MODEL-BASED ANALYSIS OF A TRACKED FORWARDER FOR SUSTAINABLE FORESTRY

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Abstract

Cut-to-length logging (CTL) is a mechanized harvesting process where trees are delimbed and cut to length directly at the stump. CTL is typically a two-man, two-machine operation with a harvester felling, delimbing, and bucking trees, and a forwarder transporting the cut logs from the felling area to a landing area accessible by trucks, or trains. The main challenges for the manufacturers of forestry machines for CTL logging are to address new customer demands and tougher ergonomic and environmental legislations by finding means that: (1) further increase the harvesting and log transportation productivity, e.g. by enabling operation on eco-soils, (2) reduce the damage to the soil, e.g. by controlling the rut depth and preserving the root layer, (3) reduce exhaust emissions, e.g. by reducing the rolling resistance and evening the contact and tractive forces between all traction units and ground, and (4) reduce the daily vibration dosage for the machine operators, e.g. with efficient chassis and cabin suspension solutions.

This paper presents a model-based study of a novel tracked medium-sized forestry machine. The machine is a standard eight-wheeled forwarder of bogie type with the four bogies replaced with four passively suspended track units adapted from an off-road military vehicle. The paper briefly summarize how a tracked forwarder can be modelled and simulated using multi-body simulation software like Adams ATV and how the performance parameters can be evaluated.

Keywords: Adams ATV, cut-to-length logging, tracked forwarder, multi-body simulation, template-based modeling, hard and uneven path

1. Introduction

The predominant forest harvesting method in northern Europe is the cut-to-length (CTL) harvesting method that is performed by two specialized machines (see Figure 1) – a harvester for felling, delimbing and bucking trees, and a forwarder that loads and carries the logs from the harvesting area to a roadside landing area. Both of these off-road machines have a frame mounted crane and they operate in very varied terrain and travel at low speed. In Scandinavia, almost 90% of the harvested trees are fell and processed by harvesters and transported by forworders [1]. Whereas in North America, only 20% to 30% of logging is performed with the CTL method, although CTL is perceived to have many environmental and value recovery advantages [2] with its long economic life [3]. On average, the actual economic life of both types of machines used in CTL logging is more than 10000 hours and may approach 18000 hours [3].
There has been continuous research on how to make forest machines more sustainable and environmentally friendly without compromising their productivity. Issues, such as soil damage and vibration dosages for the operators are of high significance in this challenge. Irreversible soil damage, as can be seen in Figure 2, caused by forestry machine operations must be significantly reduced. Previous research work has indicated that track units can reduce the ground pressure due to an increased contact area [4].

Hence it has been decided to explore the potential of using track units in foresters to reduce soil damage. The primary objective of the study is to develop a reliable multi-body dynamics simulation model of a tracked forwarder in the MSC Adams ATV module. This model will be used to evaluate the traction, handling and ride performance of the forwarder and to perform design analysis and optimization before realizing a full-scale prototype.

2. Modeling of tracked vehicles

Tracked vehicles are complex machines. It is consequently a huge challenge to design, optimize the performance, and to verify such a product. Computer-based modeling and simulation allows engineers to understand the effects from varying the design parameters, and to predict the dynamics of tracked vehicles under various operation conditions. There are mainly two methods; the super element method and the multi-body method that can be used to model the dynamic behavior of tracked vehicles.

The super element method treats the track chain as a single flexible body and the other components, like road wheel, idler, and sprocket, as discrete rigid bodies with kinematic constraints. By treating the track as a single force super element applied to each wheel, instead of individual rigid bodies with frictional contact, the size of the problem can be reduced and significantly saving computational time [5]. The derived super element that is capable of representing the spatial dynamics of the track subsystem can be used to formulate the equations of motion of the suspension system. Thus, the super element model enables high-fidelity simulations of the interaction between the track chain and other running gear components with relatively small computer resources. But, the application of this method is limited to straight line motion because the model is based on the assumption that there are only longitudinal forces in the super element. In improved versions of the super element method, the track chains are modelled as continuous uniform elastic rods. In order to discretize the nonlinear problem, the finite element method is used and forces on the track chain are modelled with linear stiffness and damping elements. This extended method is not suitable for
representing non-straight line manoeuvres, but it can be used to capture high frequency dynamic behavior of the trackwheel, and the track-terrain interactions.

