Foliage Shaker for Citrus Harvesting—Part I: Design and Kinematics of Shaker Drive System

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THE Valencia orange variety accounts for 46 percent of Florida's annual production of 149 million boxes of oranges (1972-73 season) (USDA 1973). The Valencia variety requires about 14 months to mature, and therefore, the young (immature) fruit for the following year's crop is on the tree at harvest time. To successfully harvest Valencia oranges by shaking, a shaking mode is required that will selectively remove mature fruit without removing an excessive number of the young fruit.

Foliage shakers for selective removal of Valencia oranges have been under development for several years (Hedden and Coppock 1971, Sumner 1972). The principal advantage of the foliage shaker harvest method, as compared to other shaker methods, is that the shaking motion is applied near the major fruit bearing zone of the tree, therefore better motion control of the fruit results.

Questions concerning the removal and selectivity advantages of a quick-return shaking mode as compared to a sinusoidal shaking mode led engineers at the Agricultural Research and Education Center at Lake Alfred to design and construct a shaker drive system which could incorporate both actions into one unit for testing. A four-bar, crank-rocker linkage was designed to produce both shaking modes in a vertical direction. The quick-return mode was characterized by a considerably higher acceleration at the bottom of the shaking cycle than at the top. It was theorized that the "snap" action at the bottom of the shaking cycle would maximize mature fruit removal and minimize young fruit removal on a weight-difference basis.

Fig. 1 shows the shaker drive system attached to the prototype foliage shaker

FIG. 1 Prototype foliage shaker.

furnished by ITF Corporation*, Longwood, Florida, for this study. The shaker mast of the machine (approximately 850 lb) had eight sets of tines, 8 ft long, that clamped the outer foliage of the tree. To reduce the energy transmitted to the transport unit, the shaker mast was connected by a linkage system to a counterweight which moved in the opposite direction from that of the shaker mast assembly.

The objective of this study was (a) to design a shaker drive system that could be incorporated in a foliage shaker and that would produce both a sinusoidal and a quick-return shaking mode and (b) to evaluate the kinematics of the system. Field trials and fruit removal effectiveness of the system will be discussed in Part II (Whitney et al. 1974) of this series.

SHAKER DRIVE SYSTEM

A computer program for the four-bar, crank-rocker mechanism (Sielaff 1966) was modified and used to determine displacement, velocity, and acceleration of the shaker attachment point and to obtain the desired shaking mode for various lengths of the four links. Schematics of the near-sinusoidal and the quick-return drive linkage arrangements for the design are shown in Figs. 2 and 3. Links R2, R3, and R4, were the crank arm, connecting rod, and os-
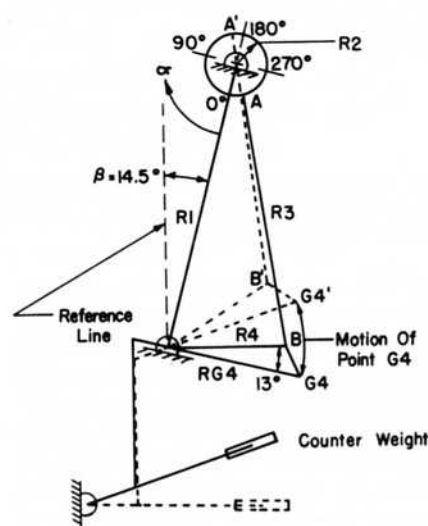
Link	Length, in.	Weight lb.	Distance, pivot to mass center, in.
R1	32.87	- -	- -
R2	3.5	49	1.6
R3	28.75	8	12.0
R4/RG4	13.5/15.5	1450*	15.5

*Includes counter-weight

FIG. 2 Schematic of near-sinusoidal mode of four-bar linkage.

cillating arm, respectively. The shaker mast was attached to Link R4 at point G4 having a radius RG4 (13 deg from radius R4). Link R1 was stationary. The design of the shaker drive was such that the two shaking modes were obtained by changing the position of the driving crank R2 and the lengths of R1, R3,
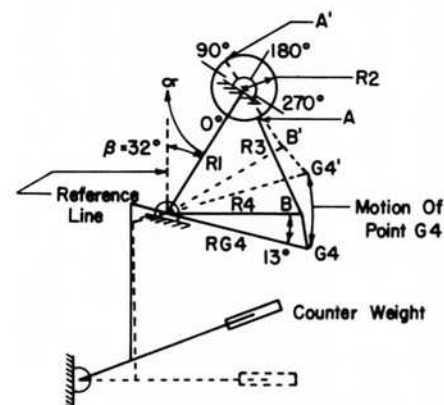
Link	Length, in.	Weight lb.	Distance, pivot to mass center, in.
R1	15.5	- -	- -
R2	3.5	49	1.6
R3	11.0	4.5	4.5
R4/RG4	14.5/15.5	1450*	15.5

