Working Model Technical Note: Performing a Quasi-Static Analysis

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Summary

This document describes how Working Model can analyze the lifting capacity of a construction excavator. Interest in this document should not be limited to those in the excavator design business as this document covers topics which are applicable to a wide variety of Working Model users:

1. **This document demonstrates how Working Model can be used early in the design process as well as in the later product analysis stages.**
2. **This document performs a quasi-static analysis. Often static analysis information is needed not for a single configuration but over a range of configurations. Instead of performing multiple static analyses, one can perform a single quasi-static analysis which covers the desired range of configurations.**

Introduction

The lifting capacity is defined as the maximum weight an excavator can support at a specified static position. The lifting capacity is a function of both the geometry of the excavator and the force limitations of the excavator's actuators.

Since the excavator's lifting capacity varies over its range of motion, a single static analysis is not sufficient. Instead of analyzing the static system at a series of positions, it is easier to perform a single quasi-static analysis which moves the system slowly through the desired range.

It is important to note that quasi-static analyses give proper results only if the speed of the analysis is sufficiently slow. At higher speeds, inertia forces become large enough to affect the results.

Quasi-Static Analyses

The following steps outline the procedure for creating a quasi-static analysis. These steps will be clarified in the examples which follow.

General Procedure for Quasi-Static Analyses

1. **Create a model of your system in Working Model. You may wish to facilitate this by transferring DXF data from a CAD application.**

2. **A static analysis calculates an unknown force at a certain configuration. A quasi-static analysis calculates the same unknown force over a range of configurations. This range of configurations is achieved by slowly rotating a joint. Define theta as this joint's angle. The user must identify:**
   a. **The starting value of theta.**
      The user must configure the system such that theta is at the desired starting value. This can be done either by carefully dragging the main link until it is in the proper position or by selecting the main link's Properties Window and entering the starting value in the theta box.
   b. **The ending value of theta**
      The user must either manually stop the simulation when it reaches the ending angle or use *Pause Control* from the *World* menu, to make the simulation stop when the end of the desired range is reached. This allows the user to leave the computer unattended while the simulation runs.

3. **A velocity actuator/motor must be introduced to move theta slowly from its starting value to its final value. This velocity actuator must be defined such that the actuator force is the unknown force for which the quasi-static analysis is solving.**

4. **Specify known quantities: Use Working Model's force tool to apply known forces. Use the motor tool to specify known joint rotations. Use the actuator tool to specify known translations.**

5. **Create a meter to view the Force/Torque produced by the actuator/motor created in step #3. Other meters may be created to graph the output or to track the maximum output (the appendix explains how to track maximum meter values).**
   Furthermore, this meter data is not stranded in Working Model. Working Model allows the following methods of transferring the data outside of Working Model:
   a. **Meter data can be exported to a text file (see the *Working Model User's Manual*, pages 227-229 and 334-336).**
   b. **Meter data can be cut-and-pasted into another application (see pages 336-337 of the *Working Model User's Manual*).**
   c. **Meter data can be exported in real time to another application by DDE or Apple Events (see pages 351-359 of the *Working Model User's Manual*).**

6. **Run the simulation by clicking on the *Run* button at the top of the toolbar.**

