PARTICLE BEHAVIOR ON AN OSCILLATING SURFACE

By

PAUL KENNETH TURNQUIST

Bachelor of Science

Kansas State University

Manhattan, Kansas

1957

Submitted to the faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
May, 1961

PARTICLE BEHAVIOR ON AN OSCILLATING SURFACE

Thesis Approved:

Jay G. Porterfield

Thesis Adviser

E. W. Schroeder

Robert MacVicar

Dean of the Graduate School

PREFACE

The work reported in this thesis was conducted as part of State Project 1020 of the Oklahoma Agricultural Experiment Station. Title of the project is "Physical Characteristics of Farm Products." One of the objectives of this project is to develop testing equipment and techniques to measure physical properties of agricultural products. Many agricultural materials are subjected to separating and conveying devices when processed. The exact behavior of particles in these devices is not known. This investigation was made to study the behavior of a single particle when placed in a separating and conveying device.

The author is grateful to Professor Jay G. Porterfield, the thesis adviser, for making the necessary arrangements to carry out this study and for his invaluable encouragement and counsel during the study. His appropriate comments and suggestions in the writing of this thesis is also acknowledged.

Appreciation is expressed to Professor E. W. Schroeder, Professor O. H. Hamilton, and Assistant Professor L. O. Roth for comments and suggestions.

TABLE OF CONTENTS

Chapter		Page
I.	INTRODUCTION	1
II.	OBJECTIVES	3
III.	REVIEW OF LITERATURE	4
IV.	THEORY	7
V.	APPARATUS AND EQUIPMENT	13
VI.	PROCEDURE	23
VII.	PRESENTATION AND ANALYSIS OF DATA	25
VIII.	DISCUSSION OF RESULTS	30
	A. Speed Fluctuation	30
	B. Interpretation of Analysis	32
IX.	SUMMARY AND CONCLUSIONS	35
BIBLIOGRAPHY		37
APPENDIX		38

LIST OF TABLES

Table | Page

I. Test Conditions Evaluated for Possible Study 11

II. Test Conditions Selected for Study 12

III. Theoretical and Observed Behavior of Particle 27

LIST OF FIGURES

Figure | Page

1. Schematic of Mechanism Which Would Impart Motion Perpendicular to Oscillating Surface 7

2. Laboratory Equipment Consisting of Recording Instrument, Mechanism, and Variable Speed Power Unit . . 14

3. View of Micro Switch, Crank Wheel, and Connecting Link . . 15

4. View Showing Flywheel, Crank Position Dial, and Counterweight 16

5. Side View of Mechanism With Crank Wheel and Connecting Rod Removed 17

6. Oscillogram Showing Recorded Data 19

7. Schematic Wiring Diagram 20

8. Oblique View of the Surface Shows the Particle on the two Conductors. The Guides Assist the Particle in Maintaining a Straight Line Path 21

9. Schematic of Speed Fluctuation Indicator Circuit 31

CHAPTER I

INTRODUCTION

Various arrangements of four bar linkages are used as separating and conveying devices in agricultural machines. Basic components of the four bar link are driver, follower, connecting element, and frame. The driver may have complete rotation or it may swing through an arc. The follower may also have complete rotation or may swing through an arc. Possible combinations of displacement, velocity, and acceleration are most numerous. One set of these conditions may or may not be suitable for achieving desired conveying and separating characteristics, thus early investigators were challenged to find acceptable types of motion. This usually entailed the construction of a device and observing its performance when subjected to certain combinations of link dimensions, speed, and position. Once a satisfactory combination had been found, investigation would cease. In reality this is a singular solution to a problem which has many possible "correct" solutions.

A second approach available for analysis of the four bar link is the use of analytical tools. The equations of motion of a four bar link have been known for many years. Not knowing the type of motion desired and knowing the tedious calculations involved, the analytical approach has received little attention prior to 1957. In this investigation one type of motion produced by a four bar link has been analyzed. The effect of this motion on a single particle has been predicted. Apparatus and tests were developed to determine compatability of theory and laboratory observation.

CHAPTER II

OBJECTIVES

The objectives of this study were to:

A. Analytically predict the behavior of a single particle when placed on a plane surface, the surface experiencing a motion produced by a slider crank mechanism.

B. Develop apparatus and techniques required to study the behavior of the particle.

C. Compare observed behavior with predicted behavior.

CHAPTER III

REVIEW OF LITERATURE

Many textbooks on mechanisms, kinematics, and machine design discuss four bar linkages. Most of these discussions offer graphical solutions to displacement, velocity, and acceleration of points in the mechanism. In many cases analytical approaches are ignored because of the complex equations and tedious calculations required to evaluate them.

Olesen (1) published an article in 1957 covering the behavior of particles in a jog conveyor. He assumed that the motion of the surface was simple harmonic and that input motion was at right angles to the oscillating links (follower). He characterized motion of the particles under certain conditions to (A) stick fast, (B) glide forward, (C) glide backward, and (D) hop. Using derived transcendental inertia equations solved graphically for the separate movement types, the transport capacity of a jog conveyor was calculated. The maximum deviation of observation from the theory was approximately ten percent. Finally, using observed values and theory he determined the best design for a jog conveyor of a specified capacity.

In 1958 Berry (2) published an article on the theory of oscillating conveyors. Specific objectives were: (A) To make a theoretical analysis of the motion of a rigid particle on an oscillating conveyor and (B) Conduct horizontal conveyance tests of granular materials to determine deviations, if any, from the theory. In the analysis it was assumed that (A) Motion of the surface was simple harmonic, and (B) That the input to the driving arm is through a link always at right angles to the driving arm.

The motion of the particle on the oscillating surface was divided into four regions: (A) Stick, (B) Stick slip, (C) Slip and (D) Loss of contact between particle and surface. The mathematical analysis leads to the steady state solution of a non-linear differential equation. The exact solution being found by graphically solving the transcendental equation.

Berry (3) reports in a later paper that inadequate bearings on the link members created difficulty in verifying the theory in the work first cited. Also, included in this paper are more details on the derivation of some of the equations of motion of the particles.

The problem of defining particle passage through a sieve or screen has received much less attention than conveyance. Soviet scientists (4) have conducted work concerning the passing of grain through a screen. The analytical approach by the Russians was to consider a single grain in the form of a rotating ellipsoid. The "go or no go" of the particle through the sieve perforation being dependent on the relative velocity of the particle with respect to the sieve. Then they proceed to establish a relationship between sieve velocity and the relative velocity of the ellipsoid. Experiments were conducted with sieve movement in a horizontal plane and movement in a vertical plane. Variables involved were:

A. Amplitude

B. Frequency

C. Maximum acceleration

D. Shape and size of perforation

E. Sieve slope

F. Type of grain used

Conclusions are given in terms of optimum passing of grain with a specific set of test conditions within the range investigated.

Gaudin (5) has developed some probability statements concerning the passage of ore through a screen. If a particle approaches an opening at a right angle, the chance for passage is much greater than at some angle less than ninety degrees. For a given size differential between particle and opening, the probability of passage increases as the number of opportunities for passage increases. Consider a horizontal screen with the wire diameter equal to the square mesh opening. If the ratio of particle diameter (spherical) to the opening is 0.5, decreasing the approach angle from 90° to 50° decreases the probability of passage from 12 percent to 8 percent. For a ratio of 0.8 the probability of passage at 90° is 2.3 percent. Maintaining a 90° approach angle for the 0.8 ratio the probability of passage for 10, 100, and 1000 chances are 20.8, 90.2, and 100 percent respectively. If the ratio is increased to 0.9, the probabilities for passage are 6.3, 47.9, and 99.8 percent.

Review of the above cited literature indicates that the theory of conveying particles on oscillating surfaces has received considerable attention. Only a limited amount of work has been done on separation theory.

