MODELING THE BEHAVIOR OF EXCAVATOR-BASED
FOREST MACHINE ROLLOVERS

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ABSTRACT

The hydraulic excavator accounts for over 50% of construction equipment sales in the world due to its versatility and its ability to work effectively in a number of industries including agriculture, construction, forestry, and mining. Tracked feller-bunchers and log loaders are typical forest machines that use a hydraulic excavator as the base machine. Because of the popularity of this machine and the exclusion of excavator-based machines from international rollover safety standards, there is a significant safety concern for excavator operators. Current excavator cab designs may not provide sufficient operator crush protection in the event the machine overturns. Currently, the standard development process is hampered because there is little data available on impact loads generated on the cab during rollover. In this study, a three-dimensional dynamic computer simulation will be used to analyze the behavior of a rolling excavator. The model developed in the ADAMS dynamic simulation software package was used to evaluate the effects of upperstructure rotation, boom position, soil slope, and roll direction on the forces associated with the soil-machine cab impact. The results indicate heavier machines with higher cabs will experience higher impact values when the cab strikes the soil surface.

INTRODUCTION

The introduction of automation to forest harvesting operations has increased productivity and provided a safer work environment for those employed in the forest products industry. However, mechanized forest operations threaten an operator’s safety as machine rollover, machine tip-over, fire, impact from a falling object, excessive vibration, and high noise levels can have adverse effects on a person’s health and well-being. International and regional standards have been developed to insure forest machine operators are offered protection from these hazards. However, problems arise when the development of a machine has outpaced the drafting of standards or when a threat to operator safety has not been identified by standards development organizations.

Roll-Over Protective Structures (ROPS) are designed to reduce the probability of an equipment operator being crushed in the event a vehicle overturns. A ROPS offers protection from crushing in the lateral, longitudinal, and vertical loading
direction. A Tip-Over Protective Structure (TOPS) does not provide protection from vertical cab loading and are only installed on machines with little chance of rolling on to the roof of the cab. To insure a machine protects an operator during rollover, international and regional standards list machines that are required to install ROPS and specify the level of performance the ROPS must achieve on a given machine. ISO (International Organization for Standardization) standards 3471 and 8082 exempt machines from ROPS performance criteria if the cab and boom structure are located on a rotating platform (ISO, 1994). ISO 12117 specifies TOPS performance for excavator-based machines, but it only applies to machines with masses under six metric tons (ISO, 1997). The lack of required ROPS or TOPS on excavator-based machines is troubling, as many of these machines are designed to work on hazardous ground conditions, such as steep slopes and soft, unstable wetland soils. There are numerous logging safety organizations that report rollover of excavator-based forestry equipment in their newsletters and web pages. Among the organizations reporting excavator rollover accidents are: the Worker’s Compensation Board of British Columbia, the Forest Resources Association, New Zealand Occupational Safety and Health Service, and WorkCover Tasmania.

One of the major obstacles in the ROPS standard development process for excavators is the lack of dynamic loading data for a wide range of excavator models. Also, full-scale physical testing of ROPS is extremely expensive. The cost of instrumentation, test site construction, and full-scale test machines restrict testing to a handful of machines under a limited set of conditions. Fortunately, new technologies have been developed to simulate the dynamic forces generated during a rollover event. The establishment of finite element methods, the development of multi-body dynamic simulation software and the evolution of the computer are the key components in the simulation, design, and development of ROPS. Computer simulations allow evaluations of ROPS structures to occur on a wide range of excavator models under a variety of conditions in a short period of time.

**OBJECTIVE**

The overall goal of this research is to provide assistance for the development of performance criteria for ROPS structures that can be installed on excavator-based machines. Specifically, this project is to develop a simulation model to allow analysis of typical excavators used in construction and forestry applications. The model will be used to examine the rollover behavior of excavators and validated with data collected during actual field tests by other research organizations.

