DESIGN OF A MECHANICAL SEALING DEVICE FOR ROBOTIC WATER DISTRIBUTION PIPE REHABILITATION

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ABSTRACT

Water distribution pipe maintenance is a global concern. In this study, we propose a Rehabilitation In-Pipe Robot (R-IPR) to perform pipe rehabilitation operations and contain induced contamination. The robot features three modules: a pipe cleaning module, a mechanical sealing module, and an in-pipe manipulator module. This study emphasizes the comprehensive design of the mechanical sealing module. We introduce a multi-layer compound structure of the seal to deal with two characteristics of tuberculated pipe surfaces: 1. macroscopical surface roughness, 2. overhang in foundation profile. The prototype excels in sealing foundation overhang and requires 45% lower compression load than a baseline seal to function. The prototype seal is integrated into the R-IPR. Finally, experiments of the overall system demonstrate the successful performance of the first contamination-less in-pipe rehabilitation.

Keywords: Design Optimization; Compliant Mechanisms; Robotics and Mechanism Systems

1 INTRODUCTION

Water pipeline maintenance is a severe and global issue. In the United States and Canada, more than 10% of the distributed

water is lost on its way to the consumers, and over 240,000 water main breaks can happen annually [1]. In developing countries, water loss rates can be up to 40% [2, 3]. Despite the urgency in saving water, the most widely applied method for water pipe rehabilitation is still replacing the entire pipe section after a water-main outburst takes place. Other preventative practices utilize heavy-duty machinery such as mechanical grinders, metal scrappers, and hydro-jets to remove pipe corrosion asperities [4], normally referred to as tubercle. This type of task, categorized as open-cut rehabilitation, is insensitive to potential outbursts, requires complete shut-off of water service, and is largely constrained by the pipe diameter.

Rehabilitation In-pipe robots (R-IPR) bring an alternative method to the industry, that is to conduct rehabilitation on the internal surface of pipes. In general, a complete pipe rehabilitation

FIGURE 1. A severely corroded water pipe sample from Boston Water and Sewer Commission. The corrosion asperities are called tubercle.

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tasks involves multiple steps, including pipe wall cleaning, leak site repair and post-treatment [5]. Thinh et al. propose an R-IPR that is equipped with a cleaning disk, which has approximately the same diameter as the pipe. It removes tubercle while moving along the pipeline [6]. The DeWaLop robot by Mateos et al. [7], and the PROKASRO robot [8] each use a multi-DOF in-pipe manipulator and an onboard grinder for the removal task. However, a significant concern is ignored by IPR researchers, which is the excessive amount of contamination generated during the rehabilitation process. The harmful byproduct, if not adequately contained, can significantly increase the virus content downstream of the pipe network [9] and lead to severe consumer health issues [10]. Unfortunately, to the author's knowledge, no existing R-IPR has taken into account the contamination concern.

Correspondingly, we propose the Contamination-Less Rehabilitation (CLR) In-Pipe Robot. The robot accomplishes two tasks: conduct in-pipe rehabilitation and contain induced contamination. The most critical onboard component is a mechanical sealing module, whose primary objective is to create a complete enclosure on corroded pipe surfaces. Such surfaces possess two challenges for a seal, namely, macroscopical roughness and foundation overhang. Existing seals, including o-rings, gaskets and suction cups, are not designed for such surfaces, and cannot be deployed on the CLR Robot. To directly address the challenge, we propose a novel compound mechanical seal. It consists of a hyper-elastic contact layer (HCL) with an optimized cross-sectional geometry to manage the direct contact with macroscopically-rough surfaces, and a discrete suspension layer (DSL) to accommodate the foundation overhang.

This paper centers on the comprehensive design process of the mechanical seal. Sec.2 describes the essential functional requirements (FR) of the CLR Robot, and its projection on the sealing module. In Sec.3, the generalized design and optimization procedure of the hyper-elastic contact layer is presented, followed by the detailed design and considerations for the discrete suspension layer. Prototypes are fabricated and evaluated in Sec.4. Last but not least, in Sec.5, the seal is integrated as a module of the CLR Robot and deployed for the first contamination-less in-pipe rehabilitation for a corroded pipe.

