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Effect of Straight Grousers Parameters on Motion Performance of Small Rigid Wheel on Loose Sand

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Abstract: For optimizing wheel configuration of planetary rover, the effect analysis of straight grousers on motion performance of a small rigid wheel was conducted in loose sand bin. All tests were done at a free wheel sinkage and 0 to 60% slip in a single-wheel test bed. By the qualitative analysis and comparisons of tractive and steering performance between smooth wheel and the wheels with different straight grousers, the results show that the grouser height and slip more significantly influence the motion performance than grouser spacing and thickness. Through applying the evaluation indexes of tractive and steering performance to the experimental results, the preferable grouser parameters for actual applications are 15° grouser spacing, 10 mm grouser height and 1.5 mm grouser thickness; the optimum value of wheel slip is 13% for the similar sand used in the experiment.

Key words: Motion performance, grouser, wheel, tractive efficiency, steering index

INTRODUCTION

A small rigid wheel of diameter from 0.2 to 0.4 m is suitable for the planetary rover at present. All rovers use wheels to carry payload, generate traction and provide maneuverability. As the component of the wheel, grousers play an important role to improve the tractive performance of the wheel. Usually, grouser parameters, such as grouser spacing, height and thickness influenced the improvement of motion performance. The kinds of grouser shape of the wheel mainly include the incline and straight grousers. The incline grousers are favorable to decreasing Steering Resistance Moment (SRM) for the differential steering rover. In contrast, the straight grousers are suitable for the rover with two steering motors in the front and rear of the rover, respectively. The motion performance of a rover is usually evaluated by its Drawbar Pull (DP), Driving Torque (DT) and SRM, which is related to the normal and shear force distributions produced by the grousers and wheel rim at the wheel-sand interface (Wong, 2001). Where, DP is the difference of total tractive effort and total rolling resistance, DT is equal to the moment developed by the total resistance from the wheel axial. Because of the complexity of grouser-sand interaction, experiments are the perfect way to analyze the effect of grouser parameters on motion performance of the wheel, which are useful for wheel configuration design as well as establishing the mathematical models for the interaction between grousers and sand.

Many research works have been done to study the influence of lugs on mobility. However, almost all of the previous works have been concerned with the lugs on cage wheels. Watyotha and Salokhe *et al.* (2001a, b) measured the pull force and lift force developed by changing the lug spacing and circumferential angle in soil bin with clay soil of 49 and 51%, respectively average soil moisture content, however, all the force measurements were done at a constant 7 cm sinkage. Wang *et al.* (1995) introduced that the cage wheel was driven under paddy soil conditions, the results showed that the pull force, lift force, slip and sinkage fluctuating periodically with the rotation angle and the period was equal to the interval of lug spacing. To obtain the better lift forces for cage wheel used in wet rice soil, reaction force on a single movable lug were also investigated by Wawan *et al.* (1997, 1998). By the theoretical analysis of off-road tyre performance with straight and angled lugs, the results indicated that the angled lugs could provide higher lateral force and lower tractive force than straight lugs (Abd EI-Gawwad *et al.*, 1999a, b). Besides the single-wheel test bed were employed to measure the interaction between lugged wheel and soil, discrete element method was used to simulate the effect of lug parameters on wheel (Asaf *et al.*, 2006; Nakashima *et al.*, 2007).

Despite many researches on lugged cage wheel and lug-soil interaction on paddy soil, there were little information available for analyzing the effect of grouser parameters on rigid wheel used for exploration on loose sand. Aiming at the necessity to find preferable grouser

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parameters and wheel slip for the rovers with steering motors and the rovers can fully exert the motion performance under limited energy consumption, this study carried out an experimental investigation on the effect of straight grouser parameters on motion performance of a closed rigid cylinder wheel in a laboratory single-wheel test bed.