CHAPTER IV

THEORY

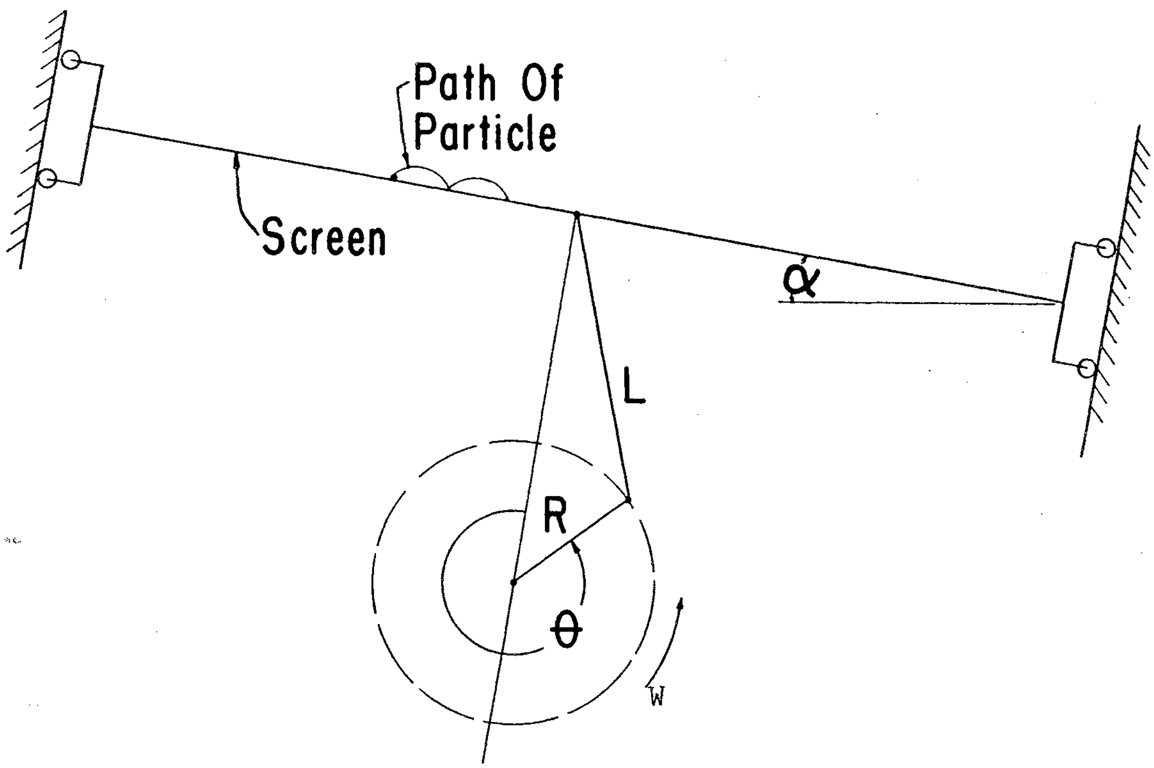


Figure 1. Schematic of mechanism which would impart motion perpendicular to oscillating surface.

Analysis was made of a single particle moving down an inclined surface when subjected to action generated by the mechanism in Figure 1. The particle is assumed to leave the surface and attain free flight and then to come in contact with the surface. These events occurring during one turn of the crank wheel. It is further assumed that the particle does not slide when on the surface and that it does not deviate from a parabolic path when in flight due to windage effects. From the mechanism in Figure 1 the following equations were derived:

$$(1)\quad Yd = R\left(K + 1 - \sqrt{K^2 - \sin^2\theta} - \cos\theta\right)$$

$$(2)\quad \dot{Y}d = RW\left(\frac{\sin\theta\ \cos\theta}{\sqrt{K^2 - \sin^2\theta}} + \sin\theta\right)$$

$$(3)\quad \frac{\ddot{Y}d}{W^2} = \frac{R}{\sqrt{K^2 - \sin^2\theta}}\left(\cos^2\theta - \sin^2\theta + \frac{\sin^2\theta\ \cos^2\theta}{K^2 - \sin^2\theta}\right) + R\cos\theta$$

Where: R = Crank length

L = Connecting rod length

$K = \frac{L}{R}$, a dimensionless ratio

θ = Crank position

W = Angular velocity, assumed constant

Yd = Surface displacement, Yd = 0 when $\theta = 0$

For the particle to leave the surface the following conditions must exist:

A. The surface must be slowing down at the upper end of the stroke. Direction of velocity is upward.

B. Acceleration component of the surface must be downward and equal to or greater than the acceleration of gravity. This condition can be expressed mathematically as:

(4) $\cos \alpha \geq \frac{g}{\ddot{Y}d}$

Where:

α = inclination of surface from horizontal

Using the reference position of the crank angle shown in Figure 1, the particle must leave the surface in the fourth quadrant. By combining equations (3) and (4) the RPM of the mechanism necessary to place the particle in free flight is:

$$(5) \quad RPM = \frac{30}{\pi} \sqrt{\frac{386.4 \quad W^2}{\ddot{Y}d \quad \cos \alpha}}$$

The particle leaves the surface with an initial velocity equal to the mechanism, it assumes free flight along a parabolic path until it again comes in contact with the surface. Thus, during one turn of the crank the particle is in contact with the surface X degrees and in free flight (360 - X) degrees. The following factors are pertinent during one hop of the particle or one turn of the crank:

A. Time that the particle is on the surface.

B. The crank position at which the particle leaves the surface.

C. Time that the particle is in free flight.

D. The angle at which the particle intercepts the surface.

E. Distance the particle advances down the surface.

Item D is associated with the separating characteristics induced by the mechanism when a particle is placed on a perforated or screening surface. A high approach angle would imply a more optimum probability of particle passage than a lower approach angle. Item E is indicative of the conveying characteristics of a screening system. Increased particle advance per hop would imply an increase in the conveying rate.

Particle behavior for a specific test condition was calculated in the following manner:

A. Select suitable values of R and L.

B. Select the crank position at which the particle leaves. This must be in the fourth quadrant for the reference chosen.

C. Calculate the RPM of the mechanism using equation (5).

D. By use of a trial and error method determine the crank position at which the particle intercepts the surface.

E. From the crank position and the mechanism speed, calculate the time that the particle is in the air and time it is on the surface.

F. Calculate particle velocity components at the interception point and determine approach angle using the relationship ϕ (approach angle) = $\tan^{-1} \frac{V_y}{V_x}$

G. Calculate particle advance from relationship established in Step D.

Thirty-four conditions were evaluated. The results are presented in Table I. From Table I five conditions were selected for study in the laboratory. These five conditions are presented in Table II.

TABLE I

TEST CONDITIONS EVALUATED FOR POSSIBLE STUDY
$\theta = 330^\circ$

K	α (Deg)	R (In)	RPM	Hops Per Inch	Sec. Per Inch	Approach Angle ϕ	Flight-time $t \times 10^{-2}$ Sec.
5	5	.50	270.36	18.69	4.15	82° 56'	7.40
5	10	.50	271.98	9.23	2.04	75° 51'	7.36
5	15	.50	274.56	6.09	1.37	68° 45'	7.28
5	5	.75	220.80	12.36	3.36	82° 53'	9.06
5	10	.75	221.94	6.14	1.66	75° 51'	9.01
5	15	.75	224.23	4.06	1.09	68° 45'	8.92
5	5	1.00	191.19	9.34	2.93	82° 53'	10.46
5	10	1.00	192.24	4.62	1.44	75° 51'	10.40
5	15	1.00	194.15	3.04	0.94	68° 45'	10.31
7	5	.25	388.40	38.61	5.97	82° 57'	5.15
7	10	.25	390.02	19.23	2.96	75° 53'	5.12
7	15	.25	397.95	12.71	1.92	68° 45'	5.03
7	5	.50	274.66	19.53	4.27	82° 59'	7.28
*7	10	.50	276.28	9.65	2.10	75° 54'	7.24
7	15	.50	292.30	6.36	1.31	68° 45'	7.16
*7	5	.75	224.04	12.97	3.47	83° 02'	8.93
7	10	.75	225.57	6.42	1.71	75° 54'	8.87
7	15	.75	227.77	4.26	1.12	68° 56'	8.78
7	5	1.00	194.25	9.67	2.99	82° 57'	10.30
7	10	1.00	195.30	4.83	1.48	75° 55'	10.24
7	15	1.00	197.21	3.18	0.97	68° 51'	10.14
9	5	.25	391.79	39.85	6.10	83° 03'	5.10
9	10	.25	394.33	17.59	2.68	76° 35'	5.71
9	15	.25	397.76	11.61	1.75	69° 53'	5.66
*9	0	.50	276.45	∞	∞	90° 00'	7.22
9	5	.50	277.05	20.00	4.33	83° 05'	7.22
9	10	.50	278.67	8.78	1.89	76° 33'	8.07
9	15	.50	281.34	5.81	1.24	69° 51'	7.99
9	5	.75	226.24	13.27	3.52	82° 58'	8.84
*9	10	.75	227.48	5.85	1.54	76° 35'	9.90
9	15	.75	229.77	3.87	1.01	69° 52'	9.79
*9	5	1.00	195.78	9.96	3.05	83° 04'	10.21
9	10	1.00	197.02	4.40	1.34	76° 36'	11.42
9	15	1.00	198.93	2.90	0.87	69° 52'	11.31

