Design and Analysis of Tri-Folded and Deployed type Transfer Ramp for Mars Rover

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ABSTRACT

Based on landing on Mars for inspection detection, this paper comes up with tri-folded and deployed type transfer ramp aims at transferring the Mars rover from the landing platform to the Mars surface safely. It is consisted of 2 ramps which are placed symmetrically on the top surface of landing platform. Every ramp consists of 3 sections. After landing, unlocking the hinge which is placed on one end, 3 sections deploy in order to be one ramp under the action of the spring. This paper analyses design conditions of ramp and calculate the length of ramp. The dynamic characteristics of the deployment and transferring characteristics are simulated and analyzed. The simulation results can provide reference for the project of transfer ramp.

1 INTRODUCTION

Mars is the closest planet next to the earth, currently the discovery proved that water exist on Mars, it is important to carry out landing inspection detection on Mars for exploring the origin and evolution process of the earth and the life. Up to now, the successful landing inspection detections on Mars is 4 times, MPF launched in 1996 and landed on Mars successfully using the airbag, MER named courage and opportunity were launched respectively to the Mars in 2003, Mars Science Laboratory carrying the curiosity rover landed Mars with air suspension in 2012[1,2]. To design the ramp, we face the following challenges.1) Bad working environment. The ramp need experience a long-time and complex flight from the earth to Martian surface. We must consider about the environment of launching, Earth-Mars transferring orbit and landing. especially, 3/8 gravity and strong dust storm weather on Mars surface. 2) High adaptability on Mars surface. We must think about the influence of landing attitude when the rover transfers, the length of ramp must adapt different landing attitude. 3) Large transferring distance. Mars rover places on the top surface of landing platform, the distance between the top surface of the landing platform and landing surface is not less than 1 meter. 4) Many designing constraints. We must think about the configuration of entry hatch and Mars rover and temperature on Mars surface. 5)Light mass. Because of limited resource of the detector system, We must control the mass and volume of the ramp while it must bear the load of Mars rover when transferring[3,4].

2 DESIGN CONDITIONS

Design conditions of the ramp include the configuration of entry cabin and Mars rover, the transferring attitude, the deploying characteristics, the transferring characteristics. The ramp does not interfere with the entry cabin and Mars rover when folded and does not contact Mars rover when deploying. The configuration of ramp when deployed must adapt 6-wheel Mars rover for safe transferring. The deploying characteristics include deploying time t and static moment margin η in order to ensure the ramp deploying well. The transferring characteristics require the stress of ramp is lower than the allowable stress of the ramp when transferring while M represents the mass of Mars rover. The length of ramp L is determined by the terrain angle of landing area α, the roughness of Mars surface h, and the attitude of landing platform β and δ. In order to descript easily, the transferring attitude of Mars rover is set up as shown in Fig.1. Coordinate system of landing platform: coordinate origin *O:* centroid of landing platform; $+X$ axis: the direction of Mars rover transfer; $+Z$ axis: over O point, perpendicular to the top surface of the landing platform; $+Y$ axis: composing the right hand coordinate system with $+X$ and $+Z$.

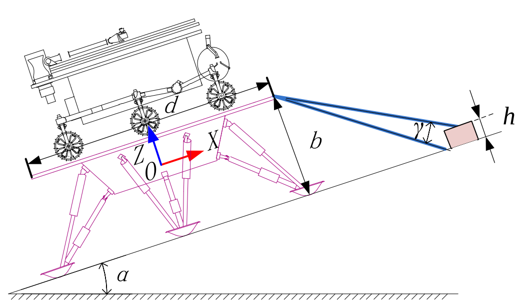

Figure 1: The transferring attitude of Mars rover

Parameters are defined as follows in Fig.1. α is the angle between the landing surface and the local horizontal plane; β is the angle between $+X$ and the landing surface; δ is the angle between $+Y$ and the landing surface; transferring angle φ is the angle between the ramp plane and the local horizontal plane; non coplanar angel of ramp γ is angel between 2 ramps after they contacting the landing surface. *h* represents raised rock or pit; In addition, according to the actual designing conditions, *b* is the height between the top surface of the landing platform and the landing surface; *d* is the length of the landing platform. Design parameters of ramp is in Tab 1.

