林地微地形の測定

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農林水産省 農林水産技術会議事務局筑波産学連携支援センター
Tsukuba Business-Academia Cooperation Support Center, Agriculture, Forestry and Fisheries Research Council Secretariat
Measurement of forest microtopography
— An approach for optimization of undercarriage of forest vehicle utilizing microtopography —

Takeshi Yamada*, Toshiaki Endo* and Shin Ikeda**

Takeshi Yamada, Toshiaki Endo and Shin Ikeda: Measurement of forest microtopography — An approach for optimization of undercarriage of forest vehicles utilizing microtopography. J. Jpn. For. Eng. Soc. 25(4): 185~194, 2010. Improved mobility for crawler vehicles on steep slopes and rough terrain depends on the ground contact area and the even distribution of ground contact pressure. Forest microtopography, assumed as the basis for undercarriage design of forest vehicles, was measured using a device that we developed. The measurement data was then used in an attempt to optimize the undercarriage specifications. The vehicle’s ability to pass over rough terrain was determined by comparing its thrust force, which was derived from the ground contact ratio in the measured microtopography data, with the required thrust force calculated using a Microsoft Excel macro program. Weight, height of the center of gravity, crawler width and lug height of the assumed vehicle model, and cohesion and internal friction angle of the soil were applied as constant parameters. Ground contact length, road-wheel interval and suspension stroke were applied as variables shifting within the probable range. Although the program determined the optimum undercarriage specifications, its validity is difficult to prove due to the lack of a verification method. However a problem of mobility of a real vehicle could be clarified by comparison between the calculation result and the examination result. Future tasks include improving the program and proving its validity.

Keywords: forest machinery, forest vehicle, crawler, microtopography, mobility

山田健・遠藤利明・池田伸：林地微地形の測定—微地形をもとにした車両足回り諸元決定方法—. 森林学誌25(4): 185~194, 2010. クローラ型林業用車両の急斜面走行性能上昇のためには、接地面積の確保、局所接地圧の増大抑制が重要である。車両の足回り装置設計のための基礎的な根拠となる地表形状のデータを、林地微地形測定装置を製作して、測定してきた。今回、蓄積した地表形状データをもとに、車両足回り装置の諸元を最適化することを試みた。Microsoft Excelのマクロにより、仮想車両の車重、重心高、クローラ幅、ラグ高、および対象地の土壌の粘着力、内部摩擦角を定数として設定し、接地長、転輪間隔、懸架ストロークを変数として逐次変化させながら、設定範囲内のすべての変数の組合せについて測定した地形データを仮想的に走行させて接地率を求めて駆動力を算出し、走行に必要な駆動力と比較して走行可能性を判定するプログラムを作成した。この結果から林地走行車両の足回り諸元の最適値を導いた。現在では検証の手段がないので、その妥当性を判断することは困難であるが、実在の車両により登坂できなかった事例と計算結果を比較したところ、諸元上の問題点が抽出できた。プログラムの改良と結果の検証が今後の課題である。

キーワード：林業機械、林業用車両、クローラ、微地形、走行性

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1. Introduction

Forest vehicles must be capable of tracing the forest-floor microtopography as precisely as possible while retaining sufficient mobility on rough terrain and causing a minimum of soil disturbance. Lower vehicle mobility results in a smaller working area. Soil disturbance reduces the productivity and public functions of a forest. To ensure that forest vehicles accurately trace the forest microtopography, the microtopographic properties must be identified and a vehicle undercarriage must be designed appropriately. However, available data on forest microtopography is very limited and there is no established measuring method. Consequently, we developed a microtopography measuring method and measurement device. There is abundant surface measuring technology such as laser 3D scanners and optical heterodyne scanners, but these non-contact devices cannot measure ground surface that is covered with plants. It is necessary to measure the profile of the ground that can support forest vehicles. We adopted a contact method to avoid measuring pseudo surfaces such as plant communities and slash piles. Various contact measurement methods have been reported such as the use of a multi-probe device for forest terrain profiles (6) and the use of wheel devices (3, 9). We developed a device with sufficient precision and resolution for microtopography measurement under the average ground contact pressure of ordinary forest vehicles. We used our device to obtain microtopographic data at 3 sites and then we built a simple program using this data to optimize the specifications for the undercarriage of forest vehicles.