* Test conditions selected for study.

TABLE II

TEST CONDITIONS SELECTED FOR STUDY
$\theta = 330^\circ$

Test No.	Screen Slope	R (In)	L (In)	RPM	Time of Flight (Sec.)	Time on Surface (Sec.)
1	0	.50	4.50	276.45	.0722	.1449
2	10°	.75	6.75	227.48	.0990	.1649
3	10°	.50	3.50	276.28	.0724	.1447
4	5°	.75	5.25	224.04	.0893	.1786
5	5°	1.00	9.00	195.78	.1021	.2042

CHAPTER V

APPARATUS AND EQUIPMENT

A four bar linkage was designed to produce the type of motion specified in the theory development. On the basis of the five test conditions presented in Table II, the following adjustments were incorporated in the mechanism:

A. R (Crank throw) = 0.25", 0.50", 0.75", and 1.00".

B. $K = \frac{L}{R} = 5, 7$, and 9.

C. Screen slope = 0°, 2-1/2°, 5°, 7-1/2°, 10°, 12-1/2°, and 15°.

Figure 2 shows a view of the complete laboratory arrangement consisting of the recording instrument, mechanism, and variable speed power unit. The mechanism is tilted in such a manner that the oscillating motion is always at right angles to the surface. The crank wheel, micro switch, and connecting link are shown in Figure 3. All moving parts were mounted in ball bearings. The flywheel, crank position dial, and counterweight are shown in Figures 4 and 5. Moment of inertia of the flywheel is approximately .42 ft-lb-sec^2. A counterweight of 1.96 pounds at 3-7/16 inches was used to minimize the unbalance produced by 10.06 pounds of reciprocating parts. One position of the counterweight with respect to the center of rotation was satisfactory for all test conditions. A guide attached to the reciprocating member is shown in Figure 3. Purpose of the guide is to minimize horizontal oscillations of the surface due to slight misalignment of the moving parts.

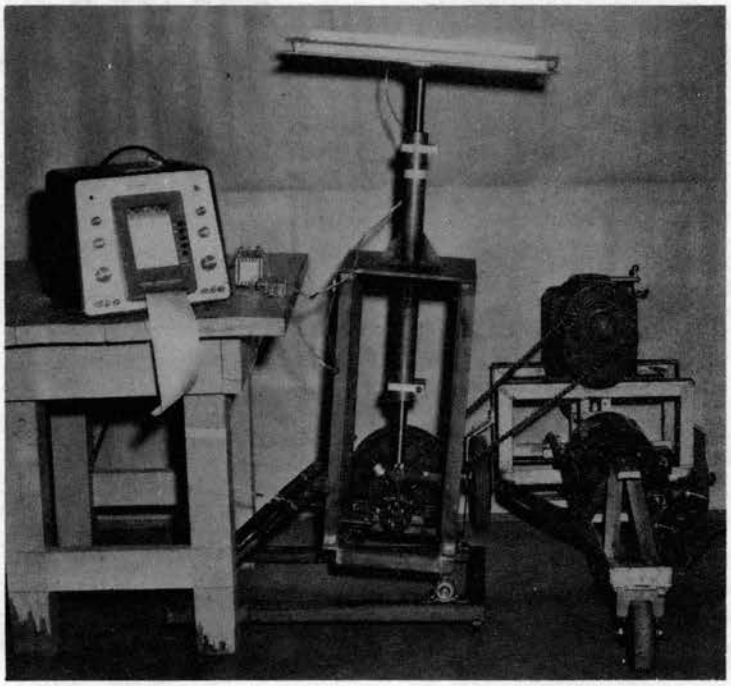


Figure 2. Laboratory Equipment Consisting of Recording Instrument, Mechanism, and Variable Speed Power Unit.

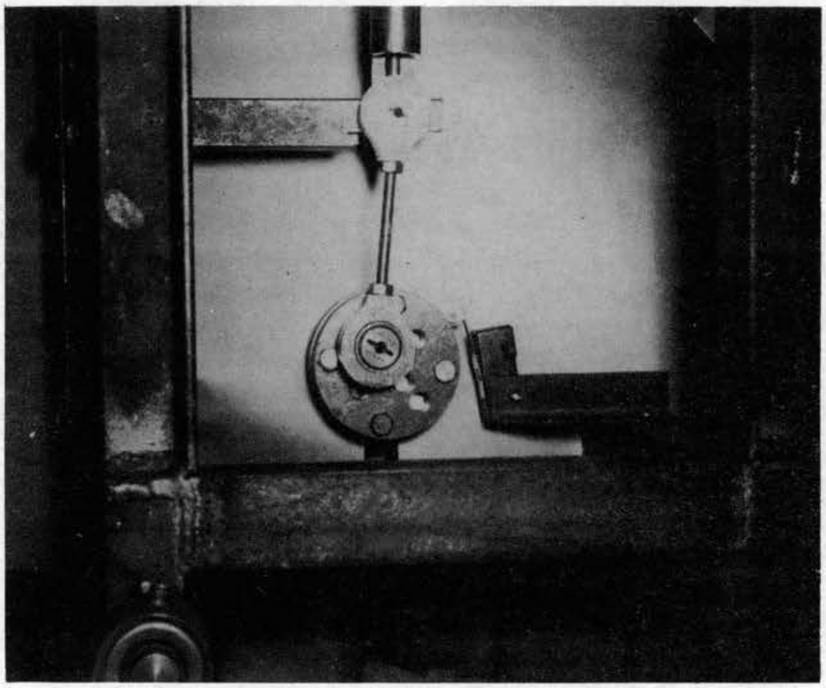


Figure 3. View of Micro Switch, Crank Wheel, and Connecting Link.

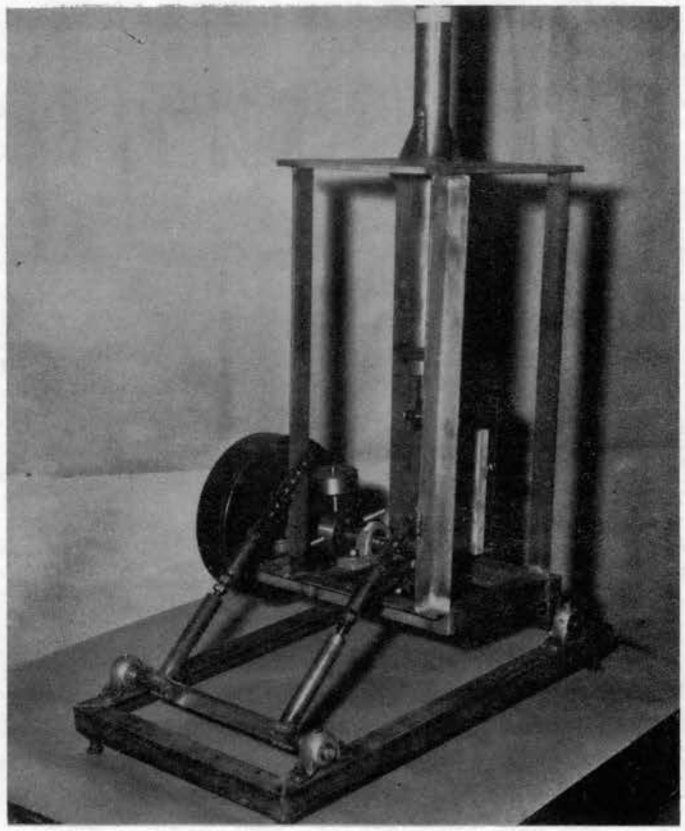


Figure 4. View Showing Flywheel, Crank Position Dial, and Counterweight.

