THE DYNAMIC FORCES AND MOMENTS REQUIRED IN HANDLING TREE-LENGTH LOGS

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The trend toward mechanized logging in recent years has resulted in the availability of a number of commercial harvesting machines, each with its own specific method of handling full trees and tree-length logs. Development of many of these machines has been on a trial and error basis, primarily due to lack of information on the forces required to handle the trees and logs. Consequently, machine manufacturers are interested in knowing the relative order of magnitude of the dynamic peak forces and moments required in handling full trees and tree-length logs. Not only could this dynamic handling data prevent costly failures of prototype equipment, but also it could prevent unnecessary overdesign.

The primary objective of this study was to determine the peak forces and moments required to handle tree-length logs of various weights. Both lifting and swinging handling modes were studied. Also, the effect of grab-point location was investigated.

EXPERIMENTAL PROCEDURE

The test involved moving a tree-length log with a commercially-made hydraulic loader through specific handling modes, while measuring and recording continuously the linear acceleration of the center of gravity of the log in three orthogonal directions and the angular accelerations of the log. The peak values of linear acceleration obtained from the recordings were then used to determine the peak handling forces and moments by a computer program.

Three preliminary steps in the procedure were determining (1) the weight of the log, (2) the center of gravity of the log, and (3) the mass moment of inertia of the log about a transverse axis through the center of gravity of the log. A cedar log 35.4 feet long and 17 inches in diameter at the butt end was used. The weight and center of gravity were determined by placing a transducer between the boom and a chain sling suspending the log[1]. The sling connections included a swivel and uniball joint to allow the log to hang freely. A point on the log vertically below the apex of the sling was marked as the center of gravity. Two log weights were used in the field tests – 505 and 1,188 pounds. The center of gravity was 13.3 feet from the butt end for both logs, because the heavier log was contrived by strapping weights at the center of gravity of the lighter log.

The mass moment of inertia of the 505-pound log was determined experimentally by using the principle of the pendulum. The log was suspended horizonally by nylon rope on a pulley. It was oscillated through a small angle ($\pm 5°$), and the period of oscillation was measured accurately by using a photoelectric cell, flashlight, mirror,

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[1] *Steinhilb, H. M. and John R. Erickson. Weights and centers of gravity for quaking aspen trees and boles. USDA Forest Serv. Res. Note NC-91, 4 p., illus. N. Cent. Forest Exp. Sta., St. Paul, Minn.*

and a Sanborn recorder with a time marker (fig. 1).[2] Knowing the weight of a log (pounds), the distance from the center of gravity of the log to the axis of oscillation (inches), and the period of oscillation (seconds), the moment of inertia about a transverse axis through the center of gravity of the log was calculated using the following equation (refer to Appendix A for the derivation of the equation):

$$\bar{I} = (T^2Wh/4\Pi^2) - (Wh^2/g)$$

The moment of inertia of the 505-pound log was 1,449 pounds-feet-seconds^2.

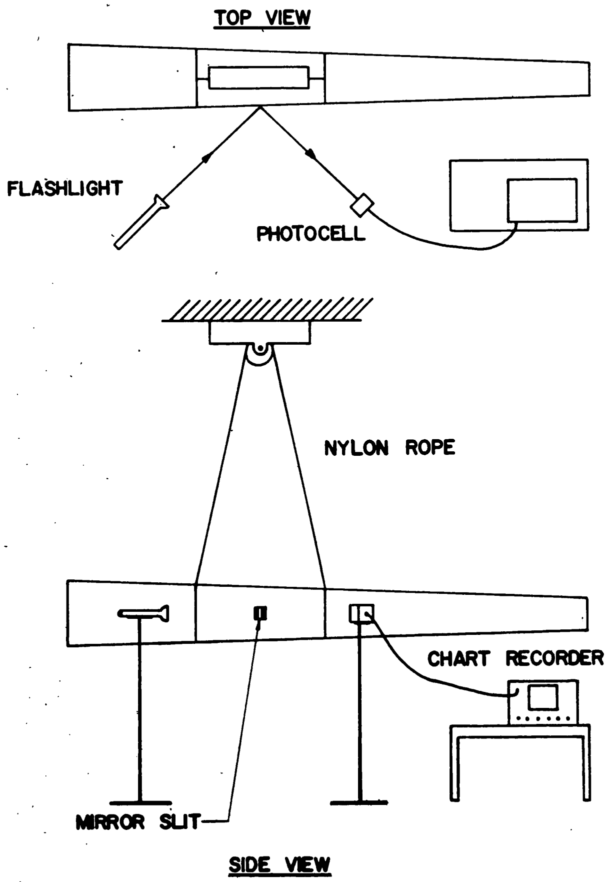

Figure 1.—Experimental set-up used in determining the moment of inertia of the log.