2. Measuring device, method and test sites

2.1 Measuring device

The mechanism of the measuring device is described below and illustrated in Fig. 1. The base part is an aluminum rail 7,680mm in length that can be disassembled into four parts for portability. Precise alignment is achieved by adjustable supports guided by laser beam. The stage, formed by aluminum slides on the rail, is stopped at intervals of 30mm by means of a click catch and screw holes. A magnetic displacement sensor slides on the stage perpendicularly to the rail as a height sensing probe. Batteries and a data logger are equipped on the stage. The probe measures the height of the ground surface at every temporal stop position. Since the probe output is analogue voltage, measurement precision depends on the resolution of the data logger, which is approximately 0.25mm. The measurement displacement range for the sensor is 1000mm. To design the vehicle’s undercarriage utilizing the measured data, measurement must be conducted applying the ground contact pressure of the real vehicle. A pressure sensor consisting of a magnet, a magnetic switch and a spring was added at the bottom of the probe (Fig. 1). The height of the terrain was measured under pressure of 50kPa (approximately average ground contact pressure of typical forest vehicles) and recorded to a data logger. Height data (257 items) was measured at intervals of 30mm on a straight line. The rail was always set in the direction of the fall line, which is assumed to coincide with the longitudinal direction of a vehicle driving on sloped terrain. According to the purpose of this study, measurement was conducted on slopes having a slant angle of less than 30°.

Preliminary measurement identified a problem with duplex measurement on one point. The device often took a primary measurement of the litter layer surface, and then a secondary measurement of the mineral soil surface after penetration through the litter layer. Thus, signals from the pressure sensor were generated for both surfaces. To prevent this problem, we equipped the device with a circuit consisting of a sensor and relays (Fig. 2). The circuit fell into an excited state only once when a proximity sensor passed above the magnetic metal plates set on the rail at every 30mm. Then it returned to the basal state by a signal from the pressure sensor. The height data was recorded only during the excited state of this circuit, which responds only to the first signal from the pressure sensor. An LED indicator on the circuit displays the state of the circuit. Details of the measuring device were also explained in our previous report (13).
2.2 Test sites

We measured the microtopography of 28 plots at 3 test sites: Nanakai Test Site (co-operative test site of the Forest Technology Center, Kanto Regional Forest Office and the Forestry and Forest Products Research Institute (FFPRI)), Tsukuba Test Site and Tengakura Test Site (test site under FFPRI). The measured plots were classified into 5 categories: natural forest, plantation forest, afforestation area, harvested area and logging road. The natural forest consisted of broadleaf species. The plantation forest consisted of planted Japanese cedars (Cryptomeria japonica). The afforestation area had been treated with site preparation. Limbs, tops and slashes were piled in lines along contours, and Japanese cedar seedlings were planted between lines one year before measurement. The harvested area was covered with heavy vegetation due to long-term abandonment and was strewn with slashes. The logging roads had been constructed for crawler tractors at the top of a ridge and hillside. As vegetation had not yet recovered due to soil compaction, soil was exposed on the entire surface and was slightly eroded. The number of the measuring plots were 2 of harvested area (at Nanakai), 4 of afforestation area (at Nanakai), 11 of natural forest (5 at Nanakai, 2 at Tsukuba, 4 at Tengakura), 6 of plantation forest (at Tengakura) and 5 of logging road (at Nanakai). The measuring device needs approximately 0.6×8.0m rectangular empty space in which the investigator can move along the rail during measurement. Measuring plots were selected from appropriate place that is considered to show average feature of microtopography. At the site with a lot of obstacles such as stands or bushes, only few measurements could be conducted. All measurements were conducted during winter to avoid difficulties caused by vegetation.