*Includes counter-weight
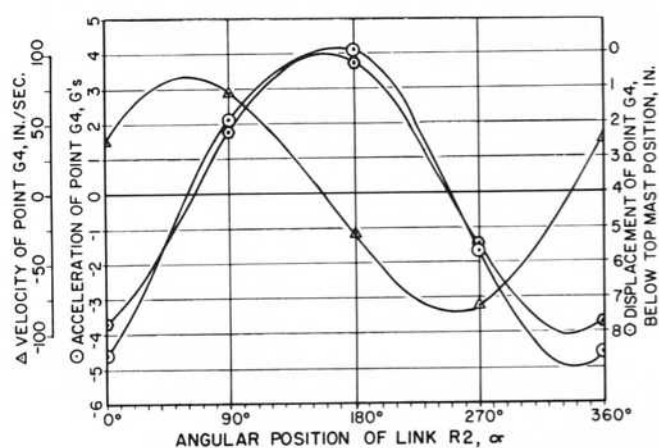
FIG. 3 Schematic of quick-return mode of four-bar linkage.

FIG. 4 Theoretical displacement, velocity, and acceleration of point G4, parallel to reference line in Fig. 2. Near-sinsoidal mode, angular velocity of Link R2 = 200 rpm.
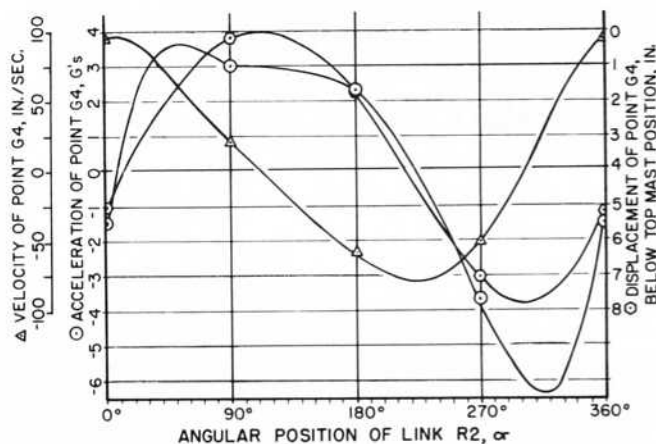

FIG. 5 Theoretical displacement, velocity, and acceleration of point G4, parallel to reference line in Fig. 3. Quick-return mode, angular velocity of Link R2 = 200 rpm.

and R4 while R2 remained unchanged. This arrangement minimized the time required to change shaking modes. The shaking mode in Fig. 2 (near-sinusoidal mode) produced a motion approximately sinusoidal at point G4 (shaker mast attachment). In Fig. 3 (quick-return mode) the shorter Link R3 produced a motion considerably different from sinusoidal at point G4. The theoretical motions for point G4 for the two shaking modes are shown in Figs. 4 and 5 for a constant angular velocity of 200 rpm for Link R2. The linkage arrangement in Figs. 2 and 3 will be referred to as near-sinusoidal and quick-return shaking modes, respectively, throughout

this report.

Link R2 of the four-bar linkage was chain-driven by a free-wheeling hydraulic motor that rotated at 2.2 times the speed of Link R2. A 114-lb flywheel (mass moment of inertia of 10.5 lb-sec²in.) was mounted on the motor shaft to minimize variations in motor shaft speed.

SHAKER KINEMATICS

The shaker kinematics was evaluated at 160 and 200 rpm to determine how the actual motion compared to the theoretical. The characteristics were similar for both speeds; therefore, only the 200 rpm results are reported.