MATERIALS AND METHODS

Model of wheel with grousers: The cylinder wheel with grousers was studied as shown in Fig. 1a. The smooth wheel radius and width are 0.135 and 0.165 m, respectively. Grousers are made of hard aluminum alloy. One kind of grousers is 1.5 mm thickness. The grouser spacing and height are various from 15°, 18° to 22.5° and from 5, 10 to 15 mm, respectively. Another two kinds of grousers with the height of 5 mm are 7 and 11 mm thickness, respectively. Grousers can be arranged equally with the central angles of 15°, 18° and 22.5°, respectively. The definitions of grouser parameters were given in Fig. 1b.

Soil condition: To achieve the desirable loose sand in the bin, the sieve was used to separate the fine particles of sand which was exposed to sun for three days. The sand moisture content, porosity ratio and bulk density are 0.282%, 0.68 and 15.729 kN m^{-3}, respectively.

Experimental apparatus and method: Experiments were conducted in a laboratory single-wheel test bed with the length of 1.78 m, the width of 1.0 m, the height of 1.44 m, as shown in Fig. 2. The depth of sand bin was 0.29 m. The apparatus was mainly made up of six force transducers, displacement transducer, torque sensor, towing motor, driving motor and steering motor, which play the roles of recording DP and side force, displacement of wheel and DT, moving the wheel on the linear guide, rotating the wheel and steering the wheel, respectively.

Wheel slip, i, is defined by the ratio of the difference between wheel circumferential velocity and the wheel moving velocity to the wheel circumferential velocity, as shown in the following Eq.

$$i = \frac{\omega R - v}{\omega R} \quad (1)$$

where, ω is the wheel angular velocity, R is the outer radius of the wheel, v is the travel velocity of wheel.

The desired values of wheel slip could be obtained by varying the rotate speed of towing motor and driving motor. In this experiment, the wheel slip was from 0 to 60%, wheel load was 80N by the mean of changing the counter weights and the moving speed of supporting frame of wheel was a constant 25 mm sec^{-1}. Furthermore, for testing the effect of straight grousers on SRM, the wheel slip was 30% when the wheel rolled forward and the steering angular velocity was 0.014 rad sec^{-1} when the wheel stopped rolling to steer. Vertical displacement of the wheel was freedom in the experiment. The benchmark of the displacement transducer was selected when the wheel just contact the surface of sand.

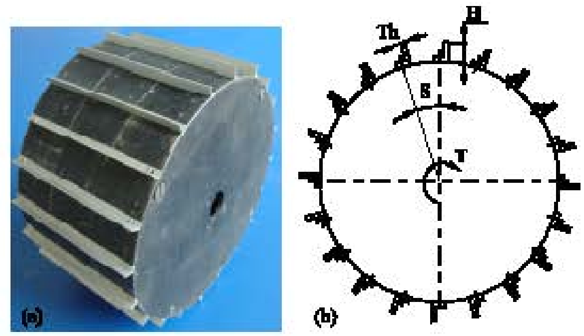

Fig. 1: Wheel and grousers for experiment (a) wheel with grousers and (b) grousers parameters

Fig. 2: Experimental apparatus

The sand was carefully controlled during the experiment in order to maintain a relatively uniform sand condition throughout all experimental runs. In the experiment, the rake and scraper were employed to rake sand and level sand, respectively.

Data processing: Wheel slip, moving velocity and steering angular velocity were imported by the software platform.

Each experiment was replicated three times. All data signals from the experiments were recorded by data collector and were converted to digital signals by A/D converter in a computer subsequently.

RESULTS AND DISCUSSION

Effect of grouser spacing on DP, DT and SRM: To the smooth wheel and the wheels with grousers of 5, 10 and 15 mm height, respectively, the results of DP and DT at different grouser spacing for various wheel slip are shown in Fig. 3.

It can be observed from Fig. 3 that DP and DT are significantly improved when the wheel are installed the grousers. And DP and DT reduce with the increase of grouser spacing from 15° to 22.5°, due to the decreasing shearing caused by the decrease of the number of grouses interacting with sand.