Example: Excavator Lifting Capacity

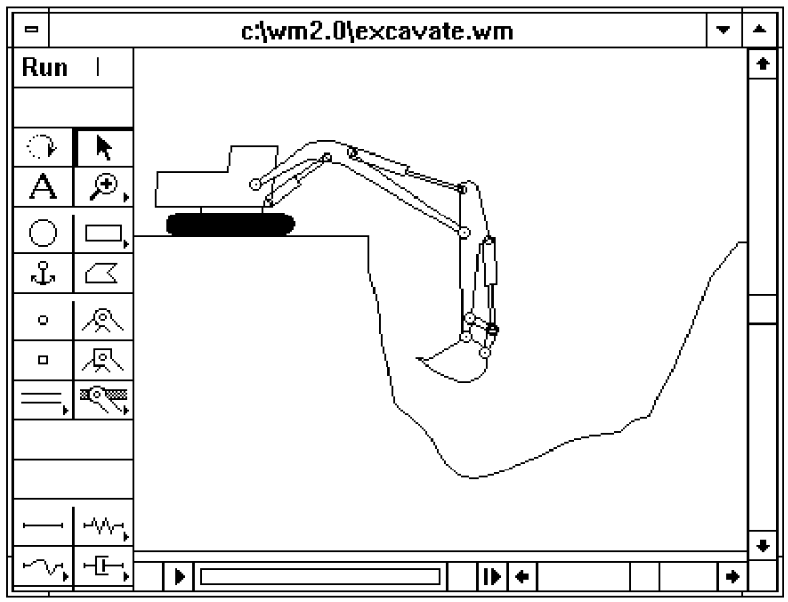
Once a Working Model file has been created, it is easy to perform many different analyses on the same system. Figure 1 shows the Working Model file which was created to analyze the dynamics of an excavator.

The cab and track of the excavator cannot move because they were anchored to the background. This leaves the excavator with three degrees of freedom:

1) The main link can rotate about the joint which connects it to the excavator cab.
2) The middle link can rotate about the joint which connects it to the main link.
3) The bucket can rotate as part of the four-bar linkage which connects the middle link with the bucket.

Working Model's polygon tool was used to quickly construct the excavator's many odd-shaped parts. Not only do the odd-shaped parts look realistic, but their inertia properties were automatically calculated by Working Model. Furthermore, Working Model's advanced collision detection senses when even odd-shaped parts collide with other objects. For more information on creating polygons in Working Model, see pages 79-82 and 99-105 of the Working Model User's Manual.

Figure 1
Excavator Working Model File



Starting with the same excavator Working Model file, the following two analyses were performed:

(a) ***Design: Actuator Sizing***
Given a desired lifting capacity, calculate how much force must be produced by the main actuator in order to achieve the lifting capacity throughout the entire range of motion. For this analysis, the middle and bucket actuators were locked.
This analysis would be used in the design process to determine the minimum force capacity needed for the main actuator. Similarly, additional analyses could be performed for the design of the middle and bucket actuators.

(b) ***Analysis: Lifting Capacity***
After performing analysis (a), the designer chooses an actuator which can provide enough force to meet the desired lifting capacity. This second analysis calculates the resulting lifting capacity of the excavator.

Note that in analysis (a), the lifting capacity was known and the main actuator force was unknown. In analysis (b), the main actuator force was known and the lifting capacity was unknown.

Analysis (a)

The design specification requires that the excavator support a bucket load of 10,000 pounds when the main link is between 25 degrees below horizontal to 25 degrees above horizontal. This analysis seeks to determine how much force is required from the main actuator to meet the above design specification. The analysis follows the steps outlined above.

1. This analysis starts with the Working Model file pictured in Figure 1.

2. This analysis requires then main joint vary from -25 degrees to +25 degrees.

   To set the initial condition:

   a. Highlight the main link by clicking on it
   b. Select "Properties..." from under the "Window" menu.
   c. Enter -25 in the Theta box.

   To automatically stop the simulation when the main actuator has pushed the main link past +25 degrees:

   a. Select "Numbers and Units..." from under the "View" menu to check that the current unit use degrees for rotational measurements.
   b. Select "Pause Control" from under the "World" menu
   c. Click on "New Condition". The top right box will display "time > 1.0"
   d. Choose "Stop when" from the menu which pops-up when you click-and-hold on the arrow next to the top left box displaying "Pause when".
   e. Since the main link is mass[7], the main joint angle is represented by mass[7].p.r. Enter:
      ```
      mass[7].p.r>25
      ```
      in the upper right box.

3. To move the main actuator at a constant velocity of 0.2 ft/sec:

   a. Select "Numbers and Units..." from under the "View" menu to check that the current units use feet for translation measurements.
   b. Highlight the main actuator by clicking on it.
   c. Select "Properties..." from under the "Window" menu.
   d. Select "Velocity" from the menu which pops-up when you click on the arrow next to the "Type" box.
   e. Enter 0.2 in the "Value" box.

