Mechanical Properties of Silicone Elastomer Seals for Space Docking Vehicles

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Abstract. Low impact docking mechanisms (LIDM) are developing. The LIDM seal is one of the key components of the LIDM, and play very critical roles during the docking and berthing of space vehicles. Due to the severe functional requirements, it is difficult to develop the LIDM seal that is a silicone elastomer seal. The excellent mechanical property is firstly required for the LIDM seal. Five design schemes of the LIDM seal are proposed by this paper, and their mechanical properties are studied by the proposed finite element method. The mechanical properties of the LIDM seal have important impacts on the required sealing performance, docking feature and separation feature. The findings are beneficial for the development of the LIDM seal for space docking vehicles.

1. Introduction

For expanding the docking and berthing capability of further space vehicles, many counties are developing low impact docking mechanisms (LIDM). The LIDM is the executive component of the space rendezvous and docking of two vehicles, and is used for the mechanical docking, the docking retention and the separation of the two vehicles. For the two vehicles involving in the space rendezvous and docking, one is the target vehicle, and the other is the tracing vehicle. After the docking is finished, both the target vehicle and the tracing vehicle are connected as a whole, so some interactive actions can be carried out in the two vehicles such as material exchange, astronaut delivery and fuel filling-up. In order to prevent leakage of the matters in the cabins such as atmospheres and fuels, the sealing performance of the interface of the two vehicles is very important, which is guaranteed by the LIDM seal. There are many key requirements for the LIDM seal that is the silicone elastomer seal, and it is one of the key research objects of the LIDM.

At present, the main research findings about the LIDM seal are from the research subjects funded by the National Aeronautics and Space Administration (NASA). Christopher C et al designed a candidate seal of LIDM, which was composed of a primary and a redundant elastomer seal retained by a metallic ring, and the elastomer used to manufacture the seal was Esterline ELA-SA-401 [1]. Patrick H D et al studied two types of seal designs for the LIDM seal, one is a Gask-O-seal, and the other is a multi-piece seals. A series of performance assessments and comparisons were performed between the two seals such as design feature, leak rate and adhesion load etc [2]. LIDM seals are typically made of silicone elastomers, they can suffer damage from ultraviolet radiation and atomic oxygen etc when such seals are exposed to low earth orbit conditions. Emily C I et al studied the effects of the space environment on the LIDM seal [3-5]. Patrick H D et al designed a test fixture which was used to evaluate the leakage of candidate full-scale LIDM seals under simulated thermal, vacuum, and
engagement conditions [6, 7]. Ian M S et al studied a LIDM seal that is a composite design consisting of elastomer seal bulbs molded into the front and rear sides of a metal ring, and the test specimens were sub-scale seals with two different elastomer cross-sections and a 12-in outside diameter [8]. Nicholas G G et al studied experimentally the leakage rate of a LIDM seal that was manufactured from silicone elastomer S0383-70 vacuum molded in a metal retainer ring [9, 10]. Nicholas P et al designed a LIDM seal, and performed some leak tests that were completed at nominal temperatures of –30, 20, and 50 °C, and the influences of both test temperature and atomic oxygen exposure on the performance of the seal were studied [11]. Nicholas G G et al studied the compressible permeation of a LIDM seal, and purposed a physics-based model to provide a predictive methodology, by which the fundamental permeation mechanics of the LIDM seal were obtained [12].

The design of the LIDM seal is the chief topic for its development. The excellent mechanical property is required for the LIDM seal, and it decides the sealing performance, docking feature and separation feature. Using the finite element (FE) method, the mechanical properties of five design schemes of the LIDM seal will be discussed, which can be referenced by the development of the seal.

2. LIDM seal

The LIDM seal is a key component of the LIDM that is the seal at the main docking interface, which inhibits the loss of cabin air once docking is complete. The diagrammatic sketch of a LIDM and its interface seal (LIDM seal) is shown in figure 1 [1-3]. The LIDM seal is designed to maintain acceptable leak rates while the LIDM is exposed to the harsh environmental conditions of outer space. Besides the good sealing performance, the LIDM seal is required to have some other properties such as low load, easy docking, easy separation and repetitive use etc.

![Diagrammatic sketch of a LIDM and its interface seal](image1)

Figure 1. Diagrammatic sketch of a LIDM and its interface seal

According to the docking interface, there are generally two configurations for the LIDM seal, one is the seal-on-flange configuration, and the other is the seal-on-seal configuration. When a docking system equipped with a seal docks to a system with a flat metal flange, the seal-on-flange configuration needs to be used, for example an application when a vehicle docks to a node on the International Space Station. The seal-on-seal configuration needs to be used when two docking systems equipped with seals dock to each other, and the two types of seal are identical. Here, the seal-on-seal configuration is discussed here, and the diagrammatic sketch of a seal-on-seal configuration is shown in figure 2. A LIDM seal is constituted by two front seals, two back seals and their retainer. In the retainer, there are many tap holes, by which the LIDM seal is fixed in the LIDM when the corresponding fasteners are used.