Table 1: Design parameters of ramp

	parameters	value
transferring attitude	α	[-15°,+15°]
	δ、β	[-6°,+6°]
	h	[-0.2m,+0.2m]
	b	1m
	d	2.6m
	φ	≤35°
	γ	≤8°
deploying characteristics	t	≤10s
	η	≥1
transferring characteristics	M	300kg

3 CONCEPT OF RAMP

We comes up with tri-folded and deployed type transfer ramp according to design conditions of transfer ramp. The working principle of the ramp is shown in Fig 2: (1) The ramp is folded and pressed when launching, Earth-Mars orbit transferring and landing. (2) After landing on Mars, the controlling system choose the deploying direction through analyzing the landing attitude, the hinge on one side unlock. (3-5) 3 sections of ramp deploy in order by the spring. (6) Mars rover transfer.

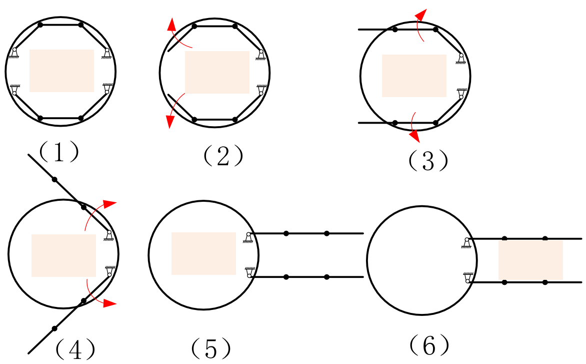

Figure 2: working principle of the ramp

3.1 System composition

According to the concept and designing conditions of ramp, we design the ramp system as shown in Fig 3. The function of each module are as follows: 1) Pressing device: pressing the ramp and deciding the deploying direction; 2) Deploying hinge: providing driving torque of deployment; 3) Swing hinge: ensuring the ramp swing, adapt and contact Mars surface after deployed; 4) Track: bearing most of load of the rover when transferring. 5) Guardrail: ensuring the rover transfer along the track and bear some of load of the rover.

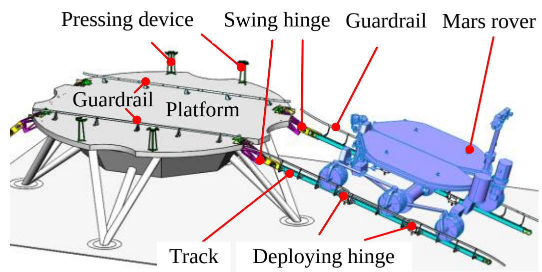

Figure 3: Composition of the ramp

The design of ramp of this paper consists of analyzing the length of the ramp, choosing suitable parameters of spring, analyzing the load of the ramp when the rover transfer.

3.2 Length of the ramp

α β δ h decide the transferring attitude, the length of ramp must adapt different transferring attitudes to ensure φ and γ meeting the requirements. Analyzing the maximum value of φ and γ changing with the length of ramp L *under* different transferring attitudes and finding the minimum value of L. In order to calculate, The landing platform is simplified into a cuboid, the ramps are simplified into two segments in space, the simplified model is shown in Fig 4.

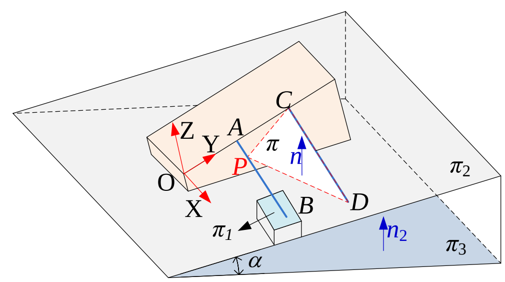

Figure 4: simplified model for calculating L

coordinate origin *O: vertex* of simplified cuboid; +*Y* axis: edge of simplified cuboid; +*Z* axis: over *O* point, perpendicular to the top surface of simplified cuboid; +*X* axis: composing the right hand coordinate system with +*Y* and +*Z*.