It can be seen that SRM is approximately proportional to the steering angle when the steering angle is below 10° and then increases at a lower rate and reaches a maximum value when the steering angle is beyond 10° (Fig. 4). The reason of this result is that the shearing force between the wheel and the sand tends to a maximum with the increase of the steering angle, which is induced by the property of wheel-sand interaction.

The increase of grouser spacing causes a slight decrease in SRM due to more grousers contacting with sand. Therefore, grouser spacing has an opposite influence on DP and SRM, as shown in Fig. 3 and 4. Furthermore, it is obvious that the decrease of grouser spacing induces the enhancement of the sand disturbance when the grousers are leaving the sand. This is unfavorable to multi-axis rover motion performance. Thus, the tractive and steering performance should be comprehensively considered to select the proper grouser spacing based on the exploration mission. This principle is also applicable to the selection of grouser height and thickness.

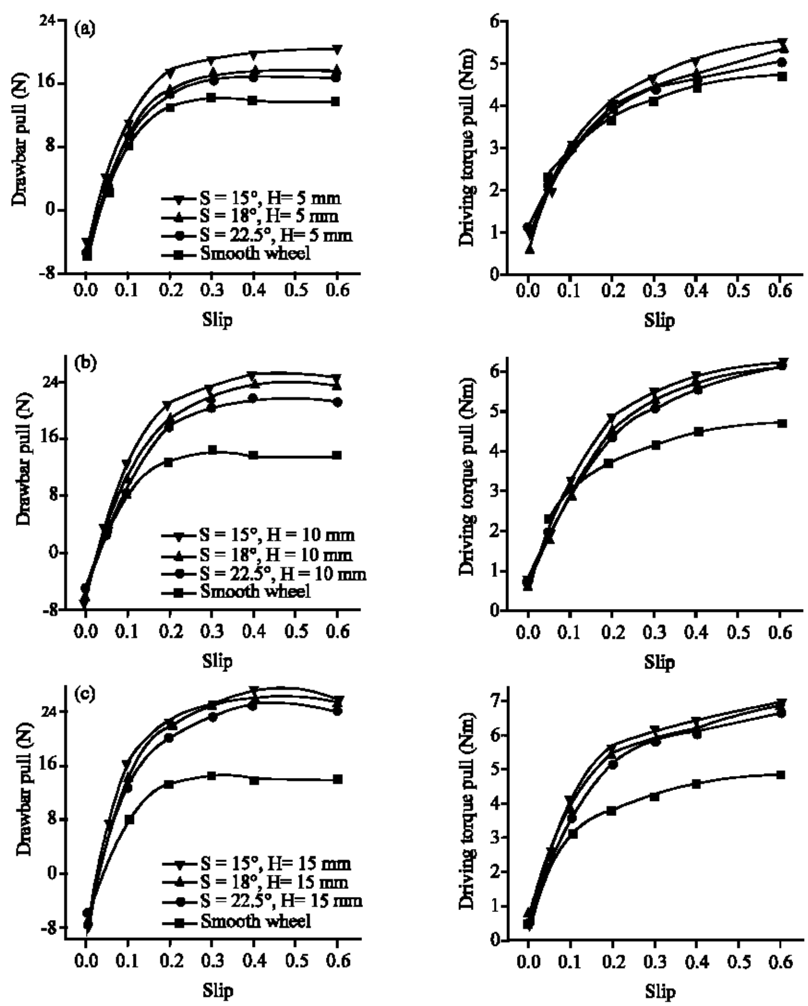

Fig. 3: Dependence of DP and DT of smooth wheel and wheel with different spacing grousers on slip when H is (a) 5, (b) 10 and (c) 15 mm, respectively, where S and H denote grouser spacing and grouser height, respectively

