Parameterized Design and Dynamic Analysis of a Reusable Launch Vehicle Landing System with Semi-Active Control

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Abstract: Reusable launch vehicles (RLVs) are a solution for effective and economic transportation in future aerospace exploration. However, RLVs are limited to being used under simple landing conditions (small landing velocity and angle) due to their poor adaptability and the high rocket acceleration of current landing systems. In this paper, an adaptive RLV landing system with semi-active control is proposed. The proposed landing system can adjust the damping forces of primary strut dampers through semi-actively controlled currents in accordance with practical landing conditions. A landing dynamic model of the proposed landing system is built. According to the dynamic model, an light and effective RLV landing system is parametrically designed based on the response surface methodology. Dynamic simulations validate the proposed landing system under landing conditions including the highest rocket acceleration and the greatest damper compressions. The simulation results show that the proposed landing system with semi-active control has better landing performance than current landing systems that use passive liquid or liquid–honeycomb dampers. Additionally, the flexibility and friction of the structure are discussed in the simulations. Compared to rigid models, flexible models decrease rocket acceleration by 51% and 54% at the touch down moments under these two landing conditions, respectively. The friction increases rocket acceleration by less than 1%. However, both flexibility and friction have little influence on the distance between the rocket and ground, or the compression strokes of the dampers.

Keywords: reusable launch vehicles; soft landing; magnetorheological fluid; numerical simulation; multibody systems with flexible elements

1. Introduction

As one of the most important technologies for aerospace exploration, advances in launch vehicles have greatly promoted aerospace developments [1]. Reusable launch vehicles (RLVs) can achieve fast and cheap launches by dividing the launch costs into several launch missions. Since the 1950s, many countries have focused on developing RLVs. From American X-series spacecraft to the Falcon-series rockets of SpaceX, RLVs have always been a hot topic in aerospace technology [2].

The landing system is a critical subsystem of RLVs, the malfunction of which can cause recycle failure [3]. The design of RLV landing systems is quite difficult, because it requires high reusability, effective impact absorption, reliability, and heat resistance [4]. The Delta Clipper proposed by the McDonnell-Douglas Corporation was the first RLV to use a vertical soft-landing system. The Delta Clipper was to be a single-stage-to-orbit vehicle that took off vertically and landed vertically [5].
However, the project was aborted due to lack of funding, and it has not been used in practical engineering. The New Shepard proposed by the Blue Origin Corporation completed a sub-orbital experiment and landed vertically via retractable landing legs. However, it was only just able to reach the Kármán Line (100 km a.s.l.) [6]. The Falcon-series rockets proposed by SpaceX were the first to realize the application of vertical landing in aerospace missions. The landing gears of the Falcon-series rockets use four sets of landing gears with liquid dampers that include primary struts, auxiliary struts, and locking mechanisms [7–9]. The Ariane Group, the French Space Agency, and the Deutsches Zentrum für Luft- und Raumfahrt have also proposed a new low-cost reusable rocket project called Callisto. Callisto uses four landing legs to absorb the impact energy, which is similar to the Falcon-series rocket [10,11]. However, it is still in the design stage. Yue [12–15] and Lei [16] proposed a vertical landing system with novel oleo–honeycomb dampers and conducted many landing experiments. The oleo–honeycomb dampers were able to improve the landing performance of the RLV under dangerous conditions. However, it was necessary to replace the aluminum honeycomb after every landing. In summary, the current landing systems employed by RLVs use passive liquid or liquid–honeycomb dampers to absorb impact energy. These two kinds of passive dampers have complex structures, as well as greater mass and rocket accelerations. Additionally, they are not able to adjust damping forces in order to meet practical landing conditions, which require a low landing velocity and angle, making the recycling of rockets more difficult. There is limited research on controllable landing systems in RLVs.

In this paper, an RLV landing system with semi-active control is proposed. Its dynamic landing model, control approach, and parameterized design are introduced. Furthermore, the proposed landing system is validated by means of multiple rigid bodies and multiple coupled flexible–rigid dynamic simulations. The influence of structural flexibility and friction during the RLV landings is also discussed in the dynamic simulations. Section 2 introduces the overall scheme, working principles, and control approach of the proposed RLV landing system. Section 3 introduces the landing dynamic model and parameterized design of the RLV landing system. Section 4 validates the proposed landing system and discusses the influence of structural flexibility and friction on the RLV landing performance with reference to the simulations.