3. Results of measurement and discussion

Height data totaled 257 items with 256 intervals, obtained by measuring each site plot. A profile of the microtopography was constructed by connecting the data. Total profile line length could be used as the microtopography roughness index. When the data was thinned and every two data items were connected, a profile was observed at intervals of 60mm. By repeating this thinning process, a profile at intervals of $30 \times 2^n$ (n = 0 to 8) mm could be obtained. This is considered to be one method of coarse graining. We named the value of these exponentially increasing intervals “scale length”. The total profile length decreases and the profile smooths out with the scale length (Fig. 3).

The most common method used to analyze forest microtopography is power spectrum analysis (2, 4, 6, 7, 10). The power spectral density for the roughest (Nanakai harvested area 2, NHA2) and the smoothest (Nanakai logging road 1, NLR1) microtopography in this study is shown in Fig. 4. The coefficient and exponential of the regression curve for NHA2 are $10^{-382}$ and $-1.65$, those of NLR1 are $10^{-126}$ and $-2.17$, respectively. According to the ISO 8608 road profile classification, NHA2 is Class H and NLR1 is Class G (7, 8, 11). It is considered that the roughest forest terrain is not passable by an ordinary vehicle, and that even the smoothest forest terrain is much rougher than
a "very poor" road.

Fig. 5 indicates the average total length of each category. Total profile length could be used as a microtopography roughness index for each scale length. Also, the maximum slant angle (absolute value) of the profile line decreases according to corresponding scale length. Fig. 6 indicates the average maximum slant angle for each category, which shows a similar tendency as that for total length. The categories were sorted in order for roughness as shown in Table 1, according to the results of Williams' test of total length of profile and maximum slant angle at small scale length for multi comparison. At large scale length, the difference between categories becomes obscure. The measurement was done only once at one place because the measurement was conducted destructively compacting soil surface by contact pressure.

If the forest microtopography displays self-similarity such as fractal profile, the total profile length must align linearly with the scale length on a logarithmic scale. In fact, it lines up concavely, which means that the frequency of small-scale roughness is higher than that of large-scale roughness. We decided that the microtopography does not have self-similarity. Actually, small-scale roughness of the ground surface depends on the density of matter such as limbs, tops, slashes, vegetation and tree roots. The original topography seems to influence only larger-scale roughness.

4. Method of simulation

We developed a computer program using the macro function of Microsoft Excel to optimize the specifications for the undercarriage of a forest vehicle. The program simulates the movement of a virtual vehicle model on the terrain given by the microtopography data, to determine whether the ground contact ratio of the crawler is sufficient for passage. The final output is the optimized specifications for a forest vehicle. This simulation is statically conducted. No dynamic factor is included.

4.1 Vehicle model

A crawler vehicle model with a very simple floating suspension system was assumed (Fig. 7). It has independent road wheels aligned at equal intervals, which move vertically and have the same suspension stroke and spring constant.

In order for the vehicle to successfully travel on varied terrain, it needs sufficient thrust force to climb a 30° slope having roughness equal to that of the roughest microtopography data collected in this study. Thrust force here means the total shear resistance of the soil under the contact area of the crawlers; it is not related to the driving force from engine power. In this program, variables change stepwise within a limited value range.
Table 1 Results of Williams’ test for difference of population mean between categories

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Total****

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*: “L” means total length of profile, “S” means maximum slant angle, “at 30” and “at 60” means at scale length 30 and 60, respectively. **: HA: harvested area, AA: Afforestation area, NF: Natural forest, PF: Plantation forest, LR: Logging road. ***: - means not significantly different, + means that left category is significantly larger than above category (P > 0.05). ****: “Total” evaluation is decision majority. *****: Categories with same letters are not significantly different.

until all combinations of variables are completed, in order to determine if the vehicle model can travel on the terrain in the microtopography data.