Writing the equation of *AB* and *CD* which represent the ramp, the equation of π_1 and π_2 which represent the contacting planes between ramp and Mars, the equation of π_3 which represent local horizontal plane.

The equation of π_1

$$y\times\sin\delta+(z+\frac{b-h_1}{\cos\delta}-d\times\tan(\frac{\delta+|\delta|}{2}))\times\cos\delta=0$$

The equation of *AB*

$$\begin{cases} y = y_A \\ \dfrac{x}{\sqrt{L^2 - {z_B}^2}} = \dfrac{z}{z_B} & \left(0 < x < \sqrt{L^2 - {z_B}^2}\right) \end{cases}$$

where $z_B = -y_A \times \tan\delta - \dfrac{b - h_1}{\cos\delta} + d \times \tan(\dfrac{\delta + |\delta|}{2})$.

Similarly, we can write the equation of *CD*.

Defining the plane π: (1) the points on *AB* with *CD*; (2) the points on *CD* with *AB*. Calculating the angel φ which is the angel between π and π_3. For example, we take a point *P* on *AB*, and write the coordinate of *P* using the equation of *AB*, direction vector of *AB* is

$$\vec{s}_1 = (x_B, 0, z_B)$$

direction vector of *CD* is

$$\vec{s}_2 = (x_D, 0, z_D),$$

normal vector of π and π_3

$$\vec{\mathbf{n}} = \overrightarrow{CP} \times \vec{s}_2$$

$$\vec{\mathbf{n}}_2 = (0, \sin(\alpha + \delta), \cos(\alpha + \delta))$$

So the value of φ and γ

$$\varphi = \arccos\left(\frac{\vec{\mathbf{n}} \bullet \vec{\mathbf{n}}_2}{|\vec{\mathbf{n}}| \times |\vec{\mathbf{n}}_2|}\right)$$

$$\gamma = \arccos\left(\frac{\vec{s}_1 \bullet \vec{s}_2}{|\vec{s}_1| \times |\vec{s}_2|}\right)$$

According to the results, when α=15° and δ=0° and *AB* meet pit which means h_1=-0.2m, the minimum value of *L*=2.92m meet the requirements is maximum, the curves max(φ)-*L* and γ-*L* under this transferring attitude are shown in Fig 5. Line 1 is constraint of γ, Line 2 is constraint of φ , Line 3 is constraint of configuration of entry cabin.

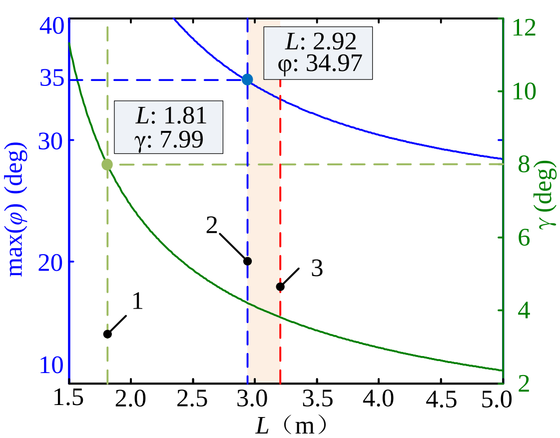

Figure 5: max(φ) and γ change with L

4 ANALYSIS AND SIMULATION OF DEPLOYING

The worst attitude for deploying is when α=15° and β=+6° which means ϕ=21° as shown in Fig 6. Analyzing and simulating the dynamic characteristics of deployment under this attitude.

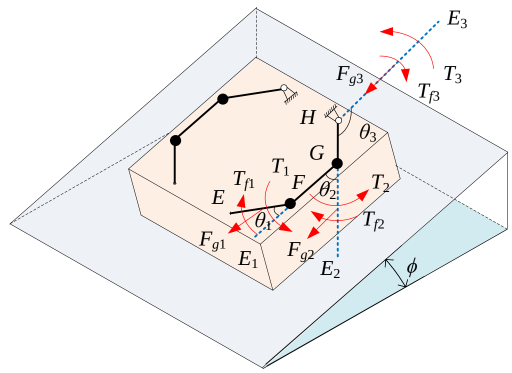

Figure 6: model of deploying

We build differential equation of deploying piecewise according to Newton's second law, and we can acquire deploying time in total *t* using numerical solution after giving initial value.