A piezoelectric accelerometer was mounted on the shaker mast to check the actual acceleration while the shaker was operating. The acceleration image on the oscilloscope was photographed, and the results are shown in Figs. 6 and 7 for both shaker modes at 200 rpm. The acceleration curves were not smooth near the zero and peak 'g' acceleration levels. These results indicated that the angular velocity of Link R2 was not constant in actual operation, although a constant velocity was desired and was assumed in the theoretical analysis. High-speed movies of both shaker modes in operation showed that the angular velocity of Link R2 varied considerably, as shown in Figs. 8 and 9. Simultaneous movies of the oscilloscope display of acceleration and the angular position of Link R2 in the quick-return mode showed that the non-smooth curve near the zero 'g' level coincided with the decrease in the angular velocity of Link R2 when a was in the vicinity of zero. In addition, the relatively flat positive acceleration peak for the quick-return mode in Fig. 5 (in the vicinity of a = 120 deg) was not duplicated in the actual measurement (Fig.

7), probably due to a significant speed increase in this vicinity of a (Fig. 9). A similar discrepancy occurred between the near-sinusoidal mode in Fig. 4 (theoretical) and that in Fig. 6 (actual). These discrepancies in angular velocity can be explained in part by the change in driving torque on Link R2 (Figs. 8 and 9) in that an increase in the required driving torque decreased the angular velocity of Link R2, and vice-versa. Note that the magnitude of torque variations was less with the near-sinusoidal mode than with the quick-return mode.
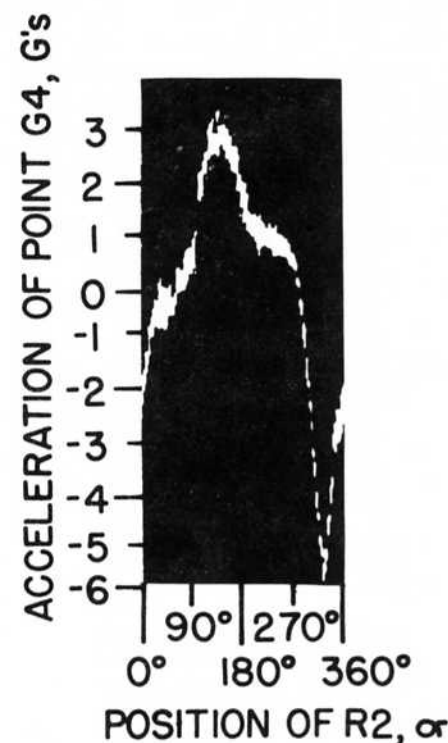
Assuming that the motor provides a

FIG. 6 Oscilloscope display of acceleration, near-sinusoidal mode. Angular velocity of Link R2 = 200 rpm.
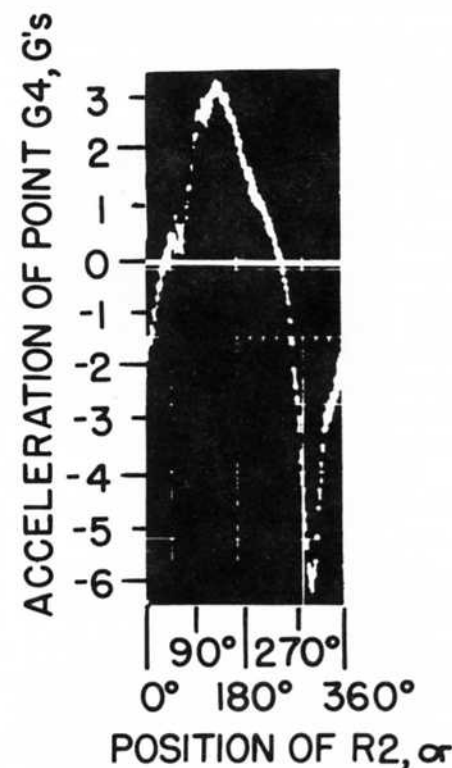

