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AN INVESTIGATION OF
DYNAMIC STRESSES IN A LANDING GEAR
AT
A PRE-DETERMINED STRUT ANGLE

A Thesis
Submitted to the Graduate Faculty
of the
University of Minnesota

by
Burr V. ^{Turner} Turner

In partial fulfillment of the requirements for
the Degree of
Master of Science in Aeronautical Engineering
August, 1949

AN INVESTIGATION OF
THE EFFECTS OF A JET ENGINE ON
THE STRUCTURE OF A WING

BY

WILLIAM H. HARRIS, JR.

THESIS

1944

A THESIS

PRESENTED TO THE FACULTY OF THE

UNIVERSITY OF

ILLINOIS

BY

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CHICAGO, ILL.

PREFACE

During the history of aviation the stresses and strains which occur in landing gears during the initial part of landing an airplane have not been thoroughly investigated. In this thesis a study was made of the stresses and deflections which occurred upon landing. The response and forces resulting from these dynamic loads will be of primary concern.

The testing apparatus is located in building No. 717, Rosemount Research Center, Rosemount, Minnesota.

The reference material used in developing this theory, consisting of periodicals and engineering texts, were obtained from the aeronautical engineering office and the engineering library of the University of Minnesota.

The author is greatly indebted to Professor J. A. Wise for his guidance and valuable assistance in the preparation of this paper. Thanks is also due H. Wood for his liberal collaboration in the construction, design and testing activities.

B. V. T.

Minneapolis--August, 1949.

INTRODUCTION

During the history of aviation the airplane and its various parts have been constantly improved. In this respect a study was made of the various and different types of airplanes. The airplane was found to be a very simple machine. It is made up of many parts, each of which has its own function. The airplane is a very simple machine. It is made up of many parts, each of which has its own function. The airplane is a very simple machine. It is made up of many parts, each of which has its own function.

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A. V. P.

Abbott Aerospace—1955

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SUMMARY

This is a preliminary study of the dynamic conditions of a landing gear and covers a range from light to above average landings. The weight assumed is approximately two-fifths of the normal static load on a landing gear. In actual landings an airplane wing still has lift during its initial phase, therefore, these assumptions are reasonable.

The experimental work covers the dropping range from two to five feet per second with varying tire pressures from twenty-four to forty pounds per square inch. These two parameters are the only conditions varied in this report.

A theoretical sample problem is worked for these conditions: A tire is assumed with 30 pounds per square inch pressure carrying a total weight of one thousand and sixty pounds and having a dropping velocity of four feet per second.

A comparison of this problem is made with the experimental values. The results indicate that the theoretical force is 22 per cent greater than the recorded data. The period resulting from setting up the equations of motion show that it is two and one half per cent less than that measured.

A moving picture was made of the dropping operations and is available to show the action in slow motion. It is filed in Visual Education, Westbrook Hall, University of Minnesota under Aeronautical Engineering Films.

A moving picture was made of the program given. It is filed in Visual Division, Washington Field, Division of Inspection and Administration, Department of Justice.

INTRODUCTION

This thesis is the initial study in a projected series of reports concerning the stresses, strains, deflections and general information of a landing gear. This is part of a plan created by the Aeronautical Engineering Department, University of Minnesota. Only a limited phase of the subject will be covered in this paper since the scope of the field is far reaching. The reason for this limitation is that excessive time was required in the original construction of the testing apparatus.

First, a method had to be devised to simulate controlled landings similar to those encountered in an aircraft. This set-up was required to be in a laboratory so that accurate readings could be observed and recorded.

A Navy SNJ landing gear was used for testing purposes. The range of tire pressure was from 24 to 40 pounds per square inch, while the sinking speeds were varied from 2 to 5 feet per second. These ranges were chosen as being close to conventional landing conditions.

The present data gives sufficient information to verify the theory, but more recordings would have given a clearer picture.

INTRODUCTION

This report is the initial study in a projected series of reports concerning the effects of ballistic and thermal loading on a landing gear. This is part of a study ordered by the Aeronautical Engineering Department, University of Minnesota. Only a limited amount of the research will be covered in this report since the scope of the study is far reaching. The reason for this limitation is that extensive data was required in the original conception of the test program.

What is needed and to be desired in a landing gear is a system which will be able to absorb the impact of a landing gear. This system is required to be in a landing gear and must be able to absorb the impact of a landing gear. This system is required to be in a landing gear and must be able to absorb the impact of a landing gear.

A very big landing gear was used for testing purposes. The design of this program was from 10 to 15 pounds per square inch. With the existing conditions, a landing gear of 10 to 15 pounds per square inch was chosen as being most representative of existing conditions. The present data gives sufficient information to verify the theory, but more research would have given a better picture.

APPARATUS AND INSTRUMENTS

The problem required a setup which would simulate the actual landing of an aircraft. A large flywheel was desired which would withstand heavy weights and could be revolved at speeds equivalent to those of landings. When a flywheel ten feet in diameter was found, an old reduction gear and test engine were used for power. This combination took care of turning such a large disc. With this material on hand the drawings of the pit and assembly were made.

The final assembly is shown in Fig. No. 1.



Fig. No. 1

APPENDIX A - SUMMARY

The project involved a major effort to

the initial testing of an aircraft. A large amount

was devoted to the initial testing of the aircraft and

the project was completed in June of 1955.

From a technical point of view, the project was

successful and the aircraft was able to

fly successfully for a period of time.

Also, with this aircraft we had the design of the

it and assembly were made.

The final assembly is shown in Fig. A.1.

The driving mechanism is illustrated in Fig. No. 2.