$$\begin{cases} J_1\ddot{\theta} = T_1 + \dfrac{L_1}{2} m_1 g \sin\phi \sin(\theta_1 - \theta) - T_{f1} \\ J_2\ddot{\theta} = T_2 - \dfrac{L_2}{2} m_2 g \sin\phi \sin\theta - T_{f2} \\ J_3\ddot{\theta} = T_3 - \dfrac{L_3}{2} m_3 g \sin\phi \sin(\pi - \theta_3 + \theta) - T_{f3} \end{cases}$$

Where J_i is the moment of inertia of ramp *i*; L_i is the length of ramp *i*; m_i is the *mass of* ramp *i*; T_{fi} is resistance moment of ramp *i* when deploying; T_i is driving moment of ramp *i*; θ_i is rotation angle in total of ramp *i*; θ is rotation angle change with time; *g* is acceleration of gravity on Mars. ϕ is the angel between the deploying plane and local horizontal plane.

4.1 Optimization of spring

1) design variable

The parameters of the spring T_i^d and k_i decide the deploying time *t* and static moment margin η. Where T_i^d is surplus torque of spring after deploying; k_i is stiffness coefficient of spring. We can calculate T_i^d according to η

$$\begin{cases} \dfrac{T_1^d}{T_{f1}} - 1 \ge \eta \\ \dfrac{T_i^d}{T_{fi} + T_{gi}} - 1 \ge \eta (i = 2,3) \end{cases}$$

Where T_{gi} is maximum resistance moment of ramp *i* generated by gravity.

According to the results

$$T_1^{\ d} = T_2^{\ d} = 4.54\text{Nm}$$
$$T_3^{\ d} = 15.74\text{Nm}$$

Stiffness coefficient of spring can be the design variables, so

$$x = [k_1 \ \ k_2 \ \ k_3]^T$$

2) objective function

The impact load is minimized when the ramp deploy into position normally. The energy of the impact is determined by the rotational kinetic energy of the ramp[5]. We take the sum of rotational kinetic energy of each ramp when they deploy into position as the objective function.

The curve of driving moment of spring T_i changes with the deploying angel θ is shown in Fig 7.

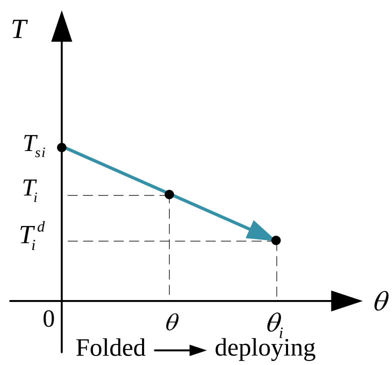

Figure 7: T_i changes with θ

We can acquire the initial torque of the spring T_{si} through the curve

$$\left.\begin{aligned} T_i &= T_i^d + k_i(\theta_i - \theta) \\ T_{si} &= T_i^d + k_i\theta_i \end{aligned}\right\} \quad (i = 1,2,3)$$

According to the law of conservation of energy,

We can acquire the objective function

$$\min f(x) = \sum_{i=1}^{3}\left[\frac{(T_{si} + T_i^d)\theta_i}{2} + m_i g h_i - T_{fi}\theta_i\right]$$

Where h_i is dropping height of centroid of ramp i after deployed.

3) constraint condition

Due to the symmetry of the ramp structure, section 1 and section 2 use the same spring and k_i can not be negative. The surplus angel of section 1 and section 2 after deploying is not more than 50°, the surplus angel of section 3 after deploying is not more than 70°

$$\begin{cases} \dfrac{T_1^{\ d}}{k_1} - \dfrac{50\pi}{180} \le 0 \\ \dfrac{T_2^{\ d}}{k_2} - \dfrac{50\pi}{180} \le 0 \\ \dfrac{T_3^{\ d}}{k_3} - \dfrac{70\pi}{180} \le 0 \end{cases} \begin{cases} k_1 - k_2 = 0 \\ -k_1 \le 0 \\ -k_3 \le 0 \end{cases}$$

The deploying time in total is not more than 10s

$$t = \sum_{i=1}^{3} t_i \le 10$$

Where t_i is the deploying time of section i.