The multi-body simulation method, on the other hand, treats the track unit as individual track shoes connected by force elements. In [6], each track shoe is treated as a rigid body connected to its neighbor by a revolute joint. The wheel-track contact is modelled with three dimensional contact force elements and the track-terrain interaction by pressure-sinkage force relations based on the Bekker and Janosi approach [7]. The multi-body dynamics simulation tool LMS-DADS was used to model the tracked vehicle suspension shown in Figure 3. Their research showed promising results in predicting normal contact stress under the track. The simulated results matched the experimental stress values. Simulating riding over an obstacle was done with the DADS tool, but a good match with physical experiments was obtained only for the lower frequencies. For higher frequency behavior, this method showed significant differences between the predicted and test results.

Ryu et al. [8] propose an alternative method to model track units for multi-body dynamic simulations. In their method, the revolute joint is replaced by compliant force elements which can be described by stiffness and damping values. This compliant track model was used to predict the dynamic behavior of a high speed, high mobility tracked vehicle. The methodology was further used to develop active track tensioners [9].

Multi-body simulation (MBS) is an effective method to investigate the dynamic behavior of tracked vehicle concepts. MSC Adams is one of the most widely used MBS tools. Adams All-Terrain Vehicle (ATV) toolkit is add-on to the Adams Car tool which provides user an effective tool to build tracked vehicles. It is based on template-based modeling and involves three stage hierarchies as shown in Figure 4. Previous research work indicates that Adams can be used to simulate complex engineering problems and give reliable results [10]. But it is crucial to verify these simulation results experimentally.
3. Modeling and Simulation

3.1 Base-model selection - Komatsu 845

The first step of the modeling process is to identify an existing forwarder, which can be modified to mount the new track unit concept. The mid-sized Komatsu 845 forwarder, as shown in Figure 5, is chosen as the base model. The Komatsu 845 is an articulated, eight-wheeled machine with the wheels mounted pairwise on four bogies and it is not equipped with any primary chassis suspension system. It has a machine weight around 16 tons and a loading capacity of 12 tons. The width of forwarder varies between 2760 and 2990 mm depending on the tire size. The propulsion is mechanically applied to all eight wheels from a 140 kW diesel engine through a hydrostatic transmission system that transmits the torque from the engine to the axles and then further on to the bogie systems. Inside each bogie system there is a chain that transmits the torque to the wheel pair, i.e. there is all-wheel traction but no traction control for the individual wheels in the bogie.

![Figure 5: Dimensions of the studied 8-wheeled Komatsu 845](image)

The mass properties are given in Table 1. The center of gravity of the front and rear parts of the forwarder, i.e. the front wagon and the rear wagon, is identified relative to the articulated steering centre that connects the two parts.

*Table 1: Mass and Centre of gravity of Komatsu 845*

<table>
<thead>
<tr>
<th>Property</th>
<th>Front Part</th>
<th>Rear Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass – Unloaded (kg)</td>
<td>8193</td>
<td>9111</td>
</tr>
<tr>
<td>- Loaded</td>
<td>8193</td>
<td>20111</td>
</tr>
<tr>
<td>C.G* – Unloaded (mm)</td>
<td>(-2128.5, 298.5)</td>
<td>(2888.7, 474.8)</td>
</tr>
<tr>
<td>- Loaded</td>
<td>(-2128.5, 298.5)</td>
<td>(3482.3, 1209.2)</td>
</tr>
</tbody>
</table>

