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SIMULATION OF THE RESISTANCE FORCES OF BULK MEDIA TO BUCKET IN A LOADING PROCESS

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ABSTRACT

In this work the process of penetration of a bucket into bulk media (for loading or excavation) is simulated based on the forces that are involved in the process. The main objective is to simulate the resistance force of medium to cutting by a tool (bucket/blade) during a loading or excavation process. The work stems from an initial purpose to evaluate the effectiveness and performance of a strategy for automation of loading of bulk media (autoloading) by an excavator. In addition to serving for that purpose, the results of this work can be used in the development of training simulators for construction and excavation machines that include animation of the motion of a bucket, but lack the behaviour of the material during the process.

The encountered resistance by a tool (bucket) dictates its motion. The medium resistance can change significantly even within a small area and it depends on the tool orientation. If not controlled, the cutting tool follows the path with the least resistance. For this simulation a planar motion is considered for the sake of simplification of the complicated process. As can be depicted by a number of examples, the paper shows that the simulation is valid and can be successfully used.

KEYWORDS

Simulation, Resistance Force, Bulk Media

1. INTRODUCTION

The problem of automation of loading by a cyclic excavator, such as a front-end-loader, has been the subject of research for more than a decade. Yet, no commercial product has been introduced to the market so far, nor a breakthrough has been reported on the subject. One reason for this is the complexity nature of the process and the fact that the essential research is time consuming and costly.

As a necessary part of research in this matter one has to examine the effectiveness of any control strategy as well as comparing various proposed control techniques. As a tool to facilitate such an evaluation and comparison, simulation software can speed up the process and determine the functionality of a control strategy at the primary step.

This work is related to what becomes necessary for simulation of the loading/excavating by a machine to be automated. It simulates the interaction between a medium and a cutting tool or blade that must overcome the resistance from the medium during loading (cutting, penetrating and scooping).

Simulation of properties of materials has become a popular way for research on many different studies to be performed. Nevertheless, the scope of application is so vast and the results for one application can be far from what is required in another. These are mostly offered in the form of commercial simulation packages for a particular application. For instance, modeling and simulation solutions for studying chemicals and materials can be at the level of molecular bonding and crystal structure, the process of crystallization, and structure-activity relationships, although all these are indeed material simulation. Or the work can focus on the formulation of deformation and fluid flow. Also, it could be concentrated on metals, a temperature treatment on metals, or the emphasis could be on certain class of material, such as bio-materials. There are plenty of references associated with simulation and materials, two keywords of this paper, but there is no point referring to any publication that is not directly related to this work. As for the objective of this paper not much previous work can be addressed.

2. APPLICATION OF THIS WORK

The results of this work can be used for applications that call for simulation of a tool or bucket interfacing with bulk media. As mentioned before, the main purpose has been using this as a tool for examination/ verification of the effect of a control policy for loading particulate media. Another very important application is in the simulators that are employed for training of operators for large excavating mashines. These days, similar to a flight simulator for training of pilots, for many such machines, like a backhoe or grader, it is much more cost effective to train an operator on a simulator, first, before he gets on to the real machine. The results of this work can be integrated with such software. In this way, when the operator trainee runs the cutting tool (blade, bucket, etc.) through the soil or fragmented rock, the software makes a distinction between moving through a medium and moving through the air.

Furthermore, based on this work, the training simulator can be enhanced through feedback of the forces exerted to the loading element to the levers, pedals and the like. In this way the trainee feels the effect of his actions in a more realistic manner.

3. LOADING RESISTANCE FORCE

When a tool is in contact with a medium the cutting edge of the tool has to interface with the medium (Hereafter the world tool will be used for the cutting element in an excavator, whether a blade, a bucket or other, depending on the machine). So, the cutting edge encounters a force that must be overcome in order for the tool to penetrate into or cut through the medium. This force must be provided by the driving elements/actuators on the excavating machine. This, however, is not the only force that must be overcome and must be provided by the actuators. Depending on the machine and the cutting tool form and size a number of resisting force components exist which have a resultant at the actuator level. The actuator, thus, must provided an active force superior to the total resistive force. For a bucket in a front-loader or a loader type excavator these force components are shown in figure 1 and are as follows [1]:

r_1: The weight of the material in the bucket

r_2: the force of the bucket body pushing (and compressing) the material

r_3: Friction forces of the material moving into the bucket

r_4: Cutting force

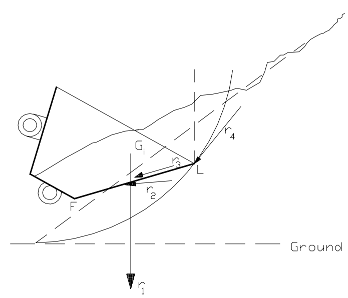

Figure 1 Forces From Media of a Bucket

In addition to these, the active forces of the excavating machine must move the bucket, its contents and the material above the bucket that moves with the bucket. Analysis, formulation, and experimental measurement of excavation force components has been vastly studied by Zelenin et al [2] in earlier decades and more recently a number of researchers have worked on the subject (see for instance [3][4])

When the active force from the actuator and the resistive force from the medium come to an interaction then the behaviour of the machine and the medium has to follow the physical laws. In this respect, the machine has stiffness and damping that can lead to its deformation. So has the medium that undergoes a physical change. Figure 2 shows the model for the tool-medium interaction. For the medium, nevertheless, the stiffness is relatively very low and damping is relatively very high.