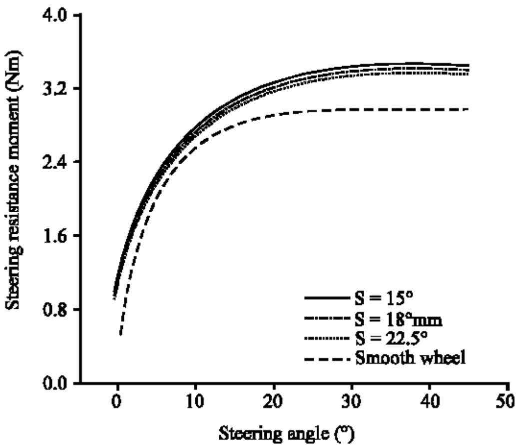

Fig. 4 Dependence of RSM of the smooth wheel and the wheels with grousers of 10 mm height on steering angle when S is 15°, 18° and 22.5°, respectively, where S denotes grouser spacing

Effect of grouser height on DP, DT and SRM: Plots of the relation between grouser height and tractive performance for various wheel slips are shown in Fig. 5.

Figure 4 and 5 indicate that DP and DT increase with the increase of grouser height and their increase rate are significant when grouser height changes from 5 to 10 mm. When grouser height changes from 10 to 15 mm, DT increases further, however, the increase rate of DP is slight. This can be explained from the regression statistical analysis of experimental results. The increase of grouser height improves the sand disturbance and wheel sinkage, as a result, the motion resistance becomes larger. Therefore, DP decreases gradually and DT increases gradually.

It is observed in Fig. 6 that the influence of grouser height on SRM is obvious. This is caused by the increasing passive earth pressure acted on contact area between grousers and sand due to the increase of grouser height.

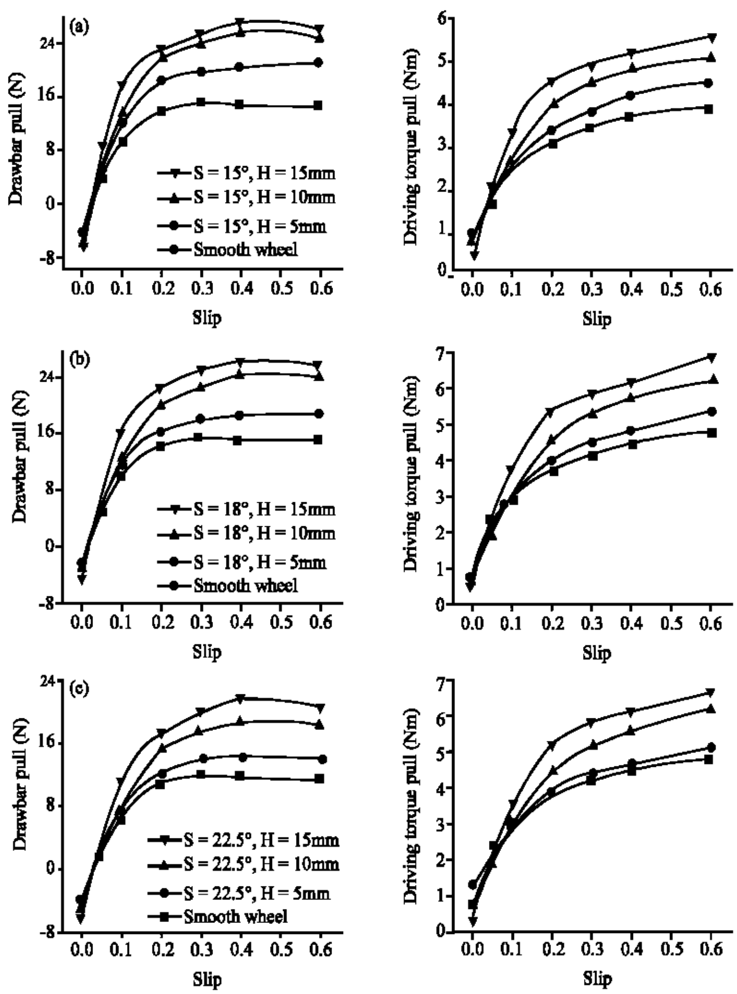

Fig. 5: Dependence of DP and DT of the smooth wheel and the wheels with different height grousers on slip when S is 15°, 18° and 22.5°, respectively, where S and H denote grouser spacing and grouser height, respectively

