PS03

楕円車輪を有する二輪小型月面探査機の走行性能に及ぼす偏心駆動の影響

The Effect of Eccentric Drive on Running Performance of Two-Wheeled Small Lunar Rover with Elliptical Wheels

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1. Introduction

In recent years, there has been a fierce competition among the world's space explorers to make solar-system celestial bodies a new home for human habitation. In January 2024, JAXA's Smart Lander for Investigating Moon (SLIM) became the first Japanese spacecraft to land on the Moon, and Japan became the fifth country in the world to land on the Moon. The results of various countries have suggested the existence of water ice[1)] and $_3$He[2)] in the region around the lunar South Pole. Water molecules are attracting attention for their use as fuel for hydrogen engines and for life support in future human habitation on the Moon, hence further investigation is needed. In exploration, small spacecrafts are attracting attention because they can be developed at low cost and the cost of lunar surface transportation can be reduced. Low-power operation is required for long-duration exploration over a wide area. We have shown that rover with elliptical wheels can climb a slope of 30 degrees[3)] in a wheeled small rover. Previous studies have also shown that rover with cylindrical eccentric wheels have excellent overtaking performance[4)]. However, cylindrical wheels have the disadvantage of sinkage. On the other hand, it is considered possible to run with even lower power consumption by using elliptical eccentric wheels, which can suppress sinkage and have better running performance than cylindrical wheels. Therefore, the purpose of this study is to evaluate the optimal eccentric position of an elliptical wheel with low power consumption and high running performance, and to clarify the effect of eccentric drive on running performance.

2. Experimental Procedures

2.1. Development of a small lunar rover

Figure. 1 shows a developed small two-wheeled lunar rover. The two-wheeled small lunar rover is designed using Fusion360 (Autodesk) and printed using a 3D printer (RAISE 3D). Servo motors (5 V, 81 rpm, XC330-M288-T, DYNAMIXEL) are used to drive the wheels. Spresense (SONY) and DYNAMIXEL Shield (ROBOTIS) are used for control. A stabilizer is attached to the rear of the main body for stability in the forward and backward directions. The dimensions of the main body of the rover are 158 mm high, 60 mm wide and 347 mm long. The eight types of wheels evaluated in this study are shown in **Figure. 2**. In order to evaluate the effect of eccentricity position on running performance, the following eccentricities are used: cylindrical eccentricity 5:2 (C-5:2), reference ellipse (E-Normal), major axis eccentricity 5:1 (E-Ma-5:1), major axis eccentricity 5:2 (E-Ma-5:2), major axis eccentricity 5:3 (E-Ma-5:3), minor axis eccentricity 5:2 (E-Mi-5:2), 45° eccentricity5:2 (E-45deg-5:2), -45° eccentricity5:2 (E--45deg5:2). The diameter of the cylindrical wheel is 100 mm, the elliptical wheel has a major axis of 100 mm and a minor axis of 75 mm, and the outermost diameter of all eight wheels, including lugs, is 120 mm. The wheel width is 20 mm. The lugs are 10 mm long and 2 mm wide, and 16 lugs are installed. **Figure. 3** shows the expression of the eccentricity distance. The eccentricity is expressed as (radius of the major axis of the ellipse (or radius of the circle)) : (eccentricity).

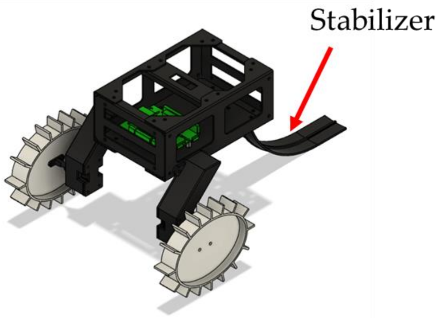
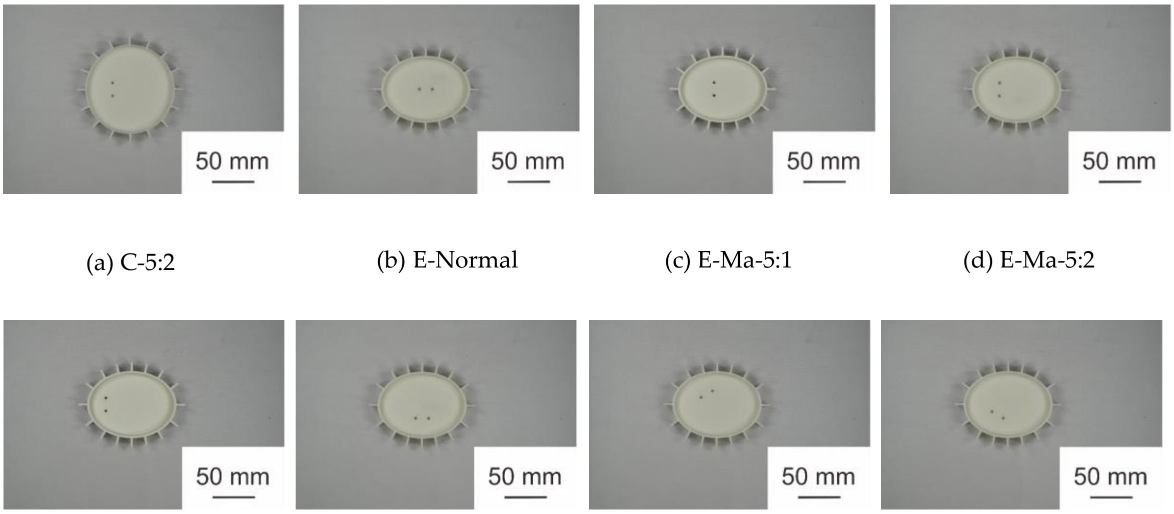


