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Application of DEM to Simulate Interaction between Soil and Tire Lug

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Abstract: Using the modified DEM (Distinct Element Model), which we proposed, the effect of cross section of tire lug on the tire performance was simulated. Though the DEM has an advantage over the FEM when it is applied to simulate the behavior of discrete assembly of particles such as soil, there was still a problem in the case of conventional DEM, that the simulated movement of particles was too free. We constructed a new mechanical model (modified DEM) which can take account of the effect of adhesion between particles. It is shown that the soil deformation is simulated by the modified DEM better than the conventional DEM. Comparing the simulated soil reaction to the tire lug with the experimental results, the adequate DEM parameters were found. It is also indicated possible to find the effect of lug cross section shape on the tractive performance of tire by the DEM simulation.
Keywords: Computational Mechanics, DEM, Modified Model, Tire Lug, Tractive Performance, Soil Adhesion

Introduction

The principle and merit of DEM were already described in previous papers [Momozu(1997), Ohkobo (1998), Oida(1997)]. It would be the most promising method to analyze a dynamic interaction between soil and machine by applying a computational mechanics. The finite element method (FEM) has been used in some research papers in the Journal of Terramechanics to simulate dynamic soil behaviors which were made by machine parts of off-road vehicles. In the case of the FEM, the object analyzed such as soil is assumed as a continuum. However, soil is originally a granular assembly. There are many phenomena where the soil is cut and separated. For those cases the FEM is hardly applied.

The distinct element method (DEM) was developed to simulate the dynamic behavior of granular materials for example the granular flow. In the DEM the object material is represented by an assembly of particles. The elastic and inelastic properties at the contact between the particles are expressed by a spring with a spring constant (elastic modulus) and a dashpot with a viscous damping constant. The contact forces between a particle and particles contacted with the particle are calculated from the overlap quantities between those particles using the spring constant and the viscous damping constant. Then the displacement of the particle is obtained for a certain time interval, solving the governed kinetic equations. This process is repeated for all particles in the analyzed region for a very short time interval as 0.0001 second and then for the total set time for example 4 seconds. The calculation results show a whole deformation of the assembly of particles and also a reaction force of the assembly to the machine part which acts onto the soil (particles' assembly), adding up contact forces between the machine part and contacted particles with the part.

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Though the DEM is utilized to simulate the behavior and reaction of an assembly of fine particles such as soil, the simulated particle movement was too much than the real movement when we used the conventional mechanical model, which was used to calculate the contact forces between particles (i.e. elements). As the result it was difficult to obtain the real order reaction forces of material, which we dealt with, by the conventional DEM.

Therefore, a new mechanical model is proposed here. In order to restrain the particle movement in the case of the conventional DEM, where no tension force is acted, the normal spring between elements is forced to act as a tension and also compression spring depending on the relative displacement direction of contacted elements. By this way we can represent the influence of so-called adhesion of soil on the behavior and reaction force of elements' assembly.

Procedures

1. Modified Mechanical Model

Fig. 1 shows the conventional mechanical model to calculate the contact forces between two elements. The overlapping of two elements is allowed and it is assumed that the normal and tangential contact forces will be calculated by the spring forces, which depend on the overlapping quantity and relative peripheral displacement, and by the viscous damping forces, which depend on the velocities of displacements. Looking at the normal spring force, the force always acts in the direction of departing of both elements

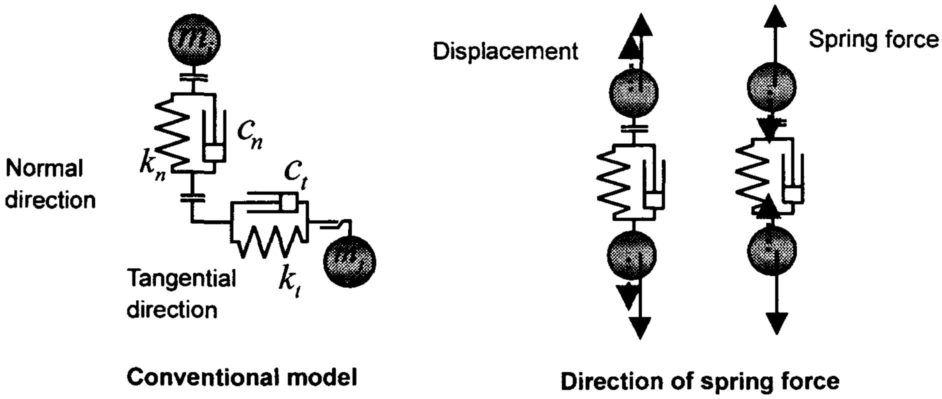

Fig. 1 Conventional mechanical model of DEM.

regardless of the direction of relative displacement. This feature will cause the too-discrete behavior of elements together with the fact that there is no tensile force between elements after their departing.

