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Monitoring the Dynamics of Scaled Vehicles Using a Sonic Digitizer

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Abstract. *Certain dynamic stability characteristics of an alternate method of mounting a front-end loader to a farm tractor were compared to those of a conventionally mounted front-end loader operating on a specified terrain. One objective of the study was to determine if the alternate method of mounting a front-end loader resulted in better stability characteristics and, in turn, safer operation than a conventional front-end loader. Another objective was to determine if a three-dimensional sonic digitizer could monitor the motion of the scale model tractor-loader systems accurately enough to perform a comparison between the systems. This article describes the second objective of the study. A battery-powered, 1/4 scale model tractor-loader was used to perform experimental tests. Both tractor-loader systems were operated on two slopes and on random combinations of two sinusoidal bump heights, two load weights, two loader heights, and two velocities. Three replications were performed of each test condition. A three-dimensional sonic digitizer was utilized to monitor the motion of the scale model tractor-loader systems. The sonic digitizing system made it possible to record position of the tractor-loader systems versus time at levels of frequency and accuracy faster than any previous methods of obtaining this type of data. This greater number of observations allowed systems to be statistically compared, which was not possible with previous data collection systems. The digitizing system was able to locate each sound emitter accurately. Elapsed time between emitter firing sequences may have resulted in the measured roll and front axle rotation angles to be less than actual peaks.* **Keywords.** *Dynamic analysis, Sonic, Tractor stability, Model tractor.*

Monitoring the dynamic position of scale models has been a limiting factor in the amount of experimental tests performed in previous stability studies, since it has been a very time consuming and complex procedure. Many techniques have been used, from camera techniques to accelerometers, all of which require an excessive amount of time to analyze each experimental test. Davis and Rehkugler, (1974a, b) developed a mathematical model (SIMTRAC) capable of predicting general overturn motions of tractors through the point of time when the tractor frame or Roll-Over Protective Structure (ROPS) strikes the ground. The model was verified using an experimental, unpowered 1/12 scale model. The motion of the model as it traversed the test terrain was studied in three dimensions by using a mirror arrangement and recording two views simultaneously in high speed movies. Ten model overturns were filmed to provide replications for five different tests. Spencer (1978) performed a study of combinations of slope angle and heading angle to show the conditions at which instability occurred using scale models. Experiments on a tilting table were carried out by placing the model at successive heading angles and steadily increasing slope of table surface until sliding or overturning occurred. Chen (1980) investigated the use of a modified version of the Highway-Vehicle-Object Simulation Model (HVOSM) to simulate three-dimensional tractor motion. A ramp test and a curb test were chosen for validation using a battery-powered scale model in the experimental tests. To validate the computer model, Chen used three video cameras orthogonal to each other. Two recorded experimental events were used in the study. Wood and Burt (1985) used a sonic digitizing system to determine the location of points in three dimensions. To alleviate the time consumption problem of previous stability studies, a sonic digitizer was used to monitor four points located on each scale model. The sonic digitizer enabled the experiments to be conducted in much less time than would have been required using previous techniques.

Objectives

This report examines the methodology and accuracy of using a three-dimensional sonic digitizer in monitoring the position of a scaled tractor model as it traversed a specified terrain. The objectives of this study were to:

- Describe the operational capabilities of a sonic digitizer and its use in monitoring vehicle dynamics.
- Evaluate repeatability of the sonic digitizing system using scale model tests.

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Experimental Methods

Certain dynamic stability characteristics of an alternate method of mounting a front-end loader to a farm tractor were compared to those of a conventionally mounted front-end loader operating on a specified terrain. One-quarter-size powered scale models of each tractor-loader system were used in the study to compare the stability of the systems. The model had pneumatic tires whose sizes were 7.11 × 5.08 (2.80 × 4.0) and 12.19 × 10.16 (4.80 × 8.0) for front and rear tires, respectively. The experiments were conducted on a tiltable platform with a concrete surface. Figure 1 illustrates the configuration of the experimental apparatus. Each model was placed parallel to the slope and was made to traverse the bump with the upslope tires. The models were operated on two different slopes with random combinations of velocity, bump height, load weight, and load height. The slopes used in the experiment were 10 and 15°. The loads carried by each model weighed 6.01 and 12.02 kg and were composed of flat cold-rolled steel plates. The loads were carried at a height of 22.9 and 45.8 cm. The two velocities used in the experiment were obtained by placing the model in either first or second gear. These model velocities were 34 and 110 cm/s for first and second gears, respectively. The bumps used in the experiment were constructed of concrete, sinusoidal in shape, perpendicular to the test surface. They had a period of 71.1 cm and consisted of one half of a sine wave. The two bump heights used were 1.9 and 3.8 cm. Three replications were made with each combination.