2. Working Principles of the RLV Landing System

2.1. Overall Scheme of the RLV Landing System with MRF Dampers

Figure 1 shows the overall scheme of the RLV landing system with magnetorheological fluid (MRF) dampers, which consists of a rocket and four sets of landing gears. Each set of landing gear includes a primary strut (including a damper and deployment), an auxiliary strut, and a pad. The primary strut damper is full of MRF, whose profile is shown in Figure 2. The primary strut damper includes a master cylinder (the inner diameter is \( D \)), a piston (compose of a magnetic core and a group of coils, the length is \( L \)), a piston rod (the diameter is \( d \)), a nitrogen accumulator, and a gap between the piston and cylinder (the width is \( h \)). The magnetic properties of the primary strut materials are shown in Table 1. The MRF-132DG produced by the Lord Company is used as an example in this paper. Its main specifications are shown in Table 2.
There are N turns coils on the magnetic core of the piston. The length of the magnetic flux density lines along the coils is $L_1$, the length of the magnetic flux density lines in the gap is $h$, and the length of the arched magnetic flux density lines out the cylinder is $L_2$. Based on the Maxwell equation and Ampere circuit rule,
of the arched magnetic flux density lines out the cylinder is $L_2$. Based on the Maxwell equation and Ampere circuit rule,

$$\int_{L_1} B_1 \cdot dl + \int_{2h} B_2 \cdot dl + \int_{L_2} B_3 \cdot dl = \mu_m NI$$

(1)

where $B_1$ is the magnetic flux density in the magnetic core area, $B_2$ is the magnetic flux density in the gap, $B_3$ is the magnetic flux density out the cylinder, and $\mu_m$ is the magnetic constant. The magnetic flux density $B$ is in T, the magnetic field intensity $H$ is in A/m, the electric current $I$ is in A. Due to the magnetic field intensity in the magnetic core area and gap is much larger than that out the cylinder, the magnetic field intensity in the gap is

$$H_2 = \frac{B_2}{\mu_m} = \frac{NI - H_1 L_1}{2h}$$

(2)

The relationship between yield stress and magnetic field intensity of MRF-132DG [17,18] is

$$\tau = 2.717 \times 10^5 \times 0.32^{1.5239} \tanh(6.33 \times 10^{-3} H_2)$$

(3)

During the landing, the viscosity and plasticity of the MRF change quickly under the magnetic fields produced by energized coils. When the piston moves and pushes the MRF to flow through the gap between the cylinder and piston, the coils energize and produce magnetic fields. The MRF becomes semi-solid from the liquid in milliseconds, and its yield stress is controlled by different magnetic fields to absorb the impact energy. After landing, MRF will return to the liquid state without the magnetic fields [19].

2.2. Working Principles of the RLV Landing System

When the rocket approaches the recycle-platform, four sets of landing gears deploy simultaneously and prepare for the landing impact. After the sensors of pads touch the recycle-platform and the RLV enters landing state, four primary strut dampers absorb the impact energy by their compressions and extensions. Their damping forces of primary strut dampers consist of the controllable parts and uncontrollable parts. The uncontrollable parts are determined by the viscosity and velocity of the MRF, and the air-spring forces of accumulators. The controllable parts are related to the yield stress of MRF, which are controlled according to the acceleration, jerk, pitch angle, and roll angle of the rocket [20].

2.3. Control Approach of the RLV Landing System

Due to the landing process is quite short, which requires a fast and robust control approach. Fuzzy control is suitable for complex systems and can decrease the response time significantly. Furthermore, the nonlinear characteristics of fuzzy control can increase the system robustness [21–24].

During the landing, the acceleration, jerk, pitch angle, and roll angle of the rocket are set as inputs. These four inputs are from rocket sensors to the control system of damping forces. Meanwhile, the yield stresses of four primary struts controlled by currents are set as outputs. The currents can control the damping forces of every primary strut, respectively. These four outputs are from the control system of damping forces and act on four primary strut dampers.

The highest acceleration of the RLV should be smaller than 2 g to protect the precise electronic instruments. Its jerk is set as $[-2a_{\text{max}}, 2a_{\text{max}}]$. The pitch angle and roll angle are set as $[-3, 3]$, due to landing angles of the current RLVs are from $-3^\circ$ to $3^\circ$ [2]. The output yield stresses of MRF in four primary strut dampers are set as $[0, 100\% \text{ Maximum}]$ to adapt to different landing conditions. Considering the control accuracy and efficiency, the acceleration $a$ is divided into four equal fuzzy sets ($Z, S, M, B$). The jerk $da$ is divided into two equal fuzzy sets ($Z, B$). Both the pitch angle $alpha$ and roll angle $beta$ are divided into three equal fuzzy sets ($N, Z, P$). The output yield stresses are divided into seven equal fuzzy sets ($Z, S, SM, M, SB, MB, B$). The membership affiliations between physical
parameters and fuzzy sets for the inputs are shown in Figure 3. The membership affiliations between physical parameters and fuzzy sets for the outputs are shown in Figure 4.

![Figure 3: Membership Affiliations of inputs](image1)

**Figure 3.** Membership Affiliations of inputs: (a) Membership affiliation of \( a \); (b) Membership affiliation of \( da \); (c) Membership affiliations of \( \alpha \) and \( \beta \).