2 FUNCTIONAL REQUIREMENT

The Contamination-Less Rehabilitation In-Pipe Robot is a continuation of the In-Pipe Robot series developed by the MIT Mechatronics Research Laboratory (MRL). Locomotion and pipe-profile inspection IPRs are presented in the previous studies [11, 12]. Therefore, it is assumed that the CLR Robot is facilitated by the locomotion and inspection robots, such that mechanical stiffness of the robot body and exact location of tubercle asperities are excluded from the scope of consideration.

As stated in the previous section, the overall objective of the CLR Robot is to perform a pipe cleaning task for corroded water

FIGURE 2. *Right:* Demonstration of manipulator and cleaning Module. *Left:* Demonstration of the integrated sealing module. The multi-DOF nested manipulator is installed on an existing locomotion IPR. The pipe cleaning module and sealing module are carried and operated by the manipulator.

distribution pipes while containing by-produced contamination. Three sub-tasks are involved, that is, tubercle removal, contamination containment, and end-effector deployment. Correspondingly, we propose the combination of a pipe cleaning module, a mechanical sealing module, and an in-pipe manipulation module. The manipulator operates the cleaning device and the mechanical seal, and the seal physically encompasses the cleaning device at all times, as depicted in Fig.2. The rehabilitation routine schemes as follows:

1. The manipulator engages the seal by compression against the corroded pipe wall to form a water-tight enclosure around the cleaning device.
2. While maintaining the enclosure, the manipulator operates the cleaning device to remove the tubercle asperities within the enclosure, and the introduced contamination is contained in the seal.
3. An external fluid pump circulates rinsing fluid within the enclosure and collects the contamination.
4. The manipulator disengages the seal and repeats procedure 1) - 3) at the next corrosion site.

From this routine, detailed functional requirements and correlated design specifications for the sealing module are derived:

1. Overall Functional Requirement:
 - (a) Completely encloses a region of corroded surface under compression.
2. Primary Specifications:
 - (a) Seal macroscopically-rough surfaces.
 - (b) Seal surfaces with foundation overhang.

3. Secondary Specifications:

- (a) Mechanically compatible with other components.
- (b) Operable in pipes with the CLR manipulator.

The main functional requirement for the seal is to create a complete enclosure on tuberculated surfaces. Upon meticulous inspection of corroded pipes, we identify two significant characteristics of pipe surfaces that make mechanical sealing exceedingly challenging. First, corroded pipe surfaces are macroscopically-rough, and second, there are steep foundation overhangs at pipe joints, on which the tubercle can grow. As a solution to these two challenges, we propose a multiple-layers compound mechanical seal. Its design and optimization methodology are detailed in the following section.

3 DETAILED DESIGN METHODOLOGY

In this section, we first break up the components of a novel compound seal. Further, we discuss in detail the design and optimization process of each component, along with the comparison with commercially available mechanical seals. More specifically, we present the problem formulation, analytical modeling, virtual simulation and physical experiment.

3.1 Module Description

There are two main challenges upon sealing a corroded pipe surface. First is its macroscopical surface roughness. The proposed solution to this challenge is a hyper-elastic contact layer, as displayed in Fig.3. The layer adopts a piece of silicon material with an optimized cross-section. It is in charge of the direct contact with the macroscopic peaks and valleys on the pipe surface.

Change in pipe profile is another critical concern. A sealing module relies only on the hyper-elastic contact layer could fail when the tubercle grows on a foundation overhang, for example, an extrusion at a pipe joint. Correspondingly, a discrete suspension layer is integrated as an auxiliary layer. It serves as a floating support for the hyper-elastic layer. In the case of a foundation overhang, it localizes the affected region and maintains the functionality of the entire module. The discrete suspension layer is installed on a support base, which serves as a mounting portal with the in-pipe manipulator.