4. To apply the bucket load:

   a. Activate the force tool by clicking on the force tool which is located near the bottom of the toolbar.
   b. Click on the bottom of the bucket to specify at which point to apply the force. This creates a point on the bucket.
   c. The point should be highlighted (darkened). If the point is not highlighted, click on the point to highlight it.
   d. Once the point is highlighted, select "Properties" from under the "Windows" menu.
   e. Specify a purely vertical force by entering 0 in the Fx box and -10000 in the Fy box.

To lock the middle actuator is locked:

   a. Highlight the middle actuator by clicking on it.
   b. Select "Properties..." from under the "Window" menu.
   c. Select "Velocity" from the menu which pops-up when you click on the arrow next to the "Type" box.
   d. Enter 0 in the "Value" box

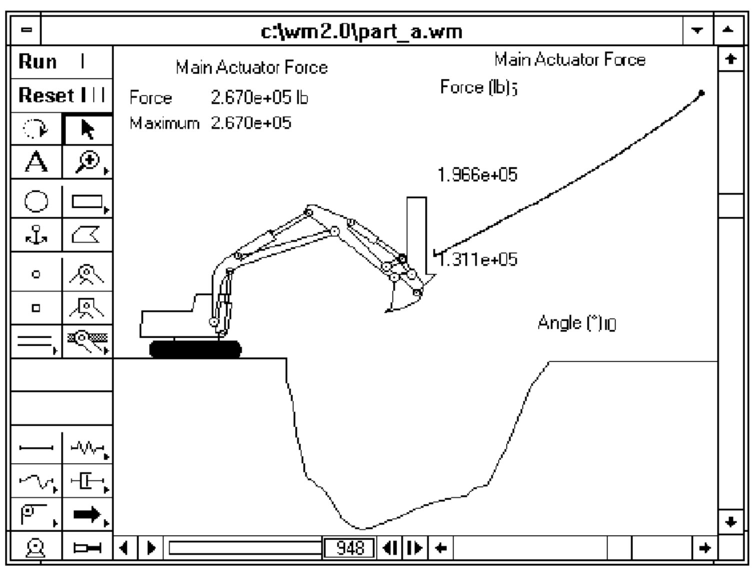
   Repeat the previous 4 steps to lock the bucket actuator.

5. To display the tension in the main actuator:

   a. Highlight the main actuator by clicking on it.
   b. Choose "Tension" from under the "Measure" menu.

   The purpose of this analysis is to aid the designer in choosing the size of the main actuator such that it can produce enough force to support the bucket load at any position in the range of motion. Since this meter displays the tension required to support the bucket load, the designer must find the maximum tension displayed by the meter. To facilitate the finding of this maximum value, you may wish see the Appendix which describes how to track a meter's maximum value.

Figure 2
Results of Analysis (a)



6. The simulation is run by clicking on the *Run* button at the top of the toolbar. The simulation results are shown in Figure 2.

The simulation shows that in order to meet the 10,000 pound lifting capacity specification, the actuator must be sized such that it can provide 269,700 pounds of force. To add a factor of safety, the designer chooses an actuator which provides a maximum of 320,000 pounds of force.

Analysis (b)

After performing analysis (a), the designer chooses an actuator which can produce 320,000 of force. Although the designer knows that the excavator has a lifting capacity of at least 10,000 pounds over the entire -25 degree to +25 degree range, a graph showing the lifting capacity over the range is desired.

This analysis follows the quasi-static analysis steps outlined earlier.

1. This analysis starts with the Working Model file pictured in Figure 1.

2. This analysis requires the main joint to vary from -25 degrees to +25 degrees.

   To set the initial condition:

   a. Highlight the main link by clicking on it
   b. Select "Properties..." from under the "Window" menu.
   c. Enter -25 in the Theta box.

   To automatically stop the simulation when the main actuator has pushed the main link past +25 degrees:

   a. Select "Numbers and Units..." from under the "View" menu to check that the current unit use degrees for rotational measurements.
   b. Select "Pause Control" from under the "World" menu
   c. Click on "New Condition". The top right box will display "time > 1.0"
   d. Choose "Stop when" from the menu which pops-up when you click-and-hold on the arrow next to the top left box displaying "Pause when".
   e. Since the main link is mass[7], the main joint angle is represented by mass[7].p.r. Enter:
      ```
      mass[7].p.r>25
      ```
      in the upper right box.