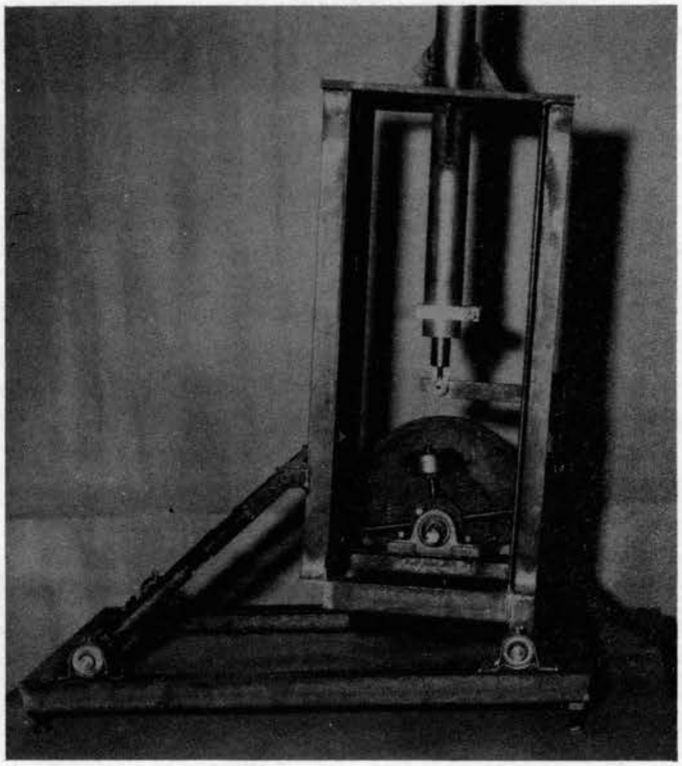


Figure 5. Side View of Mechanism with Crank Wheel and Connecting Rod Removed.

A two channel oscillograph recorder was used to obtain a permanent record of the data. For a specific test the following quantities were recorded on the oscillogram:

A. Time particle is on the surface during one oscillation.

B. Crank position with respect to time at which particle theoretically leaves surface.

C. Time particle is in air during one oscillation.

D. Time for one turn of the crank.

E. Time for particle to travel length of test run.

A picture of an oscillogram is shown in Figure 6.

A schematic of the circuitry used to measure the pertinent quantities is shown in Figure 7. The micro switch used to mark the crank position is noted in Figure 3. The switch in a normally closed position in a six volt d.c. circuit breaks the circuit once every turn of the crank wheel. The change in voltage is sensed by the recorder and is indicated by pen deflection.

Two conductors were mounted on the oscillating surface to track the particle. Figure 8 shows the surface, conductors, and particle. Guides were installed to limit deviations of the particle from a straight line path. Preliminary testing showed no measurable differences after the guides were mounted.

If the particle is in the air, the output voltage to the recorder is battery voltage of 22-1/2 volts d.c. When the particle is on the surface, a short circuit results and a change in output voltage is sensed by the recorder. Recording the voltage changes with respect to time tracks the particle for a given set of test conditions. A 50 ohm resistor and small radio capacitor were employed to prevent arcing when the particle was

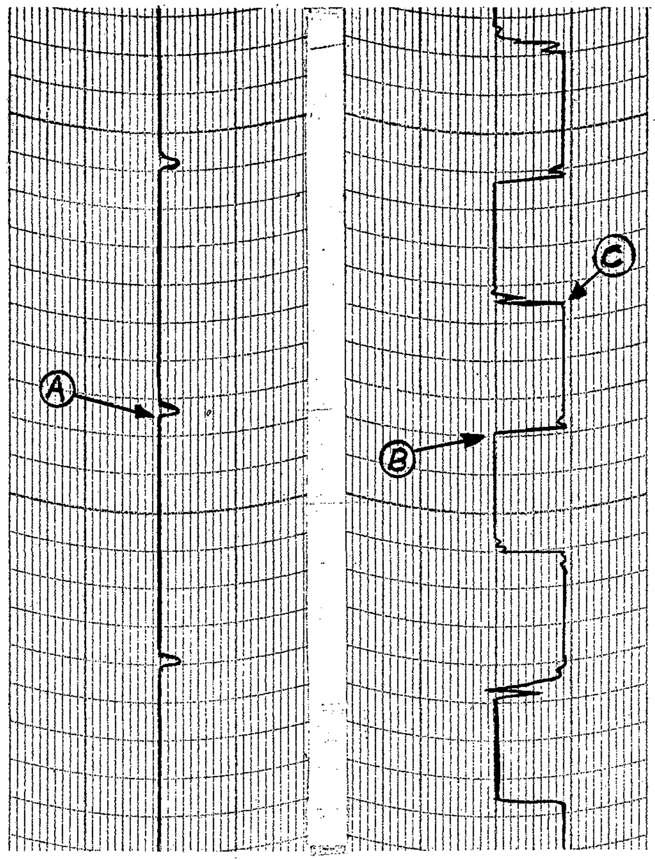


Figure 6. Oscillogram Showing Recorded Data

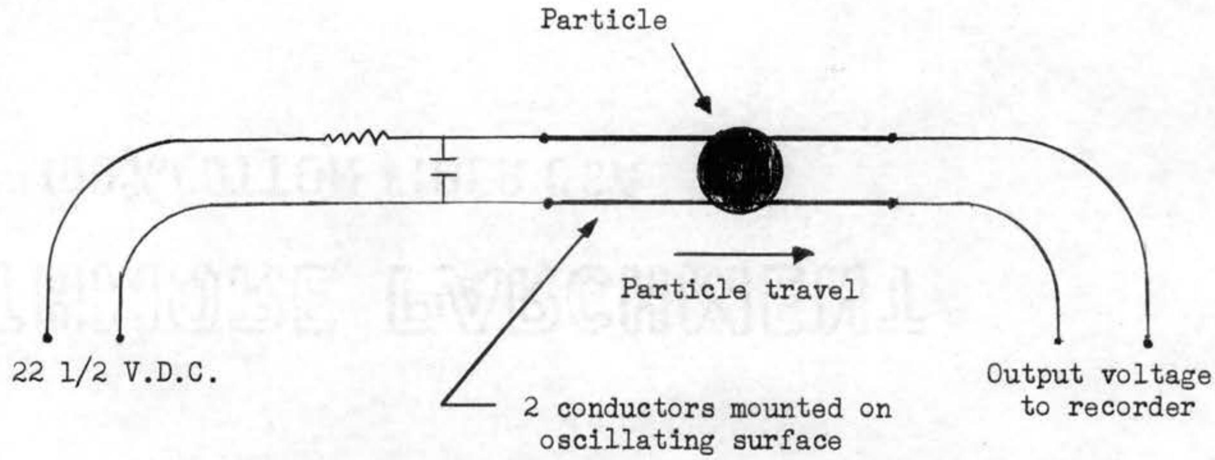
Test No. 2 with Flywheel

Distance between adjacent horizontal lines represents 0.04 second.