3.2 Hyper-elastic Contact Layer

3.2.1 Limits of Existing Seals Heat seal and induction seal are common types of static seal. However, they require special machinery and are limited in the application scenario, and are thus not considered in this study. The face seal is another subset of static seals. A face seal is placed between two mating parts. Under compression, the seal fills the irregularities on the mating surfaces and prevents fluid from trespassing. An example is a gasket on an automobile engine. Nonetheless, the

FIGURE 3. An exploded view of the mechanical sealing module. It consists of a hyper-elastic contact layer, a discrete suspension layer and a support base.

state-of-the-art face seal is designed to mate artificial surfaces, whose asperity heights are in μm order [13].

The most widely applied seals are o-rings. They are used in both static and dynamic operations. A static o-ring is a type of face seal, whose functionality and shortcomings are described above. O-rings are also compatible with dynamic operations, which makes an o-ring the right sealing module candidate for the CLR Robot. Another advantage of an o-ring is its inherent material property to seal liquid interface. However, the engagement of an o-ring requires a high axial or radial load, in the order of MPa , which could pose an excessive burden on the in-pipe manipulator. Furthermore, tubercle asperities often possess cm scale sizes. The peak-valley height difference can be greater than the thickness of an o-ring. Forced deformation of an o-ring over such surfaces can easily exceed the 10% - 40% strain range, causing it to fracture or yield.

Alternatively, the possibility of using suction foams is reviewed. Suction foams are popular for robotic grasping. Its properties are in complement with an o-ring - it is particularly superior in engaging with macroscopically rough surfaces and operating under low axial load. However, the hollowed structure prevents suction foams from sealing fluid interface under pure compression.

3.2.2 Problem Formulation The hyper-elastic contact layer adopts the material advantage of o-rings and the structural superiority of suction foams. The technical problem is formed as: a piece of silicone rubber that is bonded to a rigid plate being evenly pressed against a rough substrate. The physical parameters are denoted as follows and are illustrated in Fig.4:

- A_{nom} : nominal contact area between two bodies
- E : Compression modulus of the silicone material
- E_a : Apparent modulus due to compression
- F_a : applied compression force on the HCL
- $F_{max,act}$: load capacity of the manipulator
- $h(\mathbf{x})$: height measured from the deepest valley
- h_{max} : maximum height of the tubercle asperities
- H : cross-sectional height of the silicone piece
- l : unit length of the silicone piece
- l_{tot} : total circumference of the HCL
- $\mathbf{M}_{CLR}$: design metric of the overall CLR Robot
- P_a : applied compression pressure on the HCL
- T : cross-sectional thickness of the silicone piece
- w : penetration between the two contact bodies
- $\mathbf{x}$: $[x, y]$ coordinate on the tubercle plane
- α_1, α_2 : positive regulation coefficients
- ν : Poisson's ratio of the elastic material

The ultimate objective of this study is to minimize F_a that is applied to seal a certain substrate. In addition, large cross-sectional height is penalized because the geometric volume is extremely valuable in an in-pipe environment. The optimization problem is formulated as:

$$\begin{aligned} & \underset{T, H, E}{\text{minimize}} && \alpha_1 F_a + \alpha_2 H \\ & \text{subject to} && F_a = f(T, H, E, h(\mathbf{x}), l, w) \\ & && F_a < F_{max,act} \\ & && T, H, E, l \in \mathbf{M}_{CLR} \end{aligned}$$

The relationship between compression force and compression pressure is:

$$P_a = \frac{F_a}{A_{nom}} \quad (1)$$

The nominal contact area A_{nom} is the contact area between two bodies projected on the plane of compression. In the demonstration shown in Fig.4:

$$A_{nom} = T \cdot l \quad (2)$$

FIGURE 4. Parameters for the analytical model of the hyper-elastic layer.