4) optimization solution

According the results of optimization, when

k_1=k_2=5.2 and k_3=12.88（Nm/rad）, t=2.496s.

The results is satisfied with the designing conditions.

4.2 Simulation of deployment

We simulate the dynamic characteristics of deployment using ADAMS. And we get curve of the angular velocity of each section changing with time as shown in Fig 8 and Fig 9 and Fig 10.

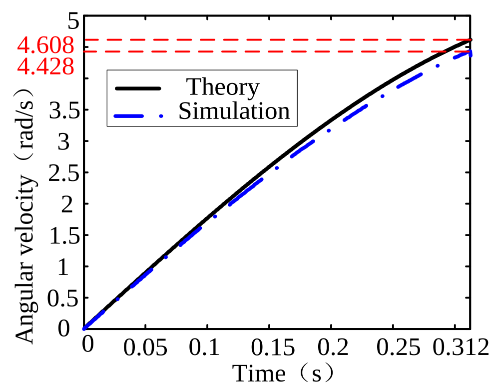

Figure 8: angular velocity *of section 1*

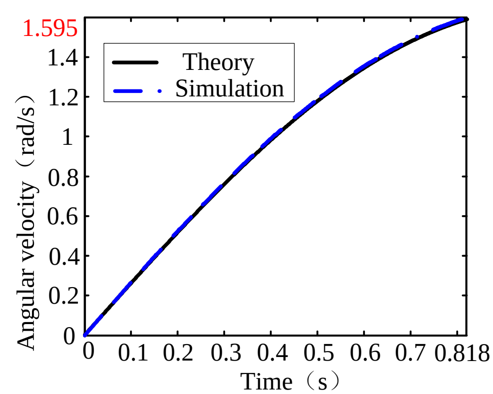

Figure 9: angular velocity *of section 2*

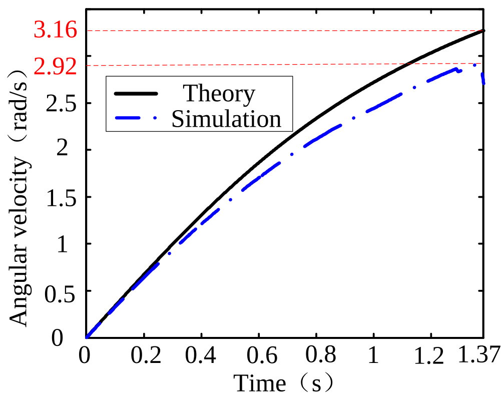

Figure 10: angular velocity *of section 3*

According to the results of simulation, when we use the spring through optimization solution, the ramp can deploy under the worst attitude, and the deploying time in total is 2.5s, the maximum angular velocity of section 3 is 2.92 rad/s.

5 SIMULATION of TRANSFERRING

Transferring characteristics is simulated under different transferring attitudes using of ADAMS, we can acquire the mechanical characteristics of track and guiderail. The simulation model is shown in Fig 11.

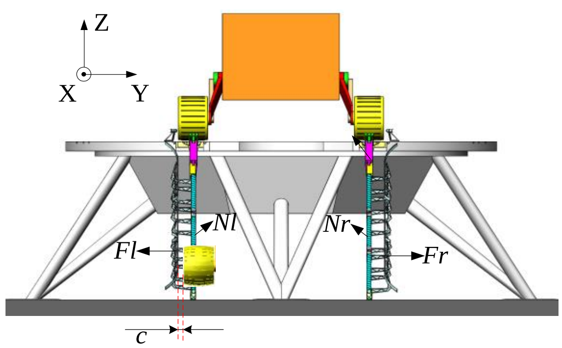

Figure 11: transferring simulation model

The input parameters include: the mass of Mars rover: M=300kg; Acceleration of gravity on Mars: g=3.675m/s^2; the distance between the wheel and the guiderail c ; the step size of simulation: 0.05s; the angular velocity of rover: 20deg/s. Inspection parameters include: F_l is lateral pressure of the left side of the guiderail; F_r is lateral pressure of the right side of the guiderail; N_l is positive pressure of the left side of the track; N_r is positive pressure of the right side of the track.