4.2 Constants and variables

First, it was necessary to extract the constants and variables from the fundamental specifications to utilize for the program. Weight (W), height of the center of gravity (H), crawler width (b), crawler lug height (h), and the results from the box shear test on soil cohesion (c) and internal friction angle (f) were required as constants, and ground contact length (L), road-wheel interval (I)
and suspension stroke \((S)\) were required as variables for processing (Figs. 7, 8). Variables would be examined and selected to optimize the specifications. Formula (1) derived by Bekker \((J)\) was the basis for determination.

\[
F = b L c \left(1 + \frac{2h}{b}\right) + \frac{W}{2} \tan \phi \left[1 + 0.64 \left(\frac{h}{b} \cot^{-1} \left(\frac{h}{b}\right)\right)\right] \quad (1)
\]

where \(F\) is thrust force per crawler. Thrust force of the vehicle is 2 times by \(F\). The required thrust force is derived from \(W \sin \alpha\). Where \(\alpha\) is the slant angle of the slope, it is fixed at \(\pi/6 (=30\) degrees\) as explained above. Thrust force while the vehicle model is traveling on the terrain can be derived using Formula (1), multiplying \(L\) by the ground contact ratio of the crawler. Then, it is necessary to obtain the real value of the ground contact ratio. Ground contact ratio was defined as the number of road wheels contacting the ground divided by the total number of road wheels. Comparing the calculated thrust force on the roughest microtopography with the required thrust force, it was possible to determine whether the vehicle model could travel on sufficiently varied terrain.

The constants are temporarily decided as below. 2,000kg of the vehicle in weight is assumed minimum value in which the vehicle has expected performance. We had developed the articulated tracked vehicle-1 whose weight is approximately 5,100kg and whose height of the center of gravity is 648mm and the articulated tracked vehicle-2 whose weight is approximately 8,200kg and whose height of the center of gravity is 574mm. They have floating suspension systems that resemble to the assumed vehicle’s suspension. Assuming the articulated tracked vehicles and the assumed vehicle are similar, the height of the center of gravity of the assumed vehicle can be derived by the following calculations respectively,

\[
648 \times \sqrt{\frac{2,000}{5,100}} = 474.3
\]

\[
574 \times \sqrt{\frac{2,000}{8,200}} = 358.6
\]

The values were averaged and rounded off to 400mm. This value seems quite low comparing with ordinary excavators with the same sizes because of heavy weight of undercarriages. The crawler width and the lug height were selected from the standard of the commercial rubber crawlers for mini-excavators with the weight of around 2,000kg.

The range of variables defined before simulation is described below. Minimum ground contact length is \(6H \tan \alpha\) under the condition that ground contact pressure must be loaded on entire length of the ground contact area of crawlers. Since it is loaded on the entire crawler length only while the center of gravity is at the middle third (center of trisected parts) of the crawler length \((L)\). Here, the center of gravity of the vehicle model is assumed to be the center of ground contact length on level land. A half of the middle third \((1/6)\) of ground contact length must be larger than displacement of the center of gravity by slant angle.

Maximum ground contact length is the value that limits ground contact pressure to higher than 25kPa. This is because 25kPa is as low as the ground contact pressure of crawler vehicles ordinarily used on poor ground; less than 25kPa requires too much ground contact length or crawler width, which degrades vehicle mobility on stable ground. Ground contact length \((L)\) is rounded off to divisible value by intervals of road wheels \((L)\) from more than the minimum value to less than the maximum value for calculation. The range of suspension stroke is determined to be 0 to 200mm at intervals of 10mm. Too much suspension stroke will make the size of the vehicle track frame overly large. The range for road-wheel intervals is determined to be 120 to 480mm at intervals of 30mm since the road-wheel diameter is assumed to be larger than 100mm. Ranges of variables are shown in Table 2. Although the spring constant should be one of the variables, it is set at a specific value which changes according to the other variables. This is because it was clarified in the preliminary calculation that the ground contact ratio of crawlers was always maximized at the value at which approximately 38 of the stroke is compressed under the average ground contact pressure despite other factors. This is considered to be due to the fact that small-scale roughness exists only as concave topography on flat terrain resulting from objects on the ground. If concave and convex topography is distributed at the same density, the ground contact ratio could theoretically reach the maximum while 1/2 of the suspension stroke is pre-compressed. The program simulates the movement of the vehicle model on the roughest microtopography under all combinations of

| Table 2 Range of variables for simulation (unit: mm) |
|----------------------------------|-------|------|-----|
| Ground contact length \((L)\)   | 1     | 2    | 3   |
| Suspension stroke \((S)\)       | 0     | 200  | 10  |
| Road-wheel interval \((L)\)     | 120   | 480  | 30  |

\(\ast 1: \text{Length that ground contact pressure is 25kPa}\)

\(\ast 2: 6 \text{ times by displacement of the center of gravity by slant angle}\)

\(\ast 3: \text{Equal to road wheel interval}\)
variables except for the ground contact length from which values divisible by the road-wheel interval were extracted.