3.2.3 Analytical Model Corroded water pipe walls have randomly distributed asperities at different length scale. A widely applied approach to quantify surface roughness is through power spectral density (PSD). Similar to the PSD counterpart in signal processing that describes the distribution of power in frequency components, surface roughness PSD expressed the power spectrum $C(q)$ in terms of q , the roughness wavevector [14, 15]:

$$C(q) = \frac{1}{A_{nom}} \left| \int h(\mathbf{x}) e^{-iq^T \mathbf{x}} d^2 \mathbf{x} \right|^2 \quad (3)$$

In a 2-D space, the wavevector space is denoted as $\mathbf{q} = [q_x, q_y]^T$ and $q = \sqrt{q_x^2 + q_y^2}$. Further, it is assumed that the tuberculated pipe surface is self-affine fractal, indicating that when a part of the surface is magnified at different magnifications, the profile is roughly the same and its statistical properties are invariant [16]. Traditional contact models by Hertz [17], Greenwood [18], or Bush [19] are not valid to describe the rough pipe surface, because they assume parabolic geometries of the substrate asperities apriori. Alternatively, Persson et al. provides a method to calculate the compression pressure when a piece of elastic material is in contact with a self-affine fractal substrate as [20]:

$$P_a = \beta \frac{E}{1 - \nu^2} e^{-u/u_0} \quad (4)$$

where two terms $\beta = f_1(C(q), q)$ and $u_0 = f_2(C(q), q)$ are constant values for a piece of substrate. The term u is the distance between the deepest valley and the bottom of the elastic piece:

$$u = h_{max} - w \quad (5)$$

Bonding effect is a significant phenomenon for rubber under compression. Since the volume of rubber stays nearly unchanged during compression, i.e., $\nu \approx 0.5$, the unloaded faces of the rubber piece accumulate strain during the process and the apparent compression modulus varies based on the geometry of

cross-section [21]:

$$E_a = E \left[\frac{4}{3} + \frac{4}{3} S^2 \right] \quad (6)$$

where $S = \frac{T}{2H}$ is defined as the 'shape factor'. Taking into account the bonding effect and the geometric variables, T and H , Eqn.4 can be re-written as:

$$P_a = \left[\frac{16}{9} + \frac{4}{9} \left(\frac{T}{H} \right)^2 \right] \beta E e^{(w-h_{max})/u_0} \quad (7)$$

To generalized the design space, the independent parameters are dimensionalized in a Π group, as listed in Table.1.

TABLE 1. Buckingham's Π Group Quantities

Π_1	Π_2	Π_3	Π_4	Π_5	Π_6
$\frac{P_a}{E}$	β	$\frac{u_0}{h_{max}}$	$\frac{T}{h_{max}}$	$\frac{H}{h_{max}}$	$\frac{w}{h_{max}}$

The design space in the dimensionless domain is constructed in Fig.5. It depicts the compression pressure required to penetrate the silicone rubber into the substrate by a certain amount. When dimensionless penetration $\Pi_6 = 1$, it represents that the rubber barely reaches the deepest valley of the substrate, indicating a minimum seal. The case where $\Pi_6 > 1$ is an idealized scenario - the silicone material is no longer penetrating the substrate, but accumulating the elastic energy in the lateral direction. It is obvious that more penetration requires an increasing amount of work, and thus reflect in a larger compression pressure.

Given the other parameters controlled, with a larger cross-sectional height, the compression strain lowers, resulting in a reduced pressure. Furthermore, a significant result from Eqn.7 and Fig.5 is the dependency of P_a on the cross-sectional thickness T . The phenomenon trace back to the bonding effect of rubber. The increment in T not only results in a larger nominal contact area, but also causes an increment in the apparent modulus and the compression pressure. By exploiting this characteristic, an effort to minimize P_a is proposed: provided a constant overall cross-sectional thickness T_{tot} , the compression pressure requirement can be lowered by adding grooves that split the cross-section in the thickness direction, as presented in Fig.6. Denoting the number of grooves as n_g , and the thickness of each segmented piece as $T_{g,i}$, the proposed method is equivalent to utilizing:

$$P_{a,n_g} := \sum_{i=1}^{n_g+1} P_a(T_{g,i}), \sum_{i=1}^{n_g+1} T_{g,i} = T_{tot}, m > n \rightarrow P_{a,m} < P_{a,n} \quad (8)$$