The scale models were used to examine the ability of a sonic digitizer to monitor the transient response of a vehicle. A three-dimensional sonic digitizer manufactured by Science Accessories Corporation , model GP8-3D, was used in the study. The sonic digitizer measured and recorded the time required for sound to travel from emitters, attached to the model, which emitted sound by causing a small electrical arc, similar to a spark plug (fig. 2), to stationary microphones (fig. 3) positioned above the test surface. From these time measurements and knowledge of the prevailing speed of sound, distances from each microphone to each emitter were determined and the coordinates of the emitter was transferred to a supporting computer for storage. The position of each emitter was thus determined as a function of time.

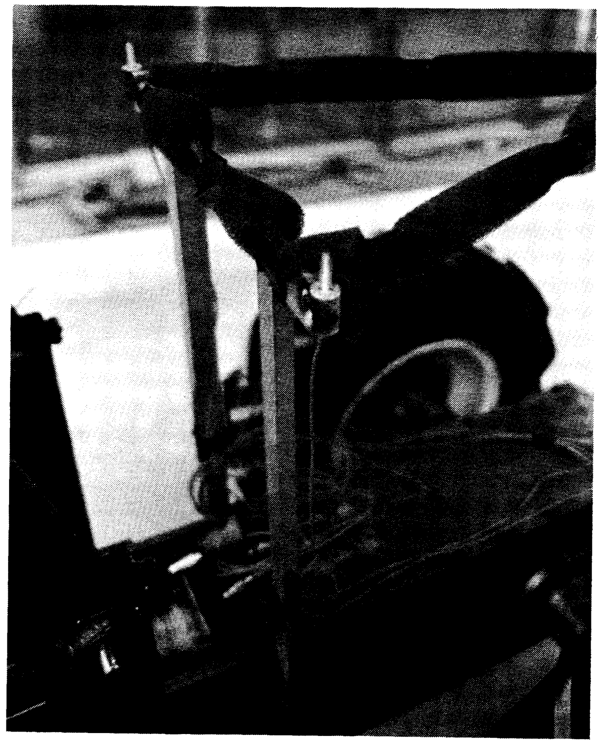

Figure 2–Sonic digitizer emitter.

The digitizing system illustrated in figure 4 consisted of four microphones, a set of emitters, a multiplexer, and a sonic digitizer. The four microphones were mounted in a rectangular array and placed above the test surface over which the model systems traveled. Three emitters were mounted on an aluminum frame attached to the model tractor body, as shown in figure 5, to determine its position and orientation during a test. They were positioned high enough in the vertical direction to allow a clear path from the emitters to the microphones positioned above.

The first emitter, emitter no. 7, was located above and behind the center of the rear axle, and on a plane perpendicular to the rear axle which contained the front-end pin axis (vertical center plane). The second emitter, emitter no. 8, was located above and ahead of the center of the rear axle, and to the left of the vertical center plane.

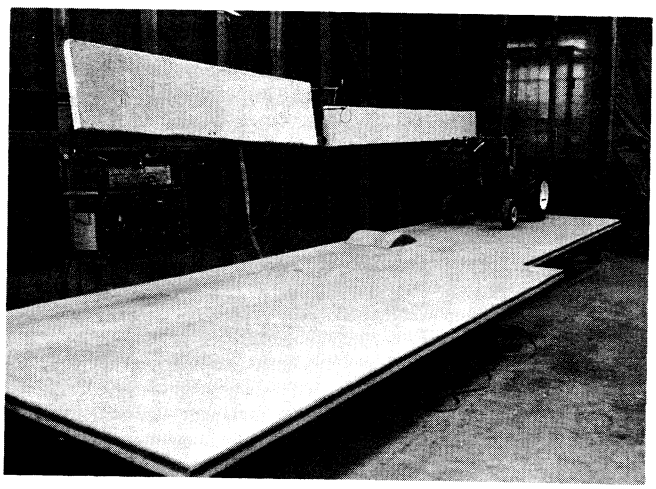

Figure 1–The configuration of the experimental apparatus.

