Study on Drag Torque Characteristics of Corrugated Joint for Spacesuit under Human-Induced Loads

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Abstract. The mobility of spacesuit joints is the key factor affecting the ability of the lower-torso space service, and the drag torque of joint is an important indicator which represents the mobility of joint. Drag torque is affected by many factors, such as contact with garment, gas pressure and materials of spacesuit, which cause difficulties in theoretical calculation. A finite element simulation on drag torque characteristics of corrugated joint of spacesuit with human body is carried out. And a detailed finite element model is established which reflects the characteristics of fabric material and the actual structure of corrugated joint. Based on this model, the dynamic simulation of joint rotation in two ways of external driving and human body driving is carried out. The cause of drag torque is analyzed. Then the influence of spacing and arc length of bellows on characteristics of drag torque is studied. The results show that the sources of drag torque during rotation are the structural elastic deformation and the work to compress gas. The drag torque of joint which is in the way of human body driving is greater than by external driving, which is because the elastic deformation and work to compress gas of the former are both larger than the latter. And methods, reducing the spacing and increasing the arc length of bellows, could reduce the drag torque of joint.

1. Introduction

The main function of the extra vehicular activity spacesuit is to provide astronauts with vacuum protection and support operations [1]. Due to the internal inflation of the space suit, the difference of pressure between the inside and the outside of the garment is generated, which causes a large drag torque of the joint during the rotation, which restricts the efficiency of the astronauts in the operation. With the development of space exploration, there are more and more extravehicular activities, requiring space joints to be more flexible and reliable. Corrugated joint is a typical spacesuit soft joints used to achieve low resistance bending of joints [2]. In the design of space suits in the United States and Russia, this structure was used in different parts of clothing [3, 4]. Therefore, the research and improvement of corrugated joints is of great significance.

The corrugated space suit joint is mainly composed of a three-layer structure in which contains a protective layer, a confinement layer and an airtight layer. The outer protective layer serves to protect the astronauts from the space environment such as rays and particle currents. The middle layer is a confinement layer, which is made of splicing and stitching of fabric materials, and is used for carrying
the gas pressure in the space suit. Fabric materials have great tensile stiffness and strength but cannot withstand compressive and bending loads. The airtight layer is located in the inner layer and is generally composed of materials such as rubber, polymer to form a closed cavity inside the space suit and prevent gas leakage from the spacesuit. Corrugated joints of spacesuit can be divided into two parts: corrugation and bands. The bands are divided into separating units and axial restriction bands. Wherein, the laterally closed belt between adjacent corrugations are called separating units, and the separating units are generally composed of a thick fabric, the circumference of which is smaller than the corrugation circumference, and is stitched between adjacent corrugations according to a certain geometric relationship to restrain the circumferential dimension of the corrugated structure after inflation. An axial restriction band composed of a belt is provided on the corrugated joint corresponding to the stitches of the two side pants, and the length of the band can be adjusted to limit the axial elongation of the corrugated structure. The structure of the corrugated joint of spacesuit is shown in Figure 1.

![Corrugated joint of spacesuit](image)

**Fig 1.** Corrugated joint of spacesuit

Vykukal H C [5], Matty J [6] and Meven F [7] conducted experimental research to analyze the drag torque of corrugated joint. Abramov [8] obtained the relationship between the drag torque of corrugated joint and the angle of rotation by establishing the equilibrium relationship between the internal force and the external force of the joint, but the model did not consider the elastic deformation of the corrugation shell. Furuya H and Yokoyama J [9-10] simulated the bending process of the inflatable tube and the inflatable bellows, and analyzed the generation and development of the folds.