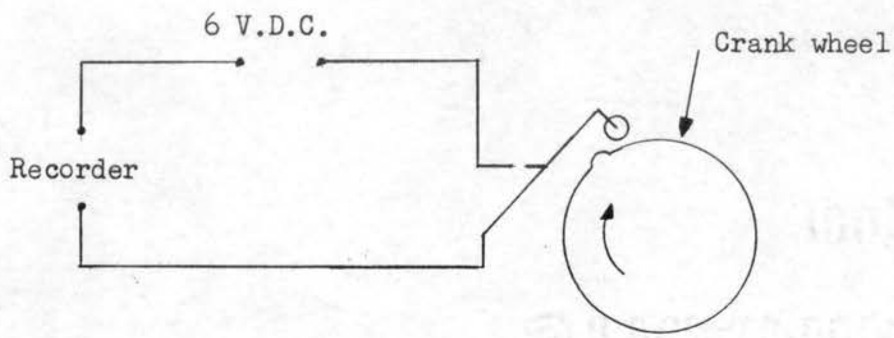
A --- Theoretical time when particle leaves surface.

B --- Actual time particle leaves surface.

C --- Actual time particle touches surface.



Particle Tracking Circuit



Revolution Counting Circuit

Figure 7. Schematic Wiring Diagram

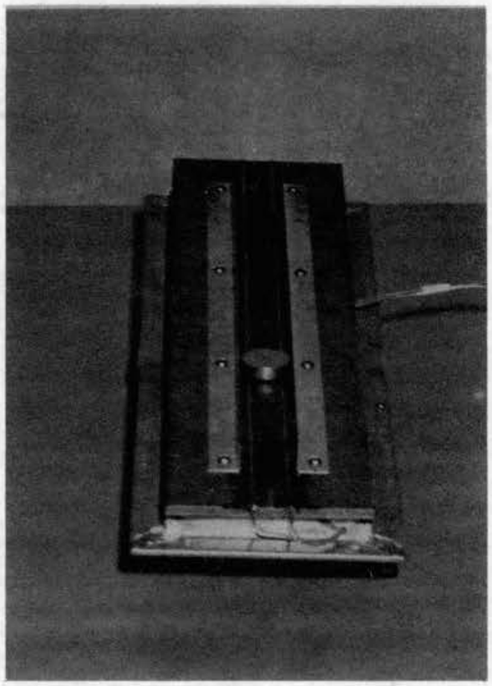


Figure 8. Oblique View of the Surface Shows the Particle on the Two Conductors. The Guides Assist the Particle in Maintaining a Straight Line Path.

leaving or encountering the surface. Using the highest chart speed on the recorder, time increments of .005 second can be measured from the trace. This is about eight degrees of crank rotation for the speeds used.

The particle used for all tests was a circular disk 1.25" in diameter made from steel and weighed .109 pound. In Figure 2 the particle is sitting on top of the recorder. Size and shape was selected on basis of stability and electrical properties. Mass of the particle insured minimum effects from windage.

The crank position dial and an Ames deflection indicator were used to position the micro switch so that actuation would occur at the desired crank position. The switch was positioned statically. An automotive timing light was used to check the switch dynamically. This check was made at the outset of the experimental work and was not performed prior to every test. Use of the timing light indicated the switch marked at the same crank position when running at test speed or slower.

The surface slope was adjusted by means of the two pivoted arms shown in the foreground of Figure 4. Increments of 2-1/2 degrees from 0 to 15 degrees are available. Adjustable legs and length adjustment in the arms provided additional flexibility. Slope was set for a given test using a protractor level. A level was used to level the surface at right angles to the direction of particle travel.

RPM variations of 0 to 400 was provided by the variable speed power unit. Power was transmitted to the mechanism by a roller chain.

CHAPTER VI

PROCEDURE

Preliminary observations were used to establish an acceptable procedure for conducting a test. Initial data was analyzed by statiscal methods to determine the number of observations required for a particular test. Thirty hops of the particle were found to be satisfactory in reducing variance to an acceptable level. For conducting a given test the following procedure was used:

A. Turn on the recording instrument for warm up.

B. Select R Value.

C. Select L Value.

D. Adjust guide to minimize horizontal oscillations of the surface.

E. Position counterweight 3-7/16" from center of rotation and (180°) opposite crank offset.

F. Mount Ames deflection dial.

G. Using crank position dial and Ames deflection dial, position micro switch to actuate at 30 degrees from top dead center. This is the theoretical crank position at which the particle leaves for all test conditions selected.

H. Remove Ames deflection dial.

I. Adjust surface to desired slope.

J. Connect power unit and mechanism with roller chain.

K. Start power unit and set speed with the assistance of a tachometer.

L. Depress the 1 mm/sec chart speed button on the recorder and adjust amplifiers to proper gain and zero settings.

M. Place particle on surface at head end.

N. When particle reaches test area, depress the 125 mm/sec chart speed button on the recorder.

O. Recorder tracks particle while in the test area.

P. When particle leaves test area, depress the 1 mm/sec chart speed button.

Q. Go back and start at Step M and continue this procedure until enough observations are obtained for analysis.

R. Depress "off" button on recorder.

S. Stop power unit.

T. Count 30 legible hops and identify each on the trace. If 30 observations were not obtained, repeat the procedure starting at Step K.

Evidence was obtained to indicate that by following the established procedure, acceptable repeatability can be achieved, irrespective of when the test was conducted.

For tests number 1, 2, 3, and 4 without the flywheel, the particle was tracked for 17.1 inches. For all other tests a length of 18 inches was used. The original length of 17.1 inches was determined on the basis of no slippage of particle when on the surface. The change to 18 inches was for convenience.

CHAPTER VII

PRESENTATION AND ANALYSIS OF DATA

The experiment consisting of five test conditions was run without a flywheel. Experimental values deviated considerably from the theory. A supplementary study to determine the cause of the deviations was initiated. Evidence was obtained to indicate the mechanism was not operating at constant speed. The theory is based on the assumption of constant angular rotation. A flywheel was constructed and installed on the mechanism. The purpose was to reduce speed fluctuation. The experiment was conducted again using the flywheel. The observed mean values for all experimental work is presented in Table III. Also included for comparison are the theoretical values. Meaning of the symbols used in the table is:

$\bar{X}$ air = Average time per hop the particle is in free flight based on 30 observations.

C.V. = Coefficient of variation.

$\bar{X}$ surface = Average time per hop the particle is on the surface based on 30 observations.

$\bar{X}$ lead = Average time per hop the particle is leaving the surface too soon based on 30 observations. Average degrees of crank position the particle is leaving too soon is also tabulated.

$\bar{X}$ hops per inch = Average hops per inch. The number of observations varied for different test conditions. Variation was due to selecting a constant number of Hops (30).

Time accounted for = $\bar{X}$ air + $\bar{X}$ surface ÷ average time for one turn of the crank wheel based on 30 revolutions chosen at random from the oscillogram.

A statistical analysis was made to determine if any population difference existed within a test condition. Model used was a two group experiment of equal size. The two treatments assigned to each test condition were: (A) no flywheel, and (B) with flywheel. It was hypothesized that no difference existed between the means of $\bar{X}$ air, $\bar{X}$ surface, $\bar{X}$ lead, and $\bar{X}$ hops per inch for the two treatments. Probability level was selected at ninety percent.

The original data obtained for all test work are presented in the appendix.