![Figure 4: Membership Affiliations of outputs](image2)

**Figure 4.** Membership Affiliations of outputs.

The control principles are (a) While the acceleration is increasing and less than the setting value, controllable damping forces are small. (b) While the acceleration is increasing and larger than the setting value, controllable damping forces are zero. (c) While the acceleration is decreasing and larger than the setting value, controllable damping forces are zero. (d) While the acceleration is decreasing and less than the setting value, controllable damping forces are big. Moreover, the output damping forces are also determined by the pitch angle and roll angle of the rocket. Detailed fuzzy control rules for inputs and outputs are shown in the Appendix A.
3. Landing Dynamic Analysis and Parameterized Design of RLV Landing System

3.1. Landing Dynamic Analysis of the RLV Landing System

Based on the working principles and control approach of the proposed RLV landing system, its landing dynamic model is required to design the detailed structures. The RLV is composed of an elastic part and four non-elastic parts, as shown in Figure 5. The elastic part includes the rocket, four primary strut deployments, and cylinders of four primary strut dampers. The non-elastic parts include piston rods of four primary strut dampers, four auxiliary struts, and four pads [25]. Due to the RLV being symmetric, a quarter landing dynamic model of the RLV is built, as shown in Figure 6.

![Figure 5. Elastic and non-elastic parts of the RLV.](image)

![Figure 6. Quarter landing dynamic model of the RLV landing system.](image)

The coordinate system is at the center of the bottom surface of the rocket. The revolute joint between the primary strut and rocket is A (x_A, y_A). The sphere joint between the primary strut and auxiliary strut is B (x_B, y_B). The projection of the revolute joint between the auxiliary strut and rocket is C (x_C, y_C). The horizontal distance x_C between the origin and C is R. The angle between the primary strut and ground is α. The angle between the auxiliary strut and ground is θ. The vertical distance y_A between the origin and A is H_1. The mass center of the elastic part is P_1 (0, H_1 + H_2). Due to auxiliary
struts occupy most mass of non-elastic parts, whose center can be simplified as the mass center of non-elastic parts. It is \(0.5(x_B + x_C, y_B + y_C)\), which is shown as

\[
P_2 \left( \frac{1}{2} \tan \alpha - \tan \theta \right) + R, \frac{1}{2} (3H_1 + H_2 + R^2 \tan \alpha + \frac{H_2 R \tan \alpha}{\tan \alpha - \tan \theta}) \right)
\]  

(4)

The landing dynamic models of elastic parts are

\[
\begin{align*}
m_{p_1} \ddot{x}_{p_1} &= -F_p \cos \alpha - F_a \cos \theta \\
m_{p_1} \ddot{y}_{p_1} &= F_p \sin \alpha + F_a \sin \theta - m_{p_1} \ddot{g}
\end{align*}
\]

(5)

where \(F_p\) is the damping force of the primary strut, \(F_a\) is the damping force of the auxiliary strut. The landing dynamic models of non-elastic parts are

\[
\begin{align*}
m_{p_2} \ddot{x}_{p_2} &= F_p \cos \alpha + F_a \cos \theta - \mu F_n \\
m_{p_2} \ddot{y}_{p_2} &= F_n - F_p \sin \alpha - F_a \sin \theta - m_{p_2} \ddot{g}
\end{align*}
\]

(6)

where \(\mu\) is the friction coefficient. \(F_n\) is the contact force between the pad and ground, shown as follows [26]

\[
F_n = \begin{cases} 
0, & q > q_0 \\
k(q_0 - q)^c - \text{cstep}(q, q_0 - d, 1, q_0, 0), & q \leq q_0
\end{cases}
\]

(7)

where \(q\) is the distance criterion of the impact function, \(q_0\) is the trigger distance of the impact function. \(k\) is the stiffness, \(c\) is the contact force exponent, \(\varepsilon\) is the contact damping, and \(d\) is the penetration depth.

According to the cross-section diagram of the primary strut damper in Figure 2, the damping force of the primary strut damper \(F_p\) is

\[
F_p = F_c + F_u + F_{Ni} \\
= \frac{3nD^2L_T}{4m} + \frac{3nLm(D^2 - d^2)}{4m} - \rho v + 0.5 \rho \frac{P_{entry}}{\Delta_{gap}^2} v^2 \\
+ 0.5 \rho \frac{P_{exit}}{\Delta_{gap}^2} v^2 + A_n \frac{P_0(V_{i} + V_{f})^{1.1}}{V_f}
\]

(8)

where \(F_c\) is the uncontrollable damping force of the MRF damper. \(F_u\) is the controllable damping force of the MRF damper. \(F_{Ni}\) is the air-spring force caused by the accumulator [27–29]. \(F_{entry}\) is local resistance caused by the abrupt enlargement, and \(F_{exit}\) is local resistance caused by the abrupt contraction. \(\rho\) is the density of MRF. \(K_{entry}\) is the local resistance coefficient of the entry, and \(K_{exit}\) is the local resistance coefficient of the exit. \(v\) is the piston velocity. \(A_p\) is the piston area. \(A_{gap}\) is the gap area between the master cylinder and piston, and \(A_n\) is the cross-section area of the master cylinder. \(P_0\) is the initial pressure of the accumulator. \(V_{i}\) is the initial volume of the accumulator, and \(V\) is the volume of the accumulator during the landing.