Liu Hong and Wang Hao [11-14] measured the drag torque of corrugated joint through experiments and fitted the experimental curve to obtain the drag torque model during joint motion, but the model could not reflect the influence of the structural parameters on the drag torque. Li Guangli [15] derived the drag torque equation of the corrugated joint based on the principle of minimum potential energy, and obtained the relationship between the drag torque and the rotation angle. However, the theoretical method does not consider the deformation of the separation units and the situation that the section of the actual separation units is non-planar and the fabric material is nonlinear. Shang Kun [16] used the finite element method to simulate the flat pattern joint of the spacesuit, obtained the relationship between the drag torque of joint and the rotation angle, and analyzed the cause of the drag torque, but the material definition in the model did not consider the hysteresis characteristics of the fabric material. Zhang Xinjun [17] used the Jiles-Atherton hysteresis model [18] to obtain a mathematical model that can reflect the hysteresis characteristics of the joint moment, fitting drag torque curves of the shoulder and wrist joint, but this method can not directly reflect the influences of joint structure size. Liu Qilin [19] combined with the characteristics of pleated structure and isotensoid structure, designed a new type of soft joint of space suit. Through experimental research, the advantages of the new joint were explained, but it was not tested in the actual garment joint. Liu Qilin [20] established a finite element model of pleated isotensoid joints to analyze the drag torque of joint, and carried out experimental verification.

In this paper, the nonlinear finite element method is used to comprehensively consider the complex geometry of the corrugated structure, the deformation of the separation units and the nonlinear properties of the fabric material, and to simulate the actual shape and motion of the corrugated joint. A finite
element model based on the actual joint structure is established in which the source of the drag torque of corrugated joint and the influence of structural parameters on the drag torque of joint are analyzed.

2. The finite element model of corrugated joint
The motion simulation of the corrugated joint is a kind of nonlinear analysis, which is mainly manifested in the geometric nonlinearity caused by the large rotation and the large displacement of the joint, the nonlinearity of the boundary condition caused by the change of the direction and magnitude of the loading force, and the nonlinear mechanical properties of the fabric material. This article uses Abaqus commercial software to build a finite element model of the corrugated joint.

2.1. Geometric model
The main force bearing structure of the corrugated joint is the fabric, so the single-layer flexible corrugated joint is established mainly based on the confinement layer during modeling. As shown in Figure 2, a geometric model of the corrugated joint was constructed by using the interactive CAD software CATIA. Through the surface modeling, the geometric characteristics of the corrugations and the restriction band are represented. The whole structure is divided into upper, middle and lower parts, and the middle part is corrugated geometry, which includes four corrugations and separation elements located between the corrugations. The joint cavity is closed at both ends of the corrugated joint by a cover. The human thigh also uses surface to describe the figure.

2.2. Material and element
The fabric is divided into two directions of warp and weft according to the direction of interlacing. Due to the nonlinear mechanical properties of the fabric yarn, the friction between the yarns, the buckling changes of the warp and weft, and the structural changes during the deformation of the fabric, the fabric exhibits nonlinear mechanical properties in warp, weft and shear properties [21]. Parameters of material model need to be determined by tensile tests in the warp and weft directions and frame shear tests [22].

According to the textile industry standard [23], the tensile tests in the warp and weft directions of the fabric materials used in garments were carried out on a universal testing machine to obtain the tensile properties of the fabric in warp and weft directions, as shown in Fig. 3(a). The fabric material exhibits anisotropy in the plane and exhibits distinct nonlinearity during the loading and unloading process in warp and weft directions, and there is energy loss during the loading and unloading process. There is hysteresis in both warp and weft directions. According to the frame shear test method of fabric described in the literature [24], the fabric shear performance curve was measured. As shown in Fig. 3(b), the fabric showed obvious nonlinearity in the shear test, and there is hysteresis during the unloading process.
In order to accurately simulate the anisotropy and nonlinear mechanical properties of the fabric, the material is defined by adding the keyword "*Fabric" and the corresponding program code in the input file. For the simulation of the tensile loading and unloading curve in the warp and weft directions and the shear loading and unloading curve, the weft loading and unloading curve shown in Fig. 3(a) is taken as an example: the weft loading and unloading curve of the fabric is obtained by experiment. The data points measured by tests and linear interpolation methods are defined in the Damage material model in Abaqus, and the region between adjacent data points will be linearly interpolated to define the material constitutive relation, which reflects the nonlinear properties of the fabric. This material model allows the material to dissipate energy during unloading, and there is no permanent deformation when completely unloaded, which can reflect the hysteresis characteristics of the unloading section of the fabric curve. Thus, the constitutive relationship of the fabric material measured by experiment is applied to the model.