4.3 Processing method

The simulation is conducted as described in Fig. 9, for example. The vehicle model travels on the microtopography profile moving from the position in which the rear end of the ground contact length coincides with the beginning of the profile, to the position in which the front end of the ground contact length coincides with the end of the profile, at intervals of 30 mm. Here, the ground contact line is defined numerically as a virtual lineal line on slanted land. Precompressed suspension shocks are biased downward by shifting of the center of gravity. While the vehicle model drives on the microtopography profile, the ground contact line is considered to fit the linear regression line of the sectional profile.

The number of road wheels and average load per road wheel can be derived from $W, L$ and $J$ as follows:

$$P_{n} = \frac{W}{2(L/I + 1)}$$

where $P_{n}$ is the average load per road wheel and $I$ is the interval between road wheels. Distribution of ground contact pressure of the crawler on slanted land is

$$y = P_{r} + \frac{P_{e} - P_{r}}{L}x$$

where $x$ is distance from the front end of the crawler, $y$ is the sectional ground contact pressure on unity area, $P_{r}$ is the load on the front end and $P_{e}$ is the load on the rear end of the crawler.

The moment at the rear end is

$$M_{e} = \frac{6}{L} y_{i} x_{i} + \frac{P_{e} L^2}{2} + \frac{P_{r} L^2}{3} = \frac{WL(L/2 + H \tan(\alpha + \theta))}{2(L/I + 1)}$$

where $\theta$ is the sectional slant angle of the profile (12). Assigning $2P_{n} \cdot P_{e}$ to $P_{r}$ on formula (4), load on the front end and the rear end of the crawler is

$$P_{r} = \left(4 - \frac{6(L/2 - H \tan(\alpha + \theta))}{L}\right) \frac{W}{2(L/I + 1)}$$

$$P_{e} = \left(4 - \frac{6(L/2 + H \tan(\alpha + \theta))}{L}\right) \frac{W}{2(L/I + 1)}$$

(13). The load on each road wheel is

$$P_{j} = (P_{e} - P_{r}) \frac{L}{L} + P_{r} = \left(-\frac{12H \tan(\alpha + \theta)}{L^2} \right) \frac{W}{2(L/I + 1)}$$

where $j$ is the order of road wheels from the front (on front end $j = 0$, on rear end $j = L/I$) and $P_{j}$ is the load on the $j$th road wheel. Sectional slant angle of the profile equals the inclination of the sectional linear regression line as explained above. As the number of sectional measured point under crawlers is $L/30+1$, the formula for the sectional linear regression line is

$$y = ax + b$$

$$a = \frac{1/n \sum x_{i} y_{i} - \bar{x} \bar{y}}{1/n \sum x_{i}^2 - \bar{x}^2}$$

$$b = \bar{y} - a \bar{x}$$

$$n = L/30 + 1$$

where $i$ is the order of microtopography data in the sectional profile ($i = 0$ on the front end of the crawler), $x_{i}, y_{i}$ are $x,y$ coordinates of the sectional microtopography data under the crawler and $\bar{x}, \bar{y}$ are the average values of sectional microtopography data, respectively. Therefore, the sectional slant angle is

$$\theta = \tan^{-1} a$$

Consequently, $P_{j}$ can be calculated by assigning Formula (9) to Formula (7). The precompressed suspension stroke by the weight on each road wheel can be derived by dividing $P_{j}$ by $K$ (spring constant). Thus, $P/K$ of the stroke remains on the tension side and $SP/K$ of the stroke remains on the compression side of the suspension. The absolute height of each road wheel on the ground contact line defined above can be calculated using
Formula (8) by assigning \( x_i \) to \( x \). Therefore,

\[
S - \frac{P_i}{K} \leq \bar{y} + a(x_{j_i} - \bar{x}) - y_{j_i} \leq \frac{P_i}{K}
\]

(10)
is the necessary condition for the road wheel to trace the terrain.