3.2. Parameterized Design of the RLV Landing System

According to the proposed landing dynamic model, \(H_1\), \(\alpha\), and \(\theta\) determine the buffer effects of \(F_a\) and \(F_p\), and the efficiency and performance of landing systems [30]. Hence, a parameterized design of the RLV landing system is proposed according to these three parameters to get an effective landing system. The lower and upper limits of these three parameters are given in Table 3. The rocket acceleration, compression strokes of dampers, and the distance between the rocket and ground are the most important indexes for the design of a landing system [31]. A large rocket acceleration will damage structures and instruments [32]. Large compressions of primary strut dampers will cause the rocket to incline or tip over. The distance between the rocket and the ground should be large enough for a safe landing [33]. The mass is also an important index for spacecraft, a lighter landing system means a lower launch cost. Hence, these four design targets of the landing system are selected as
responses, as shown in Table 4. The parameterized design principle based on the response surface methodology (RSM) is shown as follows

\[
\text{Minimize} \{D\} = \text{Min} \left\{ \sqrt{R_1 R_2 (R_{P1} - R_3) R_4} \right\}
\]

\[
s.t. \begin{cases}
24 \leq \theta \leq 30 \\
42 \leq \alpha \leq 53 \\
1200 \leq H_1 \leq 1800
\end{cases}
\]

(9)

where \(R_{P1}\) is the initial distance between the mass center of the rocket and the ground.

Table 3. Lower and upper boundaries of parameters [34,35].

| Codes | Design Parameters | Lower Limits  | Upper Limits |
|-------|-------------------|---------------|--------------|
| A     | The angle between the auxiliary strut and ground (\(\theta\)) | 24\(^{\circ}\) | 30\(^{\circ}\) |
| B     | Angle between the primary strut and ground (\(\alpha\)) | 42\(^{\circ}\) | 53\(^{\circ}\) |
| C     | The vertical distance between point A and C (\(H_1\)) | 1200 mm | 1800 mm |

Table 4. Design target parameters.

| Responses | Design Targets | Goal            |
|-----------|---------------|-----------------|
| \(R_1\)   | Highest rocket acceleration (\(\text{m/s}^2\)) | Minimize        |
| \(R_2\)   | Greatest compression stroke (\(\text{mm}\)) | Minimize        |
| \(R_3\)   | Distance between rocket and ground (\(\text{mm}\)) | Maximum        |
| \(R_4\)   | Mass of a set of landing gear (\(\text{kg}\)) | Minimize        |

\(D\) is the desirability function, which shows the desirable ranges for each response \(R_i\). The function combines these four responses in a non-dimensional way. Its design goal is the smallest rocket acceleration, compression stroke, the mass of a set of landing gear, and the largest distance between the rocket and ground.

The RSM builds an approximate model between the codes (design parameters) and responses (design targets) via function fitting. The RSM assumes every code is an \(n\)-dimensional vector \(x \in \mathbb{E}^n\), which is the independent variable of its response function \(y\). Their relationship is \(y = f(x)\). Based on lots of simulation data, an approximate function of the response \(\tilde{y}\) is obtained by the undetermined coefficient method. Considering the efficiency and accuracy, a quadratic function with cross terms is used, which is shown as follows

\[
\tilde{y} = a_0 + \sum_{j=1}^{n} a_j x_j + \sum_{i=1}^{n} \sum_{j=1}^{n} a_{ij} x_i x_j
\]

(10)

where \(a_0\) is the undetermined coefficient of the constant term, \(a_i\) is the undetermined coefficient of the one-degree term, and \(a_{ij}\) is the undetermined coefficient of the quadratic term. \(\tilde{y}\) is close to \(y\) by keeping their sum of error squares smallest via the least square principle [36].

According to the ranges of the three parameters (factors) in Table 3, landing dynamic simulations are carried to get corresponding four design targets (responses) under different parameter combinations. Their results are the RSM sampling, as shown in the appendix. Based on the RSM sampling and fit function in Equation (10), accurately fitted functions between codes and responses are obtained by the undetermined coefficient method, as shown in Table 5. These code coefficients of functions show the influences of codes on responses [37]. The influences of three codes and their extended codes on \(R_1\) is \(C > B > A > BC > AB > A^2 > C^2 > AC > AB > B^2\). The influences of three codes and their extended codes on \(R_2\) is \(B^2 > A^2 > A > AC > C^2 > GC > C > B > AB\). The influences of three codes and their extended codes on \(R_3\) is \(A > C > AC > C^2 > B^2 > A^2 > AB > BC > B\). The influences of three codes and their extended codes on \(R_4\) is \(C > A > AC > A^2, B^2, C^2 > BC > AB > B\).
Based on these four functions, the predicted values versus actual values of four responses are shown in Figures 7–10. The points above or below the line indicate that they are over or under prediction. The data points of plots are randomly scattered along the 45° oblique line, which suggests that these four functions are accurate. These fitted functions can provide powerful support for the following parameterized design.