FIGURE 5. A visualization of the analytical model with $u_0 = 6mm$ and $\beta = 0.072$. The cross-sectional geometry can significantly affect the compression load, indicated by 1,2,3.

As a result, the original optimization constraint on the cross-sectional thickness can be revised to $T_{tot} \in \mathbf{M}_{CLR}$. In addition, the analytical model implies that as $n_g \rightarrow \infty$, $T_g \rightarrow 0$ and $P_{a,n_g} \rightarrow 0$. Nevertheless, since this is infeasible in practice, a set of experiment is conducted to identify physical constraints on the optimization problem.

FIGURE 6. An illustration of the grooving method.

3.2.4 Physical Constraint A set of experiments are conducted to identify physical constraints that are not captured by the analytical model. For both the experiment and the CLR application, Smooth-on Ecoflex 00-30 is meticulously selected as the silicone material. Twenty specimens with various cross-sectional geometries, $T_{tot} = [2, 4, 6, 8]mm$ and $H = [5, 6, 8, 10, 12]mm$, are fabricated. A piece of 3D-printed mock tubercle, with $h_{max} = 6.87mm$, is designed and used as the substrate, whose topology is shown in Fig.7. The specimens are

FIGURE 7. Topology of the substrate for the experiment.

compressed against the substrate, and the required compression force to form a complete seal is recorded by a Vernier Dual-Range Force Sensor.

Each specimen is denoted in the format 'TiHj', where i, j are the thickness and height value, respectively. Five tests are conducted for every specimen. The compression pressure is computed with Eqn.1 and 2, and the experimental result is demonstrated by the box plot in Fig.8. A clear trend that agrees with the analytical model is observed: by reducing the cross-sectional thickness, compression pressure can significantly diminish. Thus, the validity of the grooving method is concluded.

In addition, some specimens fail to create a valid seal on the substrate. There are two categories of failure from our observation. In the first category are specimens with a short cross-sectional height. They tend to fail because the depth of the valleys at the contact surface exceeds the thickness. Thus, the following geometrical constraint is identified:

$$H > h_{max} \iff \Pi_5 > 1 \quad (9)$$

In the other category are specimens with small cross-section thickness. The underlying reason is that low-thickness specimens have low structural rigidity, consequently, severe buckling takes place under compression. Directly computing the structural rigidity, through the Timoshenko's plate theory [22] and

FIGURE 8. The sealing experiment for contact layers with different cross-sectional geometries.

non-linear properties of hyper-elastic materials, and bounding it would be an arduous yet trivially fruitful task for the CLR application. Instead, we make a reasonable simplification and define the aspect ratio, AR , to constrain the design:

$$AR = \frac{T}{H} = 2S = \frac{\Pi_4}{\Pi_5} \geq AR_{min} \quad (10)$$

Silicone material is considered the determining variable for AR_{min} in this study. Therefore, AR_{min} is experimentally extracted upon the selection of silicone material.