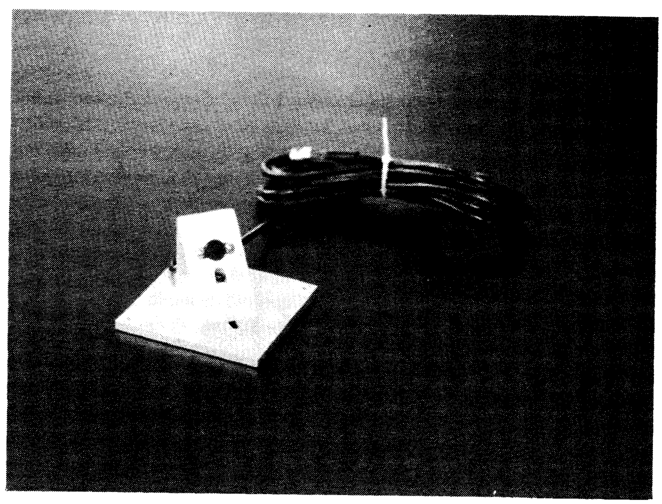

Figure 3–Sonic digitizer microphone.

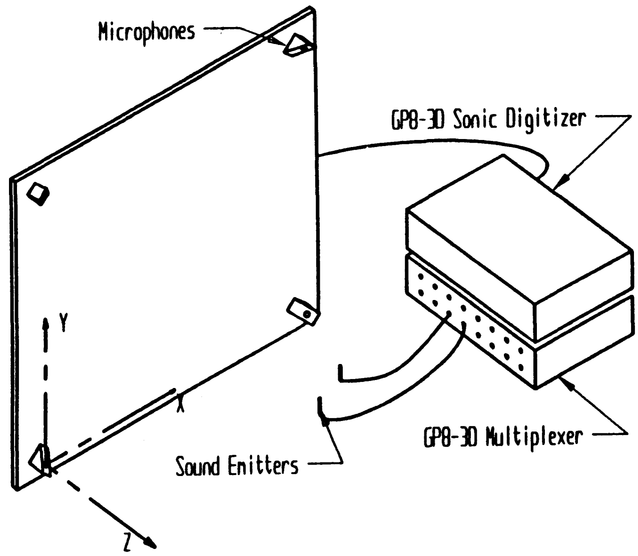

Figure 4–Sonic digitizing system.

The third emitter, emitter no. 15, was located on a line, containing emitter no. 8, perpendicular to the vertical center plane. It was located at the same distance from the vertical center plane and to the right of the vertical center plane. A fourth emitter, emitter no. 16, was attached to the front axle. It was located at the intersection of a plane perpendicular to the front-end pin axis which contained the center point of the front axle pin and the vertical center plane when the model was located on a horizontal surface. It was located above the center of the front axle pin axis. A fifth emitter was needed as a benchmark emitter to compensate for the change in sound wave velocity due to fluctuating temperature. It was mounted to a stationary frame attached to the floor.