Table 5. Fitted functions between codes and responses.

| Response | Fitted Functions |
|----------|------------------|
| $R_1$    | $R_1 = +61.879 + 0.531A + 2.978B + 5.335C - 4.194AB - 13.779AC - 0.248BC - 8.078A^2 - 25.679B^2 - 10.901C^2$ |
| $R_2$    | $R_2 = +21.472 + 7.281A - 14.109B - 6.472C + 24.821AB + 7.265AC - 0.131BC + 24.440A^2 + 34.093B^2 + 6.040C^2$ |
| $R_3$    | $R_3 = +1121.000 + 317.666A - 520.112B + 263.320C - 118.180AB + 194.039AC - 130.021BC - 35.514A^2 + 40.594B^2 + 129.553C^2$ |
| $R_4$    | $R_4 = +87.578 + 3.815A - 11.215B + 5.924 C - 3.347A^2 - 3.329AC + 3.329B^2 + 1.215BC$ |

Combining the design principle in Equation (10) and the fitted functions in Table 5, the final design result based on RSM is shown in Table 6.
The highest rocket acceleration and greatest damper compression conditions are selected as examples because they are two of the most important design parameters of landing gears. These two conditions are shown in Figure 12. Their motion parameters are shown in Table 7.

The coordinate system is at the center of the bottom surface of the rocket, as shown in Figure 6. The rocket diameter is 2250 mm. The entire RLV weighs 5200 kg. Its center of mass is located at (0, 6017 mm, 0). The coordinate system is at the center of the bottom surface of the rocket, as shown in Figure 6. The rocket diameter is 2250 mm.

Based on the design parameters in Section 3, a dynamic model of the RLV with semi-active control is built in MSC Adams to validate the proposed landing system, as shown in Figure 11. The rocket diameter is 2250 mm. The entire RLV weighs 5200 kg. Its center of mass is located at (0, 6017 mm, 0). The coordinate system is at the center of the bottom surface of the rocket, as shown in Figure 6. The highest rocket acceleration and greatest damper compression conditions are selected as examples because they are two of the most important design parameters of landing gears. These two conditions are shown in Figure 12. Their motion parameters are shown in Table 7.

### Table 6. Final design parameters and targets.

| Parameters (Design Parameters) | Responses (Design Targets) |
|--------------------------------|-----------------------------|
| A (θ)                          | Highest rocket acceleration |
| B (α)                          | Greatest compression stroke |
| C (H1)                         | Distance between rocket and ground |
|                                | Mass                        |
| 29.58°                         | 17.79 m/s²                  |
| 52.42°                         | 47.31 mm                    |
| 1800 mm                        | 1286.82 mm                  |
| 85.12 Kg                       | 85.12 Kg                    |

### 4. Landing Dynamic Simulations

Based on the design parameters in Section 3, a dynamic model of the RLV with semi-active control is built in MSC Adams to validate the proposed landing system, as shown in Figure 11. The rocket diameter is 2250 mm. The entire RLV weighs 5200 kg. Its center of mass is located at (0, 6017 mm, 0). The coordinate system is at the center of the bottom surface of the rocket, as shown in Figure 6. The highest rocket acceleration and greatest damper compression conditions are selected as examples because they are two of the most important design parameters of landing gears. These two conditions are shown in Figure 12. Their motion parameters are shown in Table 7.
obtain flexible primary struts. The flexible structures are imported into MSC Adams to conduct multiple coupled flexible–rigid dynamic simulations. Structural flexibility and friction will influence rocket acceleration, energy absorption, and compression strokes [38]. Different combinations of rigid structures, flexible structures, and frictions are simulated to analyze the proposed RLV landing system more accurately.

![Figure 11. Top view of the RLV.](image)

![Figure 12. Two typical landing conditions of the RLV.](image)

| Landing Condition       | Vertical Velocity | Horizontal Velocity | Pitch Angle |
|-------------------------|-------------------|--------------------|------------|
| Highest acceleration    | −2 m/s            | 1 m/s              | 0°         |
| Greatest compression    | −2 m/s            | 1 m/s              | 3°         |

Furthermore, the influences of structural flexibility and friction on landing performance are discussed in dynamic simulations. The end centers of the primary strut deployments and damper cylinders are fixed in their modal analysis. Their 20 order models are calculated in MSC Patran to obtain flexible primary struts. The flexible structures are imported into MSC Adams to conduct multiple coupled flexible–rigid dynamic simulations. Structural flexibility and friction will influence rocket acceleration, energy absorption, and compression strokes [38]. Different combinations of rigid structures, flexible structures, and frictions are simulated to analyze the proposed RLV landing system more accurately.

4.1. Highest Rocket Acceleration Condition

Under the highest rocket acceleration condition, four sets of landing gears touch the ground at the same time. The accelerations and the distances between the rocket and the ground are shown...
in Figures 13 and 14, respectively. L1 is taken as an example, whose damping forces and damper compression strokes are shown in Figures 15 and 16, respectively.