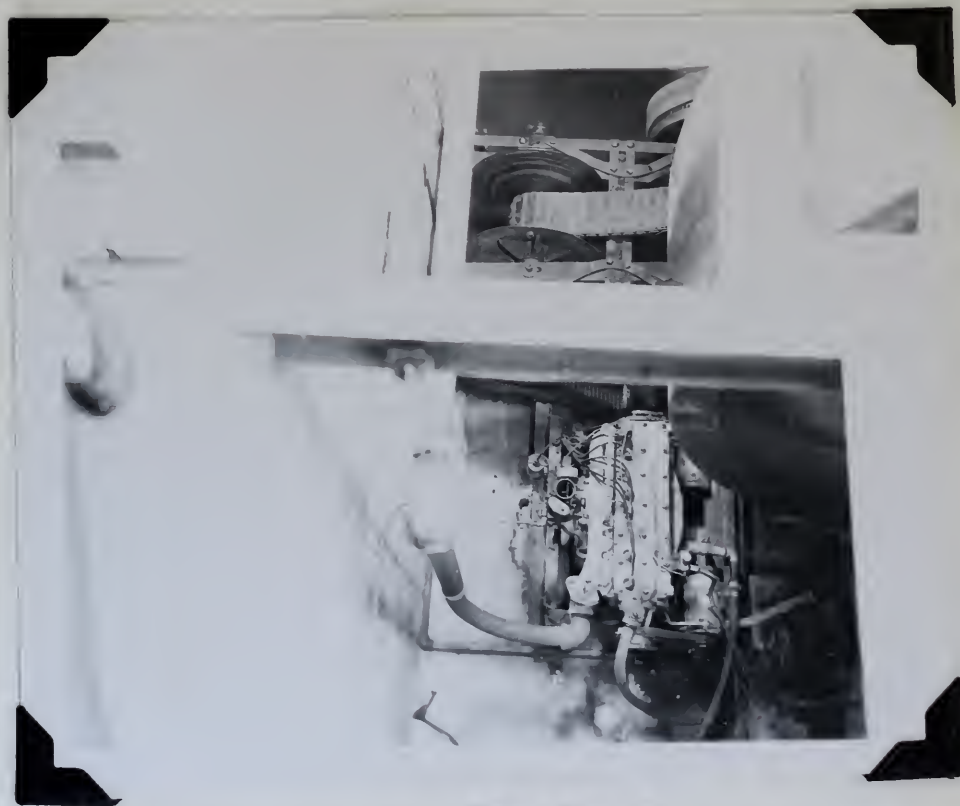


Fig. No. 2

After the apparatus was constructed type C-1, SR-4, strain gauges, made by Baldwin Southwark Division of the Baldwin Locomotive Works, were placed on the lower brace of the landing gear in a to and aft position opposite each other so the drag forces could be measured. Also, gauges were placed perpendicularly to those formerly mentioned in order to measure the axial forces. To determine the relative displacements between the oleo and the strut itself a potentiometer with a scissors lever arm was installed. A cantilever with damper was placed in an appropriate position, and strain gauges were properly located to measure the movement and deflec-

The driving mechanism is illustrated in Fig. No. 2.



Fig. No. 2

After the mechanism was constructed type C-1, the
main pump, made by Baldwin Engine Division of
the Baldwin Locomotive Works, was placed on the lower
base of the driving gear in a 10 and 1/2 position
position each other as the gear turned with the
also, gears were placed perpendicular to the
forward position in order to secure the main pump.
To determine the relative displacement between the
and the main pump a potentiometer with a voltmeter
circuit was installed. A potentiometer with a voltmeter
circuit is an economical method of determining the
very properly located as shown in the diagram and table.

tion of the wheel. These gauges can be seen in Fig. No. 3.



Fig. No. 3

The leads from the strain gauges and the potentiometer were brought into a Brush Recorder which recorded the different forces and amplitudes. The weight of the gear was determined by using platform scales and a lever system - Fig. No. 4.

For each of the three groups and the patients-
each were brought into a large hospital with patients
The different forms and methods. The results of
the group was determined by using different methods and
A large group - 110. 11. 11.



Fig. No. 4.



FIG. 10

The following table shows the results of the tests conducted on the various specimens of the material under consideration. The specimens were tested in accordance with the standard methods of testing for tensile strength, elongation, and impact resistance. The results are given in the following table:

Specimen No.	Tensile Strength (lb./sq. in.)	Elongation (%)	Impact Resistance (ft.-lb.)
1	100,000	10	100
2	105,000	12	110
3	110,000	15	120
4	115,000	18	130
5	120,000	20	140

The above table shows that the material under consideration has a tensile strength of between 100,000 and 120,000 lb./sq. in., an elongation of between 10% and 20%, and an impact resistance of between 100 and 140 ft.-lb. These results are in good agreement with the values given in the specification for the material.

TESTING PROCEDURE

The method used in calibrating these three pairs of strain gauges and the one potentiometer are as follows:

(A) Axial Force. The two opposite gauges on the fork running parallel to the axis of the strut measure this force. The strain analyser was balanced and no load conditions were recorded. In this manner a relationship was established between the deflection of the oscilloscope and the vertical load applied. A full static load was applied and again readings were recorded. In other words, so many millimeters of deflection on the recorder indicated a known amount of force. Points between full load and no load were checked and found in agreement.

(B) Drag Force. These forces were obtained in a manner very similar to those mentioned above. Attention should be called to the procedure in which a horizontal pressure was applied to the strut. A light cable was stretched through a pulley where a known weight could be suspended. The cable can be seen in Fig. Nos. 1, 3, and 4. Here, with known loads, the recorder was calibrated.

(C) Cantilever Deflections. The displacement of the cantilever was measured by adjusting the landing gear a known distance above the flywheel; then by

TESTING PROCEDURE

The subject was in calibrating these three pairs of strain gauges and the two potentiometers are as follows:

(A) Calibration. The two potentiometers on the test frame were calibrated to the scale of the strain gauges. The strain gauges were calibrated and the load conditions were measured. In this manner a relationship was established between the deflection of the potentiometers and the various load weights. A full scale load was applied and again readings were recorded. In other words, the two potentiometers were calibrated on the same amount of load. Potentiometer (B) load was an load were measured and found to be correct.

(B) Test Load. These potentiometers were calibrated to a known weight which is known as the test load. The potentiometer was calibrated to the scale of the strain gauges and the load conditions were measured. In this manner a relationship was established between the deflection of the potentiometers and the various load weights. A full scale load was applied and again readings were recorded. In other words, the two potentiometers were calibrated on the same amount of load. Potentiometer (B) load was an load were measured and found to be correct.

(C) Deflection Potentiometer. The deflection of the potentiometer was measured by adjusting the loading from a known distance from the potentiometer.

lowering the gear a known deflection was incurred. This deflection was recorded on the Brush Recorder. A relation between landing wheel movement and the recording instrument was established through this action.

(D) Potentiometer. The potentiometer was the only article in the instrumentation which was not linear in recording characteristics. Here the oleo was deflected a prescribed amount and recordings were made. This was necessary because the potentiometer was operated by a scissors arrangement, and even under these conditions the values approached a straight line.

Testing procedure was begun when all the instruments were tested and calibrated. In order to operate the mechanism the Essex (test engine) was started and allowed to attain a fair rate of speed before engaging the reduction gear. Due to the weight of the large flywheel it was necessary to turn it over manually before tying in the drive system. Even under these conditions there was a great deal of slipping in the belting arrangement. This slipping occurred until the flywheel reached an approximate speed of twenty-five revolutions per minute. From this point the engine assumed control and was able to develop the speeds which were obtained during this study. The speeds were measured by a strobotac.

Upon reaching certain flywheel speeds, the operation shifted to where the strain gauges and controls for dropping had been placed. A quick release mechanism

[illegible]

18) Reflexion. The vestibular and the only
vibrations in the instrumented whole are not linear in
recording characteristics. The line can be divided
a specified amount and recording rate ratio. This can
be used to determine the distribution of the signal up to
the instrument, and even when the instrument is
the same as the instrument.

[illegible][illegible]

1. The first step is to identify the problem or question that needs to be answered. This involves understanding the context and the specific requirements of the task.

was fastened to an overhead hoist and elevated the dropping arm to a height which would give the desired sinking speed. Drops were made from heights to represent one to seven feet per second velocity at striking.

When the dropping arm was at a desired level the apparatus was ready to simulate a landing. The Brush oscilloscopes were started and the quick release mechanism was tripped. The forces and deflections which occurred during the first few seconds of each landing were recorded. This procedure was repeated for the various dropping heights and tire pressures until the data was completed.

Motion pictures were made of drops, Fig. Nos. 10 through 12, at a rate of one hundred frames per second.

was retained as an essential item and was not
dropped out of a single which would give the desired
standing speed. From this point the design of the
one to seven feet per second velocity of rotation.
When the dropping was at a desired level the
system was ready to release a landing. The design
analysis was repeated and the final design was
not yet complete. The design and the design were
continued until the final design of the design
was completed. This procedure was repeated for the
various dropping levels and the procedure until the
data was complete.

Initial design was made of three, five, and ten.

Figure 12, at a rate of one inch per second, is a design.

DISCUSSION

A strut angle of twenty-four degrees was chosen as the optimum angle of suspension. It was used as a point of departure for this thesis work and was suggested from another thesis developed simultaneously by H. Wood.¹ Only the forces up and down the strut are considered in developing the theory. This decision was made since the gear was in what was estimated to be the best angle.