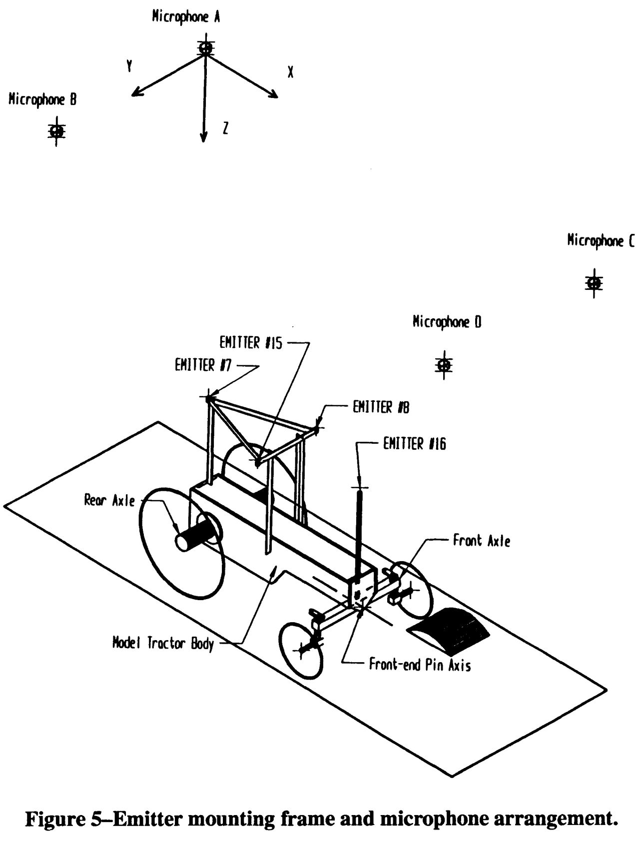

Figure 5–Emitter mounting frame and microphone arrangement.

The microphones were mounted at the corners of a 2.9 × 1.8 m (9.5 × 6 ft) rectangular frame which was located about 2 m (6.5 ft) above the test surface. The maximum active volume of the sonic digitizer specified by the manufacturer was a 2.9 m (9.5 ft) cube.

The cables between the emitters and the multiplexer were 3.0 m in length; therefore, the multiplexer had to remain close to the model. This was achieved by constructing a track system to carry the multiplexer near the model as it travelled along the terrain. The terrain chosen for use in the model test studies was an inclined plane with a sinusoidal-shaped bump input to the up-slope tires. A 19 mm (3/4 in.) thick concrete layer with a broom finish was placed on the plywood to provide uniform surface conditions for each test. The terrain was composed of two 2.44 m (8 ft) sections, one with a 1.22 m (48 in.) width and the other with a width of 1.44 m (56.5 in.). A sinusoidal-shaped obstacle was selected as the input disturbance to the up-slope tractor tires.

The position of the model was defined by the four emitters attached to the model. The digitizer activated the emitters sequentially in volleys, determined the corresponding travel times, computed the distances from each emitter to each microphone, and sent these results to the supporting computer for storage. Once a test was completed, the data were transformed from a set of distances to xyz coordinates of each emitter and stored in a data file on the supporting computer.

The output file which was generated using the available software, SACTrack developed by PixSys, Boulder, Colorado, used the following format:

SSS.SS EE F XXX.XX YYY.YY ZZZ.ZZ

where

SSS.SS was the elapsed time in seconds from when the test was started. All emitters fired in the same volley were assumed to have been fired at the same time, however, 12 to 13 ms elapsed between successive firings.

EE was the emitter number.

F was a flag indicating the quality of the measurement and the computation of the xyz coordinates. The letter "s" indicated a good measurement. The letter "e" indicated a failure, which happened if less than three microphones detected the emitter firing. A "?" mark was used to indicate that either only three microphones detected the emitter firing or all four microphones detected the firing, but gave contradictory or erroneous measurements.

XXX.XX was the x-axis coordinate of the emitter EE expressed in centimeters. YYY.YY was the y-axis coordinate of the emitter EE expressed in centimeters. ZZZ.ZZ was the z-axis coordinate of the emitter EE expressed in centimeters.

The origin of the xyz coordinate system was located at the center of the "A" microphone. The scale model was allowed to accelerate to a constant velocity before entering the digitizing volume. The model also exited the digitizing volume during each experimental test. This required the beginning and ending of each data file to be trimmed. The file was used as an input to a Basic program to obtain the model's position and orientation with respect to time. One disadvantage of the sonic digitizer was the unavoidable time delay between the individual emitter firings in a firing sequence. To account for this small time difference, a moving test was conducted to adjust for time delays between the firing of emitter no. 7 and the three other emitters fixed to the model. Emitter no. 7 was used as a benchmark location on the model. The distances between emitter no. 7 and the other emitters were determined from the stationary test by forming vectors between emitter no. 7 and the other three emitters, and determining their respective magnitudes. Once these magnitudes were found, the data were adjusted by writing the parametric equations of a line between the last recorded position of the emitter and its current position which have the form:

$$x = x_1 + lt \qquad (1)$$

$$y = y_1 + mt \qquad (2)$$

$$z = z_1 + nt \qquad (3)$$

where

l, m, n = direction cosines of a line joining the two points
t = magnitude of the correction vector
x, y, z, x_1, y_1, z_1 = coordinates

The emitter firing order was nos. 7, 8, 15, and 16. Different magnitudes of the correction vector were calculated for nos. 8, 15, and 16. The measured magnitudes were adjusted until the average differences between the magnitudes of the vectors joining emitter no. 7 and emitters nos. 8, 15, and 16 were within 0.01 cm of their respectively stationary magnitudes when the model was moving in second gear with no bump. The results are shown in table 1.