3.2.5 Implementation and Simulation Taking into account the comprehensive design constraints presented above, the finalized hyper-elastic contact layer is implemented with the following specifications and illustrated Fig.9:

$$\begin{aligned} T_{tot} &= 4mm, H = 8mm \\ n_g &= 1, T_{g,1} = T_{g,2} = 2mm \\ E &= 101kpa, AR_{min} = 0.25 \end{aligned}$$

A Finite Element Analysis (FEA) is conducted in ANSYS AutoDyn to validate the contact between the finalized design and the proposed substrate. A 2-Parameter Mooney-Rivlin Model is used to simulate the Eco-flex 00-30 material. The material constants are specified as:

$$\begin{aligned} C_{10} &= C_{01} = 15kpa \\ D_1 &= 1.21 \times 10^{-9} pa^{-1} \end{aligned}$$

From the FEA result, displayed in Fig.9, it is derived that with a per unit length force $F'_a = 90N/m$, the proposed elastic layer design can effortlessly seal the deepest valley of the mock substrate. The load capacity of the manipulator allows the length of the elastic layer to be $l_{tot} \leq l_{max} = 0.24m$.

FIGURE 9. The finalized cross-sectional geometry and its performance evaluated with ANSYS.

3.3 Discrete Suspension Layer

At pipe joints, it is common that a step difference in pipe surface geometry takes place, and tubercle inevitably grows at the step. This abrupt change in the foundation of the tubercle is called an overhang. Unfortunately, the PSD method by nature does not contain the knowledge of overhangs [14], because it only considers the profile of the contact surface. The step can cause an over-compression locally and prevent the other portion of the hyper-elastic contact layer from further compression. We introduce an auxiliary discrete suspension layer as the solution, as demonstrated by Fig.10. It consists of a cluster of compression springs to provide floating and discrete supports for the contact layer. When a region of the elastic layer is overly compressed, the discrete supports work as 'firewalls' to contain a majority of the excessive deformation.

FIGURE 10. Working principal of the discrete suspension layer.

An analytical model is developed to explore the design space. Without loss of generality, the hyper-elastic contact layer is characterized as multiple linear compression springs. Thus, as denoted in Fig.11, each silicone-support assembly is regarded as two compression springs installed in series. The nomenclature is defined as follows:

- $F_{a,HCL}$: total force on the HCL layer
- F_{tot} : force to create a complete seal with DSL installed
- k_{sil} : effective compression stiffness of silicone layer
- k_{spring} : compression stiffness of each spring
- l_m : length of HCL affected by the overhang
- l_n : length of HCL not affected by the overhang
- l_s : spacing between each spring
- l_{spring} : length of each spring
- $\mathbf{M}_{spring}$: geometric parameters of spring: diameter, etc

FIGURE 11. A simplified physical model to represent the interaction between the hyper-elastic contact layer and the discrete suspension layer.

$\alpha_3, \alpha_4, \alpha_5$: positive regulation coefficients
 δh : height of foundation overhang

To obtain the binary sealing capacity of the discrete suspension layer, the constraint of utmost importance is $l_{spring} > \delta h$. Similar to the optimization formulation in the contact layer design, the optimization objective for the DSL is formed as:

$$\begin{aligned} & \text{minimize} && \alpha_3 \cdot F_{tot} + \alpha_4 \cdot l_{spring} \\ & \text{subject to} && F_{tot} = f(F_a, k_{spring}, l_s, m) \\ & && l_{spring} > \delta h \\ & && l_{spring} \in \mathbf{M}_{spring} \\ & && k_{spring} = f(\mathbf{M}_{spring}) \\ & && \mathbf{M}_{spring} \in \mathbf{M}_{CLR} \\ & && l_n + l_m = l_{tot} \end{aligned}$$

Within every silicone-support assembly, when the silicone fully penetrates into the tubercle, the applied compression pressure is defined as $P_{a,o} := P_a|_{w=h_{max}}$. The corresponding compression force is thus:

$$F_{a,o} := P_{a,o} T_{tot} l_s \quad (11)$$

And the force of the entire contact layer is:

$$F_{a,HCL} := P_{a,o} T_{tot} l_{tot} \quad (12)$$

The effective stiffness of the silicone, k_{sil} , is defined as:

$$k_{sil} := \frac{F_{a,o}}{h_{max}} = \frac{P_{a,o} T_{tot} l_s}{h_{max}} \quad (13)$$