Since the fabrics, rubber and other materials that make up the spacesuit are layer materials, the bending stiffness of them has little effect on the structure. Therefore, the corrugated joint adopts the membrane element M3D4R. The human thigh adopts discrete rigid body element. And the two ends are blocked by using discrete rigid body element.

2.3. Constraints on deformation of corrugations
The constraints to the deformation of corrugated structure are divided into axial constraint and transverse constraint. The former is realized by axial limiting band and the latter by separation units.

In order to simulate the axial restraint of the corrugated joint, as shown in Figure 4, axial restriction bands were respectively established on both sides of the overall structure, and were stitched together with the first and fifth layer separation units according to the actual stitching position. Five layers of separation units are used as the circumferential constraint which are positioned on the upper and lower sides of each layer of corrugations.
2.4. Boundary conditions

The boundary conditions of the model consist of force boundary conditions and displacement boundary conditions.

The upper end of the corrugated joint uses a fixed constraint to form a displacement boundary condition. The gas pressure in the joint air cavity constitutes a force boundary condition within the cavity. By defining the joint cavity of the model as a fluid cavity, the joint cavity is inflated, the reference point of fluid cavity is used to control the pressure in the cavity, and to conveniently output the volume and mass of the gas. The first step is aeration. The gas is filled into the cavity according to a fixed gas flow rate to simulate the inflation process. After a certain time, the specified working pressure is reached in the cavity. After that, the gas quality in the cavity is maintained, that is, the model does not leak. The model pressure curve is shown in Figure 5. The motion of the joint is controlled by force loading. During the inflation process, the lower end is in a free state, and after the inflated structure reaches the initial balance, the joint rotation is achieved by applying a force load on the lower rigid cover. When the human body drive mode is adopted, as shown in Figure 6, the garment rotation is driven by applying a rotation load at the center of the hip joint.
Since the angle of the corrugated joint in the test is only 12.5°, there is no contact between the corrugations and no friction occurs. And the simulation results confirm this point (as shown in Fig. 7). The influence of friction factors on the joint drag torque is very small, so the ideal frictionless model is used.

3. Results

3.1. Results comparison of simulation and experiment

Figure 7 shows the simulation results of the corrugated joint rotation process. The figure shows the joint morphology and stress distribution at several typical stages during the corrugated joint motion. Compared with the initial state, the corrugated structure is expanded when the cavity reaches the working pressure. The third layer separation unit is elongated by 15.09 mm in the short axis direction and 6.51 mm in the long axis direction, and the corrugated structure tends to be cylindrical. However, due to the presence of the separating units, further expansion of the corrugated structure in the circumferential direction is constrained. After inflation, the corrugated joint has a tendency to elongate in the axial direction, and due to the presence of the axial restraining band, its axial displacement is constrained, so that there is a stress concentration in the suture. At the same time, the length of the axial restriction band will affect the degree of compression of the corrugated structure. Within a certain range, the length of the axial restriction band is short, and the rotational margin of the outer side of the corrugated structure is large, which has an advantage to rotate. After applying a force load to the joint, the inner corrugation and the separating units are rotated to compress, and the outer corrugation and the separating units are rotated to stretch.

To validate the model, the test using the same size as the model is carried out which is under the same loading conditions. As shown in Fig. 8, during the experiment, the center of the lower end of the corrugated joint is loaded by a tension meter. The loading direction is always perpendicular to the axis of the corrugated joint, parallel to the blocking plane, and the angle θ is measured by the protractor, and the dynamometer reading F is recorded.
Fig 7. Simulation of corrugated joint motion
Figure 9 shows the correspondence between the dimensionless drag torque of a corrugated joint and the joint angle. Reference [15], dimensionless drag torque is defined as:

\[ \overline{M} = \frac{M}{pr^3} \]  

(1)

Where, \( M \) is the drag torque, \( p \) is the gas pressure in the joint cavity, and \( r \) is the joint radius. The model calculation results can reflect the changing trend and characteristics of the drag torque during the motion of the corrugated joint. When the angle of the joint does not exceed 10°, the simulation results are in good agreement with the experimental results. When the angle is greater than 10°, the joint appears to be hardened. The drag torque measured by the simulation and the test are rapidly increased, and the simulation results are greater than the test results.