Seven parameters were needed to describe the location and orientation of the model: roll, pitch, yaw, the x, y, z coordinates of a known point, and the rotation angle of the front axle relative to the tractor body.

The orientation of the model tractor was found using the following procedure. A set of coordinate axes was established at the location of emitter no. 7 as shown in figure 6. The axis directions, $\underline{X}'$, $\underline{Y}'$, and $\underline{Z}'$ are, respectively: the fore-and-aft axis of rotation (positive forward), the centerline of the rear axle (positive to the driver's right side), and the direction of the vector cross-product $\underline{X}' \times \underline{Y}'$ (positive down).

This was accomplished by establishing vectors between emitters nos. 7 and 8 and between emitters nos. 7 and 15. The cross-product of these two vectors results in a normal vector, $\underline{W}$, to the plane formed by the three emitters (emitter plane). $\underline{W}$ was then normalized to obtain the direction cosines of the $\underline{W}$ vector. The emitter plane was at an angle of 0.23° to the plane containing the x′ and y′ axes, since the number no. 7 emitter was 1.52 mm vertically above emitters nos. 8 and 15.

Table 1. Magnitude of the correction vector for each emitter

Emitter No.	Correction Vector Magnitude (cm)	Average Magnitude (cm)	Standard Deviation (cm)	Average Difference (cm)
8	0.0157	40.82	0.023	–0.0038
15	0.0482	40.78	0.041	0.0008
16	0.0651	74.01	0.025	0.0082

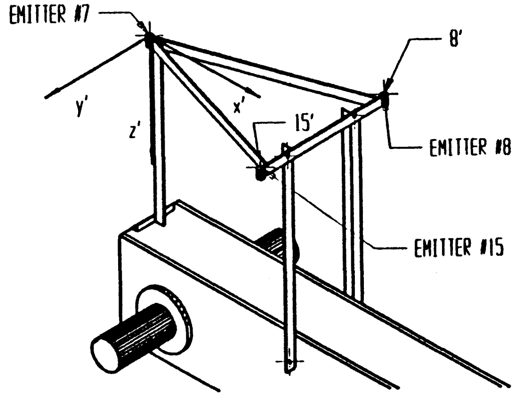

Figure 6–Initial tractor coordinate axis.

New points, 8′ and 15′, were identified above emitters nos. 8 and 15 to establish a plane parallel to the fore-and-aft axis. These new points were assumed to lie on the line perpendicular to the emitter plane above emitters nos. 8 and 15 at a distance of 1.52 mm as shown in figure 7.

Once these two points were determined, a vector was established between each of them and emitter no. 7. The cross-product of these two vectors resulted in a vector, $\underline{Z}'$, perpendicular to the plane formed by vectors $\underline{X}'$ and $\underline{Y}'$. $\underline{Z}'$ was then normalized to provide the direction cosines of z′ axis. The vector, $\underline{X}'$, was then established between the midpoint of points 8′ and 15′ and emitter no. 7, which was a vector lying in the vertical plane of symmetry passing through the center of gravity of the model and parallel to the fore-and-aft axis. This vector was normalized to obtain the direction cosines of the new x′ axis. The y′ axis was then determined by the cross-product of vectors $\underline{Z}'$ and $\underline{X}'$.

The variables used to describe the orientation of the model are shown in figure 8. They are defined as: roll – rotation about the x′ axis; pitch – rotation about the y′ axis; y – rotation about the z′ axis.