With basic structural mechanics on linear spring, the total force F_{tot} can be straightforwardly computed as:

$$\begin{aligned} F_{tot} &= F_{a,HCL} + \frac{n F_{a,o} k_{spring}}{k_{spring} h_{max} + F_{a,o}} \delta h \\ &= P_{a,o} T_{tot} l_{tot} + \frac{l_n P_{a,o} T_{tot} k_{spring}}{k_{spring} h_{max} + P_{a,o} T_{tot} l_s} \delta h \end{aligned} \quad (14)$$

The design processes of DSL and HCL are assumed to be decoupled, i.e., the parameters from the contact layer design are treated as constant values. In addition, environmental parameters such as δh and l_n are not subject to modification. Consequently, the decision variables of critical importance are l_s and k_{spring} . A visualization of the analytical model is presented in Fig.12. It is clear that with stiffer springs in the discrete support layer, the

FIGURE 12. A visualized result of the DSL analytical model: $h_{max}, T_{tot}, l_{tot}, l_n, \delta h = 6.87, 4, 212, 40, 2.5mm; P_{a,o} = 10kpa$.

overall device requires a larger compression force because more energy is needed to deform the springs. A reasonable design is to minimize the spring stiffness. However, as k_{spring} and l_{spring} have an inverse relationship, the design requires making a trade-off between them.

There is an opposite trend for the spring spacing. The compression force decreases as the spring spacing increases. This corresponds to the case where the arrangement of spring is sparser, therefore reducing the number of springs to be compressed. Nonetheless, this is not an optimal solution, as $l_s \rightarrow l_{tot}$, the discretization effect diminishes, until eventually the discrete suspension layer is abolished, and the binary sealing capacity for overhangs is lost. The exact model to describe this relationship is yet to be fully studied. At current stage, we make a hypothesis that the DSL functions properly when l_s is up to a characteristic length, above which the failure expectation of the discrete suspension layer escalates dramatically, and when l_s exceeds a distance threshold $l_{fail} < l_{tot}$, the seal entirely loses its functionality. So the cost of the optimization problem is revised as:

$$\text{minimize } \alpha_3 \cdot F_{tot} + \alpha_4 \cdot l_{spring} + \alpha_5 (l_s - l_c)$$

with l_c as the characteristic length. In the CLR application, it is assumed that l_c is on the same scale as the maximum size of the substrate asperities, approximately $5mm$. A comprehensive evaluation of the optimization problem leads to the final arrangement: $k_{spring} = 0.2 \frac{N}{mm}, l_s = 6.5mm, l_{spring} = 6mm$.

4 PROTOTYPE EVALUATION

In this section, three functional prototypes of the mechanical sealing module are implemented; each of them consists of a different level of the proposed design. Two experiments are conducted to evaluate the performance enhancement lead by each level of optimization.

4.1 Prototype Fabrication

The hyper-elastic layer in the first prototype consists of a simple T6H8 cross-section. It represents a baseline seal that doesn't involve any degree of optimization. The cross-section in Prototype 2 is the same as the finalized design. It embodies two T2H8 geometries. The hyper-elastic layer in Prototype 1 and 2 are directly installed on a rigid plate. Prototype 3 is a fully implemented sealing module. The dual-T2H8 layer is installed on a discrete suspension layer.

4.2 Evaluation Result

Two evaluative experiments are conducted. As demonstrated by Fig.13-A, the specimen is compressed against a piece of substrate during each experiment. The internal volume of the specimen is filled with colored test liquid. The minimum force to maintain no observable leak is recorded, and the corresponding compression pressure is computed via Eqn.1 and 2.

FIGURE 13. Set up for the evaluative experiment.

DOF qualitatively evaluates the binary sealing capacity of each prototype when it encounters an extreme overhang. The substrate is displayed in Fig.13-B. There is a step overhang with $\delta h = 2.5mm$ between the upper and lower portion of the substrate. As shown in Fig.14, all three prototypes successfully penetrate into the valleys in the upper substrate. However, Prototype 1 and 2 cannot seal the lower substrate because the portion of the hyper-elastic layer in contact with the upper substrate is fully compressed. For Prototype 3, its suspension absorbs the abrupt height change, and a complete seal is created across the substrate.