FIG. 7 Oscilloscope display of acceleration quick-return mode. Angular velocity of Link R2 = 200 rpm.
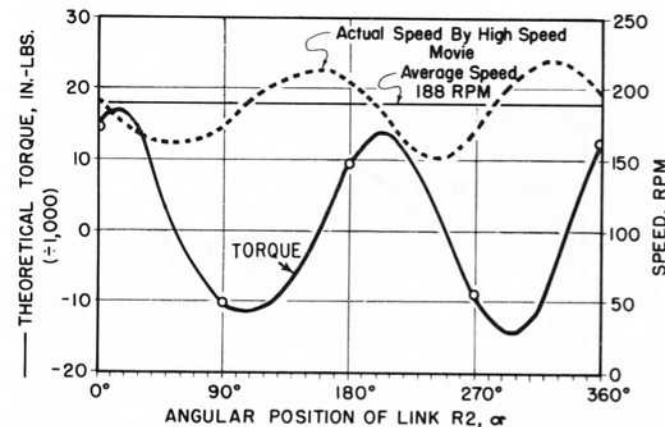
FIG. 8 Theoretical driving torque on Link R2 for near-sinusoidal mode at a constant angular velocity of Link R2 of 200 rpm. Actual angular velocity of Link R2 is plotted as determined from high-speed movies, with an overall average angular velocity of 188 rpm.
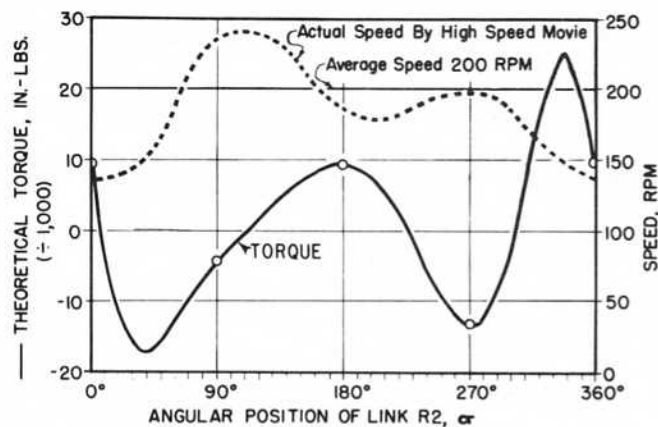

FIG. 9 Theoretical driving torque on Link R2 for quick-return mode plotted at a constant angular velocity of Link R2 of 200 rpm. Actual angular velocity of Link R2 is plotted as determined from high-speed movies, with an overall average angular velocity of 200 rpm.

constant torque input, speed reductions are inversely proportional to the flywheel's mass moment of inertia. Speed reductions of Link R2 in the high torque periods were reduced by increasing the mass moment of inertia of the flywheel by adding 90 lb or 10 lb-sec^2-in mass moment of inertia. Overspeed in the areas of negative torque (Figs. 8 and 9) was reduced by eliminating the free-wheeling feature of the drive motor through the addition of a restrictor valve to maintain a back pressure of 200 psi on the drive motor. A comparison between oscilloscope traces of the acceleration before and after

modification (Figs. 10 and 11) of the shaker drive showed a reduction of 10 to 20 percent in the peak-to-peak acceleration magnitudes of the traces made after modification and an increase in the dwell time at the bottom of the stroke. The curve of peak acceleration at the bottom of the stroke was smoother; also, the rate of acceleration change was slower. The long dwell time at the bottom of the stroke after these additions was noticeable in that it allowed the shaker drive and mast system to operate smoother and quieter and reduced the shock loading at the bottom of the stroke.

High-speed movies of the system in operation indicated a reduction in overspeed and underspeed of the drive system as a result of the drive modification. Figs. 12 and 13 show the theoretical driving torque and actual driving speed as a function of the crank position a. As observed, overspeed and underspeed peaks follow negative and positive driving torque peaks, respectively. Table 1 shows the effects of the flywheel-restrictor valve addition on the driving speed changes.

Speed fluctuations were observed while the shaker tines were attached to and shaking a citrus tree to remove the fruit. Results are shown in Fig. 12. The "in grove" underspeed fluctuations (17 percent) were greater than "in shop" underspeed fluctuations (8 percent), probably due to the increase in positive driving torque associated with shaking the limbs. Fig. 14 shows the acceleration trace of the shaker mast when the tines were clamped to a citrus tree. The trace was similar to that in Fig. 10 ("in shop"), except that the peaks were sharper and the trace was somewhat rougher.