The model shown in figure 2 is for a simple system comprising a single actuator. In practice, usually there are more than one actuators and the necessary treatment must include the whole system. As a result, the simulation becomes more involved, as well as more meaningful. As for example, when the bucket of a back-hoe or a loader moves the motion is not necessarily a straight line and the direction of all the force components vary at each instant. For this reason, the simulation code is machine dependent. That is, the simulation code (this software) should be integrated with the code for moving the various actuators in a machine.

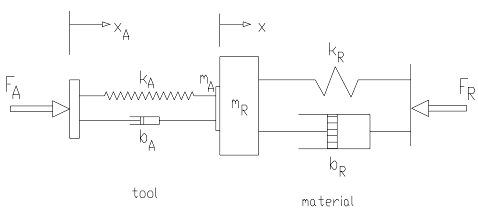

Figure 2 Tool-Medium Interaction Model

In this simulation a small front loader is used as the device the bucket of which interacts with the soil. The conceptual design of this machine is shown in figure 3, depicting the extreme lower and upper reach positions of the bucket and the dimensions. For simplicity the loading motion of the bucket is assumed to take place in a plane. In fact, such a machine has three degrees of freedom which lead to a planar motion of the bucket. The schematic of a model of this machine is illustrated in figure 4. Figure 4 is a model of the loading gear in a front-end loader excavator consisting of a prismatic joint representing the advance motion of the vehicle and two linear actuators leading to rotating motion of the bucket. Thus, the loader is represented by a robotic arm having one prismatic and two revolute joints. All the definitions for various dimensions are shown also in figure 3. The associated modeling definitions, kinematics and force relationships for this class of excavator are given in [1].

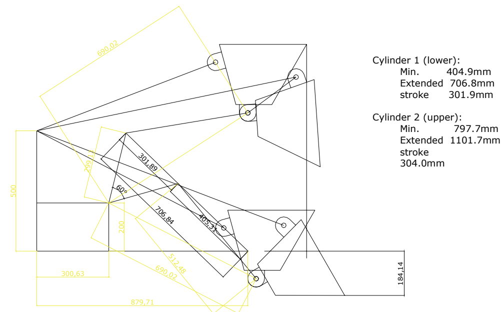

Figure 3- Schematic of a Model Loader

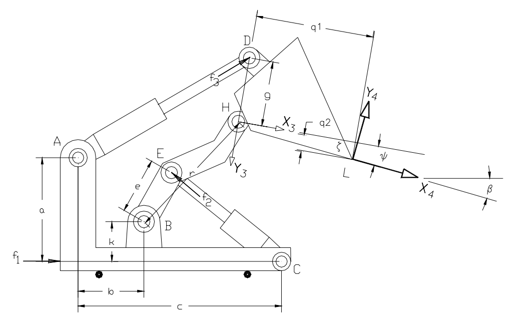

Figure 4 Robotic Model of a Loader

4. SIMULATION ANALYSIS

In the simulation we are introducing a force (either fixed or variable) to each actuator and also we define the medium properties in the form of a force vector, then the movement of the bucket under the effect of this force is considered and recorded.

Out of the five force components that were mentioned in the previous section and are shown in figure 1, the component r4 (representing the resistance to the cutting blade) is the dominant force. Since the simulation at the current stage (the objective of this paper) is for the medium resistance, considering this force component, only, is acceptable. Otherwise, the effects of the weight of the loaded material and the friction forces must also be included. The effect of the weight change can be included in the mass parameter that is used as a rigid body on which the resultant of actuators forces acts.

In the simulation, we assume that the loading is to take place from a heap of soil. Thus, the force r_4 depends on the location of the point of action inside the heap and, more importantly, if the bucket is driven out of the heap then the motion takes place in the air, for which there is no resistance. The nominal values of the soil at a number of specified mesh points are defined as 3-element vectors: two force components and a torque component. The given data are in the form of a matrix of force vectors for a limited number of points. The software generates more points, as desired, by linear interpolation from the surrounding mesh points. Since two-dimensional motion is considered, all the force components along the width of the bucket are taken as to be the same. As a result of the above, the input data does not have a large size, taking away the burden for the necessity of defining a large data base for the soil force

At each node three values for a horizontal force, a vertical force and a torque are defined. These are for the resistance to the motion of a bucket with zero orientation ($\beta = 0$; see figure 4). In the process as the bucket moves and its orientation of changes, the corresponding force/torque elements on the cutting edge are calculated and adjusted.