* Reference: Centre of articulation joint

3.2 Track unit concept

The track unit concept, as shown in Figure 6 is designed in such a way that it can be fitted directly to the Komatsu 845 forwarder. The width of the track unit is assumed to be 400 mm. The wheels and bogies will be disassembled and the drive shaft will be attached to the sprocket of the track unit. The design results in reduction of the ground clearance from 683 to 383 mm. This has to be done to avoid unrealistically high torques on road wheel suspension springs. All the components of the track unit including road wheels, sprocket, and track tensioner are designed to fit this dimension.
3.3 Modeling in Adams ATV Module

The modeling of a tracked forwarder in Adams ATV can be divided into three stages: Building Templates, Converting into Subsystems, and Final Assembly. The first step involves building different components as templates, as shown in Figure 7. The templates are parametric models which define the geometry and topology of the model. It is done using the template builder environment in the ATV module. A template consists of design parameters like hard points, construction frames, ATV parts, general parts, parameter variables, and property files. It also includes input and output communicators, which are crucial to enable information exchange with other templates when assembled together. The major role of the component is also defined here. A template can be modified by changing the values of design parameters, which will be reflected in the final assembly.

As the next step, the templates are converted into subsystems and their respective minor roles are assigned and the coordinate locations specified. The position of a subsystem in an assembly can be varied from the default position based on the requirements. This enables reuse of single templates for multiple subsystems. For e.g. the four road wheel, the subsystems are made from the single road wheel template using translate from default position option. The minor roles used to build the tracked forwarder are described in Table 2 and the location of the subsystems and orientation of the subsystems relative to global coordinate system are shown in Figure 8.

The subsystems are assembled together to make the final tracked forwarder system model. The assembly class is set to tracked vehicle. This will enable the tracked vehicle test rig. By enabling the tracked vehicle test rig, corresponding input communicators will be activated. The most crucial challenge in the assembly stage is to make the communicators work as intended. Communicators are interface objects that are responsible for the information exchange between the subsystems. Every input communicator must have a matching output communicator. The track segment subsystem is located at the center of the sprocket subsystem. This will ensure proper wrapping of the track segment. The final tracked model assembly is shown in Figure 8.
### Table 2: Subsystems properties

<table>
<thead>
<tr>
<th>Location in Figure 8</th>
<th>Sub System</th>
<th>Template</th>
<th>Major Role</th>
<th>Minor Role</th>
<th>Wrapping Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>F_Chassis</td>
<td>F_Chassis</td>
<td>Hull</td>
<td>Hull 01</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>F_idler</td>
<td>F_idler</td>
<td>Track holder</td>
<td>Ts01_01</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>F_rw1</td>
<td>F_road_wheel</td>
<td>Track holder</td>
<td>Ts01_02</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>F_rw2</td>
<td>F_road_wheel</td>
<td>Track holder</td>
<td>Ts01_03</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
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<td>F_road_wheel</td>
<td>Track holder</td>
<td>Ts01_04</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>F_powertrain</td>
<td>F_powertrain</td>
<td>Powertrain</td>
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<td>2</td>
</tr>
<tr>
<td>E</td>
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<td>F_support_wheel</td>
<td>Track holder</td>
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<td>1</td>
</tr>
<tr>
<td>F</td>
<td>F_track_segment</td>
<td>F_track_segment</td>
<td>Track section</td>
<td>Ts01_07</td>
<td>7</td>
</tr>
<tr>
<td>G</td>
<td>R_Chassis</td>
<td>R_Chassis</td>
<td>Hull</td>
<td>Hull 02</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>R_idler</td>
<td>R_idler</td>
<td>Track holder</td>
<td>Ts02_01</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>R_rw1</td>
<td>R_road_wheel</td>
<td>Track holder</td>
<td>Ts02_02</td>
<td>5</td>
</tr>
<tr>
<td>I</td>
<td>R_rw2</td>
<td>R_road_wheel</td>
<td>Track holder</td>
<td>Ts02_03</td>
<td>4</td>
</tr>
<tr>
<td>J</td>
<td>R_sprocket</td>
<td>R_road_wheel</td>
<td>Track holder</td>
<td>Ts02_04</td>
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<td>Powertrain</td>
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<td>2</td>
</tr>
<tr>
<td>K</td>
<td>R_track_segment</td>
<td>R_track_segment</td>
<td>Track section</td>
<td>Ts02_06</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>R_support_wheel</td>
<td>Track holder</td>
<td>Ts02_07</td>
<td>7</td>
</tr>
</tbody>
</table>