An accelerometer attached to a

shaker clamping tine ("in shop", no load), 56 in. away from the tine pivot point on main mast, gave the trace in Fig. 15. The peak-to-peak acceleration on the tine was considerably higher and the trace was rougher than when the accelerometer was attached to the shaker mast (Fig. 10). The trace indicates a springing action and points out a sizable difference between the motion produced by the shaker drive and that which might be transferred to the limb. This is a major problem in foliage shaker design.
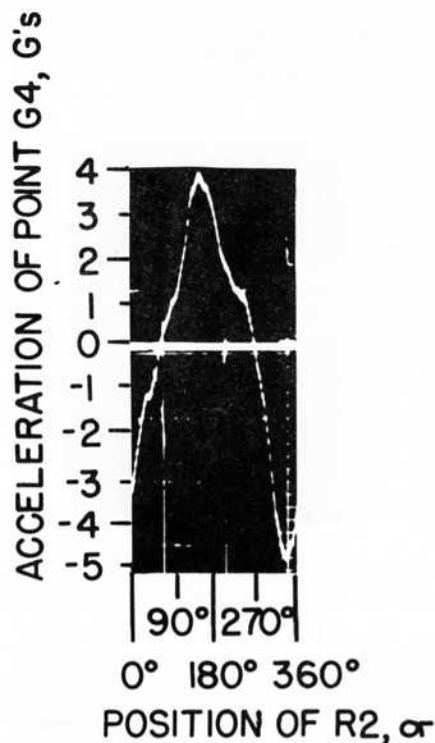

FIG. 10 Oscilloscope display of acceleration, near-sinusoidal mode, flywheel-restrictor valve added. Angular velocity of Link R2 was 218 rpm.
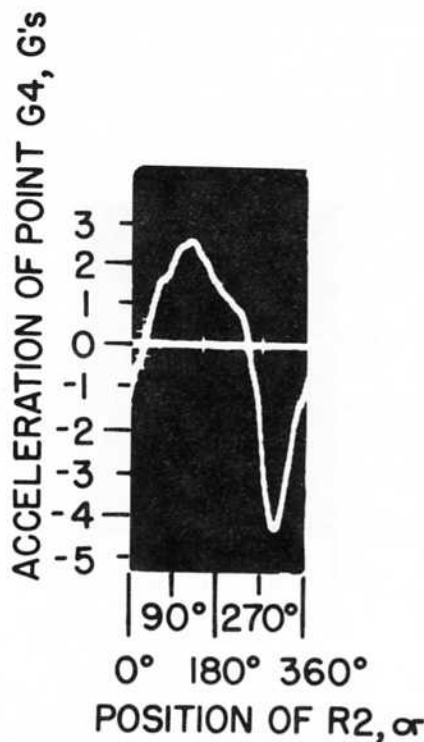

FIG. 11 Oscilloscope display of acceleration, quick-return mode, flywheel-restrictor valve added. Angular velocity of Link R2 was 203 rpm.
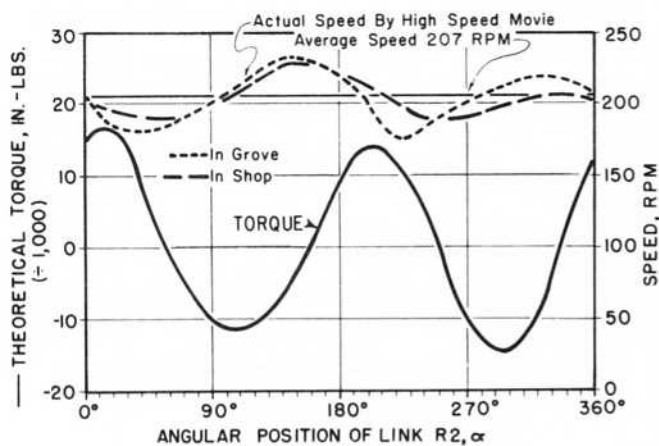
FIG. 12 Theoretical driving torque on Link R2 for near-sinusoidal mode (flywheel-restrictor added) at a constant angular velocity of Link R2 of 200 rpm. Actual angular velocity of Link R2 is plotted as determined from high-speed movies "in shop" and "in grove", with an overall average angular velocity of 207 rpm.

FIG. 13 Theoretical driving torque on Link R2 for quick-return mode (flywheel-restrictor valve added) is plotted at a constant angular velocity of Link R2 of 200 rpm. Actual angular velocity of Link R2 is plotted as determined from high-speed movies "in shop", with an overall average angular velocity of 207 rpm.

TABLE 1. EFFECT OF FLYWHEEL-RESTRICTOR VALVE ADDITION ON DRIVING SPEED FLUCTUATIONS

| | Max. change in driving speed as percentage of average speed* | | | |
| | Near-sinusoidal | | Quick-return | |
Condition	Overspeed	Underspeed	Overspeed	Underspeed
Before addition	17	21	20	30
After addition	12	8	4	17

* By high-speed movie analysis

SUMMARY

A foliage shaker drive system was designed for shaking citrus trees and its kinematics were evaluated at two shaking modes. A computer program was used to determine the arrangements of a four-bar crank-rocker mechanism that would provide the quick-return and near-sinusoidal shaking modes. Theoretical acceleration curves were compared with those actually obtained from oscilloscope traces.