The second experiment is a comprehensive evaluation of the binary sealing capacity of overhang and the grooving method. The leak tests are conducted at six different locations on the substrate, as shown in Fig.13-C. More specifically, at location 3,4 and 5, there are step overhangs underneath the tuberculated surface, simulating a real-world condition. The experimental result is concluded in Fig.15. At location 3,4 and 5, Prototype 3 is the only operable specimen that creates seals for all tests. In contrast, neither Prototype 1 nor 2 can create a seal, due to the lack of a discrete suspension layer.

FIGURE 14. Experiment 1: The prototypes are pressed against a substrate with step height difference (pink).

At locations 1,2 and 6, all prototypes function properly. No artificial overhang is integrated at these locations; as a result, the surface roughness is the determining factor. Indeed, Prototype 2 and 3, because of the optimized contact layer, have significantly superior performances than Prototype 1 - the average compression pressure to create a complete seal is reduced by over 45%.

FIGURE 15. Experiment 2: Experiment result displays the functional of HCL and DSL.

5 INTEGRATION AND DEPLOYMENT

A CLR Robot is constructed, and the sealing module is integrated on the manipulator module, as demonstrated by Fig.16-A. Based on Prototype 3, the final sealing module is modified according to the pipe curvature, and the support base is revised to couple with the manipulator module, highlighted in Fig.16-B. A water-proof interface is combined with the support base to prevent fluid leakage into the manipulator during operation.

A 100mm-diameter corroded cast-iron pipe section was raised, and a real-world CLR deployment was conducted for

FIGURE 16. Demonstration of the prototyped CLR Robot.

it. The pipe section contained approximately 3-4mm tall asperities. The fully integrated CLR Robot was installed on a mock Locomotion-IPR fixture and fixed in the section. An external circulation device was linked to the fixture, exhibited in Fig.17-A. The manipulator engaged the seal in Fig.17-B, and the pipe-cleaning tool removed an approximately 10mm by 15mm corroded area on the pipe surface in Fig.17-C. The hyper-elastic contact layer before and after the operation is displayed in Fig.17-D,E. The darkened color on the HCL indicates full contact during the operation. The rinsing fluid circulated through the sealed enclosure, and the generated contamination was collected without any observable fluid leakage. This concludes the first real-world deployment of the CLR Robot is successful.

FIGURE 17. The first CLR deployment in a real pipe.

6 CONTRIBUTION AND DISCUSSION

In this paper, we introduced the Contamination-Less Rehabilitation In-Pipe Robot. It consists of three major modules: a pipe cleaning module, a mechanical sealing module, and an in-pipe manipulator module. This study emphasizes the comprehensive design of the mechanical sealing module. In particular, we proposed the multi-layer compound structure that comprises of: a hyper-elastic contact layer to seal the tuberculated pipe surface directly, and a discrete-suspension layer to overcome foundation overhang under the tubercle. The compound sealing device is the first of its kind that successfully address the two challenges.

For each layer, we present a thorough design analysis and optimization process. In addition, a grooving method to reduce the compression load is discovered and validated. The sealing module is implemented and proved to be superior to regular seals through multiple evaluations. Eventually, a fully functional CLR Robot is successfully deployed in a corroded pipe environment. In the current R-IPR community, the CLR Robot is the most compact R-IPR, equipped with one of the highest-DoF in-pipe manipulators.

The design process leads to some topics that worth exploring in the future. For example, in Sec.3, we present a hypothesis on the geometry of the discrete suspension layer and substrate topology. An exact relationship may be found via extensive experiments. Furthermore, in the real-world deployment, the sealing effect is evaluated in a qualitative manner. It will be beneficial to control the deployment environment and gather quantitative data on the sealing effect.

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