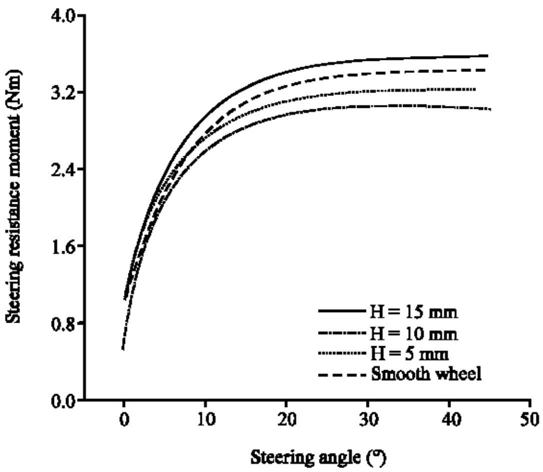

Fig. 6: Dependence of RSM of the smooth wheel and the wheels with grousers of 15° spacing on steering angle when H is 5, 10 and 15 mm, respectively, where H denotes grouser height

Effect of grouser thickness on DP and DT: Figure 7 shows the relation of DP and DT to slip for the wheels with 5 mm height, 18° grouser spacing and 1.5, 7 and 11 mm thickness grousers, respectively.

From the experimental results in Fig. 7, it can be seen that grouser thickness from 1.5 to 11 mm has slight influence on DP, which decreases slightly with grouser thickness. However, the changes in trend of DT give rise the imprecision to summarize the rules for the effect of grouser thickness on DT.

The increase of grouser thickness improves the ratio of total area of grousers to total area of wheel rim. It is equivalent to increase the diameter of the wheel at the position of grousers. In theory, DP and DT of the smooth wheel, to a certain extent, increase with the increase of wheel diameter. Here, the results in Fig. 7 show the subtle balance between the effect of grousers which cause sand shear and the area between the grousers which is dominated by frictional effects.

SRM is a function of wheel diameter, besides the wheel width, grouser parameters and sand characteristic. With the rise of wheel diameter, wheel sinkage becomes smaller. As a result, SRM got smaller. Figure 8 shows the experimental results of SRM as grouser thickness changes from 1.5 to 11 mm.

Effect of wheel slip on DP and DT: It can be observed from Fig. 3, 5 and 7 that DP and DT increase rapidly at the initial stage with the increase of wheel slip from 0 to about 10%. With the increase of wheel slip, wheel sinkage increases rapidly. This induces the increase of the total