In the case of the modified mechanical model, which is proposed here, the normal force always acts in the inverse direction of relative displacement between two elements. As shown in fig. 2, the spring in the normal direction of both contacted elements is used to represent two actions: a compression when both elements are approaching to each other and a tension when the elements are tending to depart from each other. The natural length of the spring is changed as follows: it is the sum of radii of two contacted elements when the spring acts as the compression spring and it varies to the past minimum distance between centers of two contacted elements when the spring acts as the tension spring. It should be noted that the mentioned spring forces only act during the overlapping of elements.

2. Preliminary Simulation

In order to find whether the new modified mechanical model can make the effect of tension spring as same as the soil adhesion on the deformation of elements' assembly and whether the modified model is adequate to investigate the mechanical interaction between a running device and soil, a preliminary simulation was conducted.

Conditions of Preliminary Simulation

The DEM simulation is done in two-dimensional plane. So that a virtual soil bin (100 cm wide, 1 cm deep) is prepared and 8,379 elements were filled till the height of elements' assembly reached to about 17 cm (cf. fig. 3). A rigid wheel (radius 21 cm, mass 1.5 kg) with lugs (height 2 cm) at 18 degrees interval was put on the elements' assembly, a vertical load of 8 N and a horizontal load of 6 N were applied to the wheel, then the wheel was rotated on the surface of elements' assembly with the velocity of 80 degrees/s. The movement of the wheel is also governed by the Newton's Law. It means that the magnitude and direction of acceleration of the wheel are found from a horizontal resultant force acted to the wheel, which is obtained by summing up horizontal components of all contact forces between the tire and elements and subtracting the pull force from it.

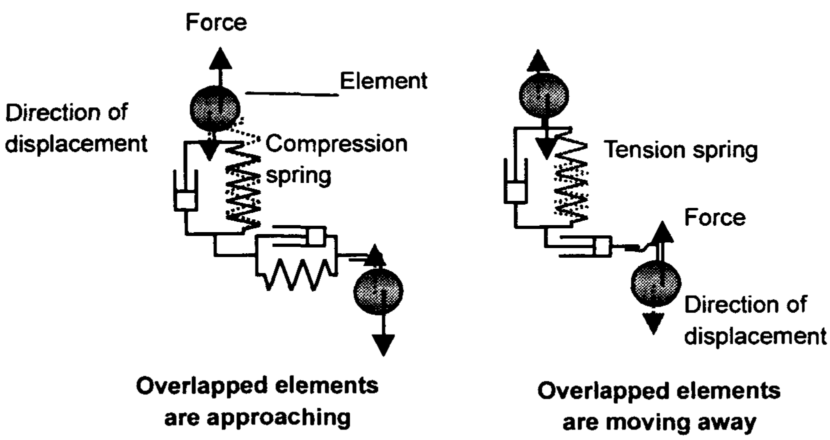

Fig. 2 Modified mechanical model of DEM.

The DEM parameters used in the preliminary simulations were as follows: normal compression spring constant of 1,800 N/m, normal tension spring constant 900 N/m, tangential spring constant 450 N/m, viscous damping coefficient (m: mass of element, k: normal spring constant at that time), friction coefficient 1.8 between element and wheel surface and 2.0 between elements.

Results of Preliminary Simulation

Fig. 4 shows one of simulated deformation results of elements' assembly by the wheel with lugs, using the conventional and modified mechanical models of DEM. As easily found in the figure, in the case of the conventional model the elements around the surface of the assembly moved much even in front of the wheel, but in the case of the modified model the behavior of elements was rather stable and holes made by lugs can be found after running. The volume change of elements' assembly (corresponding to the soil compaction) is also observed in deeper field in the case of modified model than the conventional one. These behaviors of elements' assembly are similar to the rut formation and compaction of actual cohesive soil after the wheel with lugs is running.