**Figure 8: Tracked forwarder model in Adams ATV**
3.4 Track wrapping and road setup

Adams ATV provides dynamic track wrapping, which is the procedure where the track system will be wrapped around the defined track system. The individual track segment build template will be assembled in series connected with compliant force elements. The wrapping method used in this study is Dynamic Track Wrapping. The wrapping can be done as full vehicle, where all the four track units are wrapped, or as half vehicle, in which only one side will be wrapped. Half vehicle wrapping is used to save simulation time and can be used only when straight line simulations on flat ground are in focus. Since the simulations involved motion over irregular surfaces full vehicle simulation has to be done to give accurate results.

The road and soil property file can be added to the simulation model using the hard road setup option and the appropriate orientation and location is set. It should be noted that the road need to set up at sufficient distance from the tracks. Otherwise, while performing the simulation the contact between track unit and the ground will not be enabled and an error contact is missing will pop up. Figure 9 shows the actual Skogforsk test track in their facility. Figure 10 presents the virtual model of the tracked forwarder build inside Adams ATV on the Skogforsk test track. The test track is build inside ATV as a road file, by giving the coordinate values of each discretized bump.

Figure 9: Skogforsk test track

Figure 10: Forwarder on Skogforsk test track in Adams ATV
4. Results and discussion

The motion of the forwarder is simulated under different operating and terrain conditions. The simulation results are analyzed to see how they can be used in the overall track vehicle development process. Forwarders are fundamentally off-road non-guided ground vehicles and can be evaluated by the characteristics of off-road vehicles. A non-guided ground vehicle is one which is supported by the guide and can move by choice in any direction. The characteristics of the forwarder can be classified into performance, handling, and ride. Performance characteristics include motion resistance of vehicle running gear, drawbar performance, ability to overcome obstacles, ability to accelerate and decelerate, etc. The lateral dynamics characteristics like response of the vehicle to driver’s command, ability to stabilize the motion against external disturbances are studied under the handling. The ride quality of the forwarder can be defined as the ability of the vehicle not to transfer the external excitations due to surface irregularities to operators/passengers and goods.

During the simulations, the global coordinate system (GCS) is oriented in such a way that the vehicle moves in the negative $x$ direction (longitudinal direction). The $z$-axis, which is pointed upwards, represents the vertical direction. The $y$-axis represents the lateral direction. The angular rotations $roll$, $pitch$, and $yaw$ are rotation with respect to $x$-axis, $y$-axis, and $z$-axis respectively, as shown in Figure 11.

![Forwarder in Global Coordinate System](image)

*Figure 11: Forwarder in Global Coordinate System*

The motion of the forwarder on different road conditions is performed. As the first step, static equilibrium operation is performed to identify a reasonable value for the torsional spring stiffness for the road wheel. The stiffness shouldn’t be too low resulting in unstable static equilibrium or too high resulting in rigid suspensions and compromising the ride quality. The rotational angle of the road wheel and the torque in the torsional spring is shown in Figure 12.

![Rotation angle and torque on road wheel spring](image)

*Figure 12: Rotation angle and torque on road wheel spring (front track road wheel No: 2)*
The tensioner force plays a key role in the performance of track unit. There has to be enough tensioner force to ensure smooth operation of a track unit. The simulated tensioner force is shown in Figure 13. In this simulation the design length option is used so that the tensioner length does not change and hence the tensioner force remains almost constant. If needed, a desired value for the tensioner force can be set automatically by setting the spring length.