![Figure 13. Rocket accelerations of the RLV under the highest acceleration landing condition.](image1)

![Figure 14. Distance between rocket and ground under the highest acceleration landing condition.](image2)
Adding friction to the flexible model, the highest rocket acceleration increases to 13.13 m/s². During the landing, the controllable damping forces $F_c$ of four primary strut dampers belong to Z and S. Their uncontrollable damping forces $F_u$ slowly decrease versus time due to compression velocity decrease. The highest rocket acceleration of the entire rigid model is 25.95 m/s². The highest rocket acceleration of the entire rigid model with friction is 27.57 m/s², which is the largest in these four situations. The highest rocket acceleration of the model with flexible primary struts is 12.73 m/s², which is the smallest in these four situations. Additionally, structural flexibility causes fluctuations in acceleration and damping force. Adding friction to the flexible model, the highest rocket acceleration increases to 13.13 m/s², and the fluctuations of the rocket acceleration and damping force also increase. The highest rocket accelerations for these two flexible situations decrease by about 51% at the touch down moment. At the same time, the damping force peaks of L1 decrease by about 5%, because the flexible structures absorb parts of the impact energy. However, after the instantaneous contact, rocket accelerations and damping forces of these four situations are close to each other.

The highest rocket acceleration of current landing systems with passive liquid dampers is 37.2 m/s² under the highest acceleration landing condition [2,17]. Compared to this, the highest

**Figure 15.** Damping forces of L1 of the RLV under the highest acceleration landing condition.

**Figure 16.** Damper compression strokes of L1 of the RLV under the highest acceleration landing condition.

Figure 13 shows that all rocket accelerations of these four situations possess the same tendency. At about 0.003 s, four pads touch the ground, and peaks appear vertically. Subsequently, the rocket accelerations decrease vertically and remain at about 4 m/s². During the landing, the controllable damping forces $F_c$ of four primary strut dampers belong to Z and S. Their uncontrollable damping forces $F_u$ slowly decrease versus time due to compression velocity decrease. The highest rocket acceleration of the entire rigid model is 25.95 m/s². The highest rocket acceleration of the entire rigid model with friction is 27.57 m/s², which is the largest in these four situations. The highest rocket acceleration of the model with flexible primary struts is 12.73 m/s², which is the smallest in these four situations. Additionally, structural flexibility causes fluctuations in acceleration and damping force. Adding friction to the flexible model, the highest rocket acceleration increases to 13.13 m/s², and the fluctuations of the rocket acceleration and damping force also increase. The highest rocket accelerations for these two flexible situations decrease by about 51% at the touch down moment. At the same time, the damping force peaks of L1 decrease by about 5%, because the flexible structures absorb parts of the impact energy. However, after the instantaneous contact, rocket accelerations and damping forces of these four situations are close to each other.

The highest rocket acceleration of current landing systems with passive liquid dampers is 37.2 m/s² under the highest acceleration landing condition [2,17]. Compared to this, the highest
rocket acceleration of the proposed landing system with semi-active control decrease about 30.2%. By controlling the damping forces of the four primary strut dampers, the RLV has much lower rocket accelerations and impact forces, which can protect the structures and instruments better during rocket recycle. As shown in Figures 14 and 16, the distance between the rocket and the ground and the compression strokes of L_1 are close to each other in these four situations. In conclusion, friction has little influence on landing performance. However, structural flexibility has a strong influence on rocket acceleration and the damping forces of primary struts.

4.2. Greatest Damper Compressions Condition

Under the greatest damper compressions condition, L_3 touches the ground first. Second, L_2 and L_4 touch the ground together. Finally, L_1 touches the ground. In brief, it is a kind of 1–2–1 landing condition. The rocket accelerations and the distances between the rocket and the ground are shown in Figures 17 and 18. Because L_3 touches the ground first, L_3 is taken as an example. The damping forces and compression strokes of L_3 are shown in Figures 19 and 20.

![Figure 17. Accelerations of RLV under the greatest compressions landing condition.](image1)

![Figure 18. Distance between rocket and ground under the greatest compressions landing condition.](image2)
At about 0.005 s, L₃ touches the ground, and rocket accelerations and damping forces increase vertically. At about 0.085 s, L₂ and L₄ touch the ground at the same time. The rocket accelerations increase vertically again. At about 0.167 s, L₁ touches the ground, and the rocket accelerations increase vertically for a third time. From 0.167 s to 0.310 s, the controllable damping force $F_c$ of L₃ belongs to Z, and the controllable damping forces $F_c$ of L₂, L₃, and L₄ belong to S. Their uncontrollable damping forces $F_u$ decrease versus time slowly due to the decrease of compression velocities. The air-spring forces $F_{Ni}$ increase because damper compressions increase. Hence, their resultant forces remain basically stable. Additionally, the pitch angle gradually decreases to 0 due to the horizontal velocity and control of the damping forces. The rocket accelerations increase slightly during this time. After 0.310 s, four controllable damping forces $F_c$ belong to Z together, and the rocket accelerations have a small vertical decrease.
Under the greatest damper compressions condition, the compression strokes of the proposed landing system with semi-active control are close to those of current landing systems. However, the highest rocket acceleration of current landing systems with passive liquid dampers is about 22.5 m/s² [2]. The highest rocket acceleration of the proposed landing system with a rigid model is 5.37 m/s², which is a decrease of about 76.1%. Additionally, the highest rocket accelerations also decrease by about 54% at the three touch down moments in these two flexible situations. At the same time, damping forces decrease by about 11% in these two flexible situations. Except for the three touch down moments, the rocket accelerations and damping forces of flexible situations are a little higher than those of rigid situations. Structural flexibility also causes an approximately 0.005 s delay, and fluctuations of rocket accelerations and damping forces. The compression strokes of primary strut dampers and distances between the rocket and ground are also close in these four situations.

