NEW DESIGN OF FLEXIBLE JOINT FOR SPACESUIT AND ITS DEFORMATION ANALYSIS

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Introduction

Future human space exploration programs toward the moon, Mars and beyond require highly advanced spacesuit system compared with current one operated on the International Space Station. Development of spacesuit system has several technological challenges especially on its joint flexibility, weight reduction, dust durability, size-adjusting capability, easy maintainability, reliability and safety. Among those, improving joint flexibility of spacesuit has been a technical challenge for a long time, and still sufficient performance has not been realized yet.

An EVA (Extravehicular Activity) pressurized space suit is inherently exposed against pressure gap between outside and inside of the suit. This gap causes expansion of the suit fabric like a balloon and makes joints much rigid to be bent; therefore, internal pressure was reduced to 29.6 kPa for current U.S. EMU (Extravehicular Mobility Unit). However, it still gives astronauts heavy fatigue during EVA, and additionally prebreathe procedure costing several hours to avoid decompression sickness became necessary. To increase the efficiency of EVA, newly designed mobility system enhancing locomotion even at 60kPa, at which the prebreathe is not required, is expected.

In this study, new design concept of joint structures named Membrane-Beam Folding Structure (MBFS) is proposed, and feasibility of the design is investigated.

Design of Membrane-Beam Folding Structure

Membrane-Beam Folding Structure consists of membrane and rigid beams. The rigid beams are attached on the membrane following a particular pattern (see Fig. 1(a)). The rigid beams keep the shape of the structure folded against pressure difference to enhance the flexibility of bending motion. The pattern selected in the present work is called Yoshimura pattern, which enable to fold cylindrical thin-walled shell or membrane along axial direction completely. To fold the pattern, angle \( \alpha \) between valley line and mountain line in Fig. 1(b) is defined as \( \alpha = \pi / 2n \), where \( n \) is the number of valley lines in a circular cross section. While Yoshimura pattern has been studied as one of the folding patterns at axial compression, little attention has been paid to bending property of this pattern. The purpose of the present study is to investigate bending property of inflatable tubes with Yoshimura folding pattern.

Experimental

The cantilever bending test is set up focusing on one degree-of-freedom joint, for example, elbows and knees. 0.17 mm-thick nylon fabric cylindrical tubes (diameter: 128 mm, length: 236 mm) are initially pressurized with air up to 15 kPa (gauge). To keep airtightness, 0.03 mm-thick polyethylene layer is inserted under the fabric layer. Tubes are closed from both ends with a plastic cap. A free end is loaded perpendicular to tube’s axial direction, and a fixed end is inclined to keep the angle between loading direction and tube’s axial direction perpendicular. The angle of the inclination represents deformation angle \( \theta \).

Three kinds of tubes are tested; 1) plain type, 2) bellows type, and 3) MBFS type. Plain type means non-modified nylon cylindrical tubes. To make MBFS type of tubes, four stainless steel pipes are connected with stainless steel wire in a square frame. These frames are attached to the nylon cylindrical tube following Yoshimura pattern's valley lines with a proper distance between the frames (ca. 20.7 mm). Bellows type tube is made by the same way as the MBFS type of tube, but instead of frames wire rings are attached to the fabric with the same distance between them. The length of the wire ring for bellows type and the square frame for the MBFS type are same as circumference of the fabric tube.

The test is carried out under a static loading \( F \) from 0 to 10 kgf with 250 gf step. Photograph of the shape is taken to measure deformation angle \( \theta \), and internal pressure \( P_{IN} \) is recorded.
Results and discussion

The relationship between load and deformation angle is shown in Fig. 2. Plain and bellows type tubes show very similar trend: until about 4000 gf the deformation angle slowly increases, and after that, more intensive deformation is initiated. From these results, it is found that the work of the load up to 4000 gf is consumed to counterbalance prestress on fabric of tube, and that circumferential restraints attached on bellows type do not affect bending property of inflatable tubes.

On the other hand, the MBFS tube starts large bending as soon as the tip load is applied; thus, much less load is required for bending deformation. To bend the MBFS tube from 0 degree to 10 and 20 degree, for instance, 61% and 51% less load is required, respectively, in comparison with the plain type of tube. This trend can be explained by the structural elasticity which is given by attachment of rigid beams. The elasticity contributes to reduce bending rigidity of the MBFS. In case of plain type of tube, the pressure difference across the membrane induces the tensile stress along longitudinal and circumferential direction. Although outer joint part of membrane need to be stretched more as well as inner joint part of membrane is compressed to start bending deformation, the longitudinal tensile stress prevents the deformation. However, as for the MBFS, the tensile stress on membrane is mitigated by the structural elasticity; thus, the MBFS starts deformation immediately after loading.

Fig. 3 shows the relationship between internal pressure and deformation angle. In case of plain and bellows tubes, internal pressure rapidly increases with deformation propagation. However, the pressure growth inside the MBFS tube is rather slower. It can be said that tubes of MBFS type are able to deform with lower volume change, that decreases the work necessary for air compression inside the tube during bending.

Summary

In this paper, a new joint structure of spacesuits, named Membrane-Beam Folding Structure (MBFS), is designed and proposed.

The cantilever bending test demonstrates that the bending property of the MBFS is superior to a normal pneumatic tube. The reason is explained from two points of view. Firstly, the structural elasticity alleviates tensile stress on membrane caused by pressure. Hence, less torque to bend is needed. Secondly, the MBFS has a capability to maintain internal volume during bending deformation by both folding and unfolding membrane on inner and outer sides of the MBFS; thus, less work is required.

Publications

The study results were presented at the following two international conferences. Both presentations were given in oral style.

- Kengo Ikema, Anna V. Gubarevich, Osamu Odawara, “Deformation Analysis of a Joint Structure Designed for Space Suit with the Aid of an Origami Technology”, The 27th International Symposium on Space Technology and Science, July 5-10, 2009, Tsukuba, Japan