TABLE III

THEORETICAL AND OBSERVED BEHAVIOR OF PARTICLE

Test No. 1	Theoretical	Without Flywheel	With Flywheel	
$\bar{X}$ air (Sec)	.0722	.0950	.0957	N.D.
C.V. (%)	--	3.66	4.06	--
$\bar{X}$ surface (Sec)	.1449	.1185	.1198	N.D.
C.V. (%)	--	4.16	3.00	--
$\bar{X}$ lead (Sec)	0	.0098	.0078	*
(Deg)	0	16.40	13.00	--
C.V. (%)	--	21.40	36.26	--
$\bar{X}$ hops per inch	∞	--	--	--
C.V. (%)	--	--	--	--
Time act. for (%)	100	98.93	98.93	--

Test No. 2	Theoretical	Without Flywheel	With Flywheel	
$\bar{X}$ air (Sec)	.0990	.1320	.1237	*
C.V. (%)	--	6.50	4.28	--
$\bar{X}$ Surface (Sec)	.1649	.1226	.1353	*
C.V. (%)	--	7.30	4.65	--
$\bar{X}$ lead (Sec)	0	.0105	.0123	N.D.
(Deg)	0	16.10	16.80	--
C.V. (%)	--	37.70	38.13	--
$\bar{X}$ hops per inch (19 observations)	5.85	1.76	1.91	*
C.V.	--	2.91	1.91	--
Time act. for (%)	100	98.15	99.10	--

TABLE III (Continued)

Test No. 3	Theoretical	Without Flywheel	With Flywheel	
$\bar{X}$ Air (Sec)	.0724	.1063	.1058	N.D.
C.V. (%)	--	5.20	5.14	--
$\bar{X}$ Surface (Sec)	.1447	.1087	.1093	N.D.
C.V. (%)	--	5.10	5.73	--
$\bar{X}$ Lead (Sec)	0	.0072	.0108	*
(Deg)	0	12.00	18.00	--
C.V. (%)	--	50.00	32.40	--
$\bar{X}$ Hops per inch (6 observations)	9.65	2.60	2.91	*
C.V. (%)	--	1.88	0.97	--
Time Act. for (%)	100	99.10	99.46	--

Test No. 4	Theoretical	Without Flywheel	With Flywheel	
$\bar{X}$ Air (Sec)	.0893	.1195	.1213	N.D.
C.V. (%)	--	4.70	4.33	--
$\bar{X}$ Surface (Sec)	.1786	.1425	.1452	N.D.
C.V. (%)	--	3.88	2.63	--
$\bar{X}$ Lead (Sec)	0	.0103	.0140	*
(Deg)	0	13.90	18.80	--
C.V. (%)	--	33.70	27.14	--
$\bar{X}$ Hops per inch (5 observations)	12.97	4.98	4.68	N.D.
C.V. (%)	--	2.80	1.95	--
Time Act. for (%)	100	98.13	99.19	--

TABLE III (Concluded)

Test No. 5	Theoretical	Without Flywheel	With Flywheel	
$\bar{X}$ Air (Sec)	.1021	.1505	.1383	*
C.V. (%)	--	5.46	4.86	--
$\bar{X}$ Surface (Sec)	.2042	.1557	.1612	*
C.V. (%)	--	4.83	4.13	--
$\bar{X}$ Lead (Sec)	0	.0260	.0136	*
(Deg)	0	30.60	16.00	--
C.V. (%)	--	18.00	36.00	--
$\bar{X}$ Hops per inch (8 observations)	9.96	3.60	3.51	*
C.V. (%)	--	1.98	1.97	--
Time Act. for (%)	100	93.74	98.04	--

* - A significant difference at the 90 percent level.
N.D. - No significant difference at the 90 percent level.

CHAPTER VIII

DISCUSSION OF RESULTS

A. Speed Fluctuation

A supplementary study was initiated to determine if the mechanism was varying in speed within a revolution. After considerable thought and experimentation a means for detecting speed differences between two crank positions was devised. A schematic of the device is shown in Figure 9. For the arrangement shown, $RPM_c \neq RPM_m$. Periodically both switches will be actuated at the same time and a voltage change will be sensed by the recorder. For a given speed differential between the check motor and mechanism a definite marking pattern on the oscillogram is established. If the switch on the mechanism is rotated, say 15^o, and keeping all other things constant an indication of the speed at that point relative to the original position will be obtained. If, after rotating the switch 15^o, the marking pattern on the oscillogram remains the same, there is no difference in speed between the two points. However if the marking pattern does change, then speed fluctuation between the two positions is occurring. This is a qualitative measurement and gives no indication of magnitude of speed change or whether speeding up or slowing down is occurring.

A test was conducted using the above approach. The switch on the crank wheel was positioned at the theoretical crank position at which the particle leaves the surface. The units were allowed to run for about 10 minutes and the marking pattern was established. Then the switch

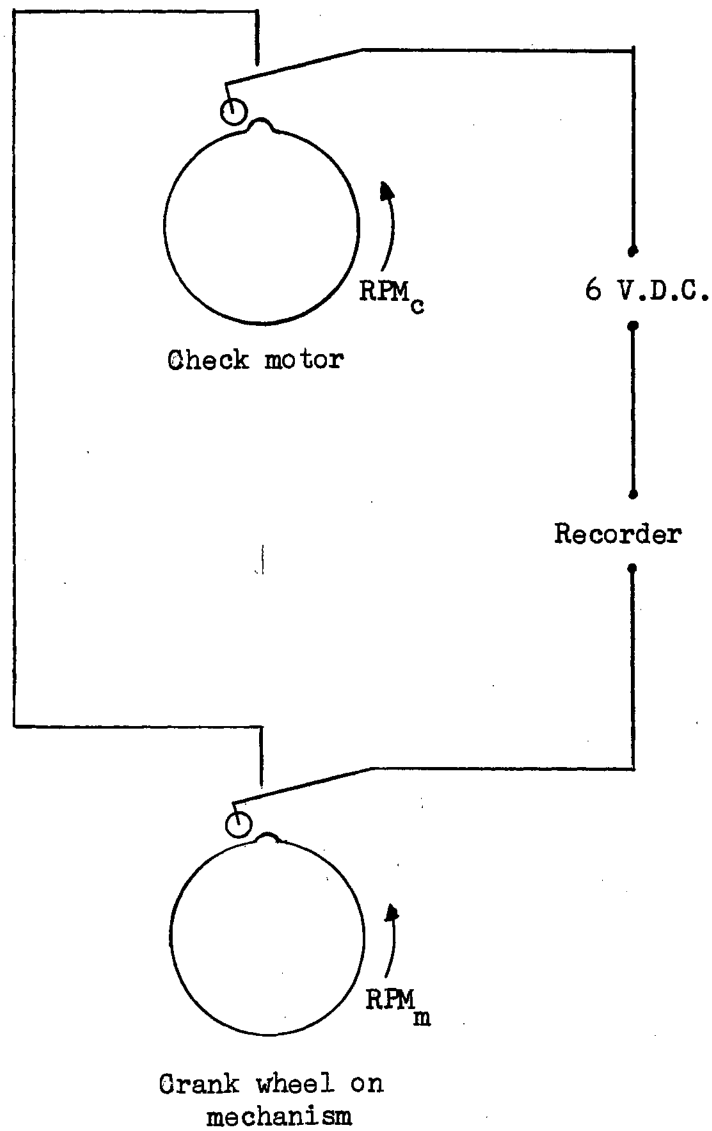


Figure 9. Schematic of Speed Fluctuation Indicator Circuit

was rotated 15° into the general area where the particle actually was leaving the surface. This was done while the check motor and mechanism were running. The marking pattern for this position was obtained by running the units for about 10 minutes. Comparing the two oscillograms on a light table revealed that a phase shift occurred. The oscillograms were not identical and variation in speed between the two points was concluded to exist. The experiment was conducted with and without the flywheel. Under both conditions variations were obtained.

Further indication of speed fluctuation was noted when test number 5 was run without the flywheel. The mechanism did not operate smoothly and the roller chain developed a whipping motion. This could be caused by speed fluctuation of the input shaft or output shaft of the power transmission system. It is believed that the input shaft to the mechanism was responsible for the behavior noted.

B. Interpretation of Analysis

1. For all test conditions observed mean values differed significantly from theoretical values. Inspection of individual observations showed that the theoretical value did not lie in the range of the observed values. Exceptions to the above statement are: (A) In test 1, with the flywheel the particle was observed to leave the surface at the predetermined position once in thirty observations. (B) This was also true for test 2 with flywheel. (C) In test 3 without flywheel in three out of 30 runs it was noted the particle left at the predetermined crank position. (D) In test 4 without flywheel the particle left the surface at the predetermined position once in thirty observations. In 976 individual observations, six were in agreement with the theory.