In order to find the possibility to get the reasonable reaction force from the elements' assembly to a single lug and to compare the effect of lug cross section shape on the force, four kinds of lug cross sections were assumed as shown in fig. 5 and the thrust, rolling resistance and effective traction force of the each single lug were calculated along the wheel contact length with the elements' assembly (cf. fig. 6). These force distribution patterns are surely similar to

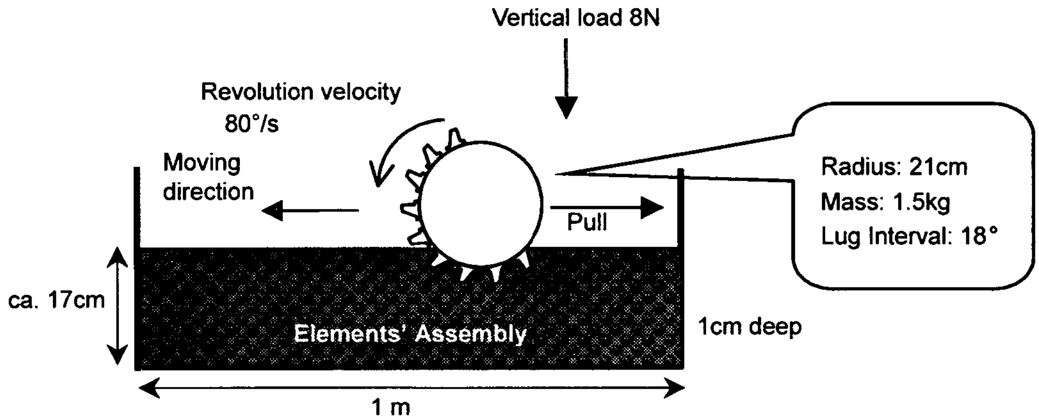

Fig. 3 A field of preliminary simulation by the DEM.

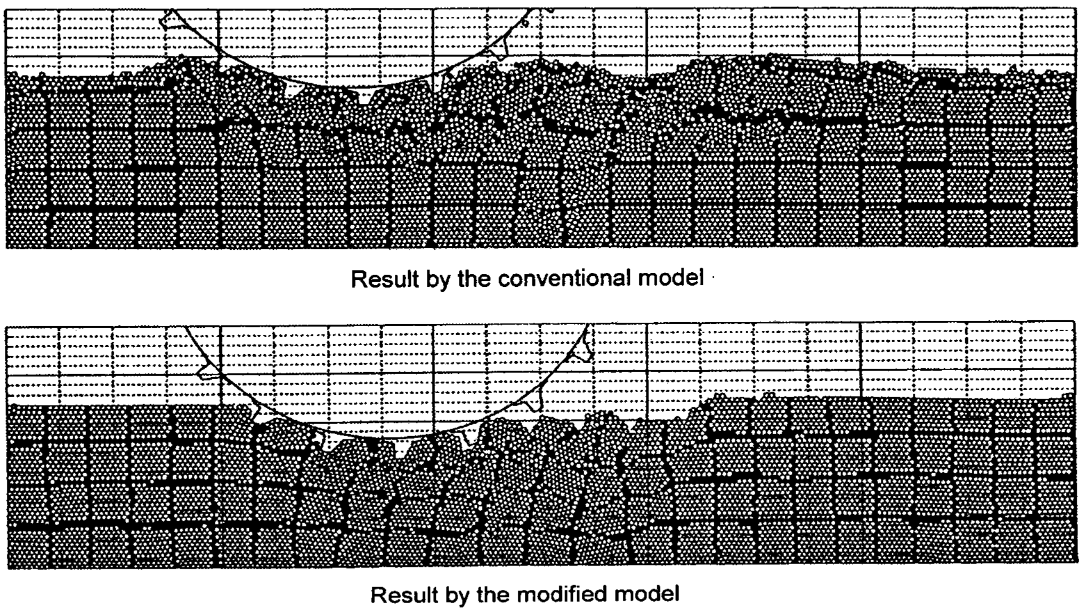

Fig. 4 Comparison of deformations of elements' assembly by conventional and modified mechanical models of DEM.

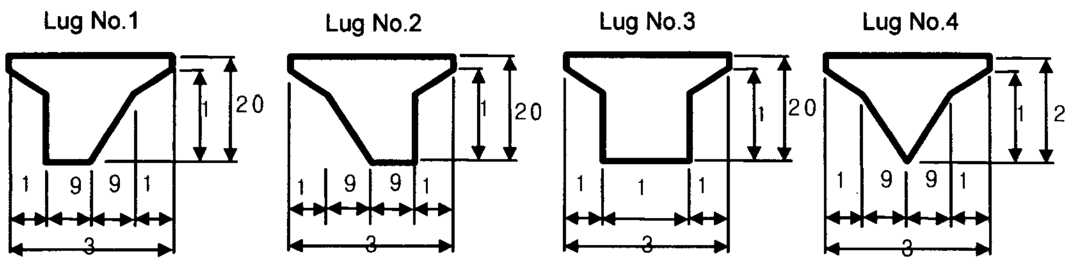

Fig. 5 Four kinds of lug cross section shapes.

