory of beam shaping considering the retro-bending phenomenon is explained with use of a gap model. The characteristics of the gap model are:

1. There is a gap between the beam and the roller.
2. The beam shape is a continuous circular arc.
3. The curvature radius is constant if the displacement of the upper stage is constant.
4. At the entrance of the shaper, the beam is perpendicular to the bottom of the shaper.
5. The roller diameter is constant.

The parameters of the gap model are defined as:

R : curvature radius of the beam

r : radius of roller

h : height from the bottom of the shaper to the center of the roller

d : diameter of beam

l : distance between the rollers

C : difference between l and d ($= l - d$)

Fig.12 illustrates the retro-bending phenomenon. The left figure shows the small displacement case of the upper stage and the beam bends in the same direction. The right shows the large displacement case and the retro-bending phenomenon occurs. If the displacement is small, the beam touches only one roller, but if the displacement is large, the beam touches both the rollers and is bent in the opposite direction.

Fig. 12. Left is small displacement case, and right is large one.

There are three shaping modes. When the displacement is small, the beam touches only one roller and bends in the same

direction. This mode is called a positive bending. When the displacement becomes large enough, the beam touches the two rollers but the direction remains the same. This mode is called a critical bending (start to inverse). When the displacement is large, and the beam touches the two rollers it bends in the opposite direction. This mode is called an inverse bending. The retro-bending phenomenon is when the beam transitions from the critical bending to the inverse bending.

Positive bending

Fig.13 shows the geometric condition of the positive shaping, where R^+ is the curvature radius of the outside of the beam. From Pythagorean theorem,

$$(R^+ + a)^2 + h^2 = (r + R^+)^2 \quad (1)$$

By solving equation (1), equation (2) is obtained.

$$R^+ = \frac{a^2 + h^2 - r^2}{2(r - a)} = R + \frac{d}{2} \quad (2)$$

As the displacement of the upper stage increases, the curvature of the beam increases.

Fig. 13. A gap model of the positive bending.

Critical bending (start to inverse)

After the beam touches the second roller, the beam bends in the same direction as the upper stage. This shaping is the critical bending (start to inverse). Fig.14 shows a geometric model of the critical bending. Until the point where the beam touches the left roller, the curvature radius of the beam is R^+ with center O_3 . After that point, the curvature of the beam becomes R_L with center O_4 .

Because the triangles O_1AO_3 and O_1HO_2 become homothetic, equations (3) and (4) can be written as:

$$h_L = h \times \frac{l}{R^+ + r} = \frac{hl}{R^+ + r} \quad (3)$$

$$r + d + a_L = (a + R^+) \times \frac{l}{R^+ + r} = \frac{l(a + R^+)}{R^+ + r} \quad (4)$$

From Pythagorean theorem of triangle O_2HO_4 , equation (5) is written as:

$$(R_L^- - a_L)^2 + h_L^2 = (R_L^- - r)^2 \quad (5)$$

From equations (3) (4) (5), R_L^- is written as:

$$R_L^- = \frac{(R^+ + r)(r^2 - (r + d)^2) + 2l(r + d)(R^+ + r)(a + R^+) - l^2(a + R^+)^2 - l^2h^2}{2(R^+ + r)(R^+ + r)(2r + d) - l(a + R^+)} \\ = R_L - \frac{d}{2} \quad (6)$$

Hence, the curvature reduces as the displacement of the upper stage is increases.

Fig. 14. A gap model of the critical bending.

Inverse bending

After the point of the retro-bending phenomenon, the direction of the beam is reversed. This beam shaping is the inverse bending. Fig.15 shows a geometric relation of the inverse bending. The curvature of the beam changes at the point at which the beam touches the roller as in the critical bending. The center of curvature is opposite with the case of the critical bending after the point.