The horizontal force problem which is neglected in this study is mentioned in the following remarks:

First: This force may be solved by equating internal energy to the external energy, but varying sectional moments of inertia pose another condition.

Second: In noting Fig. Nos. 8 to 23 inclusive, the drag and axial forces act in a uniform manner. Studying the areas under the force time curves might lead to a solution.

Third: A dynamic study of bearing friction and friction when striking contacts are made, may point to an answer of the drag force resulting from landing. Drag force is a function of friction and is of major

¹ "A Study of Dynamic Forces in Aircraft Landing Gear Struts with Relation to the Optimum Angle of Suspension", H. Wood, A Thesis for Degree of Master of Science in Aeronautical Engineering, July, 1949.

A direct analysis of the above-mentioned data was made as the optimum angle of observation. It was found that the points of maximum for the data were all well separated from the other points developed kinematically by H. H. H.

Only the focus on the first two categories in developing the theory. This section will be the first to be written in the next few days. The theoretical framework which is being used is the one that is being used in the first two categories.

This study is included in the following research:

Approved by the Board of Directors

the drug and metal content of the water supply.

[illegible]

1. A study of dynamic forces in aircraft landing gear systems with reference to the design of the landing gear system, a thesis for the degree of Master of Science, by J. J. Jones, Jr., Department of Mechanical Engineering, University of Michigan, 1954.

importance. A system of vectors and a knowledge of abrasion might suggest a solution.

The damping constant of the oleo was computed as follows for all the runs taken at twenty-four degrees. The axial force was known at a given time along with the spring constant of the strut. The amount by which the landing gear deflected for the above period of time was also known. These, too, were obtained from Fig. Nos. 8 through 23. Since

$$F = CX + kX$$

C can be obtained. Following this the average value of C from all the readings was computed.

The spring constants for the system were computed by applying static loads to the gear and measuring the deflections of the tire and oleo. By repeating this process a sufficient number of times a rather constant graph was obtained, Fig. No. 7.

The original proposal of this thesis was to study the variations of five parameters, but because of mechanical failure of the driving apparatus only two--dropping velocity and tire pressure--were investigated.

In the design of the apparatus a curvilinear drop is used instead of a true vertical motion. A pivot point is located in line with the top of the large fly-wheel joining a dropping arm. Therefore, from the time the tire initially touches the landing surface and until

important. A system of vents and a separator in
the main engine is required.

The design of the engine is based on
the fact that the engine is a two-stage engine.
The main engine is a two-stage engine with the
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engine. The engine is a two-stage engine with
the main engine being a two-stage engine.

the strut is completely deflected, the landing strut changes angle from one to two degrees. The amount of change depends on the original angle setting. The suspension angle is the angle referred to when the scissors of the gear are closed.

the effect is actually obtained, the resulting effect
changes with time in the system. The result of
the change depends on the initial angle of attack. The
relationship angle is the angle between the line
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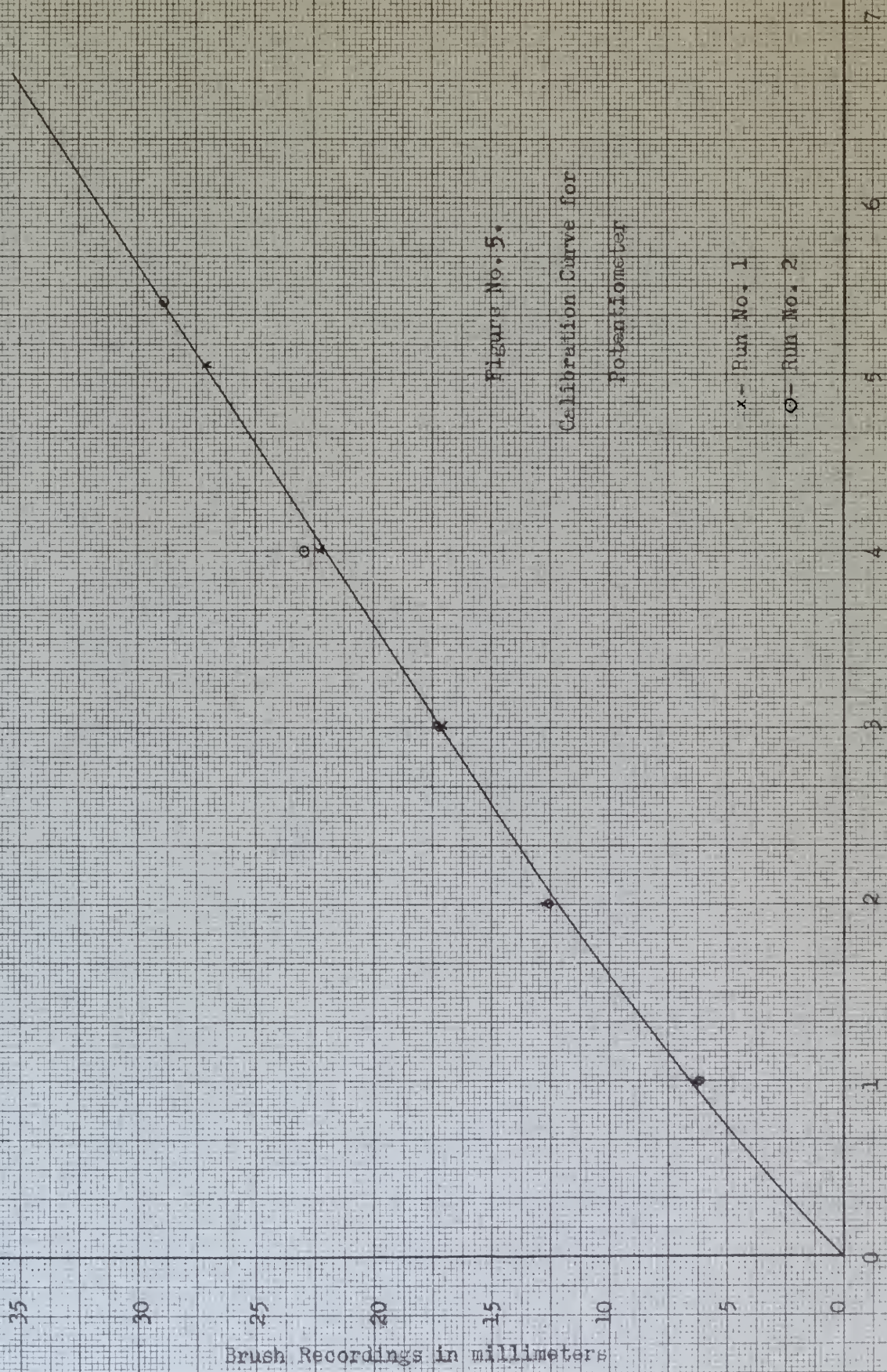


Figure No. 5.