The simulation results show that, when α=15°and β=-6°, the positive pressure on the left and right track is same and the value is maximum of all transferring attitudes. The maximum value is 500 N as shown in *Fig 12.*, the worst attitude for transferring is when α=15°and δ=+6°we change the value of c, and the value of c can influence lateral pressure of left side of guiderail especially at the beginning and end of the transferring process as shown in Fig 13. So it is important to choose the suitable c. And when c=10mm, the lateral pressure of the left guiderail is minimum and the minimum value is 370N.

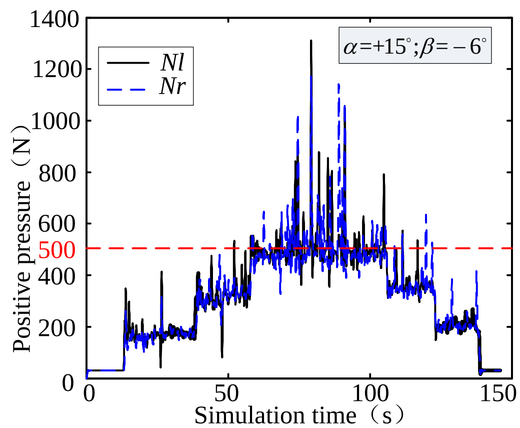

Figure 12: positive pressure of the track

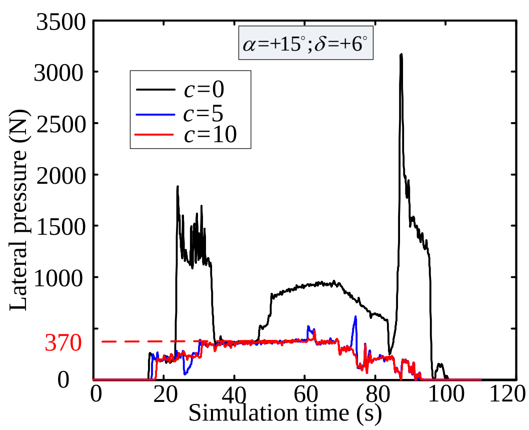

Figure 13: Lateral pressure of the left guiderail change with c

6 CONCLUSION

Based on landing on Mars for inspection detection, this paper comes up with tri-folded and deployed type transfer ramp aims at transferring the Mars rover from the landing platform to the Mars surface safely. we acquire the minimum length of ramp to meet the designing conditions that is L=2.92m. We analysis and simulate the dynamic characteristics of the deployment under the worst deploying attitude and acquire optimized spring parameters which is satisfied with the designing conditions. The result of simulation show that the ramp can deploy into position under the worst deploying attitude. Transferring characteristics is simulated under different transferring attitudes, the simulation results show that the maximum value of positive pressure of track is 500N of all transferring attitudes, when α=15° and δ=+6° and c=10mm the value of lateral pressure of guiderail is minimum, and the minimum value is 370N.

these analysis can provide reference for the project of transfer ramp.

References

[1] HAN Hongshuo, CHEN Jie (2008) 21st Century Foreign Deep Space Exploration Development Plans and Their Progresses. SPACECRAFT ENGINEERING 21:7-23.

[2] Chen Zhewu, Wen Guilin (2012) Research of the Transport Mechanisim for the Lunar Rover. Mechanical Science and Technology for Aerospace Engineering 31:1754-1759.

[3] Liu B, Li X L, Chai H Y, et al (2014) Rover release and transfer techniques of Chang'E-3 probe's lander (in Chinese). Sci Sin Tech 44:576-581.

[4] ZHU Renzhang, WANG Hongfang et al (2010) Overview of the US Mars Surface Missions(Part One). SPACECRAFT ENGINEERING 19:17-33.

[5] LI Li (2007) Dynamic simulation and optimization design of deployment of folding-wing. STRUCTURE &ENVIRONMENT ENGINEERING 34:17-21.