Once the direction cosines of each axis were known the orientation of the model body can be determined using the following equations (Snyder, 1985).

$$\text{Yaw} = \text{ATAN}(n_{y'}/n_{x'}) \qquad (4)$$

$$\text{PITCH} = \text{ATAN}\{(-n_{z'})/[n_{x'}\text{COS(YAW)} + n_{y'}\text{SIN(YAW)}]\} \qquad (5)$$

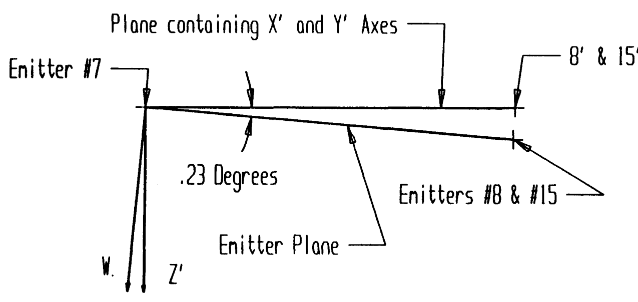

Figure 7–Axes adjustment from emitter plane axes.

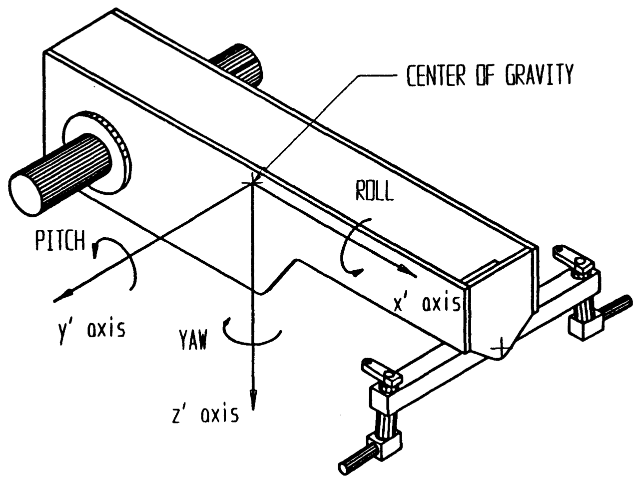

Figure 8–Body-centered axis system.

$$ROLL = ATAN\{[s_{x'} SIN(YAW) - s_{y'} COS(YAW)]/[o_{y'} COS(YAW) - o_{x'} SIN(YAW)]\} \quad (6)$$

where

$n_{x'}, n_{y'}, n_{z'}$ = direction cosines of the x′ axis
$s_{x'}, s_{y'}, s_{z'}$ = direction cosines of the y′ axis
$o_{x'}, o_{y'}, o_{z'}$ = direction cosines of the z′ axis

The rotation of the front axle about the model body was determined using the following procedure. The location of emitter no. 16 (attached to the front axle) was transferred from the fixed coordinate system of the sonic digitizer to the x′y′z′ coordinate system of the model. Once this was accomplished, a vector, 16′, was established between the front-end pin axis and the position of emitter no. 16 in the x′y′z′ coordinate system as shown in figure 9. Since the front-end rotated around an axis parallel to the x′ axis, the angle of rotation, THETA, can be determined by taking the dot product of 16′ with a unit vector in the z′ direction and dividing by the magnitude of 16′, which was equal to the cosine of THETA.

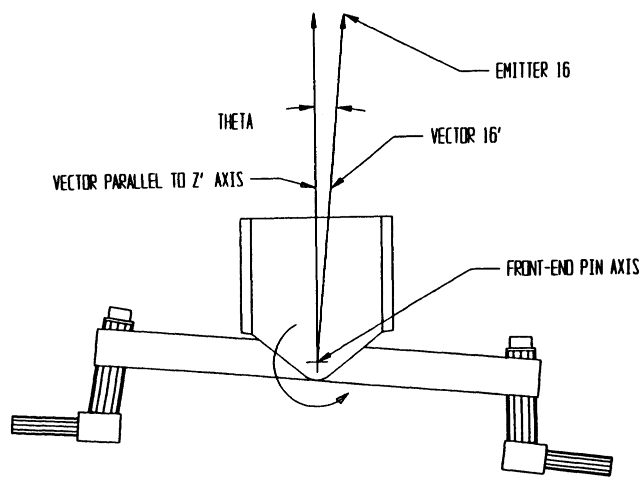

Figure 9–Front-end rotation angle (θ).