Calibration Curve for
Potentiometer

x - Run No. 1

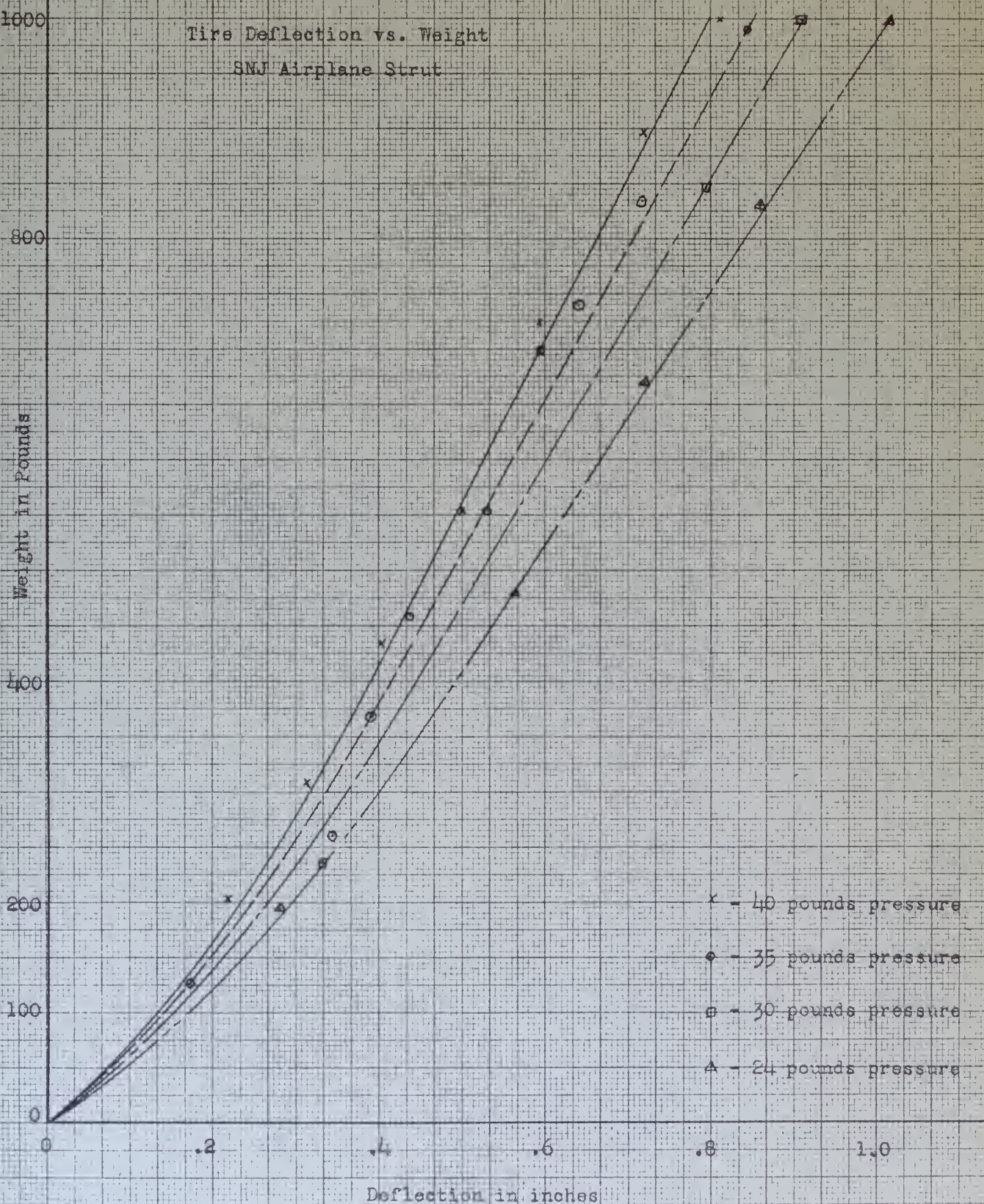
o - Run No. 2

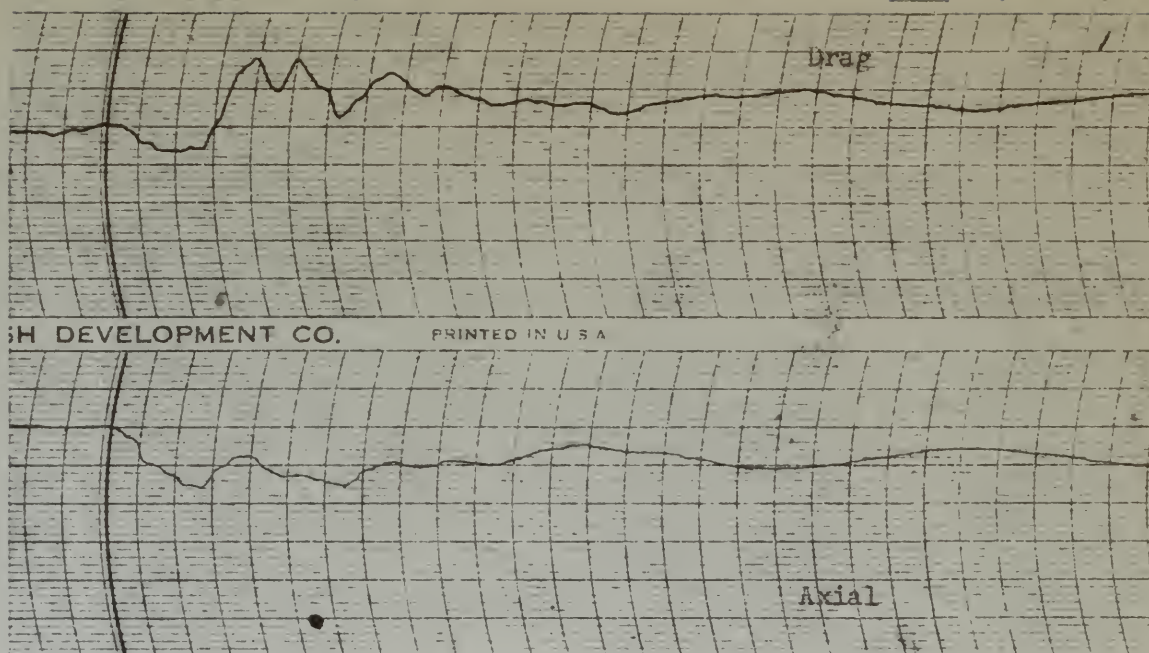
Cleo Deflection in inches.

Brush Recordings in millimeters

Figure No. 6

Tire Deflection vs. Weight
SNJ Airplane Strut





Calibration:

Drag - 1 mm - 220#
Axial - 5 mm = 930#

Cantilever - 1 mm = .375"
Potentiometer - Refer to Fig. No. 5.