[2] *The names of manufacturers and models of equipment are mentioned in this paper for identification only, and no endorsement by the USDA Forest Service is implied.*

Because the heavier log was contrived by strapping weights at the center of gravity of the 505-pound log, the moment of inertia of an actual 1,188-pound log could not be determined. In a separate field study, the results of which have not yet been published, the moments of inertia of 13 red pine and 12 aspen trees and tree-length logs were determined by an experimental procedure similar to that mentioned above. The results showed the average moment of inertia of a 1,188-pound red pine log to be 2.95 times that of a 505-pound log, while the moment of inertia of a 1,188-pound aspen log was 4.05 times greater. Therefore, to obtain approximate dynamic moment values, it was assumed that the moment of inertia of the 1,188-pound log is three times that of the 505-pound log, or 4,347 pounds-feet-seconds^2.

Five Statham Model A5 linear accelerometers were used in this study. Three accelerometers were mounted in three orthogonal directions on a steel collar at the center of gravity of the log (fig. 2). These accelerometers gave the translational acceleration of the log in the vertical lateral, and longitudinal directions. Also, two accelerometers were mounted in the vertical and lateral directions on another collar 10 feet from the center of gravity toward the small end of the log. The difference between the two vertical acceleration readings divided by the distance between them (10 feet) was equal to the angular acceleration of the log in the vertical plane.

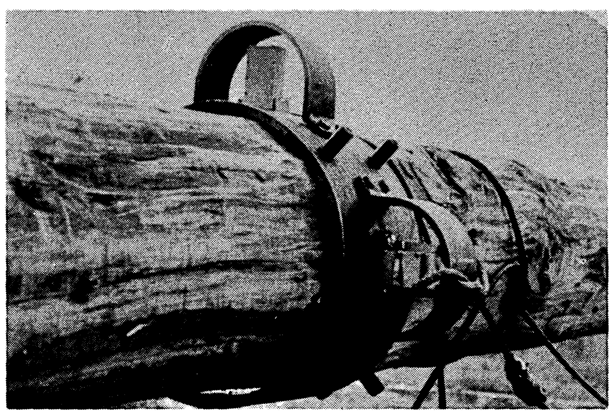

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Figure 2.—The accelerometers mounted on a steel collar at the center of gravity of the log.

Likewise, the two lateral acceleration readings were used to determine the angular acceleration in the horizontal plane. The accelerometers were connected by low-noise extension cables through a CEC Type 1-118 carrier amplifier to a portable CEC Type 5-124 recording oscillograph. Fluid-damped galvanometers (CEC Type 7-316) with a frequency range from zero to 1,200 c.p.s. were used in the oscillograph, along with five static reference trace galvanometers (CEC Type 7-002). The acceleration-time curves were recorded as permanent records for all of the test runs.

A Model HOBC Prentice truck-mounted hydraulic loader was equipped with a pull-type jib and a heeling boom for handling tree-length logs. The loader was operated at maximum speed for all test runs. For the swinging mode this meant approximate 2.5 r.p.m. Pointed metal studs were welded on the grapple jaws to prevent the log from rotating relative to the grapple. Before each test run, the truck stabilizers were checked to make sure they were grounded.

A level was used to position the accelerometer mounting collars on the log, thus assuring that the respective mounting surfaces on the two collars were parallel. The accelerometers and their protective covers were then mounted on the collars and the cables connected to the amplifiers. The accelerometers were balanced and zeroed with the log in the horizontal position, which was checked with a level.