In conclusion, these two typical landing conditions prove that the proposed landing system has better landing performance than current landing systems with passive liquid or liquid–honeycomb dampers. On one hand, structural flexibility decreases rocket acceleration and damping force. On the other hand, friction increases rocket acceleration and damping force a little. Both flexibility and friction have little influence on the compression strokes of the primary strut dampers and the distances between the rocket and the ground. Structural flexibility should be considered in the design of RLV landing systems.

5. Conclusions

A landing system for reusable launch vehicles with semi-active control was proposed in this paper. Its control approach and landing dynamic model were built. According to the dynamic model, an effective and light landing system was parametrically designed based on the response surface methodology. The parameterized design achieved the best-desired design targets under limited ranges of design parameters, guiding the design by fitted functions between design parameters and targets. The parameterized design provided a fast and high-efficiency approach to designing a landing system. Dynamic landing simulations validated the proposed landing system under landing conditions with the highest rocket acceleration and greatest damper compressions. The simulation results proved that the proposed landing system with semi-active control has better landing performance than currently available landing systems that use passive liquid or liquid–honeycomb dampers. Additionally, the simulation results show that structure flexibilities decrease rocket accelerations by about 50% at the touch down moments. At the same time, they also decrease the damping forces of the primary strut dampers by 5% and 11% at the touch down moments under two typical conditions. However, the friction has little influence on landing performance.

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Notation

The following symbols are used in this paper:

- $\alpha$: Angle between the primary strut and ground
- $\theta$: Angle between the auxiliary strut and ground
- $\mu$: Friction coefficient
- $\tau$: Maximum yield stress of MRF
- $\rho$: Density of MRF
- $\eta$: Viscosity of MRF
- $a_0$: Undetermined coefficient of the constant term
- $a_j$: Undetermined coefficient of one-degree term
- $a_{ij}$: Undetermined coefficient of the quadratic term.
- $c$: Contact damping of the impact function
- $d$: Penetration depth of the impact function
- $e$: Contact force exponent of the impact function
- $k$: Stiffness of the impact function
- $q$: Distance function of the impact function
- $q_0$: Trigger distance of the impact function
- $v$: Piston velocity
- $A_p$: Piston area
- $A_{\text{gap}}$: The gap area between the master cylinder and piston
- $A_n$: Cross-section area of the master cylinder
- $D$: Diameter of piston
- $D$: Diameter of piston rod
- $F_a$: Force of auxiliary strut acting at point C
- $F_c$: Controllable damping force of MRF damper
- $F_p$: Force of primary strut acting at point A
- $F_u$: Uncontrollable damping force of MRF damper
- $F_{\text{Ni}}$: Air-spring force caused by the accumulator
- $K_{\text{entry}}$: Local resistance coefficient of the entry
- $K_{\text{entry}}$: Local resistance coefficient of the exit
- $H_1$: Vertical distance between the origin and point A
- $H_2$: Vertical distance between the mass center $P_1$ of elastic parts and point A
- $L$: Length of coils
- $R$: Horizontal distance between the origin of rocket coordinate system and point C
- $R_1$: Highest rocket acceleration
- $R_2$: Greatest compression stroke
- $R_3$: Distance between rocket and ground
- $R_4$: Mass of a set of landing gear
- $R_{P1}$: Initial distance between the mass center of the rocket and the ground
- $V$: Volume of accumulator
- $V_0$: Initial volume of accumulator
## Appendix A

Table A1. Fuzzy control rules for inputs and outputs [39].