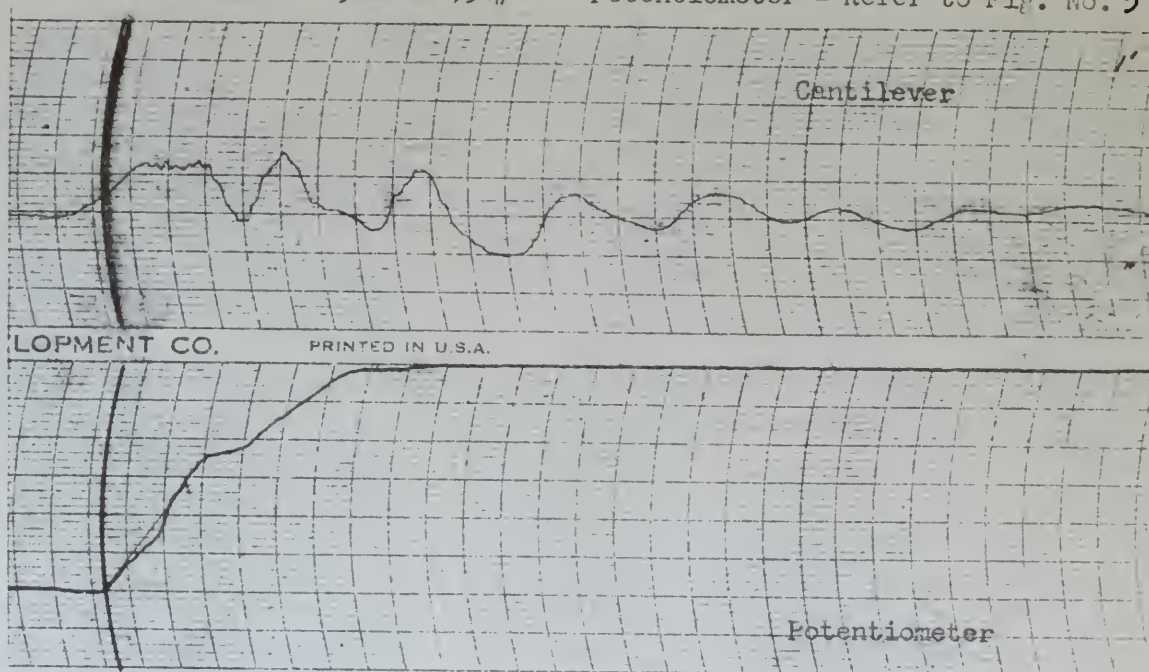
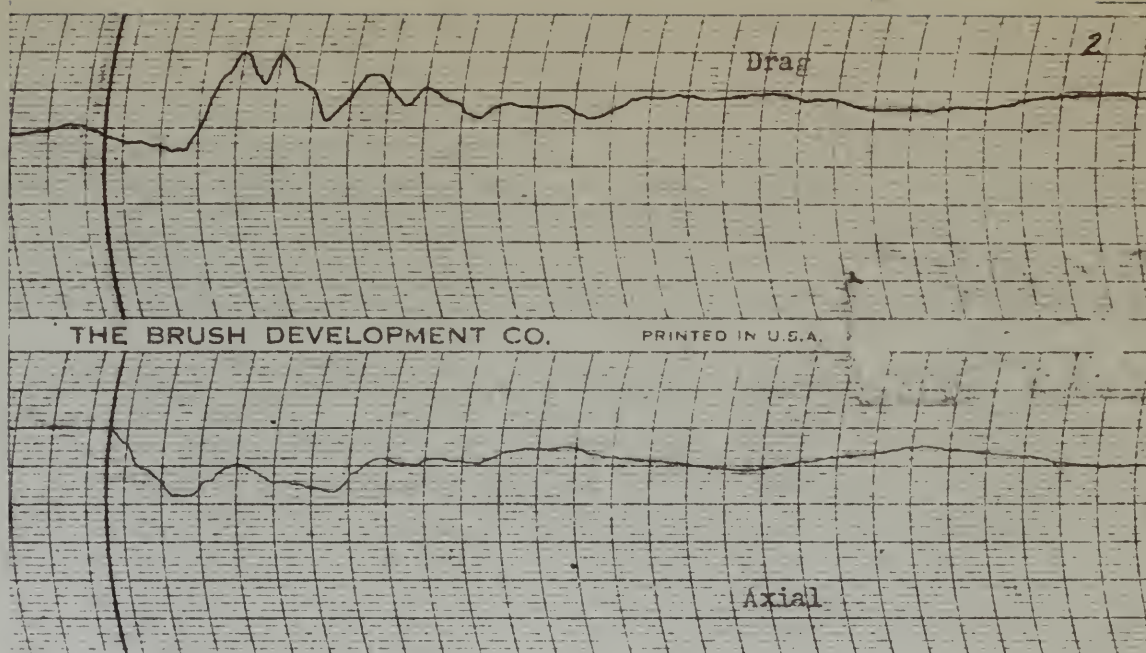


Fig. No. 8

Date: 7/10/49
Strut Angle - 24°
Weight - 1060#
Paper Speed 125 mm/sec

Tire Pressure - 24#
Landing Velocity - 58 FPS
Dropping Velocity - 2 FPS.



Calibration:

Drag - 1 mm = 220#

Axial - 5 mm = 930#

Cantilever - 1 mm = .375"

Potentiometer - Refer to Fig. No. 5.