Figure 1. Appearance of the rover



(a) C-5:2 (b) E-Normal (c) E-Ma-5:1 (d) E-Ma-5:2

(e) E-Ma-5:3 (f) E-Mi-5:2 (g) E-45deg-5:2 (h) E--45deg5:2

Figure 2. Eight types of wheels

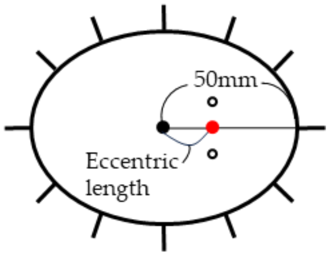


Figure 3. Eccentric length

2.2. Test course

Figure. 4 shows an overview of the running test course. The test course is 450 mm wide, 308 mm high and 1,820 mm long; and was fitted with an acrylic plate to allow the running to be observed from the side. A mixture of silica sand No. 5 (Takeorikogyosho) with a particle diameter of 0.3 mm to 0.8 mm and silica sand No. 6 (Takeorikogyosho) with a particle diameter of 0.2 mm to 0.3 mm, a ratio of 1:1, is used for soil.

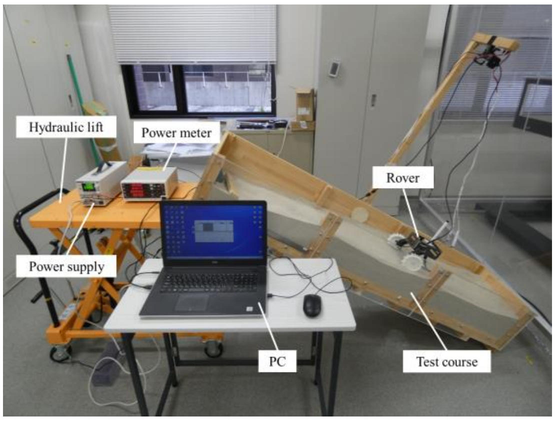


Figure 4. Overview of the test course

2.3. Performance test

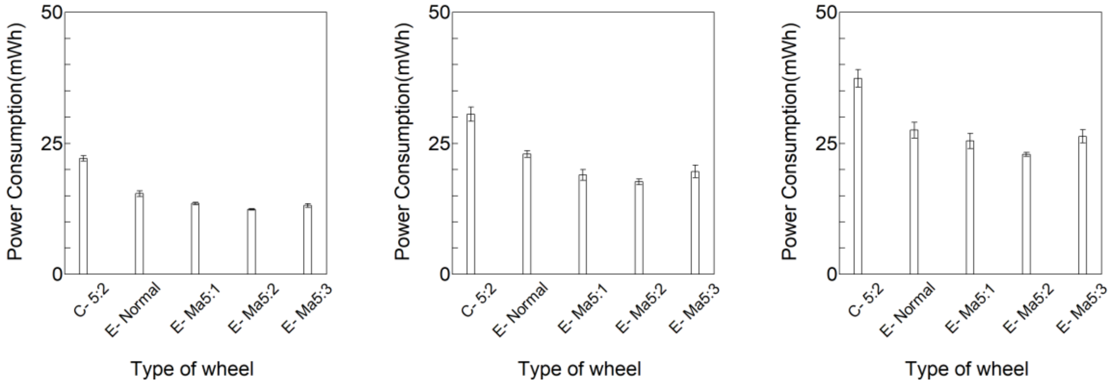
Running time and energy consumption are evaluated. The distance of the running course is 700 mm, and the inclination is set from 0 ° to 30 ° in 7 steps of 5 °. The left and right motors are driven at 30 rpm during the test. The voltage is set at 5 V, the rated voltage of the motors. The angle was set so that the average of the angles at nine points on the running course is within ±1 °. A regulated DC power supply (PMX18-5A, KIKUSUI) is used as the power source, and an electricity meter (PW3335, HIOKI) is used to measure the power consumption.