![Diagrammatic sketch of a seal-on-seal configuration](image2)

Figure 2. Diagrammatic sketch of a seal-on-seal configuration
For the designs of the LIDM seal, there are mainly two types for the seal-on-seal configuration now, one is the gask-O-seal, and the other is the multi-piece seal. Both types of seals have a pair of seal bulbs to satisfy the redundancy requirement. The materials used for both the front seals and the back seals mainly are the silicone rubber.

For the design of the LIDM seal, the design of the front seals is pivotal, which plays an important role on the combination properties. Here, five design schemes for the front seals are discussed. The diagrammatic sketches of cross-sections of the five front seals are shown in figure 3. The seal material is also a silicone rubber.

![Diagrammatic sketches of cross-sections of five front seals](image)

**Figure 3.** Diagrammatic sketches of cross-sections of five front seals

3. Mathematical methods

The FE method is adopted to study the mechanical property of the front seal based on ANSYS® software. The 2D-axisymmetric FE models are developed to investigate the five front seals, and the FE model of the scheme E is shown as figure 4. In the FE models, the PLANE183 element is used to represent the seals, and the Coulomb model is adopted for the contact and friction analysis. Both the TARGE169 element and the CONTA172 element are used for the contact elements.

![FE model of the scheme E](image)

**Figure 4.** FE model of the scheme E

In the FE model, a Yeoh formulation is selected as the hyperelastic constitutive model where the strain energy is defined as a function of the first strain invariant and the Jacobian. The Yeoh model is taken into account as [13]

\[
W = \sum_{i=1}^{N} c_i \left( I_i - 3 \right)^3 + \sum_{k=1}^{6} \frac{1}{d_k} (J - 1)^{2k} \\
\frac{\partial W}{\partial I_1} = \sum_{i=1}^{N} i c_i \left( I_i - 3 \right)^{3-i} J^{-2/3} \\
\frac{\partial W}{\partial I_2} = 0 \\
\frac{\partial W}{\partial J} = \sum_{k=1}^{6} k d_k (J - 1)^{2k-1}
\]

Where \( W \) is the strain energy, \( I_1, I_2 \) and \( I_3 \) are the principal invariants, and \( J \) is the Jacobian. Both \( c_i \) and \( d_k \) are the material constants. \( N \) is the order of the polynomial fit, which is chosen to cubic so that the larger strain behaviour can be captured and the material response remains stable at all strains. So, the simplified Yeoh model is stated as

\[
W = c_1 \left( I_1 - 3 \right)^3 + c_2 \left( I_1 - 3 \right)^2 + c_3 \left( I_1 - 3 \right) + \frac{1}{d_1} (J - 1)^3 + \frac{1}{d_2} (J - 1)^2 + \frac{1}{d_3} (J - 1)
\]

3
4. Analysis and discussions
By the FE method, the mechanical properties of the five front seals will be investigated. The key material and structural parameters are described in table 1. The sealing medium is atmospheric, and the operating pressure is the normal atmospheric pressure and the temperature is 25 °C. The compression amounts of all the seals are all identical [13].

| Parameters                  | Values     |
|-----------------------------|------------|
| Inner diameter of front seals | 1.24 m     |
| Outer diameter of front seals | 1.28 m     |
| Young’s modulus             | 3.15 MPa   |
| Poisson’s ratio             | 0.47       |
| $c_1$                       | 0.2693     |
| $c_2$                       | -0.0644    |
| $c_3$                       | 0.0278     |
| $d_1$                       | 0.00112    |
| $d_2$                       | 8.38×10^{-5} |
| $d_3$                       | 6.43×10^{-6} |

The Mises stress contours of the five front seals are shown in figure 5, from which the following conclusions can be obtained.
(1) The stress of the scheme A is detrimental to both the sealing performance and the stability.
(2) The stresses of the last four schemes are similar, and the maximum Mises stress decreases with the cross-sectional area.

![Figure 5](image-url)

The $\sigma_{22}$ axial stress of the five front seal is important for the docking and separation features. The $\sigma_{22}$ axial stress contours of the five front seals are shown in figure 6. Compared with the other schemes, the docking and separation features of the scheme A is poorer.
The sealing performance of the front seal is decided by the contact pressure of the contact area. The contact pressure distributions of the five front seals are as shown in figure 7. The pressure distribution of the scheme A is relatively flat, which is disadvantage for the sealing performance.
5. Conclusions
The five design schemes of the LIDM seal are introduced, and their mechanical properties are investigated by the proposed FE method. The mechanical properties have important impacts on the required sealing performance, docking feature and separation feature. The mechanical properties of the scheme A is found to be disadvantage for the sealing performance, docking feature and separation feature of the LIDM seal. The mechanical properties of the schemes from B to E are similar, and all can be selected as the alternatives. Of course, there are some differences for the four design schemes including of the stress distribution, the sealing load, the sealing area. According to the actual development requirements of the LIDM seal as a silicone elastomer seal, the suitable design scheme will be selected and optimized further.

Acknowledgments
The authors acknowledge the financial support by the Project study on mechanism of novel space docking seal of spacecraft by National Natural Science Foundation of China (No. 51675056).

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