ANALYSIS OF DATA

The equations of motion were derived by using free-body diagrams of the log. (Refer to Appendix B for the derivations and legend of symbols.) The equations derived for the lifting handling mode (translation plus rotation in the vertical plane) are as follows:

$$F_z = m\ddot{z} + mg\cos\theta$$

$$F_y = m\ddot{y} + mg\sin\theta$$

$$F_R^2 = F_z^2 + F_y^2$$

$$M_x = \bar{I}\ddot{\theta}_x + F_z d$$

The equations of motion derived for the swinging handling mode in addition to the equations above are as follows:

$$F_x = m\ddot{x}$$

$$F_R^2 = F_x^2 + F_y^2 + F_z^2$$

$$M_z = \bar{I}\ddot{\theta}_z - F_x d$$

$$M_R^2 = M_x^2 + M_z^2$$

A computer program was written for a digital computer to perform the calculations in the above equations of motion. The input data consisted of the weight and moment of inertia of the logs, the distance from the log center of gravity to the grab point, and the acceleration readings from the five accelerometers.

A typical recording of a vertical acceleration of the log is shown in figure 3. Free-body diagrams of the log at two specific instants within the same lifting cycle are compared: when the log was horizontal ($\theta = 0°$) but just after the log was accelerated vertically, and when the log was at a 30° angle to horizontal ($\theta = 30°$) and moving at constant velocity. The peak accelerations occur the instant the log is moved. The data from the oscillograms plus the other input data were recorded on prepared cards for the computer program.

The effect of the location of the grab point was also studied by repeating the handling modes with the 505-pound log after the grab point was shifted 4 feet toward the log center of gravity. The computer output gave the component and resultant handling forces and moments in tabular form for each handling mode, log weight, and grab-point location.

RESULTS

The major objective of this study was to determine the dynamic forces and moments required at the grab point on the log for the lifting and swinging handling modes. The forces and moments required for the lifting mode are greater than those required for the swinging mode (tables 1, 2, 3 and 4). The results given in the tables summarize the tabular computer output for each handling mode and log weight.