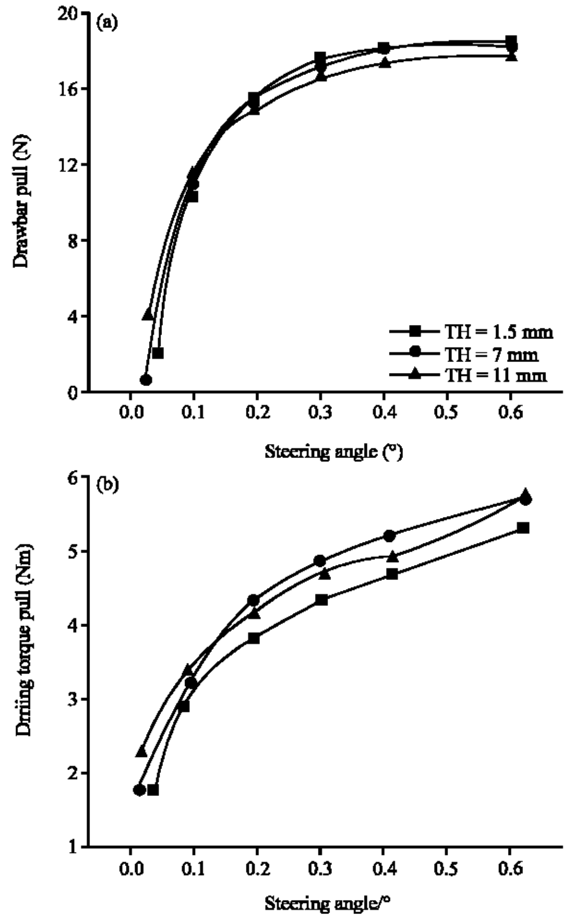

Fig. 7: Dependence of DP and DT of the wheels with various thickness grousers of 5 mm height and 18° grouser spacing on slip, where TH denotes grouser thickness

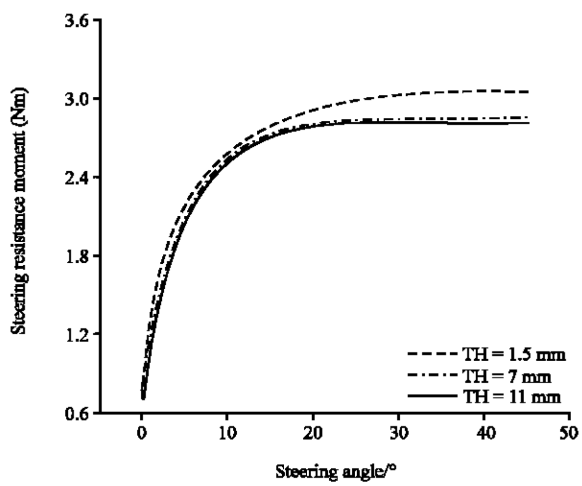

Fig. 8: Dependence of SRM of the wheels with various thickness grousers of 5 mm height and 18° grouser spacing on steering angle, where TH denotes grouser thickness

resistance. Then, DP gradually reaches a certain maximum value with the continuous increase of slip from 10% to 45%. DP gradually reduces due to the significant increase of total resistance as slip changes from 45 to 60%. In the process of slip varying from 0 to 60%, the value of sinkage and total resistance get higher, which causes the continuous increase of DT. This change trend in the relation between tractive performance and wheel slip relates to sand behavior.

The rover can't perform the best driving capability at the smaller slip. And the excessive slip leads to the wheel acutely digging the sand and being sucked in the sand, which is the fatal factor for the exploration. To the similar sand used in the experiment, the preferable slip range for wheel driving control is from 10 to 45%.

It also can be seen from the Fig. 3, DP is negative value at slip of less than 3%. In this case, the wheel became a towed wheel which should beavoidedin application. Whereas, DT is a positive value because some amount of input torque is utilized to overcome the inertia forces and bearing friction of the driven rigid wheels even at a smaller slip, it is also confirmed by Watyotha *et al*. (2001).

EVALUATION OF GROUSER PARAMETERS ON WHEEL MOTION PERFORMANCE

Motion performance indexes: To characterize the efficiency of a wheel in transforming engine power to the power available at the drawbar, the tractive efficiency η isoften used (Wong, 2001). It is defined in terms of drawbar pull DP, travel velocity v, driving torque DT and wheel angular velocity ω:

$$\eta = DPv/DT\omega \quad (2)$$

According to the Eq. 1, the expression of ω can be deduced to be:

$$\omega = v/(1-i)R \quad (3)$$

where, R is the outer radius of the wheel which includes the grouser height.

Substituting Eq. 3 into Eq. 2, the expression for tractive efficiency becomes

$$\eta = \frac{Dpv}{DT}(1-i)R \quad (4)$$

For illuminating the steering maneuverability qualitatively, Eq. 5 was established as following equation:

$$\eta_s = \frac{\omega_s}{(SRM/W)} \quad (5)$$

where, ω_s is the steering angular velocity and W is the payload of wheel.

In Eq. 5, the larger value of η_s indicates that steering maneuverability is more excellent.

Using Eq. 4 and 5, the effect of the grouser parameters on the motion performance of the wheel can be evaluated.