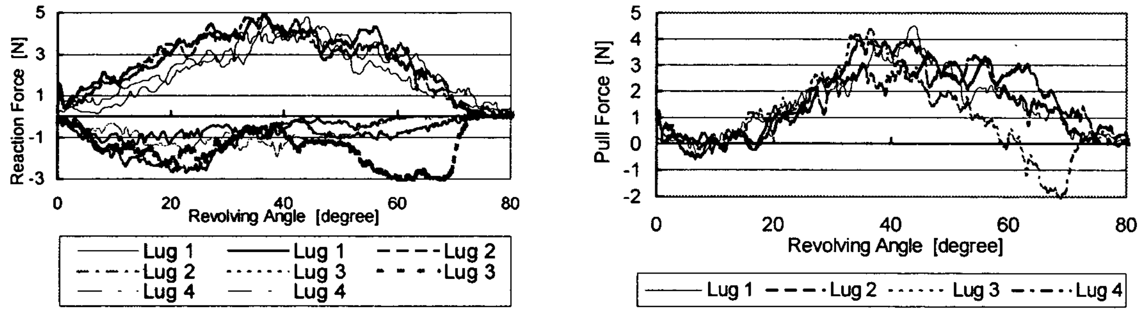

Fig. 6 Reaction forces to a single lug along the wheel contact surface.

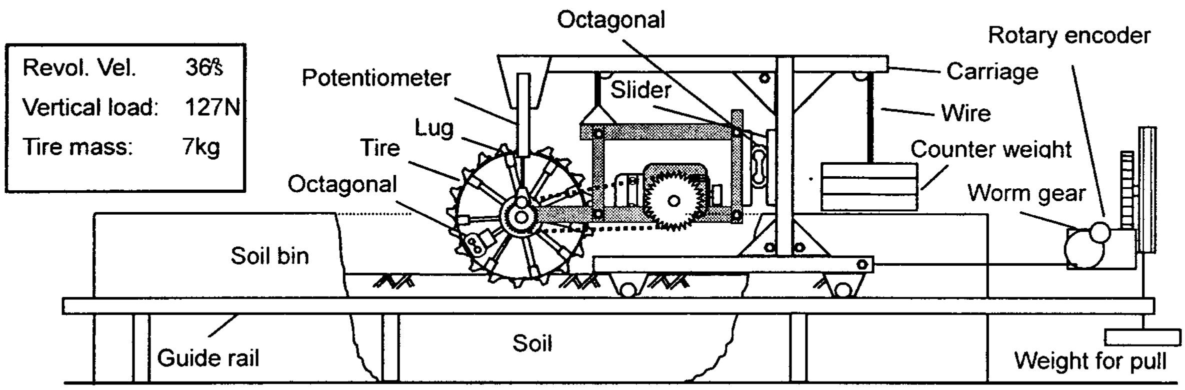

Fig. 7 A schematic view of the test apparatus.

experimental results for example by Oida et al. (Oida, 1991). These simulation results show us the possibility to utilize the modified DEM model to simulate the effect of lug cross section shape on the tire performance. The problem still remains about the identification of adequate DEM parameters. An experiment was done to select the parameters by comparing the simulation results and experimental ones.

3. Experiments

Test Conditions

Fig. 7 shows the test apparatus. The test rigid wheel of width 5 cm has lugs, of which cross section shape is type 1 in fig. 5, with 18 degrees interval. The test wheel was driven by a motor through a reduction gear. This unit could freely move vertically. It means the sinkage of the wheel depends on the balance of vertical reaction force from the soil (silty sand with 10 % m.c.) and an applied vertical load which is controlled by the counter weight. A horizontal pull force was also applied to the wheel by the weight. The rotational velocity and running velocity of the wheel were detected by a rotary encoder and a rotary potentiometer. The wheel sinkage was measured by a linear potentiometer. The radial and tangential reaction forces to the single lug and the pull force of the wheel were detected by each octagonal ring force transducer.

After getting data at the several values of pull force per unit width (1.69 N, 7.4 N, 11.1 N, 13.6 N, 19.8 N and 23.3 N), the slippage and sinkage of the wheel and reaction forces to the single lug were found by a computer processing.