3. Results

3.1. Results of performance test related to eccentric distance

The running time and power consumption of five wheels with different eccentricity of the rotation axis are measured at each inclination. The results of power consumption at 20°, 25°, and 30° are shown in **Figure. 5**. Both running time and energy consumption are smaller for E-Ma-5:2 than that for C-5:2 and E-Normal. The running performance of E, which has the largest eccentricity distance, is found to be lower than that of D.

Therefore, E-Ma-5:2 is found to have the highest driving performance.



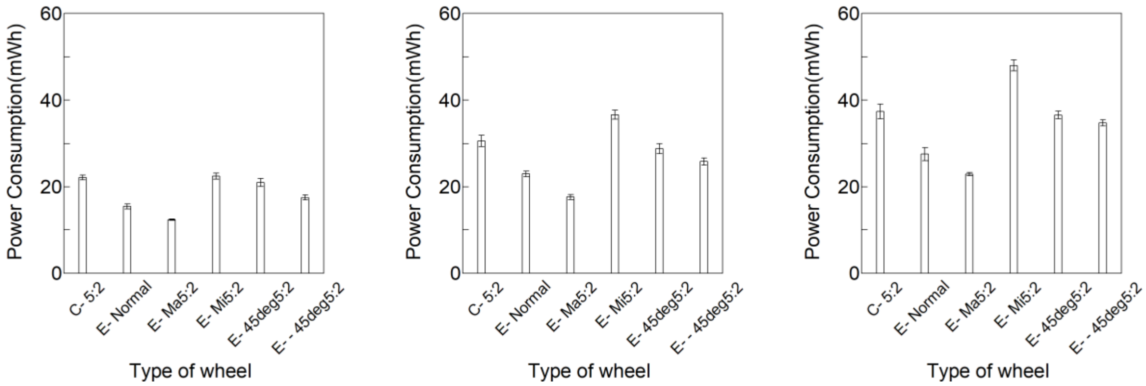
(N=5,mean±S.D.)

(a) 20 degree (b) 25 degree (c) 30 degree

Figure 5. Results of power consumption

3.2. Results of performance test related to eccentric direction

The running time and power consumption of six wheels with different eccentricity of the axis of rotation on the same ellipse are measured at each inclination. The results of power consumption at 20°, 25°, and 30° are shown in **Figure. 6**. Among the six wheels, E-Ma-5:2 wheel with the eccentricity in the long axis direction shows the highest running performance in terms of running time and energy consumption.



(N=5,mean±S.D.)

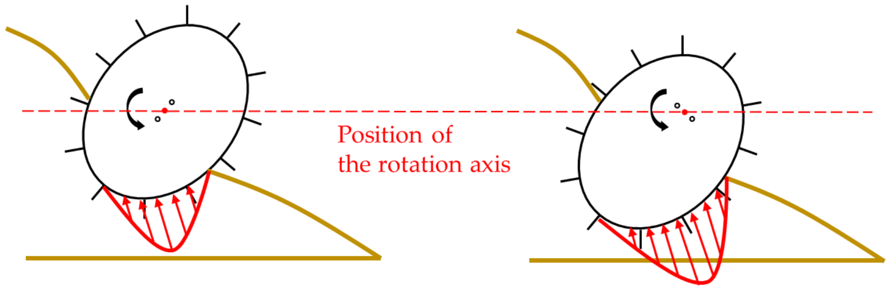
(a) 20 degree (b) 25 degree (c) 30 degree