2. Comparison of no flywheel and with flywheel reveals: (A) $\bar{X}$ air - no difference in Tests 1, 3, and 4; significant difference in Tests 2 and 5. (b) $\bar{X}$ surface - no difference in Tests 1, 3, and 4; significant difference in Tests 2 and 5. (C) $\bar{X}$ lead - no difference in Test 2; significant difference in Tests 1, 3, 4, and 5. (D) $\bar{X}$ hops per inch - no difference in Test 4; significant difference in Tests 1, 2, 3, and 5.

3. In test 1, installation of the flywheel significantly changed the crank position at which the particle leaves the surface. The position was the only variable in test 2 that did not change significantly when the flywheel was used. In test 3 the position and hops per inch were significantly different. The particle left the surface at a significantly different place in test 4 for the two treatments. All other variables were not affected. Indications are that observations for the two treatments in test 5 were not from the same population.

It is hypothesized that the experimental results differ from the theory because:

1. Due to speed fluctuation (qualitative evidence) the surface is slowing down at the upper end of the stroke more rapidly than predicted. This would induce higher acceleration in the mechanism and would cause the particle to leave sooner in terms of crank position.

2. This in turn would change the initial velocity of the particle when it leaves the surface. Under these circumstances a different flight time would be expected.

3. Since the observed time of flight is greater than calculated, an increase in the approach angle from the theoretical

values would be expected. Increasing the approach angle would increase the probability of particle passage in the event the surface were replaced with a screen.

4. Observed hops per inch are less than calculated due to a longer flight time and due to sliding when the particle is on the surface. As a result, the number of opportunities per inch of travel for particle passage would decrease.

CHAPTER IX

SUMMARY AND CONCLUSIONS

A theory was presented to predict the behavior of a particle on an oscillating surface. The oscillating effect being produced by a slider crank mechanism. Behavior was predicted for hopping of the particle, travel down an incline, and approach angle. Apparatus and instrumentation was developed to study particle behavior in the laboratory.

Specific conclusions reached from the study are:

A. Due to speed fluctuation within one turn of the crank wheel, observed behavior differed significantly from predicted behavior.

B. Installation of a flywheel altered the speed fluctuation but the behavior still differed significantly from predicted values.

C. Observed particle behavior would indicate a higher probability of partial passage due to increased approach angle as compared to the theoretical value.

D. Observed particle behavior would indicate a lower probability of particle passage due to increased flight time from theory and due to sliding of particle when on the surface.

E. The net probability change is not known. Derivation of probability expressions for the system used was excluded from this study.

In conducting this study several questions arose which remain unanswered. Additional investigations and study could be initiated to consider the following points:

1. Develop equipment and techniques to measure speed fluctuation. Quantitative measurements within five degrees of rotation would be desirable.
2. With the assistance of a speed fluctuation indicator, approaches to designing constant speed equipment could be developed.
3. Develop probability statements concerning particle passage.
4. Expand theory and probability statements to mass flow of particles.

BIBLIOGRAPHY

Selected References

(1) Calculations on Jog Conveyor. H. Toftdahl Olesen, ACTA POLYTECHNICA, Mechanical Engineering Series, Vol. 3 No. 11.

(2) Research on Oscillating Conveyors. P. E. Berry, Journal of Agricultural Engineering Research, Vol. 3 No. 3, 1958.

(3) Basic Theory of Low Acceleration Oscillating Conveyors. P. E. Berry, Journal of Agricultural Engineering Research, Vol. 4 No. 3, 1959.

(4) Investigation of the process of passing grain through a screen. I. I. Vasilenko, Sbor. Trud. Zemled. McKhan., Vsesoyuz. Lenin. Akad. Selkhoz. Nauk, 1956, 3, pp. 86-96. Translated by D. K. Brooks, National Institute of Agricultural Engineering.

(5) Gaudin, A. M. Principles of Mineral Dressing. New York: McGraw Hill, 1939.

APPENDIX

DATA SHEET (1)

TEST NO. 1 WITHOUT FLYWHEEL

R = .50"   L = 4.5" $\alpha = 0^{\circ}$ Observed RPM = 278.04

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.090	.120	.005
2	.095	.110	.010
3	.095	.125	.015
4	.095	.110	.010
5	.095	.120	.010
6	.095	.120	.010
7	.095	.125	.010
8	.095	.120	.010
9	.090	.115	.005
10	.100	.120	.015
11	.100	.115	.010
12	.090	.120	.010
13	.100	.115	.010
14	.090	.120	.010
15	.095	.115	.010
16	.090	.125	.010
17	.090	.130	.010
18	.095	.120	.050
19	.090	.125	.010
20	.100	.120	.015
21	.095	.120	.010
22	.095	.120	.010
23	.095	.110	.005
24	.095	.120	.010
25	.095	.115	.010
26	.100	.120	.010
27	.100	.110	.010
28	.100	.115	.010
29	.095	.120	.010
30	.095	.115	.010

DATA SHEET (2)

TEST NO. 2 WITHOUT FLYWHEEL

R = .75"   L = 6.75" $\alpha = 10^{\circ}$ Observed RPM = 228.72

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.130	.135	.015
2	.120	.140	.005
3	.125	.125	.005
4	.135	.130	.015
5	.140	.115	.015
6	.140	.125	.010
7	.140	.120	.010
8	.115	.130	.010
9	.130	.135	.015
10	.130	.130	.015
11	.125	.145	.010
12	.130	.120	.005
13	.130	.135	.010
14	.135	.115	.010
15	.125	.125	.005
16	.125	.130	.010
17	.130	.120	.010
18	.135	.120	.010
19	.130	.130	.010
20	.130	.130	.015
21	.125	.130	.005
22	.130	.135	.015
23	.150	.110	.015
24	.145	.120	.010
25	.120	.135	.010
26	.130	.130	.010
27	.130	.125	.010
28	.125	.135	.010
29	.135	.125	.010
30	.130	.120	.010

DATA SHEET (3)

TEST NO. 3 WITHOUT FLYWHEEL

R = .50" L = 3.50" $\alpha = 10^{\circ}$ Observed RPM = 276.50

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.110	.100	.010
2	.105	.110	.005
3	.110	.105	.005
4	.105	.105	.000
5	.105	.105	.005
6	.100	.115	.010
7	.105	.110	.005
8	.110	.105	.005
9	.100	.110	.010
10	.095	.120	.000
11	.105	.110	.010
12	.105	.105	.005
13	.105	.115	.010
14	.105	.110	.005
15	.120	.100	.010
16	.110	.110	.015
17	.105	.110	.010
18	.105	.110	.010
19	.105	.110	.010
20	.105	.115	.005
21	.105	.115	.005
22	.120	.100	.010
23	.100	.115	.005
24	.100	.105	.000
25	.110	.105	.005
26	.100	.115	.005
27	.110	.100	.010
28	.115	.100	.005
29	.110	.115	.010
30	.105	.110	.010

DATA SHEET (4)

TEST NO. 4 WITHOUT FLYWHEEL

R = .75"   L = 5.25" $\alpha = 5^{\circ}$ Observed RPM = 224.72

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.120	.140	.010
2	.125	.130	.010
3	.120	.140	.010
4	.120	.140	.010
5	.115	.150	.010
6	.130	.135	.010
7	.120	.145	.010
8	.120	.145	.015
9	.115	.145	.010
10	.125	.140	.015
11	.120	.140	.010
12	.125	.140	.015
13	.130	.140	.015
14	.125	.145	.015
15	.120	.140	.010
16	.110	.145	.010
17	.120	.150	.010
18	.110	.150	.005
19	.120	.145	.010
20	.120	.135	.010
21	.120	.145	.010
22	.110	.150	.010
23	.110	.140	.000
24	.120	.140	.015
25	.110	.150	.010
26	.115	.150	.005
27	.125	.130	.005
28	.120	.140	.010
29	.120	.145	.010
30	.125	.145	.015