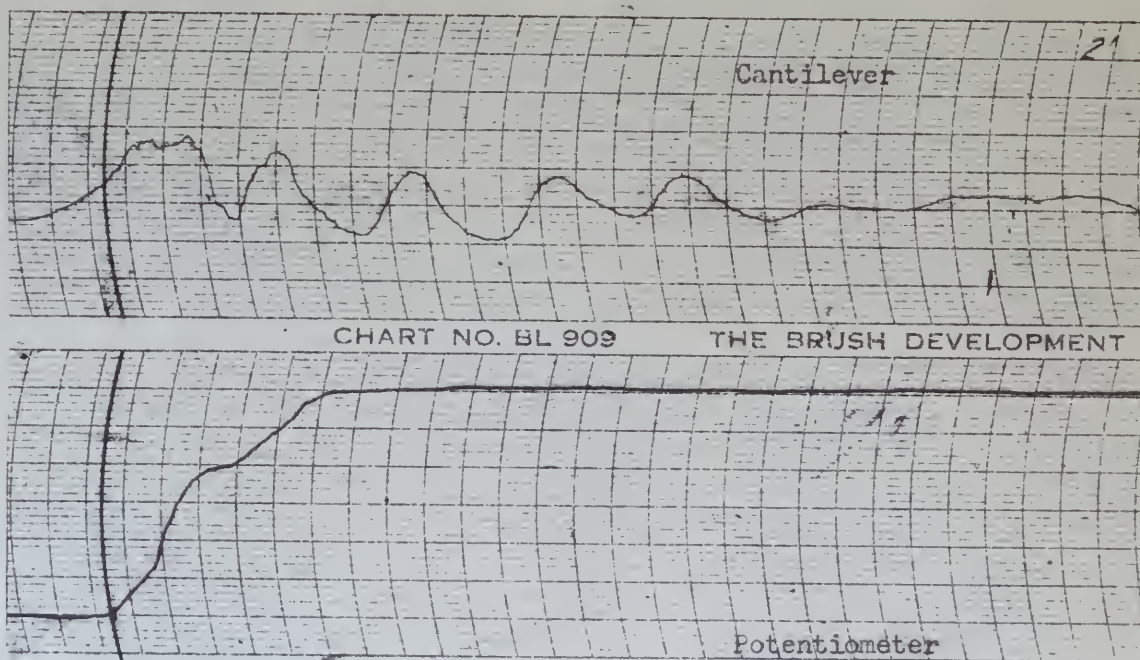


Fig. No. 9

Date: 7/10/49

Strut Angle - 24°

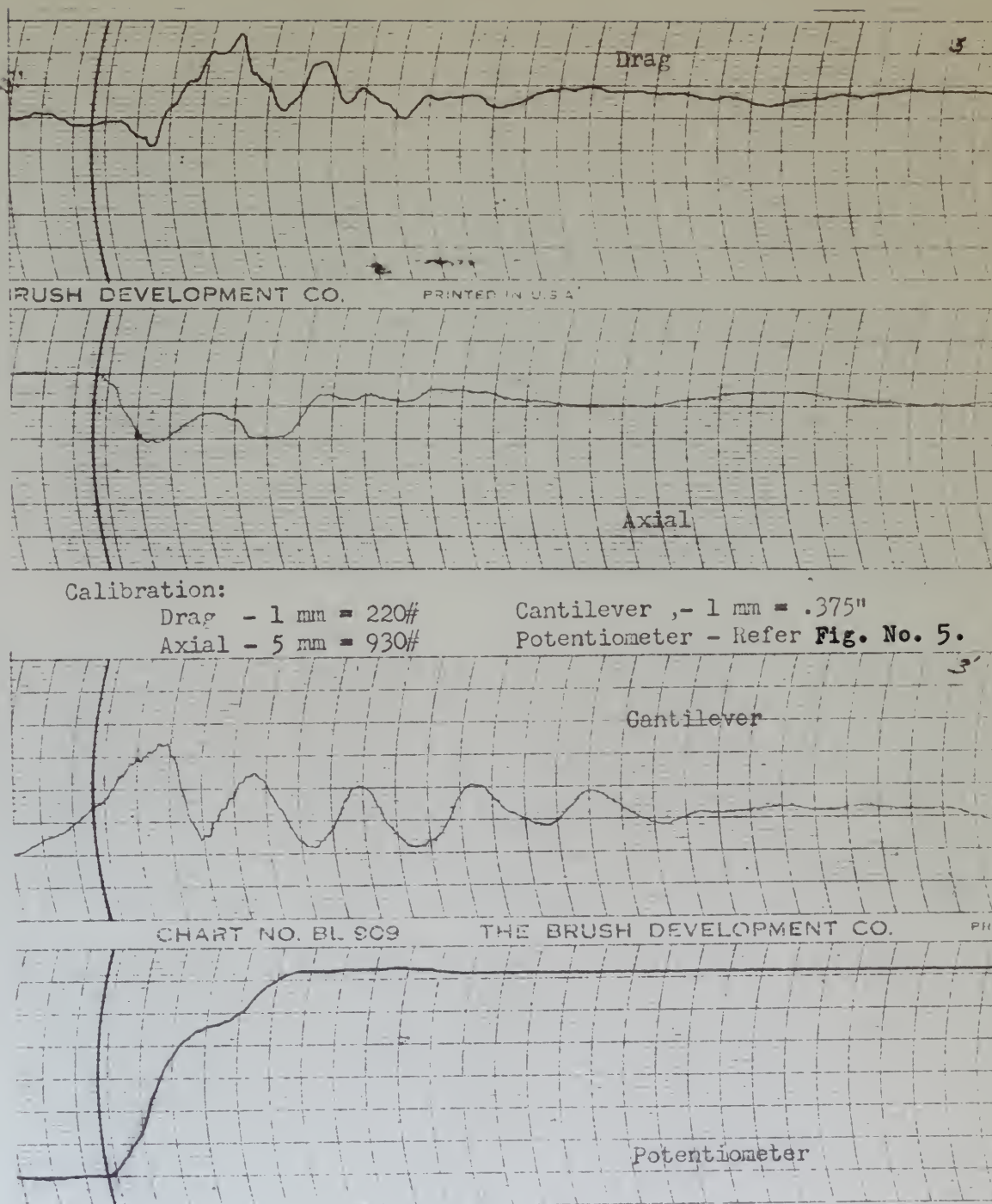
Weight - 1060#

Paper Speed 125 mm/sec

Tire Pressure - 24#

Landing Velocity - 58 FPS

Dropping Velocity - 3 FPS.



Calibration:

Drag - 1 mm = 220#

Axial - 5 mm = 930#

Cantilever, - 1 mm = .375"

Potentiometer - Refer Fig. No. 5.

Fig. No. 10

Date: 7/10/49

Strut Angle - 24°

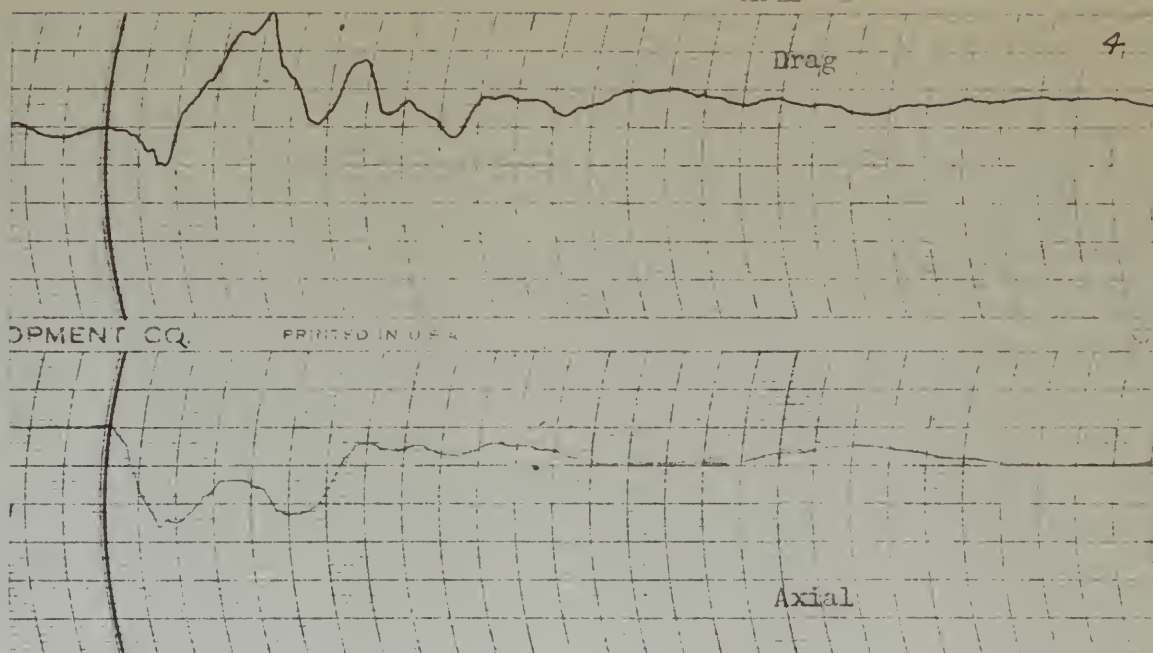
Height - 1060#

Brush Speed 125 mm/sec

Tire Pressure - 24#

Landing Velocity - 58 FPS

Dropping Velocity - 4 FPS.



Calibration:

Drag - 1 mm = 220#
 Axial - 5 mm = 930#

Cantilever - 1 mm = .375"
 Potentiometer - Refer Fig. No. 5.