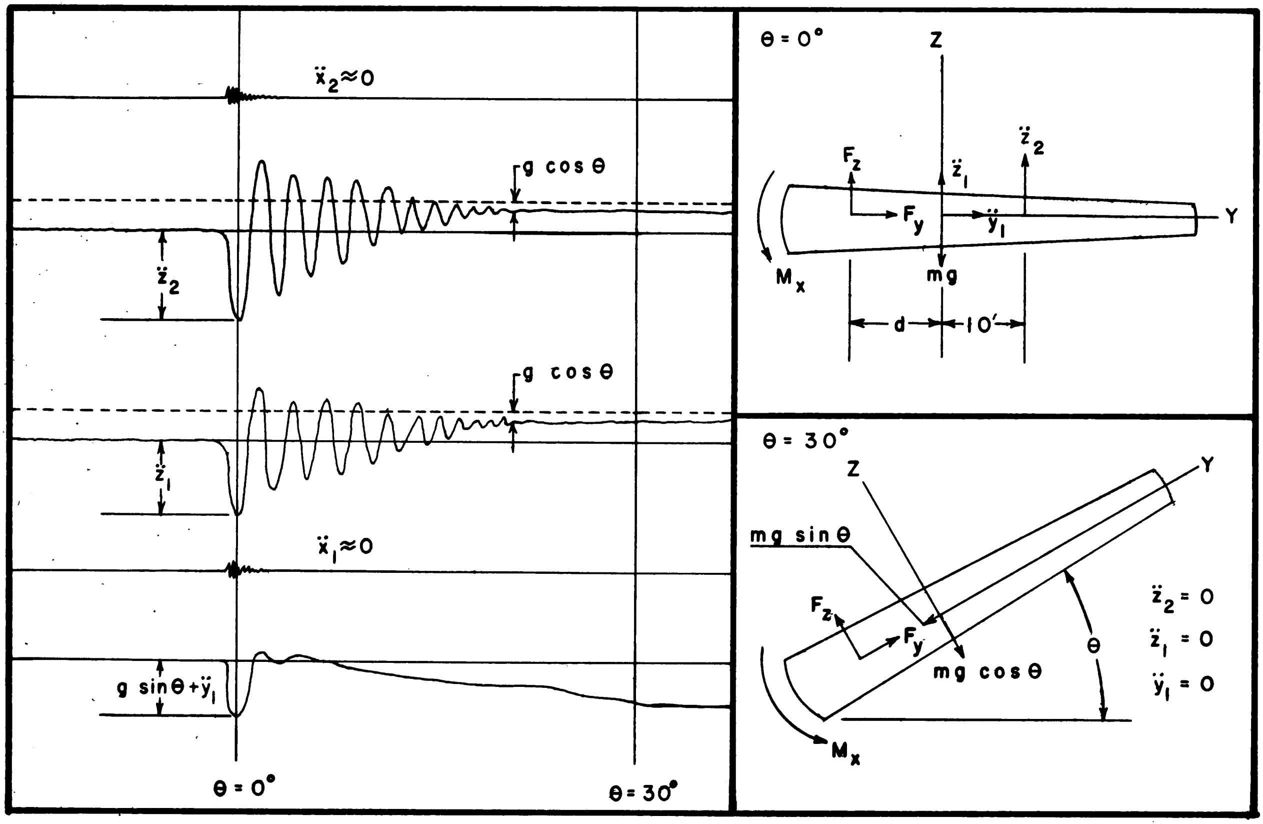

Figure 3.—A typical recording of the vertical acceleration of the log plus free-body diagrams of the log at two specific instants, namely when $\theta = 0°$ and $30°$.

The computer program calculated the maximum component forces and moments for each test run. The average of these values is the mean value given in the tables. The 95-percent upper confidence limit (U.C.L.) on the mean can be explained as follows: If a 505-pound log was lifted up and down a number of times (in this case 15 times) and the maximum vertical force noted each time, it can be concluded with 95-percent confidence that the average maximum vertical force would be no greater than 1,563 pounds. In the field tests with the 505-pound log, vertical forces as high as 2,358 pounds were encountered. The total or resultant force or moment can be calculated by adding vectorally the component forces or moments. The dynamic moments in table 4 are approximate values because the moment of inertia of the 1,188-pound log was assumed to be three times that of the 505-pound log.

Another method of expressing the dynamic handling requirements is by the dynamic force and moment factors. These dynamic factors are defined as the ratios of the maximum dynamic force and moment to the required static force and moment. For a 505-pound log, the mean dynamic force factor is 2.64 and the mean dynamic moment factor is 2.90 (table 5). The values in table 5 were obtained by comparing the required static values (vertical force and moment about x-axis) with the dynamic values taken from tables 1, 2, 3 and 4. These dynamic factors show that it is possible to encounter dynamic forces and moments three to five times greater than the corresponding static values.

Because the accelerations of the logs were recorded continuously throughout the handling cycle, the forces and moments were determined

Table 1.—Dynamic forces required to handle a 505-pound log

Component force	Handling mode	Dynamic force (pounds)			
		Mean value	Standard deviation	95 percent U.C.L.[1/] on mean	Maximum experimental value
Vertical	Lifting	1,332	417	1,563	2,358
	Swinging	730	158	875	1,010
Longitudinal	Lifting	349	70	388	480
	Swinging	281	109	383	414
Lateral	Swinging	337	116	444	505

1/ U.C.L. = Upper confidence limit

Table 2.—Dynamic moments required to handle a 505-pound log

Component moment	Handling mode	Dynamic moment (foot-pounds)			
		Mean value	Standard deviation	95 percent U.C.L. on mean	Maximum experimental value
Moment about x-axis	Lifting	15,059	4,054	17,304	24,664
	Swinging	8,304	1,610	9,793	10,403
Moment about z-axis	Swinging	5,002	1,648	6,527	7,534

Table 3.—Dynamic forces required to handle a 1,188-pound log

Component force	Handling mode	Dynamic force (pounds)			
		Mean value	Standard deviation	95 percent U.C.L. on mean	Maximum experimental value
Vertical	Lifting	3,135	861	3,682	4,752
	Swinging	1,485	425	2.161	1,984
Longitudinal	Lifting	1,551	742	2,023	3,374
	Swinging	329	110	601	392
Lateral	Swinging	469	97	624	594