DATA SHEET (5)

TEST NO. 5 WITHOUT FLYWHEEL

R = 1.00" L = 9.00" $\alpha = 5^\circ$ Observed RPM = 195.97

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.160	.165	.020
2	.160	.155	.030
3	.155	.165	.025
4	.155	.155	.030
5	.160	.160	.030
6	.150	.160	.025
7	.165	.150	.025
8	.160	.135	.030
9	.150	.160	.030
10	.155	.145	.030
11	.135	.160	.020
12	.145	.170	.020
13	.150	.155	.025
14	.150	.155	.030
15	.150	.160	.020
16	.150	.160	.020
17	.160	.150	.030
18	.150	.150	.020
19	.145	.160	.020
20	.150	.145	.030
21	.155	.165	.025
22	.140	.160	.030
23	.150	.155	.030
24	.135	.150	.020
25	.130	.165	.030
26	.150	.145	.030
27	.150	.155	.020
28	.150	.155	.030
29	.160	.150	.035
30	.140	.155	.025

DATA SHEET (6)

TEST NO. 1 WITH FLYWHEEL

R = .50"   L = 4.5" $\alpha = 0^\circ$ Observed RPM = 275.44

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.100	.115	.005
2	.100	.120	.010
3	.095	.120	.010
4	.100	.120	.010
5	.085	.125	.005
6	.090	.120	.005
7	.100	.115	.005
8	.095	.120	.010
9	.100	.115	.010
10	.095	.120	.010
11	.090	.125	.005
12	.090	.125	.005
13	.095	.120	.010
14	.090	.120	.010
15	.095	.120	.010
16	.100	.125	.010
17	.095	.120	.005
18	.100	.115	.005
19	.095	.120	.010
20	.100	.110	.000
21	.095	.120	.005
22	.095	.115	.010
23	.095	.120	.010
24	.095	.120	.005
25	.100	.120	.010
26	.095	.120	.005
27	.095	.120	.010
28	.100	.120	.010
29	.095	.120	.010
30	.095	.125	.010

DATA SHEET (7)

TEST NO. 2 WITH FLYWHEEL

R = .75" L = 6.75" α = 10° Observed RPM = 227.85

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.130	.135	.015
2	.125	.135	.010
3	.120	.140	.015
4	.125	.140	.020
5	.120	.140	.010
6	.125	.140	.020
7	.125	.140	.015
8	.130	.135	.015
9	.120	.145	.015
10	.125	.145	.015
11	.140	.125	.020
12	.125	.130	.005
13	.120	.135	.010
14	.125	.135	.015
15	.120	.140	.010
16	.125	.145	.010
17	.120	.130	.005
18	.130	.130	.010
19	.135	.125	.020
20	.130	.140	.015
21	.120	.140	.010
22	.130	.130	.010
23	.120	.140	.010
24	.120	.130	.010
25	.130	.135	.010
26	.125	.140	.010
27	.135	.120	.015
28	.120	.135	.010
29	.130	.130	.015
30	.125	.130	.000

DATA SHEET (8)

TEST NO. 3 WITH FLYWHEEL

R = .50" L = 3.50" α = 10° Observed RPM = 277.35

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.100	.120	.015
2	.110	.100	.010
3	.100	.110	.010
4	.110	.110	.010
5	.110	.105	.015
6	.105	.100	.005
7	.105	.110	.015
8	.105	.115	.010
9	.100	.110	.005
10	.105	.110	.010
11	.095	.110	.005
12	.105	.120	.020
13	.100	.105	.005
14	.105	.120	.010
15	.110	.110	.010
16	.115	.115	.015
17	.105	.110	.010
18	.105	.110	.010
19	.110	.100	.010
20	.115	.100	.010
21	.100	.110	.010
22	.100	.110	.015
23	.100	.110	.010
24	.105	.115	.010
25	.100	.115	.010
26	.110	.105	.015
27	.110	.115	.010
28	.115	.095	.010
29	.115	.105	.015
30	.105	.110	.010

DATA SHEET (9)

TEST NO. 4 WITH FLYWHEEL

R = .75" L = 5.25" $\alpha = 5^{\circ}$ Observed RPM = 223.33

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.120	.145	.015
2	.125	.145	.015
3	.120	.145	.015
4	.120	.140	.015
5	.130	.135	.015
6	.120	.150	.010
7	.125	.140	.020
8	.120	.150	.010
9	.120	.145	.015
10	.110	.150	.010
11	.130	.140	.015
12	.110	.150	.010
13	.115	.140	.010
14	.115	.155	.015
15	.125	.150	.010
16	.125	.145	.010
17	.130	.140	.020
18	.130	.145	.015
19	.120	.150	.010
20	.120	.140	.015
21	.120	.150	.010
22	.125	.140	.015
23	.125	.145	.010
24	.120	.145	.020
25	.115	.150	.020
26	.120	.150	.015
27	.120	.140	.010
28	.125	.145	.020
29	.120	.145	.010
30	.120	.145	.020

DATA SHEET (10)

TEST NO. 5 WITH FLYWHEEL

R = 1.00"   L = 9.00" $\alpha = 5^{\circ}$ Observed RPM = 196.40

Observation No.	X air Sec.	X surface Sec.	X lead Sec.
1	.130	.175	.010
2	.140	.160	.010
3	.140	.160	.010
4	.135	.175	.010
5	.150	.165	.020
6	.145	.155	.020
7	.140	.170	.010
8	.140	.160	.020
9	.150	.150	.020
10	.140	.165	.005
11	.140	.155	.015
12	.140	.170	.010
13	.140	.160	.015
14	.130	.165	.015
15	.140	.160	.010
16	.135	.160	.010
17	.135	.165	.020
18	.130	.170	.010
19	.140	.155	.015
20	.150	.160	.020
21	.130	.160	.010
22	.140	.165	.015
23	.130	.160	.010
24	.140	.155	.020
25	.140	.160	.010
26	.140	.150	.015
27	.130	.160	.010
28	.150	.150	.025
29	.130	.155	.010
30	.130	.165	.010

DATA SHEET (11)

HOPS PER INCH

Test No. 2		Test No. 3	
Without Flywheel	With Flywheel	Without Flywheel	With Flywheel
1.696	1.889	2.573	2.944
1.754	1.833	2.632	2.889
1.813	1.944	2.632	2.944
1.813	2.000	2.632	2.889
1.813	1.889	2.515	2.889
1.754	2.000	2.632	2.889
1.813	1.944		
1.754	1.944		
1.754	1.889		
1.754	1.889		
1.696	1.944		
1.754	2.000		
1.813	1.833		
1.813	1.889		
1.754	1.778		
1.696	1.889		
1.637	1.889		
1.754	1.833		
1.813	1.833		

Note: Hops per Inch for Test No. 1 has no meaning.

DATA SHEET (12)

HOPS PER INCH

Test No. 4		Test No. 5	
Without Flywheel	With Flywheel	Without Flywheel	With Flywheel
5.146	4.667	3.555	3.611
4.912	4.611	3.667	3.500
5.088	4.667	3.611	3.500
4.971	4.833	3.722	3.555
4.795	4.611	3.611	3.555
		3.611	3.500
		3.555	3.389
		3.500	3.444

VITA

Paul Kenneth Turnquist

Candidate for the Degree of

Master of Science

Thesis: PARTICLE BEHAVIOR ON AN OSCILLATING SURFACE

Major Field: Agricultural Engineering

Biographical:

Personal data: Born at Lindsborg, Kansas, January 3, 1935.

Undergraduate study: Kansas State University, 1952-1957.

Graduate study: Oklahoma State University, 1958-1961.

Professional experience: Research Engineer, Caterpillar Tractor Company, Peoria, Illinois, 1957. Instructor (Teaching and Research), Agricultural Engineering Department, Oklahoma State University, 1958-1961.

Associate Member of the American Society of Agricultural Engineers.