Then, if the ground height of the microtopography data is within the suspension stroke of a road wheel, that is to say if Formula (10) is true, it is marked as “0”; otherwise as “1”. Ground contact ratio is defined as the value of the number of road wheels marked “0” divided by the total number of road wheels.

\[
R = N_0 / (L / I + 1)
\]

(11)

where \( R \) is the ground contact ratio and \( N_0 \) is the number of road wheels marked as “0”. Temporary thrust force is derived using Formula (1), multiplying \( L \) by \( R \). This examination is done from the beginning to the final position on the microtopography profile. After the simulation, the smallest thrust force is compared with the required thrust force. If the former is equal to or larger than the latter, it is considered that the vehicle model is able to pass over the terrain in the microtopography data.

\[
2 \min(F) \geq W \sin \alpha
\]

(12)

If Formula (12) is true for the roughest terrain, the vehicle model is considered to have sufficiently able specifications to drive on the forest terrain. This process uses every combination of ground contact length, suspension stroke and road-wheel interval within the defined ranges explained above.

Of course, the longer the ground contact length and the suspension stroke, the greater thrust force. On the other hand, the shorter these variables are, the smaller the weight, the greater the strength and steering ability, and the lower the production cost. It is necessary to search for a compromise between traction and other factors. Therefore, we decided that the optimized specifications would be the minimum value of the product of the ground contact length and suspension stroke that allows the vehicle model to pass over the roughest terrain in the microtopography data. As it is difficult to estimate how the ground height of the microtopography data is harvested area 2 (NHA2 : which has the largest total profile length at 30mm scale length) and Tengakura natural forest 1 (TNF1 : which has the largest maximum slant angle at 30mm scale length) were identified as having the roughest terrain, and Nanakai logging road 1 (NLR1 : which has the smallest total length and maximum slant angle at 30mm scale length) the smoothest terrain. We derived the optimized forest vehicle specifications using the microtopography data from these 3 sites, assigning the assumed value of constants shown in Table 3. A soil sample from the Nanakai Test Site was analyzed to input soil properties. Table 4 indicates the results.

At this time, there are very few examples of tracked forest vehicles with floating suspension system which can be compared with these results to prove the validity. It is very difficult to obtain detail specification of them. Only example that can be shown is the articulated tracked vehicle-2 developed by us. It had been driven on NHA2, and in truth it couldn’t climb the slope by slippage. When corresponding value including intervals of road wheels is input into the program and is calculated, the result indicates that suspension stroke and ground contact length are insufficient. Comparison of real value and calculated value are shown on Table 5. Although the articulated tracked vehicle-2 is quite different from the assumed vehicle such as articulated structure, the result is considered to extract the problem of the vehicle.

### 6. Problems and tasks in this study

Remaining problems and expected improvements in this study are listed below.

1) Program modification for more realistic simulation: The

### 5. Results of simulation

In the results of microtopography measurement, Nanakai harvested area 2 (NHA2 : which has the largest total profile length at 30mm scale length) and Tengakura natural forest 1 (TNF1 : which has the largest maximum slant angle at 30mm scale length) were identified as having the roughest terrain, and Nanakai logging road 1 (NLR1 : which has the smallest total length and maximum slant angle at 30mm scale length) the smoothest terrain. We derived the optimized forest vehicle specifications using the microtopography data from these 3 sites, assigning the assumed value of constants shown in Table 3. A soil sample from the Nanakai Test Site was analyzed to input soil properties. Table 4 indicates the results.