Table 2. Emitter readings obtained in the stationary tests

Emitter No.	Average x (cm)	Average y (cm)	Average z (cm)	Standard Deviation x (cm)	Standard Deviation y (cm)	Standard Deviation z (cm)
7	167.81	123.11	−135.62	0.0065	0.0104	0.0220
8	179.56	84.49	−129.66	0.0077	0.0118	0.0181
15	151.72	86.08	−129.81	0.0033	0.0047	0.0137
16	164.09	49.92	−124.56	0.0048	0.0048	0.0151

A stationary test was conducted to establish the consistency and accuracy of the sonic digitizer readings. The model was placed near the middle of the test track and the locations of the emitters were recorded. Each emitter was fired for a short period of time which resulted in 73 firings. The results are shown above in table 2.

Results and Discussion

The results from the stationary test are shown in table 1. The low standard deviation shows that the sonic digitizer consistently gives readings of emitter location which were generally accurate within 0.1 mm in any given direction.

The increase in roll angle as each system traversed the sinusoidal bump was calculated using the procedures outlined in the previous section. Figures 10 and 11 show the roll angle of the scale-model on a 15° slope traversing a 3.8 cm (1.5 in.) sinusoidal bump at two different velocities. Some of the variations in the measured roll angle may have been caused by small changes in locations of some of the emitters after being replaced following failure. Also, it was impossible to initiate the emitter firing sequence at exactly the same position of the scale-model on the test terrain during various experiments. However, the maximum value of the measured roll angle of each tractor-loader-load system was consistent among replications. The maximum difference in measured roll angle due to the bump among replications was 0.3°.

The front-axle rotational angle about the front-axle hinge pin, THETA, due to a sinusoidal bump of 3.8 cm (1.5 in.) at two different velocities is shown in figures 12

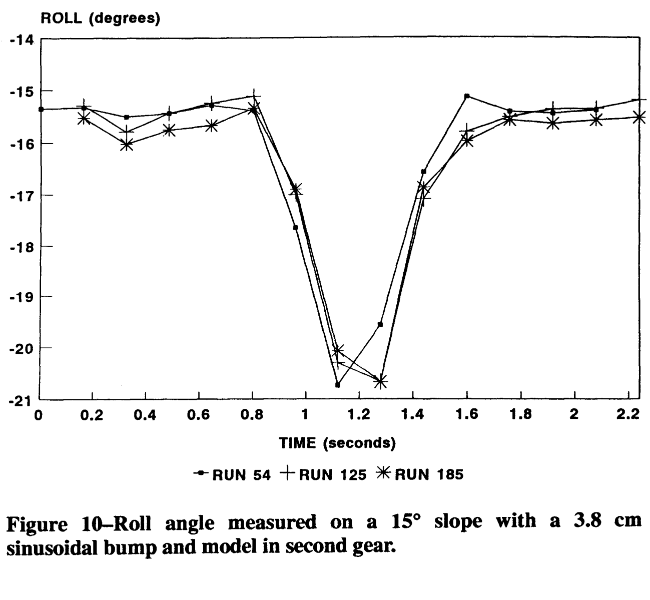

Figure 10–Roll angle measured on a 15° slope with a 3.8 cm sinusoidal bump and model in second gear.

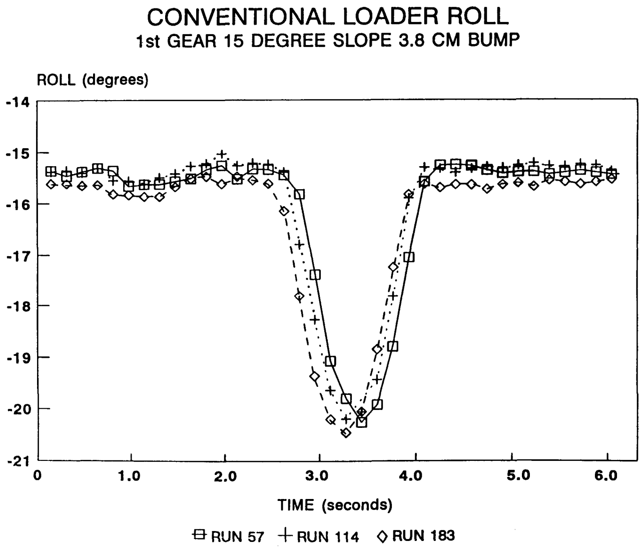

Figure 11–Roll angle measured on a 15° slope with a 3.8 cm sinusoidal bump and the model in first gear.