Experimental results analysis by tractive performance indexes: According to analysis of experiment results in Fig. 3, it indicates that the values of DP and DT increase with the increase of slip and DP reaches a maximum value wheel driving control. Applying Eq. 4 to analyze experimental data in Fig. 3, tractive efficiency reaches the when slip is about 45%, which is the upper limit for the maximum value at about 13% slip, as shown in Fig. 9. Therefore, the slip of 13% is the optimal value for the wheel rolling on terrain which is similar to the

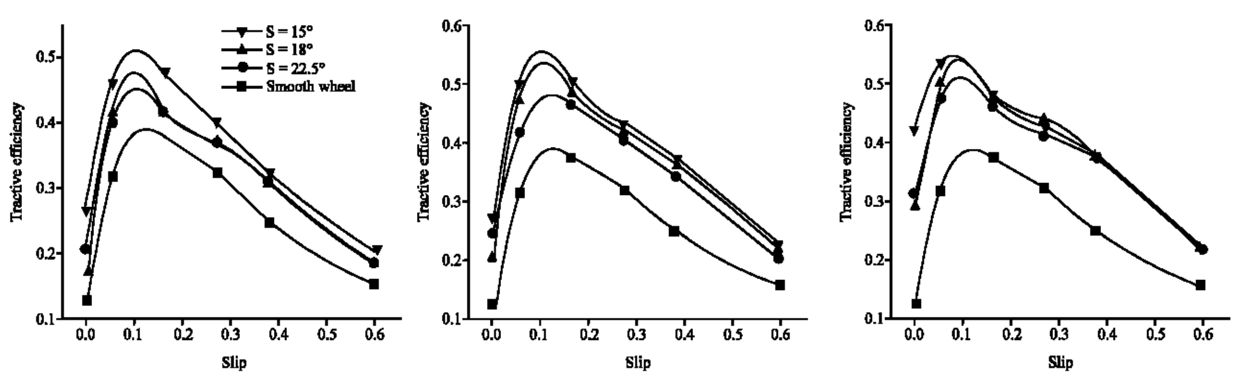

Fig. 9: Tractive efficiency of wheel with different spacing grousers at slip, where S denotes grouser spacing