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1) Program modification for more realistic simulation: The

### Table 3 Fundamental specifications of the vehicle model

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
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<td>Weight ((W))</td>
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<tr>
<td>Height of the center of gravity ((H))</td>
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<tr>
<td>Crawler width ((b))</td>
<td>180 mm</td>
</tr>
<tr>
<td>Lug height ((h))</td>
<td>30 mm</td>
</tr>
<tr>
<td>Cohesion of soil ((c))</td>
<td>0.34 N/cm²</td>
</tr>
<tr>
<td>Internal friction angle of soil ((\phi))</td>
<td>24.1 degrees</td>
</tr>
</tbody>
</table>

### Table 4 Optimized specifications of the vehicle model (unit: mm)

<table>
<thead>
<tr>
<th>Specifications</th>
<th>NHA2</th>
<th>TNF1</th>
<th>NLR1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground contact length ((L))</td>
<td>1,800</td>
<td>1,680</td>
<td>1,920</td>
</tr>
<tr>
<td>Suspension stroke ((S))</td>
<td>50</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>Road-wheel interval ((I))</td>
<td>120</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>
movement of a vehicle model on microtopography is basically simulated numerically and is rather simplified. Part of the real motion of the vehicle is not reflected in the simulation process, such as the pitching motion of the vehicle when the suspension cannot trace the terrain. Although the program needs to include realistic factors, extremely realistic simulation would make the program complex, requiring too much processing time. It is necessary to compromise between simplification and preciseness.

2) Program modification for more complex vehicle model: The program is based on a very simple vehicle model. For more realistic and diverse vehicle design, it should be adapted to a vehicle without assumed conditions such as non-uniform road-wheel interval, non-vertical suspension movement such as in a swing-arm suspension system, dependent road wheels such as in a bogie system, unequal spring constant, or articulated construction.

3) Greater accumulation of microtopography data: There is little data available on the types of rough terrain that a forest vehicle could potentially encounter.

4) Generation of standard microtopography: The order of total length and maximum slant angle at large-scale length does not coincide with their order at small-scale length. Thus, it is better to examine the roughest data for various scale lengths. We intend to generate a standard roughest microtopography model having an envelope curve for the maximum value at every scale length, utilizing the measured data from this study.

5) Method for proving the validity of the simulation results: Since there are currently no methods for inspecting the validity of the simulation results, we need to produce one and improve the precision of the program to ensure more realistic simulation results.

6) Improvement of user interface: The user interface of the program seems incomplete. In particular, it is necessary to modify the input for soil cohesion and internal friction angle, due to the laboriousness of the box shear test. They should be selected from a menu of soil types without the need for a box shear test. Also, soil cohesion and internal friction angle reinforced by plant root systems must be reflected through investigation.

7. Conclusions

Microtopography has a notable effect on the mobility of forest vehicles. We measured the forest microtopography at varied sites in 5 different categories using a device that we had developed. The roughness of the ground could be investigated using both the total profile length and the maximum slant angle of the microtopography. Site categories could be sorted in the order of roughness from rough to smooth: harvested area ≥ afforestation area ≥ natural forest ≥ plantation forest > logging road. This result is attributed to the fact that small-scale roughness depends on the objects strewn on the ground.

We intended to utilize the results for designing the undercarriage of forest vehicles. We developed a computer program to optimize the specifications of a crawler forest vehicle. A vehicle model was configured with constants and variables. The thrust force of the vehicle model on the roughest microtopography was calculated by inspecting the number of road wheels that trace the terrain. The program estimates whether or not the vehicle model can pass over the terrain given through the microtopography data by comparing the calculated thrust force with the required thrust force. Optimized specifications were determined using the minimum values of ground contact length and suspension stroke that enabled the vehicle model to pass over the roughest terrain, compromising mobility with weight, size, strength and cost. Optimized specifications were successfully derived through this program; although it is impossible to prove validity of the results, a problem of mobility of a real vehicle could be clarified by comparison between the simulation result and the examination result. It will be necessary to improve the program and to include proof of validity.

| Table 5 Comparison between optimized and real specification of the articulated tracked vehicle-2 at NHA2 (unit: mm except slope angle and weight) |
|-----------------------------------|--------|--------|
| Slope angle (α)                  | real   | optimized |
| Weight (W)                       | 8,200 kg |        |
| Height of the center of gravity (H) | 574    |        |
| Crawler width (b)                | 400    |        |
| Crawler lug height (h)           | 30     |        |
| Ground contact length (L)        | 2,100a | 2520   |
| Suspension stroke (S)            | 100    | 120    |
| Road-wheel interval (f)          | 374    | 360    |

*: Sum of two vehicles

Literature cited


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