3.2. Analysis of sources of error
The finite element model extracts the main structural features and material properties of the actual structure, and simplifies the physical joints. So there are certain numerical deviation. Due to the complexity of the actual corrugated structure, the geometric model will have deviation in the size and spacing of the corrugations. There is uncertainty error in the dynamometer reading during the test. The arm of force and joint angle are measured outside the test piece, so the measurement result has deviation with the actual drag torque and angle.

3.3. Results of human body drive mode

![Graph showing contrast of drag torque in two kinds of methods](image)

**Fig 10.** Contrast of drag torque in two kinds of methods

Figure 10 shows the contrast of drag torque in two kinds of methods. The human thigh starts from the initial position, rotates 5.1° and then comes into contact with the human body, after which the human body begins to drive the garment to rotate. As shown in the figure, when the human body drives the hip joint to rotate, the value of the joint drag torque is greater than by external driving. And as the joint rotation angle increases, the difference between the drag torque of human body driving and that by external driving gradually increases. When the angle of joint is 10°, the drag torque of the human body driving is increased by 58.51% compared with the external driving. And when the angle of joint is 15°, the drag torque of the human body driving is increased by 61.55% compared with the external driving.

4. Analysis of cause of drag torque

4.1. Variation of joint cavity volume in two kinds of driving methods

In the study of joint drag torque, previous research show that the work to compress gas in the cavity during rotation of the joint is the main source of drag torque [15]. Only considering the volume change of the air cavity, The calculation formula of drag torque is

$$M = -p \frac{\partial V}{\partial \theta}$$  \hspace{1cm} (2)

Where $V$ is the joint cavity volume and $\theta$ is the corresponding joint motion angle.

Figure 11 shows the change of the volume of joint cavity along with the angle of joint during rotation of corrugated joints. During the bending of the corrugated joint, the volume of the joint cavity decreases as the joint angle increases, and the rate of decrease gradually increases, and the pressure in the cavity remains substantially unchanged. Moreover, when the human body drives, the volume decreases faster
and the volume changes more, so the work to compress gas is more, resulting in a larger drag torque. During the whole rotation of the corrugated joint, when the joint is driven by human body, the volume of the joint cavity does not change by more than 1.32% of the original volume, and the volume in the way of external driving does not change by more than 1.17%, indicating that the corrugated joint has good isovolumetric capacity. However, due to the large initial volume of the joint cavity, small changes in volume can also cause large work to compress gas.

![Figure 11](image-url) Variation of joint cavity volume with joint angle

4.2. Energy analysis of two kinds of driving methods

From the perspective of energy, during the rotation of corrugated joint, the following energy changes exist:

\[ E_{SE} + E_{KE} + E_{FD} + E_{\text{compress}} = E_{\text{ext}} \]  

(3)

Where, \( E_{SE} \) represents the elastic strain energy, \( E_{KE} \) represents the kinetic energy, \( E_{FD} \) represents the frictional dissipation energy, \( W_{\text{compress}} \) represents the work done for the compressed gas, the value can be obtained by integrating the pressure \( p \) on the volume \( V \), i.e.,

\[ W_{\text{compress}} = -\int p dV \]  

(4)

\( E_{\text{ext}} \) represents the work of external force, this value is obtained by integrating the joint resisting moment \( M \) on the joint rotation angle \( \theta \), i.e.,

\[ E_{\text{ext}} = \int M d\theta \]  

(5)

The changes in various types of work and energy during joint inflation and rotation are shown in Figure 12. The period from 0 to 1 second is the inflation process, and the period after 1 second is the rotation process. In the process of inflation and rotation, the kinetic energy and frictional dissipation energy of the model are far less than other kinds of work and energy. So the dynamic response in the model can be neglected, and the influence of friction on the drag torque of corrugated joint is small. During the inflation process, the increment of elastic strain energy is similar to the work to compress gas. During the rotation process, the work to compress gas increases all the time, the change of elastic strain energy is smaller than the former, and it changes more gently.
Fig 12. Variation of different types of work and energy