| Inputs | Outputs |
|---|---|
| **Acceleration** | **Jerk** | **alpha** | **beta** | **τ**<sub>1</sub> | **τ**<sub>2</sub> | **τ**<sub>3</sub> | **τ**<sub>4</sub> |
| B | All | All | All | Z | Z | Z | Z |
| Z | B | Z | Z | MB | MB | MB | MB |
| S | Z | Z | Z | SB | SB | SB | SB |
| S | B | Z | Z | M | M | M | M |
| M | Z | Z | Z | SM | SM | SM | SM |
| M | B | Z | Z | S | S | S | S |
| Z | Z | P | Z | S | SB | MB | SB |
| Z | B | P | Z | S | M | SB | M |
| Z | Z | N | Z | MB | SB | S | SB |
| Z | B | N | Z | SB | M | S | M |
| Z | Z | Z | P | SB | S | SB | MB |
| Z | B | Z | P | M | S | M | SB |
| Z | Z | Z | N | SB | MB | SB | S |
| Z | B | Z | N | M | SB | M | S |
| Z | Z | N | P | MB | SB | SB | MB |
| Z | B | N | P | SB | M | S | SB |
| Z | Z | P | N | SB | MB | MB | SB |
| Z | B | P | Z | M | SB | S | MB |
| Z | Z | N | N | SB | MB | MB | SB |
| Z | B | N | N | SB | SB | M | M |
| Z | Z | P | P | SB | SB | MB | MB |
| Z | B | P | P | M | M | SB | SB |
| S | Z | P | Z | Z | M | SB | M |
| S | Z | Z | M | SM | Z | SM | M |
| S | B | N | Z | M | SM | Z | SM |
| S | Z | Z | P | M | Z | M | SB |
| S | B | Z | P | SM | Z | SM | M |
| S | Z | Z | N | M | SB | M | Z |
| S | B | Z | N | SM | M | SM | Z |
| S | Z | P | P | M | M | SB | SB |
| S | B | P | P | SM | SM | M | M |
| S | Z | P | Z | Z | M | SM | M |
| S | B | P | N | B | Z | M | S |
| S | Z | N | Z | SB | M | Z | M |
| S | B | N | Z | M | SM | Z | M |
| S | Z | Z | P | Z | M | SM | Z |
| S | B | Z | Z | M | SM | Z | M |
| M | Z | N | Z | SM | Z | M | SM |
| M | B | N | Z | S | Z | SM | S |
| M | Z | Z | N | SM | M | SM | Z |
| M | B | Z | N | S | SM | S | Z |
| M | Z | Z | P | SM | Z | SM | M |
| M | B | Z | N | S | SM | S | Z |
| M | Z | N | N | M | SM | SM | M |
| M | B | N | N | SM | SM | S | S |
| M | Z | N | P | MB | SB | MB | SB |
| M | B | P | N | SB | M | M | MB |
| M | Z | P | P | MB | SB | MB | SB |
| M | B | P | P | MB | SB | MB | SB |
| M | Z | N | N | M | SM | SM | M |
| M | B | N | N | SM | SM | M | M |
| M | Z | P | P | M | M | SM | SM |
| M | B | P | P | SM | SM | M | M |
| M | Z | N | P | Z | Z | SM | Z |
| M | B | P | N | Z | Z | SM | Z |
| M | Z | Z | P | Z | M | SM | M |
| M | B | Z | P | SM | SM | M | M |
| M | Z | N | N | SM | SM | M | M |
| M | B | N | P | S | SM | M | M |
| M | Z | P | P | SM | SM | M | M |
| M | B | P | P | SM | SM | M | M |
Table A2. RSM sampling.

| Run | Factor 1: \(A(\theta/\degree)\) | Factor 2: \(B(\alpha/\degree)\) | Factor 3: \(C(H_1/mm)\) | Response 1: \(R_1\) \((a_{max}/m/s^2)\) | Response 2: \(R_2\) \((Strokes/mm)\) | Response 3: \(R_3\) \((Distance/mm)\) | Response 4: \(R_4\) \((Mass/kg)\) |
|-----|-------------------------------|-------------------------------|-------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 1   | 27                            | 42                            | 1800              | 23.349                      | 79.5787                     | 2240                        | 108.446                     |
| 2   | 24                            | 42                            | 1500              | 17.7913                     | 64.4743                     | 1112.8                      | 91.6878                     |
| 3   | 30                            | 42                            | 1500              | 33.193                      | 113.355                     | 2113.5                      | 109.83                      |
| 4   | 27                            | 42                            | 1200              | 20.5145                     | 82.2504                     | 1448.6                      | 89.412                      |
| 5   | 30                            | 53                            | 1500              | 30.0239                     | 46.4953                     | 902.999                     | 79.913                      |
| 6   | 27                            | 47.5                          | 1500              | 61.8792                     | 21.4722                     | 1121                        | 85.2949                     |
| 7   | 27                            | 47.5                          | 1500              | 61.8792                     | 21.4722                     | 1121                        | 85.2949                     |
| 8   | 24                            | 47.5                          | 1800              | 69.0255                     | 18.5479                     | 1028.8                      | 87.5495                     |
| 9   | 24                            | 47.5                          | 1200              | 21.6645                     | 56.0716                     | 894.954                     | 85.2949                     |
| 10  | 27                            | 47.5                          | 1500              | 61.8792                     | 21.4722                     | 1121                        | 85.2949                     |
| 11  | 27                            | 53                            | 1800              | 29.5464                     | 40.7394                     | 873.652                     | 82.5555                     |
| 12  | 30                            | 47.5                          | 1200              | 44.3331                     | 70.8267                     | 1013.2                      | 82.452                      |
| 13  | 30                            | 47.5                          | 1800              | 36.5765                     | 62.3615                     | 1923.2                      | 98.0229                     |
| 14  | 27                            | 53                            | 1200              | 27.7053                     | 43.8536                     | 602.336                     | 72.0231                     |
| 15  | 24                            | 53                            | 1500              | 31.3973                     | 95.6979                     | 375.021                     | 75.1617                     |
| 16  | 27                            | 47.5                          | 1200              | 61.8792                     | 21.4722                     | 1121                        | 85.2949                     |
| 17  | 27                            | 47.5                          | 1500              | 61.8792                     | 21.4722                     | 1121                        | 85.2949                     |

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