Table 4.—Dynamic moments required to handle a 1,188-pound log

Component moment	Handling mode	Dynamic moment (foot-pounds)			
		Mean value	Standard deviation	95 percent U.C.L. on mean	Maximum experimental value
Moment about x-axis	Lifting	57,268	21,215	70,747	93,846
	Swinging	14,841	3,706	20,738	18,618
Moment about z-axis	Swinging	19,222	1,140	21,036	20,276

Table 5.—Dynamic force and moment factors determined for the vertical force (F_z) and the moment about the x-axis (M_x) for the lifting handling mode

Log weight (pounds)	Dynamic factors					
	Mean value		95 percent U.C.L. on mean		Maximum experimental value	
	Force	Moment	Force	Moment	Force	Moment
505	2.64	2.90	3.10	3.33	4.67	4.74
1,188	2.64	4.68	3.10	5.78	4.00	7.67

at those instants when acceleration spikes occurred. For the lifting handling mode, the acceleration spikes occurred at the following instants: (1) upward acceleration of the log at the beginning of the cycle (log horizontal); (2) deceleration at the top of the cycle (log at about 60°); (3) downward acceleration at the top of the cycle; and (4) deceleration of the log at the end of the cycle (log horizontal). As would be expected, the dynamic forces and moments varied considerably during this handling cycle. The maximum values occurred either during the acceleration at the beginning, or the deceleration at the end of the cycle.

The effect of the location of the grab point on the dynamic moments was investigated only with the 505-pound log. The lifting and swinging test runs were repeated after the grab point was moved 40 percent closer to the center of gravity (from 10.3 to 6.3 feet). The average decreases in the dynamic moments for the lifting and swinging handling modes are as follows: 21 percent decrease in M_x for the lifting mode, and 20 percent decrease in M_x and 46 percent decrease in M_z for the swinging mode (fig. 4).

CONCLUSIONS

Instead of designing a tree or log harvesting device statically, realistic dynamic loading requirements have been determined on which a design should be based. This study has shown that dynamic forces and moments four times as great as those required statically can occur in the field. A designer of timber harvesting equipment must consider this information in his stress analysis work in order to prevent fatigue and shock-load failures, and also to design a machine with the highest possible strength-to-weight ratio.

Though the tests were made with a specific hydraulic loader, and certain simplifying assumptions were made, the resulting dynamic loading data can be considered typical for original design purposes. Particularly important are the dynamic load factors that indicate much error can be made if the design is based on static analysis. In conventional static design a safety factor would normally be applied to cover the "unknowns"; however, with the information contained herein, the designer is better equipped to specify a more optimum design with the first prototype.

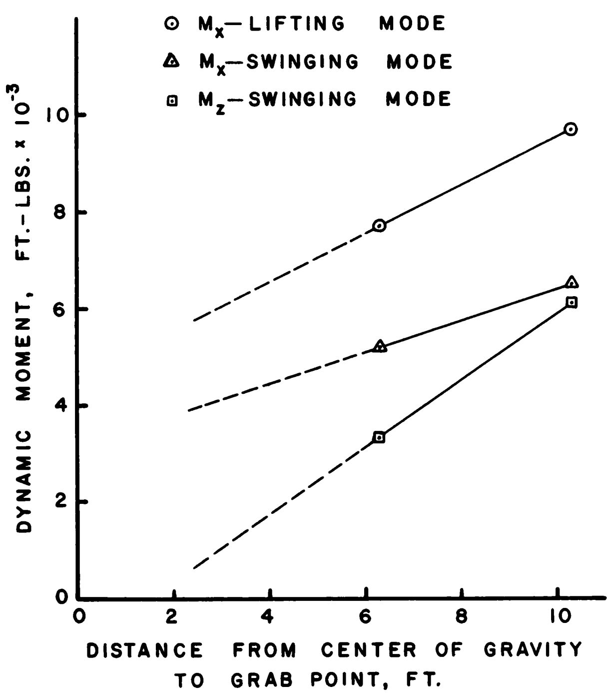

Figure 4.—The effect that grab point location has on the dynamic moments required in handling a 505-pound log.