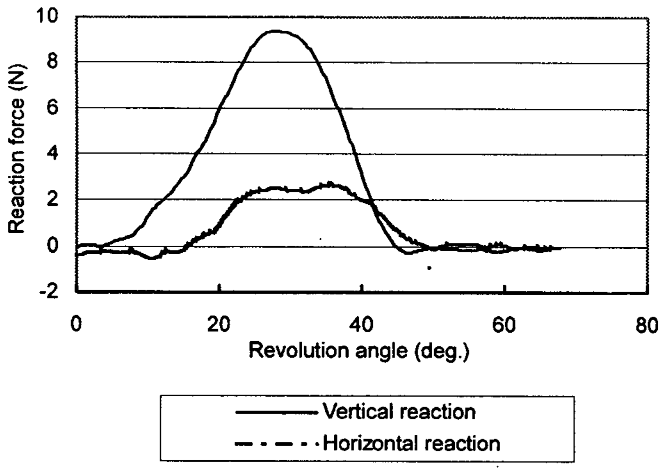

Fig. 8 Measured vertical and horizontal reaction forces tothe single lug along the wheel contact surface.

Test Results

An example of measured vertical and horizontal reaction forces is shown in fig. 8 at the pull force of the wheel 7.4 N. The results of wheel slippage and sinkage are shown in fig. 9 later with the simulation results. The DEM parameters were selected by a try and error method so as for the simulated values to approach the experimental values.

Results and Discussion

1. Attempt to Use Different Sizes and Masses of Elements

In order to express the moving restriction such as an interlocking of elements two kinds of radii of element discs were set as 2.0 mm and 2.5 mm. And the density of element was also tried to vary according to its depth. Three cases were made: a standard case with a constant density (50,000 kg/m^3), an exponential case where the density increases exponentially with the depth (6,000 to 120,513 kg/m^3), and a linear case where the density increases linearly with the depth (6,000 to 120,000 kg/m^3). The compression spring constant was set at 12,500 N/m in the standard case, increased exponentially with the depth (1,500 to 30,128 N/m) in the exponential case and increased linearly with the depth (1,500 to 30,000 N/m) in the linear case. The tension spring constant was set at the 20% of the compression spring constant in each case. The friction coefficient was assumed as 0.52 between elements and also between element and wheel surface.

2. Simulation Results with Different Density Variations

Pull force and sinkage

Fig. 9 shows the simulation results of relations of pull force vs. slippage and sinkage vs. pull force for three cases of density variations with the experimental results. It is found that the both simulated relationships

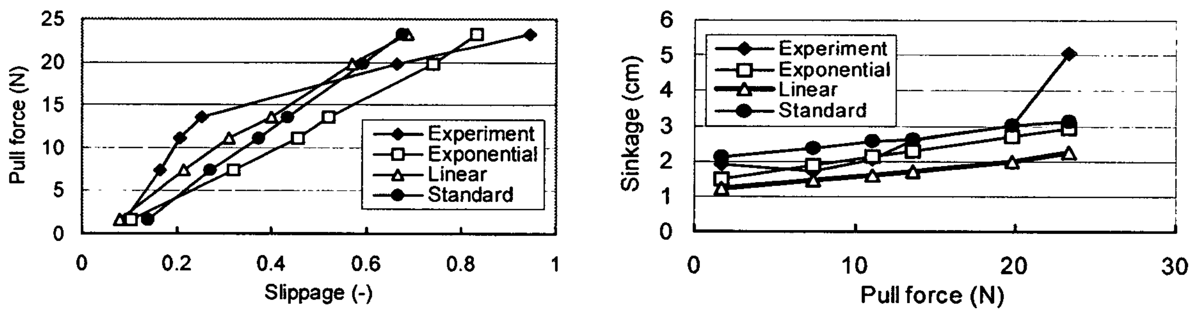

Fig. 9 Comparison of simulated pull force vs. slippage andsinkage vs. pull force relationships with the experimental ones.