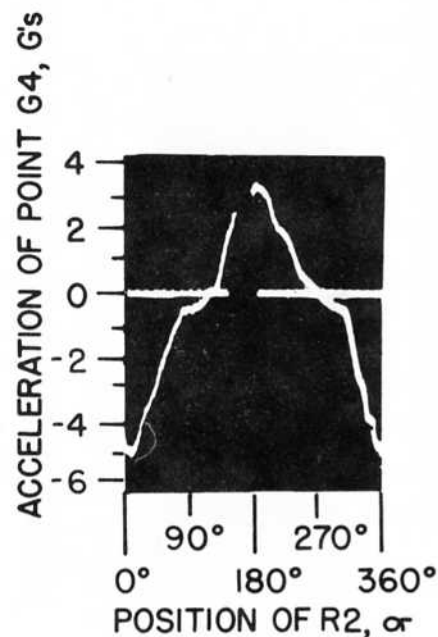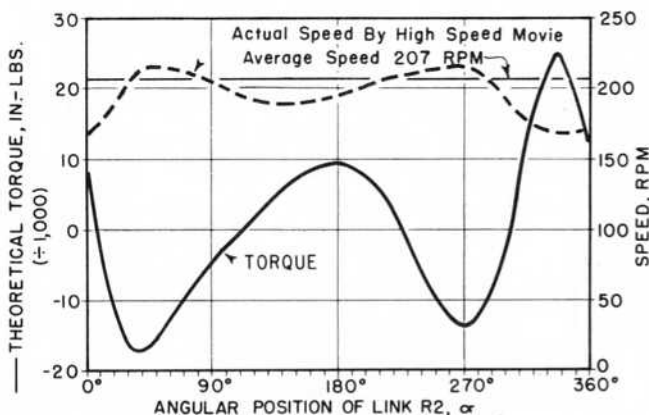During initial testings measured 'g' forces were approximately the same for both shaking modes because the underspeed of the quick-return mode was greater than that of the near-sinusoidal mode near the bottom of the shaking cycle. These driving link speed fluctuations associated with varying torque requirements were determined by high speed movie analysis and explained the discrepancies between theoretical and actual accelerations. Underspeed occurred at points of peak acceleration and the magnitude of peak-to-peak acceleration was 20 to 30 percent less than the theoretical.

Modification of the shaker drive, by increasing the flywheel mass moment of inertia and adding a drive motor-restrictor valve, reduced the driving speed fluctuations and the actual motion became more nearly that of the theoretical design. This modified design was further tested and considered satisfactory for use on the foliage shaker field trials described in Part II of this series.

References

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2 Sielaff, Ulrich. 1966. Dynamic analysis of a crank-rocker mechanism. Master of Science report, Department of Mechanical Engineering, Kansas State University, Manhattan, Kansas.
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4 USDA. 1973. The fruit situation. U. S. Department of Agriculture, Economic Research Service, TFS-186, February.
5 Whitney, J. D., H. R. Sumner and S. L. Hedden. 1974. Foliage shaker for citrus harvesting. Part II-Harvesting trials. TRANSACTIONS of the ASAE (this issue).

FIG. 14 Oscilloscope display of acceleration, near-sinusoidal mode, with shaker in the tree. Angular velocity of Link R2 was 210 rpm.
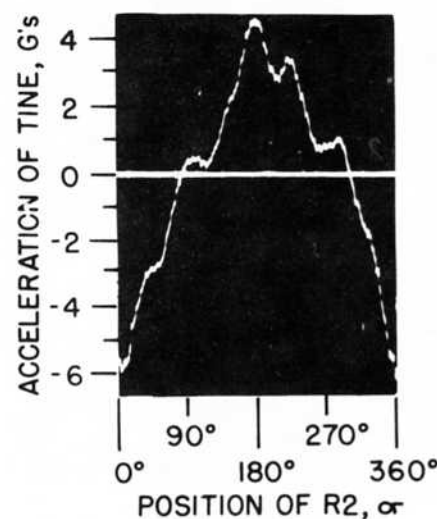

FIG. 15 Oscilloscope display of acceleration on clamping tines 56 in. from the tine pivot point on main mast near-sinusoidal mode. Angular velocity of Link R2 was 200 rpm.