APPENDIX A

The moment of inertia of a compound pendulum about its axis of oscillation (I′) is given by the following equation:[3]

$$I' = T^2Wh/4\Pi^2$$

where
- T = period of oscillation (seconds)
- W = weight of pendulum (pounds)
- h = distance from the center of gravity of the pendulum to the axis of oscillation (feet).

Therefore, by using the parallel-axis theorem, the moment of inertia of a pendulum about its center of gravity ($\bar{I}$) is given by the following equation:

$$\bar{I} = I' - Wh^2/g = (T^2Wh/4\Pi^2) - (Wh^2/g),$$

where
g = acceleration due to gravity (feet/second^2).

The effect of the amplitude of the oscillations and the damping at the point of suspension are assumed negligible.

APPENDIX B
Legend of Symbols

$\bar{a}$ = Resultant acceleration (ft./sec.^{2})

g = Acceleration due to gravity (32.2 ft./sec.^{2})

d = Distance between the grab point and the center of gravity (feet)

m = Mass of the log (lbs.-sec.^{2}/ft.)

$\ddot{x}_1$ = Acceleration of the center of gravity of the log along the x-axis (ft./sec.^{2})

$\ddot{y}_1$ = Acceleration of the center of gravity of the log along the y-axis (ft./sec.^{2})

$\ddot{z}_1$ = Acceleration of the center of gravity of the log along the z-axis (ft./sec.^{2})

$\ddot{x}_2$ = Acceleration in the x-direction of a point on the log 10 feet toward the small end from the center of gravity (ft./sec.^{2})

$\ddot{z}_2$ = Acceleration in the z-direction of a point on the log 10 feet toward the small end from the center of gravity (ft./sec.^{2})

[3] *E. Hausmann and E. P. Slack. Physics. (Ed. 2) New York, D. Van Nostrand Co., p. 159, 1939.*

θ_x = Angle of the log in the vertical plane measure from the horizontal position (radians)

$\ddot{\theta}_x = \dfrac{\ddot{z}_2 - \ddot{z}_1}{10}$ = Angular acceleration of the log about the x-axis (radians/sec.^{2})

$\ddot{\theta}_z = \dfrac{\ddot{x}_2 - \ddot{x}_1}{10}$ = Angular acceleration of the log about the z-axis (radians/sec.^{2})

C = Center of gravity of the log

P = Grab point of the log

$\bar{I}$ = Mass moment of inertia of the log about the x-axis or z-axis (lbs.-ft.-sec.^{2})

F_x = Force in the x-direction applied at the grab point (lbs.)

F_y = Force in the y-direction applied at the grab point (lbs.)

F_z = Force in the z-direction applied at the grab point (lbs.)

F_R = Resultant force applied at the grab point (lbs.)

M_x = Moment about the x-axis applied at the grab point (ft.-lbs.)

M_z = Moment about the z-axis applied at the grab point (ft.-lbs.)

M_R = Resultant moment applied at the grab point (ft.-lbs.)

Derivation of the Equations of Motion

The equations of motion for the lifting handling mode were derived by using a free-body diagram of the log in the vertical plane (fig. 5). The coordinate system is a right-handed rectangular XYZ system fixed at the center of gravity of the log with the Y-axis in the longitudinal direction of the log. Therefore, the coordinate system rotated with the log. F_y and F_z are the instantaneous forces required at the grab point (P) to accelerate the log in the Y-Z plane, with $\ddot{y}$ and $\ddot{z}$ being the respective accelerations at the center of gravity (C). M_x is the instantaneous moment required at the grab point in addition to the moment $F_z d$ to rotate the log about the center of gravity at an angular acceleration equal to $\ddot{\theta}_x$. The moment of inertia of the log about its center of gravity is denoted by $\bar{I}$, and the weight of the log is equal to mg. One assumption that is made in writing the equations of