3. Since the bucket load exerts a purely vertical force on the bucket, the actuator which moves the excavator must apply only a vertical force. If the actuator applies a non-vertical force on the bucket, the force of the actuator be an inaccurate representation of the vertical bucket load.

   The following procedure ensures that the actuator applies a vertical force on the bucket:

Figure 3
Close-up of Horizontal/Vertical Actuator Pair

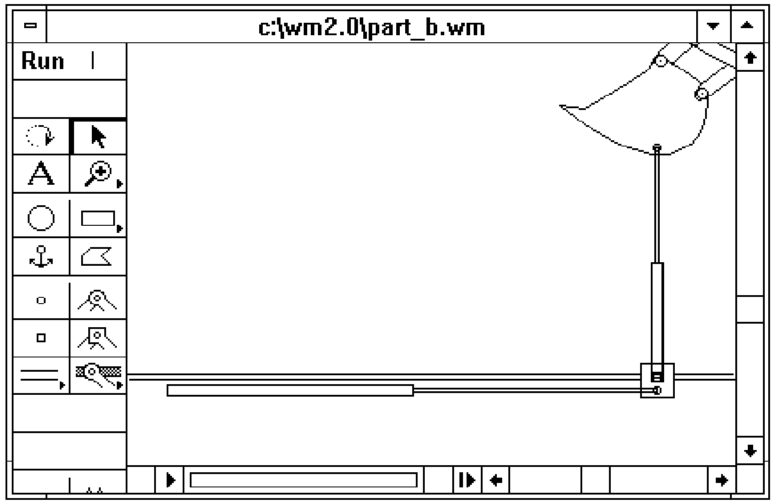


Figure 3 shows the two actuators which must be implemented to apply a purely vertical load to the bucket. A small block is moved along a horizontal slot by an actuator whose length is controlled such that the block is always below the bucket.

Figure 4
Property Window of Horizontal Actuator

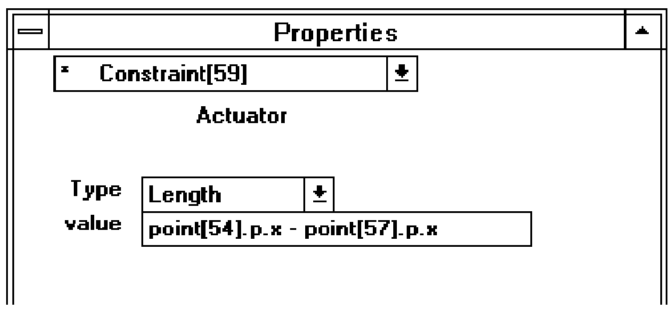


Figure 4 shows the Properties Window for the horizontal actuator. Point 54 is a point on the bucket while point 57 is the left endpoint of the horizontal actuator. The above length equation keeps the right endpoint of the horizontal actuator directly below point 54 on the bucket.

Figure 5
Property Window of Vertical Actuator

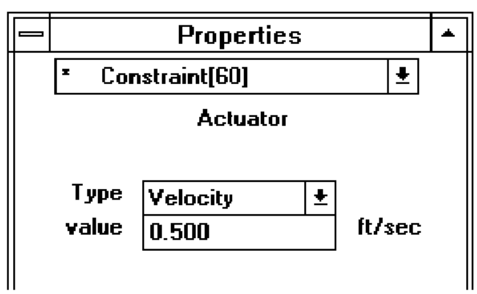


Figure 5 shows the Properties Window for the vertical actuator. The excavator is moved through its range as the vertical actuator expands at a rate of 0.5 feet/second.