Because triangles O_1AO_3 and O_1HO_2 become homothetic, equations (7) and (8) can be written as:

$$h_H = h \times \frac{l}{R^+ + r} = \frac{hl}{R^+ + r} \quad (7)$$

$$r + d + a_H = (a + R^+) \times \frac{l}{R^+ + r} = \frac{l(a + R^+)}{R^+ + r} \quad (8)$$

From Pythagorean theorem of triangle O_2HO_4 , equation (9) can be as:

$$(R_H^+ + a_H)^2 + h_H^2 = (R_H^+ + r)^2 \quad (9)$$

From equations (7), (8) and (9), R_H^+ can be written as

$$R_H^+ = \frac{-(R^+ + r)^2 \left(r^2 + (r + d)^2 \right) - 2l(r + d)(R^+ + r)(a + R^+) + l^2(a + R^+)^2 - l^2h^2}{2(R^+ + r)(R^+ + r)(2r + d) - l(a + R^+)} \quad (10)$$

$$= R_H^+ + \frac{d}{2}$$

Fig. 15. A gap model of the inverse bending.

These three modes relate the input of the shaper to the beam curvature on the basis of the gap model theory. Fig.16 shows the relation with the parameters defined as $l=21.6\text{mm}$, $d=5.4\text{mm}$, $r=8\text{mm}$, $h=32.6\text{mm}$. In this graph, the opposite curvature is plotted as negative. The curvature from the positive shaping to the inverse bending moves smoothly.

Fig. 16. A relation of displacement and curvature of beam.

3.2 Roller rotation mechanism for beam shaping

The roller slide mechanism demonstrates the retro-bending phenomenon which makes control difficult and necessitates a transfer mechanism from the rotation motion of the motor to the linear motion making the structure large and heavy. To solve these problems, a roller rotation mechanism which rotates the roller of the upper stage of the shaper for the beam shaping is proposed. Fig.17 shows this structure which has two rollers on the upper stage of the shaper. The beam is extended and bent when the state rollers are tilted. The retro-bending phenomenon does not occur with this structure. This structure can use rotational motion of the motor directly and minimize the structure.

Fig. 17. A concept of the roller rotation mechanism.

Fig.18 shows a model of the roller rotation mechanism. In this model the upper two rollers rotate about their center resulting in a constant curvature of the beam.

Each parameter is defined as follows:

R_1, R_2 : upper rollers radii

R_3, R_4 : lower rollers radii (on the extender)

θ : angle of upper rollers for the horizontal plane

L : distance between upper rollers and lower rollers

l_1 : distance between upper rollers

l_2 : distance between lower rollers

D_1 : diameter of upper roller

D_2 : diameter of lower roller

P_1 : intersection of the right side of beam and the line which is perpendicular to the beam and on the contact point of upper left roller and beam.

P_2 : intersection of the upper right roller and the beam

P_3 : intersection of the lower right roller and the beam

α : The angle between line from P_3 to P_1 and the vertical line

Equation (11) can be written from the geometry.

$$\tan \alpha = \frac{\frac{l_2 - D_2}{2} - \frac{l_1}{2} \cos \theta + \frac{D_1}{2} \cos \alpha}{L - \frac{l_1}{2} \sin \theta - \frac{D_1}{2} \sin \alpha} \quad (11)$$

P_1' is defined as the center of a virtual roller which has the intersect of the beam at point P_1 . Then the two equations can be written as:

$$P = k(\vec{R}_1 - \vec{P}_1') + \vec{P}_1' \quad (12)$$

$$|\vec{PP}_1'| = |\vec{PR}_2| \quad (13)$$

Equation (14) can be derived from equations (12) and (13).

$$k = \frac{|\vec{R}_2|^2 - |\vec{P}_1'|^2 - 2\vec{P}_1'(\vec{R}_2 - \vec{P}_1')}{2\vec{P}_1'(\vec{R}_2 - \vec{P}_1')} \quad (14)$$

From equations (12), (13) and (14), the outside curvature of the beam is given as the length of vector $\vec{PP}_2'$.

Fig. 18. A model of rotational motion.