The excavation force encountered by an excavating element can significantly vary from point to point inside a medium. For this reason, at any point a random value is added to the nominal force values. In the simulation this randomly generated value was always positive, but its range of variation was quite large. Since the simulation is for the medium resistance, we are not concerned about the flexibility and damping of the structure of the bucket and its driving linkages. In this way, we can assume that the active force of each joint is readily available when transformed at the tool cutting edge. As for the flexibility and the damping in the medium, the material is less likely to perform like a spring and push back the bucket. In fact, when the active force is more than the resistive force, then a motion results, but when the active force is inferior to the resistive force, there is no backward motion; there will be no motion, instead. In this sense, it is reasonable to assume that the medium stiffness is very small (material deforms) such that it can be ignored in comparison with damping constant. A nominal value for the damping can be selected such that the motion is sufficiently damped.

5. EXAMPLES

The model loader used can raise its bucket by 0.874m from ground. An advance motion of 1.500 m seems to be reasonable for loading. Also, there is 60° orientation change from a horizontal (ready for loading, $\beta = 0$) configuration to filled configuration ($\beta = 60$). The bucket motion is dictated by the lengths of the actuators at each instant. For the two cylindrical actuators if at any time the minimum or maximum length is reached no more retraction or extension can take place.

In the examples that follow the bucket of the model loader is run into the medium without any control. The outcome is, thus, a motion governed by the difference between the active forces provided by the actuators and the resistive forces at the bucket cutting edge transformed to coordinates at the actuator level.

Simulation is carried out at two levels by any number of desired steps. The reason for having two levels is to allow for changing the active forces, effective mass values and so on. The number of steps represent the duration of operation. This duration is the same in all the examples. In the following illustrations the graphs representing the results of the simulation reflect the motion of the bucket in the horizontal and vertical directions, measured in metre.

5.1 Example 1

In this example the actuator forces, vehicle push, first cylinder push and second cylinder pull, respectively, are 2000, 1500 and 1500 from the beginning and stay constant for the whole time of simulation. Metric units are used. The effective mass values are increased by 10% for five times, evenly spaced during the period.

In this example the initial values of the actuator forces have not been sufficiently large to give rise to a noticeable motion of the bucket. The bucket has hardly changed orientation or moved in the vertical direction.

Figure 5 shows the position (x and y-coordinates) of the cutting edge of the bucket and its orientation at the starting point. The numbers represent the displacement in meters, in the horizontal and vertical directions. All the examples have the same starting configuration. As is depicted by negative values shown in figure 5, the bucket has stayed below the vehicle platform, near the ground. In other words, the active forces have not been sufficient to move the bucket through the medium (for loading).

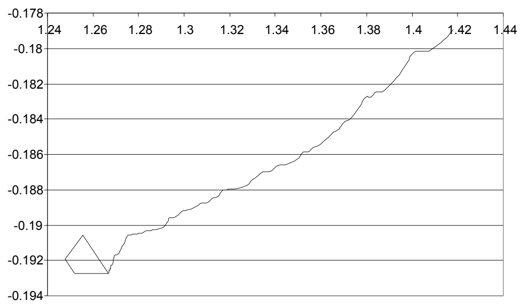

Figure 5 Bucket Motion for Example 1

5.2 Example 2

For this example all the data are the same as before except for the active forces provided to the actuators that are increased five times by 20% in each step. The bucket movement and its orientation at a few points are shown in figure 6. In this case the bucket has maneuvered a complete loading cycle by the time it is in the forth position shown.

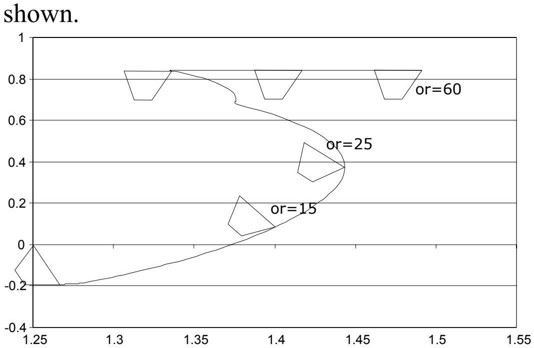

Figure 6 Bucket motion for Example 2

In this position, the linear actuators have reached their limits and, thus, the orientation has not changed afterwards, but the bucket has been pushed further forward. At the level of this paper, we are not concerned about if the motion is correct or if the bucket is filled. Obviously, the forces are not determined beforehand and the process is not controlled. What we are interested in is that if the simulation of the behaviour of the material is reasonable. From the figure we may realize that during the first portion of the motion the forward push of the bucket has not been sufficient or, saying it differently, the forces of the actuators 2 and 3 have been more than necessary.