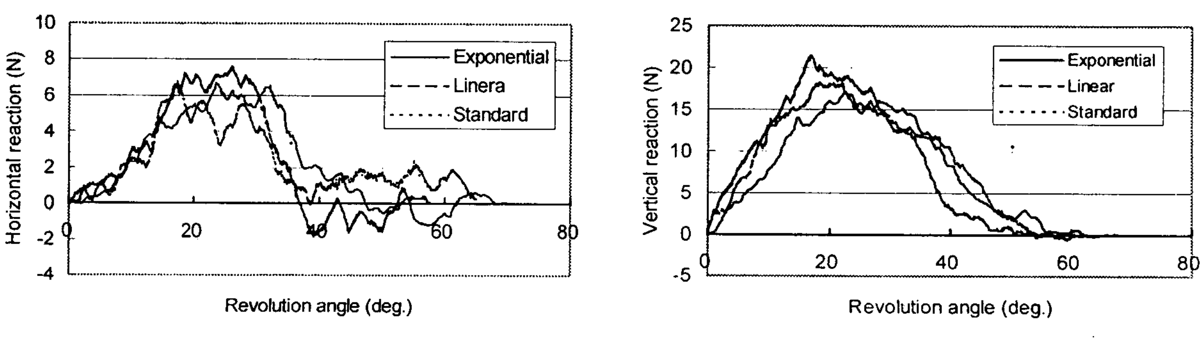

Fig. 10 Distribution of horizontal and vertical reaction forces to the single lug along the contact surface in three cases of density variation.

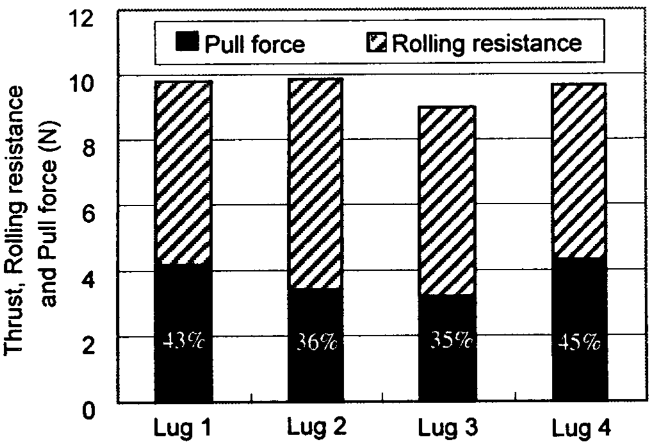

Fig. 11 Comparison of thrust, rolling resistance and tractive force of the single lug for four kinds of lug cross section shapes.

are linear for any density variations and a little different from the experimental ones. The magnitudes of calculated pull force, slippage and sinkage were almost equal to the test results. From the relation between pull force and slippage, it would be said that the most realistic simulation was that used the linear density variation.

Horizontal and vertical reaction forces to the single lug

Fig. 10 shows the simulated results of horizontal and vertical reaction forces to the single lug for 3 cases of density variations when the pull force of the wheel was 7.4 N. There is no significant difference between these force distributions of the 3 cases and also with the experimental one in fig. 8 from the qualitative evaluation point of view. Other simulation results with other pull forces of wheel also show the similar force distributions.

As for the deformation of elements' assembly, the deep region was considerably deformed at the standard case, but scarcely deformed at the other two cases. However, the deformation of shallow region up to about 8 cm was almost the same in each case.

Effect of Lug Cross Section Shape on Tractive Performance

From the reaction force distributions to the single lug along the wheel contact surface the total thrust and rolling resistance caused by the single lug are determined by integrating the distributions over the contact surface. Fig. 11 shows the thrust, rolling resistance and tractive force (= thrust-rolling resistance) with its percentage in the thrust for each lug cross section shape in the case of linear density variation when the pull force of the wheel was 7.4 N.

In the figure we can find not only the absolute value of tractive force but also its percentage in the thrust for each lug cross section shape. It means that the most effective lug cross section shape would be determined as the one which has the highest percentage of tractive force in the input thrust. In this simulation it was the lug No. 4 of which tractive force was 45% of the thrust. There is, however, not so significant difference between the percentages between lug No. 1 and 4. On the other hand, it is also found that the lug No. 3 has a low absolute tractive force and a low percentage of the tractive force in the thrust, so that this shape would not be recommended.

Conclusions

It was confirmed that the proposed modified mechanical model of DEM could simulate the actual cohesive soil deformation such as the compaction and the rut of lugs and wheel. It is because the modified model can express the effect of soil adhesion by considering the tension force when two contacted overlapped elements move away from each other.

Applying the modified DEM model, which has DEM parameters found by comparing the simulation results with experimental ones, the effect of lug cross section shape on the tire performance could be found. It would be possible to design more effective lug cross section shape by the DEM simulation from the energy saving point of view. Furthermore the modified DEM can be applied to evaluate the running and tractive performances of any types of running devices of off-road vehicles because of the simple theoretical base and the f lexible application of the DEM.

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