![Figure 13: Front tensioner spring force and length](image)

Motion of the forwarder on hard flat surface is simulated by providing an angular velocity of 100 degrees/seconds to the powertrain, as shown in Figure 14. The torque required for the motion is presented in Figure 14. This results in a longitudinal velocity of 382 mm/s, which can be observed in Figure 15. This speed is equivalent to 1.4 km/h.

![Figure 14: Torque generated at powertrain and angular sprocket velocity.](image)
The vertical force exerted by the tracks on the ground has significant effect on soil damage and rutting. A good track solution will exert relatively lower and uniform pressure on the ground. This is one of the most important research objectives of the project. The force under the track segment in three directions; vertical, longitudinal and lateral is measured at an instant of time with the help of a macro in Adams ATV. The vertical force exerted by the forwarder front left track on flat ground is shown in Figure 16 and the vertical force when going over a bump is presented in Figure 17. It can be observed from the Figure 17 that on flat road, even though the track unit was able to reduce the maximum vertical force by distributing the contact force among the track wheels, when traversing a bump the vertical force spikes due to localized wheel contact. This means that only one wheel is in contact and the rest of the wheels are “in the air”. This will capsize the effectiveness of track unit to reduce ground pressure. Suitable design modifications have to be done to ensure an even force distribution under the track.

![Figure 15: Forwarder velocity and displacement](image1)

![Figure 16: Vertical contact force between track segment and hard flat terrain](image2)
It is also important to study the lateral and longitudinal forces under the track segment. The longitudinal force under the track segment, as shown in Figure 18, is due to rotation of the track unit. It results in shearing of the soil under the track and will directly influence tractive performance. Lateral forces, on the other hand, are due to side-way motion. Lateral forces are significant when the forwarder takes a turn. As represented in Figure 19, the lateral force is negligible in a straight line event. The longitudinal and lateral forces under the track unit in a straight line motion with a vehicle speed 1.4 km/h are shown in Figure 18 and Figure 19.
The dynamic behavior when the tracked forwarder was traversing the Skogforsk hard ground test track, is shown in Figure 20. The road bumps gives vertical motions, which is shown as vertical displacement. In the figure, each vertical spike represents a bump motion that results in a swaying motion of the forwarder, which can be visualized as pitch, roll, and yaw motion of the hull. Individual rotational components can be studied separately by altering the joints in the articulated steering of the forwarder model.

![Figure 20: Forwarder displacement, yaw, pitch, roll angle when moving over the Skogforsk test track](image)

5. Conclusions

The Komatsu 845 forwarder is re-modelled to fit a track unit. The developed track unit concept satisfies all the geometrical constrains except for the required ground clearance. The concept can be further improved by adding a frame that can lower the position of the track unit thereby increasing the ground clearance. The concept forwarder was modelled in the Adams ATV module using template-based modeling. The Skogforsk hard ground test track was incorporated in the simulation as a road file. Simulations, limited to straight line drive events were performed and results have been extracted. These results can be used to study traction and ride performance of the machine. The simulation results show that tracks reduce the maximum contact pressure, which makes the tracked forwarder potentially gentler to soft soil.

A result from the presented research was also methodology for model-based design of novel tracked forwarders based on using multi-body simulations with the Adams ATV modeling and simulation tool. The template-based modeling approach in ATV has several advantages, including reduced modeling time, ability to edit the model quickly and easily. On the other hand, the software presents a steep learning curve to an unfamiliar user. The simulation model developed must be verified with experimental results and it is recommended as the next stage of the presented research work. An experimentally verified simulation model can be used to design and optimize the tracked forwarder for specific forest conditions. It enables cutting cost and time for developing a tracked forwarder for sustainable forestry to be cut.

References