The relationship of the angle of the roller and the curvature of the beam is shown in Fig.19. In this graph the parameters are defined as $D_1=D_2=20.1\text{mm}$, $l_1=23.4\text{mm}$, $l_2=22.8\text{mm}$, $L=30\text{mm}$, $D=2.7\text{mm}$.

Fig. 19. The relationship of the roller angle and the beam curvature.

When the angle of the set of two rollers is 20deg, the curvature radius of the beam becomes about 25mm which is the minimum curvature radius of the beam.

The whole range of the beam curvature radius is achieved by rotating the set of two rollers from 0 to 20deg. However, when the angle is near 0, the rate of change of the curvature radius is large, which implies that a high accuracy control is needed to avoid large errors in the output curvature.

4. Verification Experiment of the Beam Shaping Structure

4.1 Experiment of the roller slide mechanism

In this section, verification of the gap model theory in section3.3.1 is shown. In this experiment the prototype model of the MBD is used. For each displacement of the shaper, the beam is extended and the resulting curvature is measured using a 3 dimensional measurement sensor. The curvature is calculated using the least-square method from the measured data.

Figs. 20 and 21 show the experimental results for the relationship between the displacement of the upper stage of the shaper and the curvature of the beam. Fig.20 shows the result in the case that the gap between the roller and the beam is 0.25mm ($C=0.25\text{mm}$). Fig.21 shows the result in the case of $C=1.0\text{mm}$.

Fig. 20. A relationship between displacement and curvature of the beam when $C=0.25\text{[mm]}$.

Fig. 21. A relationship between displacement and curvature of the beam when $C=1.0\text{[mm]}$.

It is found that the overall characteristics of the experimental data and that of the theory are similar. However, the graph shows that the curvature line of experiment is shifted in the right part of the line of theory. It is believed that the lower stage of the shaper is not so horizontal as shown in Fig.22. For this reason the beam may not have extended vertically and resulting in some angle between the pole-z and the beam causing the change of curvature of the beam as seen in the graph.

Fig. 22. A modified model of roller slide mechanism.

4.2 Experiment of the roller rotation mechanism

The roller module as shown in Fig.23 was made to verify the roller rotation mechanism of beam shaping. In this experiment, the beam was extended and the curvature was measured at intervals of the angle of roller at every 2.5deg. Fig.24 shows an experimental setup. It is confirmed that the beam maintains constant curvature while extending. Fig.25 shows a relationship between the angle of the roller sets and the curvature of the beam. From the results of the experiment, it is found that the characteristics of the curvature achieved in the experiment are the similar to these of theory but differed in magnitude. In the roller rotation mechanism model, the characteristics of the materials are not considered in the theory and this seems to cause a difference in the predictions by the theory.

Fig. 23. A prototype roller module.

Fig. 24. Experimental setup of beam extension.

Fig. 25. The relation of the angle of roller set and the curvature of beam.

5. Conclusion and Future Works

For the MBD proposed as the appearance check camera system, two beam shaping mechanisms and the theory of beam shaping were discussed and compared with experiments.

Both the linear motion and roller rotation mechanisms exhibit similar characteristics. However, the roller slide

mechanism has two singular points: at the point where the displacement is 0 and the other one where the retro-bending phenomenon occurs. On the other hand, the rotational motion has only one singular point when the displacement is 0 and the control of beam is easier.

The roller slide mechanism necessitates a transfer structure making the device large and heavy. On the other hand, the roller rotation mechanism does not need such a transfer structure allowing the device to be smaller and lighter compared with the roller slide mechanism.

The beam of MBD is weak in external forces like a gas jet thruster because of the flexible feature of the beam. If the MBD is used repeatedly, when the beam bent, the MBD should store and re-extend the beam. If the MBD is used only once, a support against external forces is necessary. For example the inflatable tube seems to be suitable as a support against external forces.

Future works aim to develop the roller rotation mechanism and an associated control algorithm and to verify the algorithm through experiments. A vision feedback control using a camera is also a future work.

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