5.3 Example 3

In this example it is assumed that the same force scenario as in example 2 is used, with the exception that the material is heavier. The variable representing the material mass are five (5) times larger than those in example 2. Everything else (except the random values that determine the final resistive force) is the same as in example 2. The results are shown in figure 7. The bucket has stopped at the final point shown, meaning that for the period (simulation duration) the bucket could be moved only halfway. The motion has to be continued for completion.

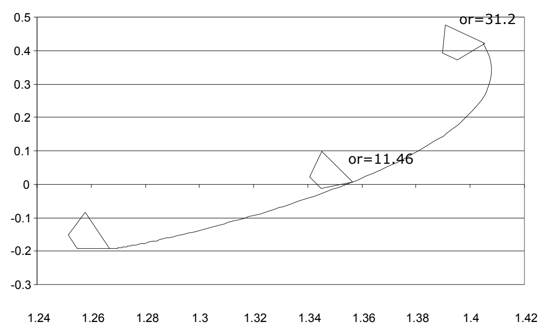

Figure 7 - Bucket Motion for Example 3

5.4 Example 4

Two changes have been introduced here compared to the previous example. The stepwise increases in the actuators and mass have been modified from 20% and 10%, respectively, to 33% and 20%. The outcome is depicted in figure 8.

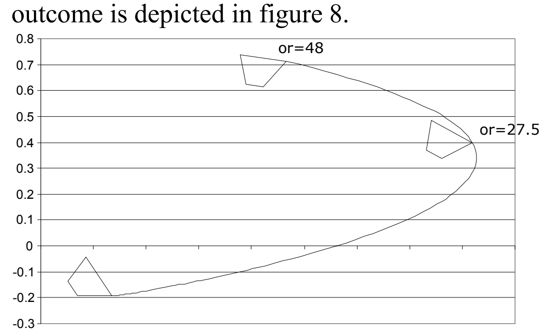

Figure 8 - Bucket Motion for Example 4

5.5 Example 5

The material density related values (mass representations as well as damping coefficients) have been further increased from its values in example 4; they have been doubled, for a heavier substance. The results are depicted in figure 9, which show a reasonable change (note that the motions for all the three degrees of freedom are smaller).

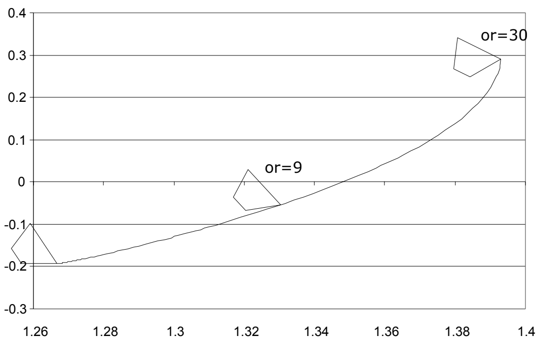

Figure 9 Bucket Motion for Example 5

5.6 Example 6

For the final example, we have kept all the characteristic data of example 5, except that the initial forces have all been increased by 200 units. As a result, the bucket has been moved further, particularly, the actions of the linear actuators are more pronounced.

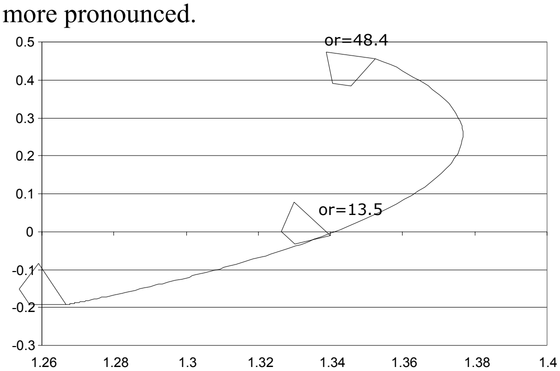

Figure 10 - Bucket Motion for Example 6

6. SUMMARY AND CONCLUSIONS

The process of interaction of a tool with a medium is complicated. The resistive force components involved depend on the tool orientation when a blade or bucket is moved.

These facts are brought into consideration in a software developed for simulation of the behaviour of a medium to cutting in a loading or excavation process. The simulation software is machine dependent. The paper discusses the more important points and the general approach. It shows that the simulation is valid and can be successfully used, as can be depicted by a number of examples. As such, the methodology and the simulation code may be incorporated with the training simulator software for any type of machine interfacing with bulk or particulate material. As well, it can serve for the purpose of evaluating the control strategies for loading automation and so on.

7. REFERENCES

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