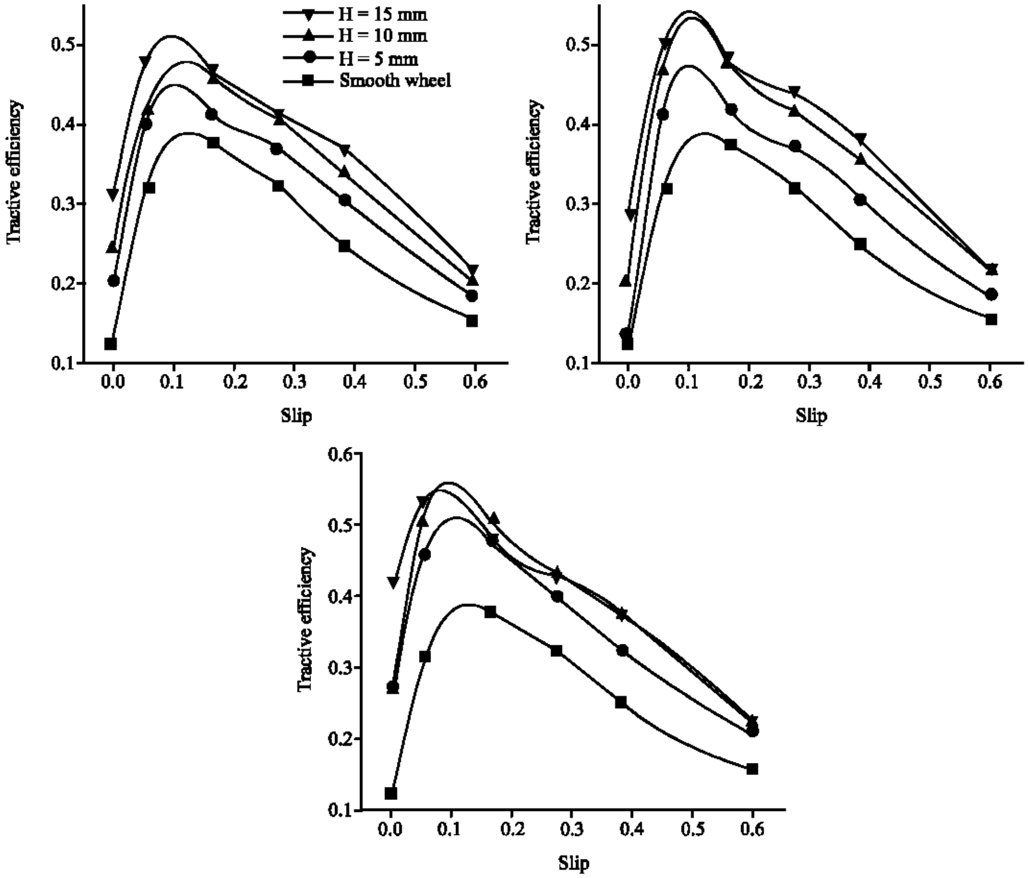

Fig. 10: Tractive efficiency of wheel with different height grousers at slip, where H denotes grouser height

loose sand in the experiment. And with the increase of grouser height and numbers, the maximum value of tractive efficiency gradually increase, which can be seen from Fig. 10.

In Fig. 9, tractive efficiency increases with the decrease of grouser spacing and the increase rate at the grouser spacing from 18° to 15° is less than that from 22.5° to 18°.

Moreover, according to the similar analysis from Fig. 10 and 11, it can be deduced from the perspectives of tractive performance and the actual application that the preferable grouser spacing, grouser height and grouser thickness of wheel used in the experiment were 15°, 10 and 1.5 mm, respectively.

Experimental results analysis by steering performance indexes: Applying Eq. 5 to the results in Fig. 4, 6 and 8, it can be obtained from the perspectives of steering that lower and thicker grouser with bigger grouser spacing is favorable to steering maneuverability. In addition, the selection of grouser parameters should be considered comprehensively for tractive performance in actual applications.

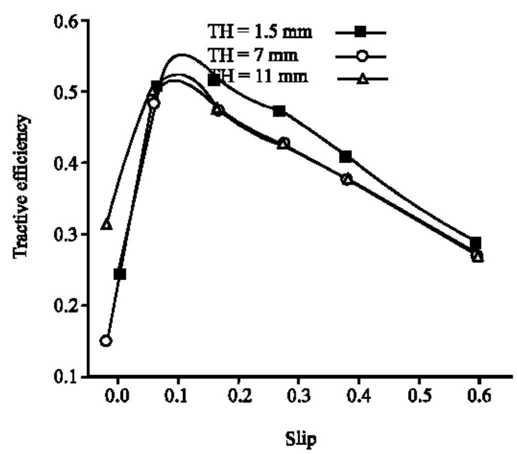

Fig. 11: Tractive efficiency of wheel with different thickness grousers of 18° grouser spacing and 5 mm height, where TH denotes grouser thickness

CONCLUSIONS

Experimental research and analysis on the effect of straight grousers on motion performance of a small rigid wheel in loose sand bin were carried out. Tractive and steering performance of the wheels with different straight grousers at various wheel slip are compared against that of smooth wheel, the results show that the grouser height and slip produce more significantly influence on the motion performance than dose of grouser spacing and thickness. Applying the evaluating indexes of tractive performance and steering performance to the experimental results, the preferable grouser parameters of grouser spacing, height and thickness were deduced to be 15°, 10 and 1.5 mm respectively for the wheel. And the optimal value of slip should be 13% for wheel driving control. These results may be useful in optimizing wheel configuration of planetary rover and are useful for wheel configuration design as well as establishing the mathematical models for the interaction between grousers and sand.

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