Note that this step is significantly more complex than step 3 of analysis (a). Recall the general instructions for step 3 on page 2:

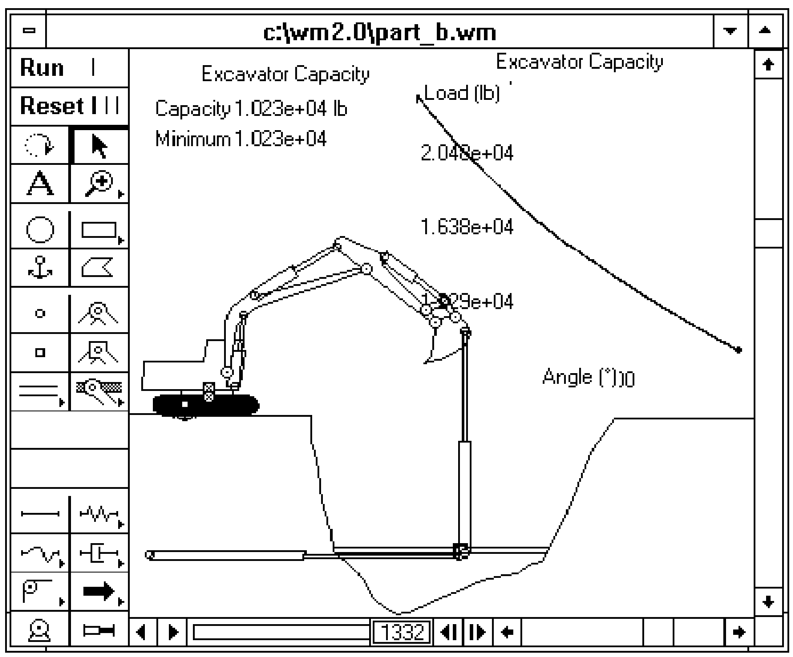
> **This velocity actuator must be defined such that the actuator force is the unknown force for which the quasi-static analysis is solving.**

In analysis (a), the unknown force was the force produced by the main actuator. Thus the main actuator could be used as the velocity actuator which moves the system. In analysis (b), the unknown force was the bucket load force. Since gravitational forces are always vertical, the velocity actuator which moves the system must apply only a vertical load.

4. The main actuator is set to produce a constant force of 320,000 pounds, which is the maximum force that the chosen actuator can produce. This is done by:
   a. Highlight the main actuator by clicking on it.
   b. Select "Properties..." from under the "Window" menu.
   c. Select "Force" from the menu which pops-up when you click on the arrow next to the "Type" box.
   d. Enter 320000 in the "Value" box.

5. A meter is created to display the force applied to the bucket by the vertical actuator. This force is the excavator's loading capacity.

Figure 6
Results of Analysis (b)



6. Run the simulation by clicking on the *Run* button at the top of the toolbar. The simulation results are shown in Figure 6:

The simulation shows that the excavator's minimum lifting capacity is 10,230 pounds, which confirms that the excavator meets the 10,000 pound design specification. In addition, the simulation shows the lifting capacity is well over 20,000 pounds when the bucket below horizontal.

Appendix

Tracking the Maximum Value of a Meter

When simulations are run to find the maximum value of a parameter, it is inconvenient to search through the entire history of the meter in order to find the maximum value of the parameter. Instead, the maximum value can automatically be displayed by use of Working Model's Formula language.

The procedure for tracking a maximum value of a parameter is as follows:

1) Select one mass object, point, or constraint whose properties you wish to measure. In Figure 7, an actuator was selected.
2) Select the property you wish to measure from under the "Measure" menu. In Figure 7, the actuator's tension was selected.
3) Use an "if" statement (see page 369 of the Working Model's User's Manual) to track the maximum tension.
   An "if" statement takes three parameters:
   a. a condition
   b. expression to evaluate if the condition is true
   c. expression to evaluate if the condition is false.

   The "if" statement in Figure 7 first evaluates the first parameter's expression (output[50].y1>output[50].y2) which checks whether the updated value for the first cell (y1) is larger than the previously-calculated maximum in the second cell (y2). (When a cell's formula references itself, the cell's value from the previous time step is used. All other cell references use values from the current time step.) If the condition is true, the second parameter's expression (output[50].y1) is assigned to the cell. If the condition is false, the third parameter's expression (output[50].y2) is assigned to the cell.

Figure 7
Properties Window
for Tracking a Meter's
Maximum Value