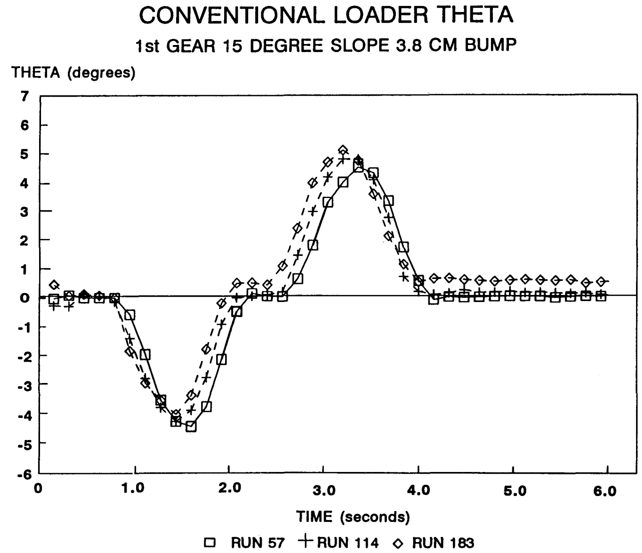

Figure 13–Front axle rotation measured on a 15° slope with a 3.8 cm sinusoidal bump and model in first gear.

and 13. Different tests appeared to give different initial front-axle rotational angles. This, however, was due to a small change in emitter location which occurred when failed emitters were replaced. Therefore, the difference between the initial THETA and the final THETA for each test was used to determine response to the obstacle. The maximum difference in THETA among the replications containing the same model inputs was 0.4°. More variation occurred at different times during the respective runs, which is due to models entering the digitizing area at a different frame and the emitters not firing at exactly the same locations on the test terrain.

At a slower model tractor velocity, a greater number of positions could be plotted as the loader systems traversed the test track and smoother plots could be made of tractor roll and front axle rotation.

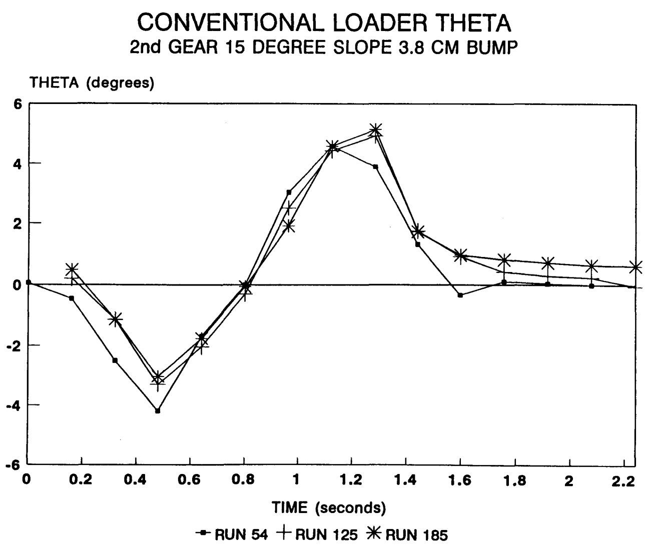

Figure 12–Front axle rotation measured on a 15° slope with a 3.8 cm sinusoidal bump and model in second gear.

Summary and Conclusions

The sonic digitizer was able to consistently determine the location of emitter in stationary tests. Also, the repeatability of the scale-model tests on the test terrain provides evidence that the data obtained from the experimental tests were reliable. The data showed that the sonic digitizer is an accurate method of obtaining the location and orientation of scale-models operating on test terrain. One shortcoming of the sonic digitizer was the time lapse between successive firing of emitters, during which the actual peak value of roll or front axle rotation may have occurred. However, taken as a whole, the scale model tractor and sonic digitizer system produced data faster than any previously used methods found in the literature. Statistical analysis has been difficult in this type of experiment up to the present time because time restricted the number of replications. Replications are faster with this system and the resulting larger number of replications provides better statistical analysis.

Recommendations

Increasing the speed of sonic digitizer firing sequence speed would allow more model position points to be obtained during an experimental test. This could be accomplished by speeding up the communication baud rate between the supporting computer and the digitizer. A finite amount of time will still be required between emitter firings in a firing sequence due to the nature of the system.

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