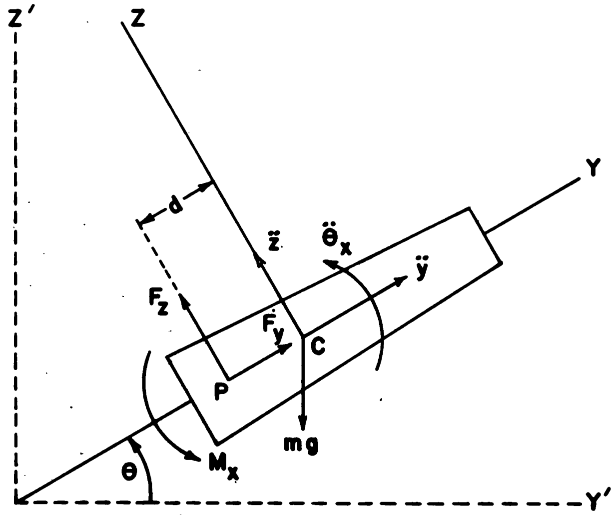

Figure 5.—Free-body diagram of a log being translated and rotated in the vertical plane.

motion is that the theoretical grab point is one-half the distance between the grapple and the heel boom. Therefore, the external forces and moments are assumed to be applied at one point.

The derivation of the equations of motion for the lifting handling mode (translation plus rotation of the log in the vertical plane) is as follows:

From Newton's Second Law: $F_R = m\bar{a}$,

therefore:

$$\Sigma F_z = m\ddot{z} = F_z - mg\cos\Theta$$

$$F_z = m\ddot{z} + mg\cos\Theta$$

$$\Sigma F_y = m\ddot{y} = F_y - mg\sin\Theta$$

$$F_y = m\ddot{y} + mg\sin\Theta$$

$$F_R^{\,2} = F_z^{\,2} + F_y^{\,2}$$

$$\Sigma\bar{M} = \bar{I}\ddot{\Theta}_x = M_x - F_z d$$

$$M_x = \bar{I}\ddot{\Theta}_x + F_z d\,.$$

A free-body diagram of the log in the horizontal plane was used to derive the equations of motion necessary for the swinging handling mode in addition to the equations above (fig. 6).

F_x and F_y are the instantaneous forces required at the grab point to accelerate the log in the X-Y plane, with $\ddot{x}$ and $\ddot{y}$ being the respective accelerations at the center of gravity. M_z is the instantaneous moment required at the grab point in addition to the moment $F_x d$ to rotate the log about the center of gravity at an angular acceleration equal to $\ddot{\theta}_z$.

The derivation of the equations of motion for the swinging handling mode (translation plus rotation of the log in the horizontal plane) as as follows:

$$\Sigma F_x = m\ddot{x} = F_x$$

$$\Sigma F_y = m\ddot{y} = F_y$$

$$\Sigma\bar{M} = \bar{I}\ddot{\Theta}_z = M_z + F_x d$$

$$M_z = \bar{I}\ddot{\Theta}_z - F_x d\,.$$

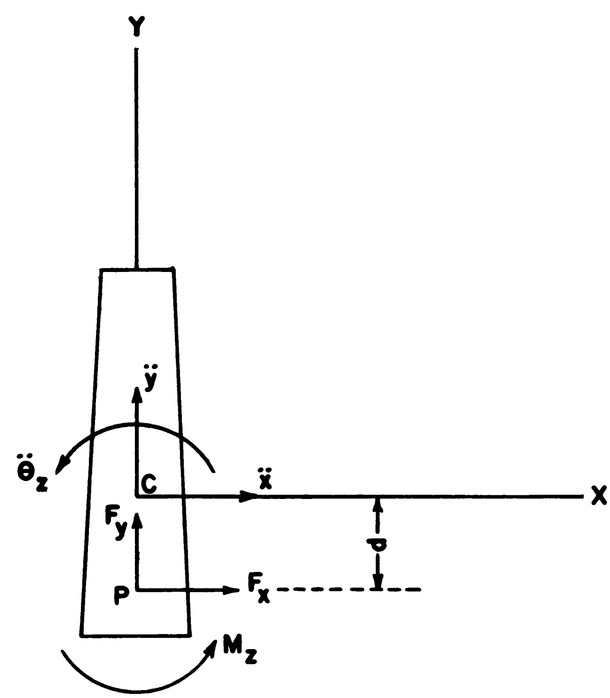

Figure 6.—Free-body diagram of a log being translated and rotated in the horizontal plane.