Figure 6. Results of power consumption

4. Discussion

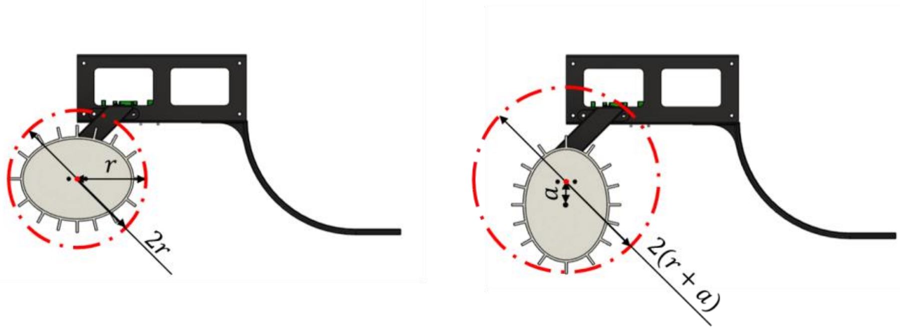
4.1. Effects of eccentric distance

One possible reason for the improved running performance when the eccentric distance is increased is the increased ground contact area with the sand. **Figure. 7** shows a diagram of the state of the wheels of the elliptical wheel when traveling on a slope. **Figure. 7** shows that for the elliptical wheel, major axis of the wheel is parallel to the slope, the lugs penetrate the sand and rotate, and the lugs in the longitudinal direction become perpendicular to the slope. By the time the longitudinal lugs become perpendicular to the slope, the eccentric wheel has a larger contact area with the sand, which increases to the extent that the wheel can compact the sand. Therefore, the larger area that can be compacted leads to an increase in the propulsive force obtained by the wheel[5], and the running performance of E-Ma-5:2 is considered to be better than that of E-Normal. **Figure. 8** shows the turning radius. Even with the same wheel size, eccentricity of the rotation axis increases the amount of rise due to the expansion of the turning radius; and E-Ma-5:2 with a larger eccentric distance is considered to exhibit higher running performance.



(a) E-Normal (b) E-Ma5:2

Figure 7. Wheel rotation dynamics during ascent



(a) E-Normal (b) E-Ma5:2

Figure 8. Radius of the wheel

The rover with E-Ma-5:3 showed lower running performance than that of E-Ma-5:2, despite a larger eccentricity distance. One possible cause is that E-Ma-5:3 has a 30 mm eccentricity of the rotation axis, which results in an extremely small turning radius when traveling on a slope. **Figure .9** shows difference in backward distance per revolution depending on the position of the wheel's axis of rotation. The 30 mm eccentricity of the rotation axis increases the vertical motion during hill climbing, which is considered to be effective in slope running[6]. On the other hand, if the turning radius of the wheel becomes small when traveling on a slope, the wheel idles when traveling on already collapsed sand, and the wheel can not obtain sufficient reaction force necessary for forward motion and moves backward. Therefore, the distance of backward motion is the largest among the wheels with eccentricity in the long axis direction. For these reasons, E-Ma-5:2 wheel (5:2 long axis eccentricity) with a rotation axis eccentricity of 20 mm had the highest running performance.

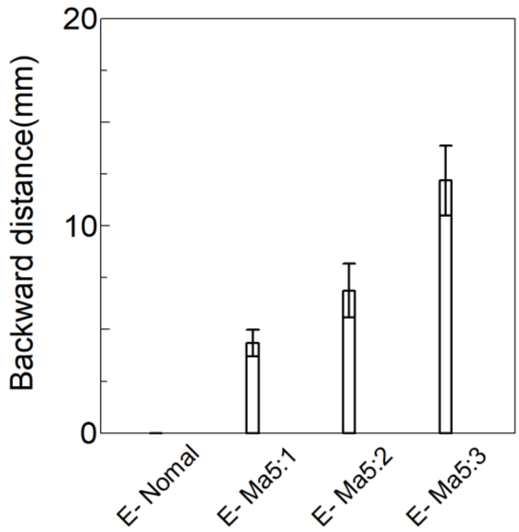


Figure 9. Backward distance (30 degree)

4.2. Effects of eccentric direction

Among the wheels with eccentricities in the long axis direction, short axis direction, 45° direction, and -45° direction, the wheel with the eccentricity in the long axis direction had the best running performance. The reason for this is thought to be that the eccentricity in the long axis direction increases the turning radius when running on a slope, resulting in a larger propulsive force obtained by the wheel. When considering the effect of eccentricity direction on running performance, the wheel with the eccentricity in the long axis direction has the largest eccentricity distance when the ratio is fixed on the ellipse and the rotation axis is eccentric. For wheels with eccentricities in the 45° and -45° directions, when the lugs penetrate the slope, the sides of the wheel are parallel to the slope and the contact area with the sand is larger, resulting in a larger reaction force from the sand. However, the effect of the eccentric distance is considered to have a greater effect on running performance than the reaction force obtained from the sand. For these reasons, when the direction of eccentricity of the rotation axis is changed on the same ellipse, the rover with the wheels showed higher running performance when the eccentricity is in the long axis direction.

5. Conclusions

In this study, the effects of eccentricity distance and eccentricity direction on running performance of the rover with elliptical wheels are clarified. The investigation yielded the following conclusions.

1) The rover with elliptical wheels had better traveling performance than that with cylindrical eccentric wheels.
2) A long axis eccentricity of 5:2 with an eccentric distance of 20 mm is considered to have a larger contact area with the ground, resulting in a larger reaction force from the sand, leading to shorter travel time and lower power consumption.
3) Eccentricity in the long axis direction showed the highest driving performance.

References

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