The different kinds of energy and work obtained by the model are corresponding to different kinds of sources of drag torque. Whether it is an external drive or a human body drive, the source of drag torque of the corrugated joint includes two parts: the drag torque generated by the compression of the gas in the cavity and the drag torque generated by the elastic deformation of the joint. The first part of the drag torque is determined by the change of the volume of the joint cavity, and the numerical value can be obtained by the formula (1). The second part of the drag torque is affected by the material, geometry and loading mode of the corrugated joint. It could be obtained by differentiating elastic strain energy.

During the rotation of the corrugated joint, the amount of numerical change in the work to compress gas is large, and the amount of numerical change in the elastic strain energy is small. When the rotation
of joint is driven by external force and the angle is greater than $10^\circ$, the elastic strain energy caused by the elastic deformation begins to increase. When the rotation of joint is driven by human body, the work to compress gas and elastic strain energy are both greater than that in the external drive mode. And the elastic strain energy begins to rise rapidly when the joint angle is greater than $5^\circ$. Since the two sources both contribute more to the resistance torque when the rotation is driven by the human body, the drag torque of joint is greater than that in an external drive mode.

Therefore, it is important to improve the structure and material design of the corrugated joint, for maintaining the isovolumetric capacity of the corrugated joint and reducing the volume change of the air cavity during the rotation, and at the same time, reducing the drag torque generated by the elastic deformation is needed.

![Variation of different types of work and energy along with joint angle](image)

Fig 13. Variation of different types of work and energy along with joint angle
5. The Influence of structural parameters

Since the structural elastic deformation and work to compress gas are the sources of drag torque of corrugated joint, and the corrugation spacing and corrugation arc length which are crucial structural parameters of corrugated joints factors affect two kinds of energy. To study the effect of structural parameters, the actual structure of corrugated joint is simplified into a regular structure as shown in Fig. 14, and the material still uses the fabric as described above.

Parameters h/r and L/r represent the spacing and arc length of corrugation respectively. For the convenience of comparison, the initial parameters of the structure are set to h/r = 0.25, L/r = 0.5, to study the impact of each parameter separately. The results are shown in Figures 15 and 15. Figure 14 shows when L/r = 0.5, the drag torque curve of corrugated joint in which h/r is 0.2, 0.225, 0.25, 0.275 and 0.3 respectively. When the corrugation spacing reduces relatively to the initial value, the drag torque shows a decreasing trend; while the corrugation spacing increases relatively to the initial value, the drag torque increases rapidly. When the angle of joint exceeds 8° , the drag torque rises rapidly, which is because the increase of the corrugation spacing will reduce the rotational margin due to fabric accumulation which is located on the outer side of the corrugated structure during the rotation process. As the angle increases, the outer corrugation is gradually flattened and the elastic deformation of the fabric rises rapidly, thereby causing the drag torque to rise rapidly. Figure 16 shows when h/r = 0.25, the drag torque curve of corrugated joint in which L/r is 0.5, 0.75, 1, 1.25, and 1.5 respectively. When the arc length of the corrugation increases relatively to the initial value, the drag torque shows a decreasing trend.

The results show that when the angle of the corrugated joint is within 10° , reducing the corrugation spacing or increasing the arc length of the corrugation is beneficial to reduce the drag torque joint.
6. Conclusions
A finite element model of corrugated joint of spacesuit which considers the characteristics of fabric materials and the characteristics of actual structures is established, and the model is verified by experiment. The method has great applicability and can be applied to other corrugated structures.

There are two sources of drag torque of corrugated joint: structural elastic deformation and work to compress gas. The drag torque of joint under the human body driving mode is greater than that under the external driving mode, because the structural elastic deformation and the work to compress gas of the former are relatively greater.

On the basis of maintaining the isovolumetric capacity of the joint, reducing the corrugation spacing and increasing the arc length of the corrugation within a certain range is beneficial to reduce the drag torque of joint.

7. References
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