**RESEARCH METHODS**

In order to collect the most accurate data on the impact event associated with excavator cab and soil surface contact it was decided that a three-dimensional (3D) modeling approach would best reflect the true rollover behavior of an excavator. The 3D computer model was developed using the MSC.ADAMS mechanical system simulation package, Version 12.0. ADAMS is an acronym that stands for Advanced Dynamic Analysis of Mechanical Systems. This particular package was chosen because of its widespread use throughout industry, the ability to quickly import parts from various computer-aided design (CAD) packages, and the simplicity of using a graphical user interface (GUI).
The development of solid models representing actual excavator-based machines was based on information contained in manufacturer specification sheets and field measurements. To create the 3D solid model, the major machine excavator components were drawn in AUTOCAD® 2002. The major components that were developed included: the undercarriage, the upper structure, the counterweight, the engine assembly, the engine, the cab, the riser, the boom, the stick, the thumb. There were a total of six excavator models which represented machines with masses between 10 and 60 metric tons in 10 ton increments. For each base excavator, three additional models with 457 mm, 1219mm, and 1829mm cab risers. All rollover simulations were conducted on a 30° slope.

The best solution for estimating these contact forces in ADAMS is to develop a nonlinear spring-damper system to describe soil-machine contact. Using force-deflection values for soils used to construct rollover test slopes used in previous off-highway vehicle rollover experiments, a suitable stiffness and non-linear exponent value for the ADAMS model were calculated. The values for the damping and friction were derived from examples used in literature and from recommendations made by the developer of ADAMS. These values produced a roll behavior consistent with the behavior observed during full-scale field tests.

To simulate a machine rollover, an excavator was leveled at the top of the virtual test slope. The upperstructure and undercarriage were place parallel to each other with the cab side of the machine closest to the slope. The tracks farthest from the slope were slowly lifted until the machine tipped. The boom was placed in a position that allowed all components to remain below the top of the cab. Figure 1, shows an example of the rollover simulation and the output.

**Figure 1. ADAMS Model Examples**

To validate the results of the ADAMS simulation, data collected during limited full-scale rollover tests were used. The data was provided by industry cooperators and the tests were completed on 12, 20, and 45 metric ton excavators. The full-scale testing and ADAMS simulation values were generally within 10 to 20% of...
each other for impact magnitudes, rollover duration, and the values were identical for rotation magnitude (i.e. how many degrees did the machine roll through).

The lateral, longitudinal, and vertical loading values associated with the first impact of the cab with the soil surface are shown in Figure 2. Please note that the graphs report cab heights, this value is simply the height of the top of the cab when a given riser is used and there are two 30 metric ton excavators used in the analysis.

From the data presented in Figure 2, primarily the lateral loading graph, it is evident that the forces associated with the soil impact of a heavier machine are greater than those associated with the impacts of lighter machines. For reference, the load line used to design ROPS for crawler tractors is specified on each graph. This load line is a function of overall machine mass. The data in Figure 2 also suggests that longitudinal loading is relatively small and remains fairly stable regardless of machine mass. However, Figure 2. Lateral, Longitudinal, and Vertical Loading Values for 1st Cab-Soil Impact.

in this rollover testing scenario the machine was tipped without initial forward (or reverse) movement. If the machine is rolling directly onto the cab side of the machine, one would expect the longitudinal loading to be a minor loading component.

For the purposes of further studying the longitudinal loading component and additional rollover scenario was developed. In this new test, the upper structure of the excavator was rotated 45° towards the slope. Now, the machine would impact the front of the cab as well as the side. Figure 3, shows the longitudinal loading result of the rotated upperstructure test. Comparison of Figures 2 and 3, shows that rotating the upperstructure has at least doubled the longitudinal loading values.

Figure 3. Longitudinal Loading Values for Rotated Upperstructure.
Further analysis was completed on factors such as boom position and roll direction. The boom position did not affect the impact force values that resulted from the excavator rollover. However, the boom position did affect the excavator roll behavior. When the boom was placed in a position such that is was significantly above the cab, there was a reduction in rotation magnitude of the machine. Roll direction did play an important role in determining the impact magnitudes that occurred during a rollover. When the boom side of the machine struck the ground first, there was a reduction in the magnitude of impact forces. However, boom side rolls produce longer rotation durations from a time and magnitude standpoint. Cab side rolls are faster and usually much shorter. As an example, a 37 metric ton excavator rolled 360° when the cab side struck the soil first, but when the boom side of the machine struck the soil first the machine rolled 540° with a 25% reduction in peak cab loading.

CONCLUSIONS

- Boom position is not a significant factor influencing impact forces.

REFERENCES