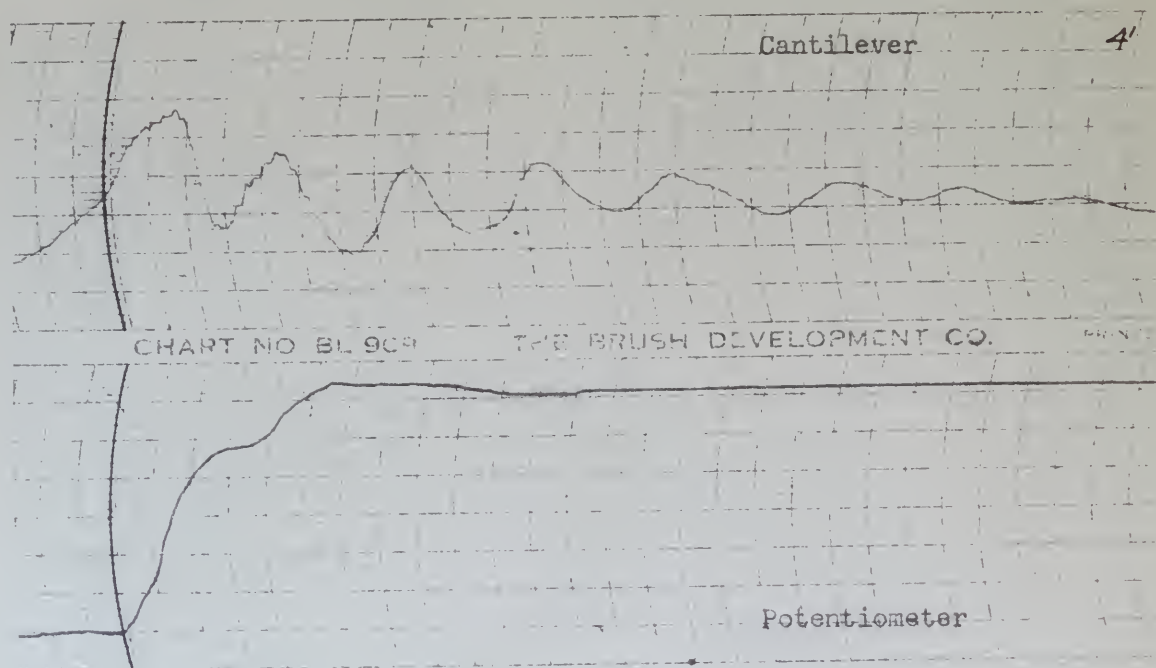


Fig. No. 11

Date: 7/10/49

Strut Angle - 24°

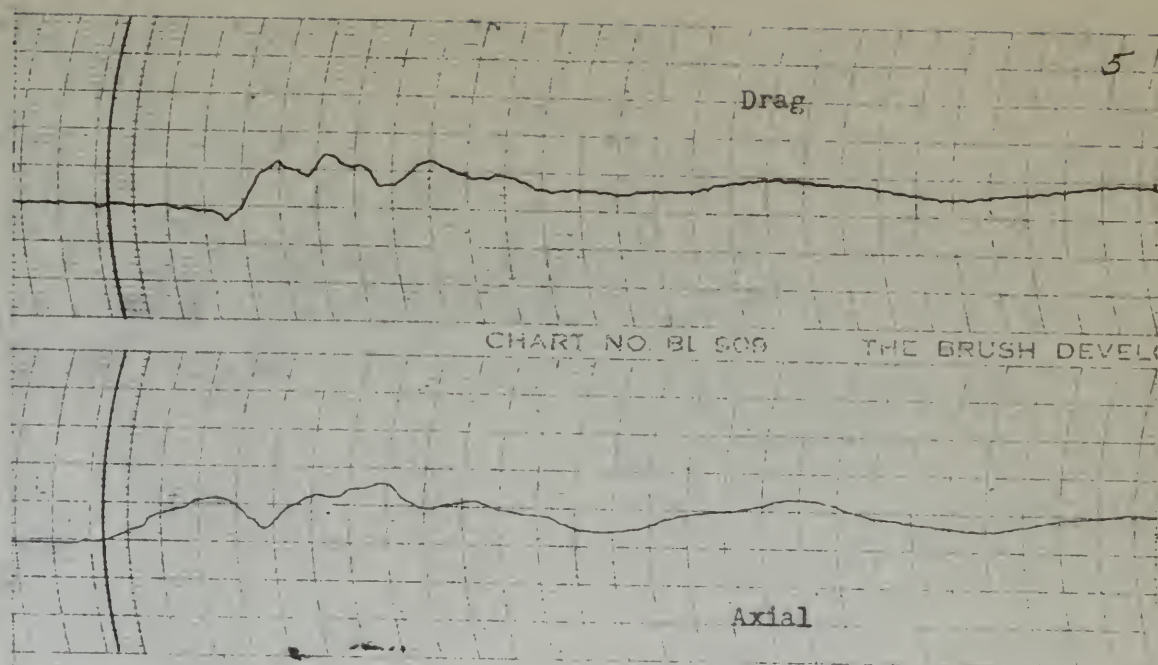
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 24#

Landing Velocity - 58 FPS.

Dropping Velocity - 5 FPS.



Calibration:

Drag - 1 mm = 110#

Cantilever - 1 mm. = .416u

Axial - 5 mm = 835#

Potentiometer - Refer to Fig. No. 5

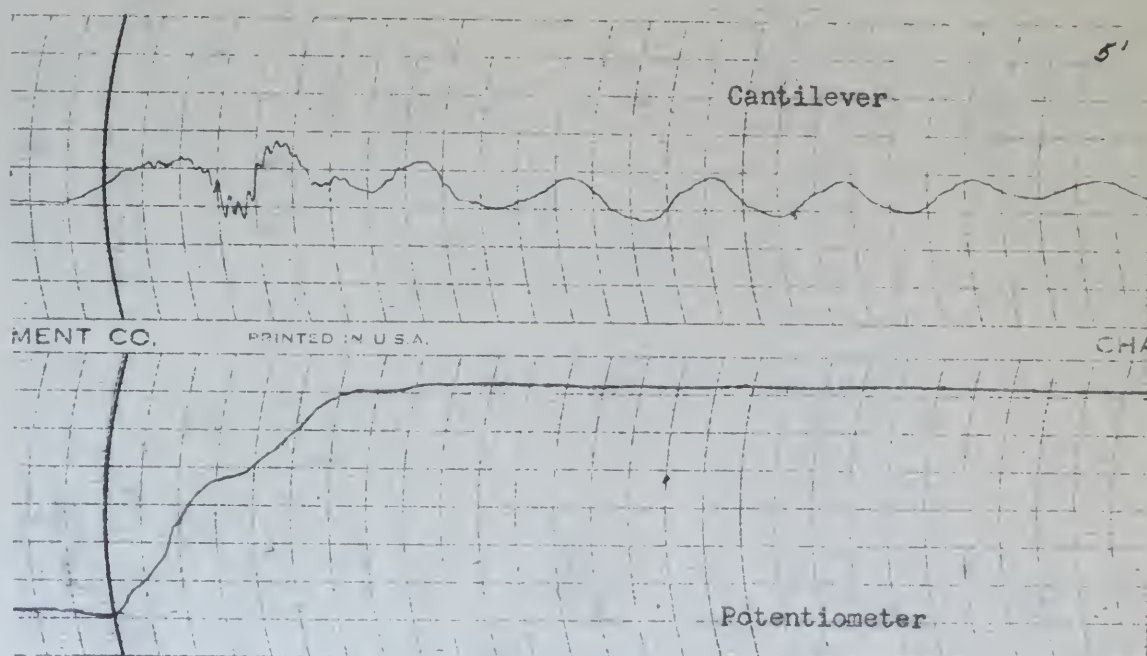


Fig. No. 12

Date: 7/13/49

Strut Angle - 24°

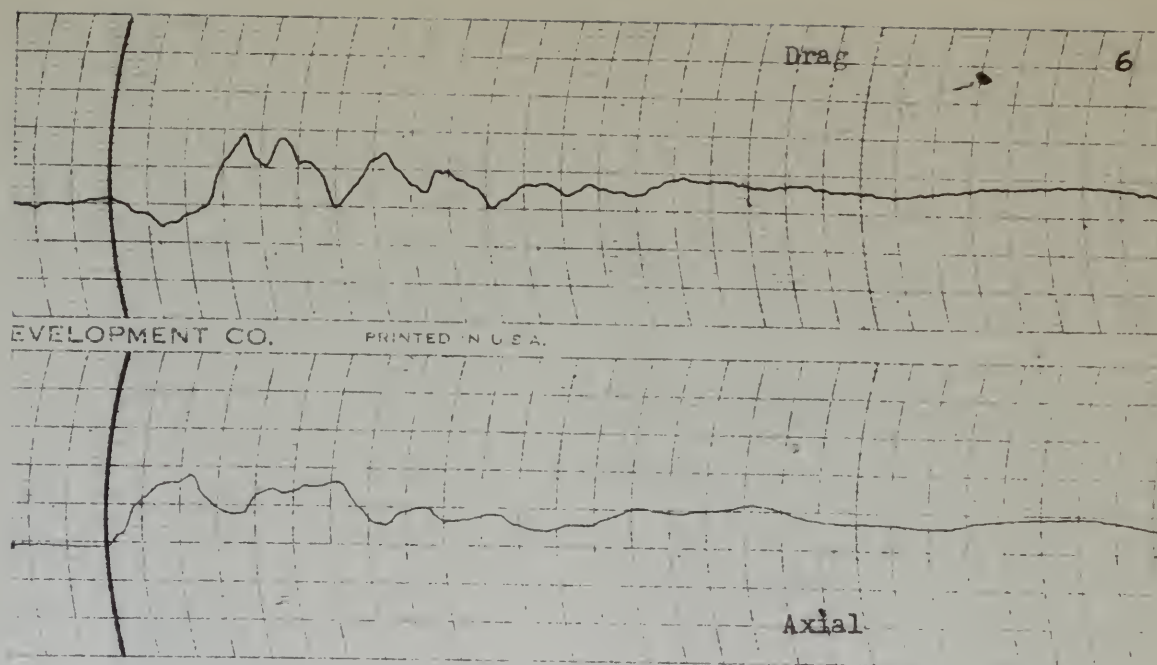
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 30#

Landing Velocity - 55.5 FPS

Dropping Velocity - 2 FPS.



Calibration:

Drag - 1 mm = 110#
Axial - 5 mm = 835#

Cantilever - 1 mm = .416"
Potentiometer - Refer to Fig. No. 5.

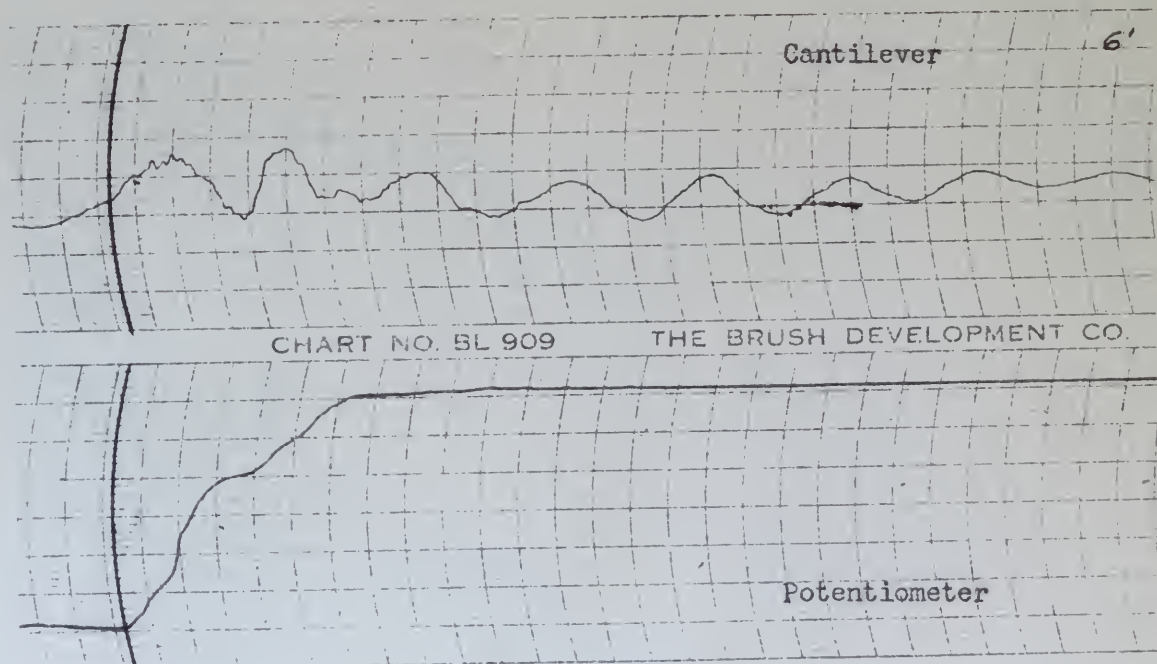
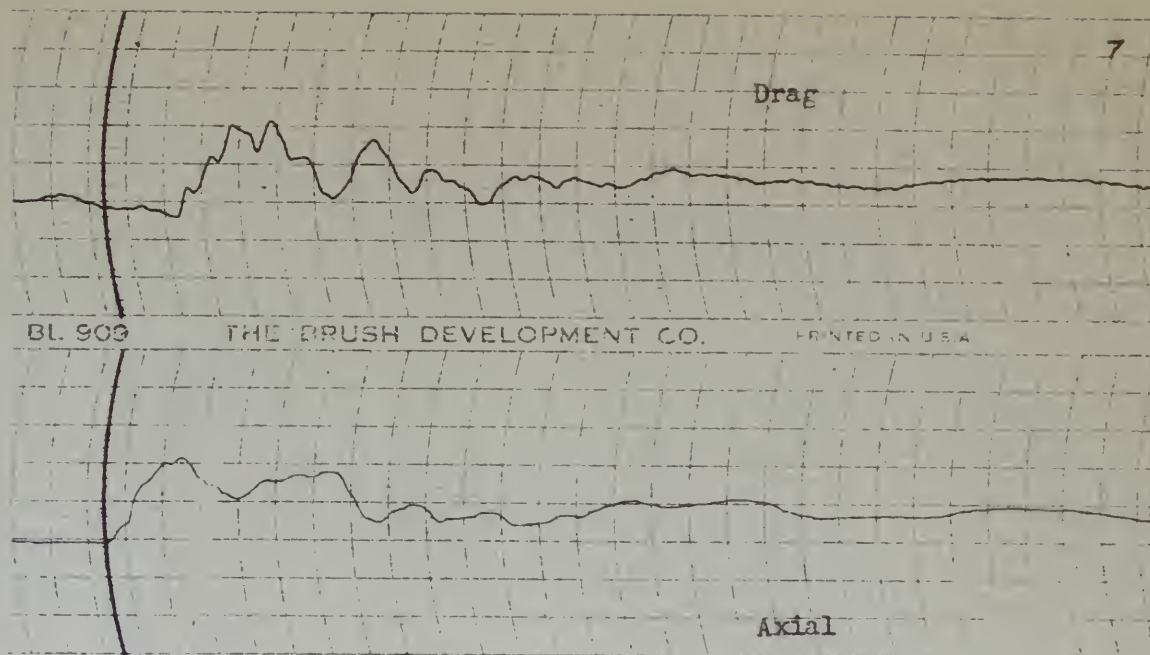


Fig. No. 13

Date: 7/13/49
Strut Angle - 24°
Weight - 1060#
Brush Speed 125 mm/sec.

Tire Pressure - 30#
Landing Velocity - 55.5 FPS.
Dropping Velocity - 3 FPS.



Calibration:

Drag - 1 mm = 110#
 Axial - 5 mm = 835#

Cantilever - 1 mm = .416"
 Potentiometer - Refer to Fig. No. 5.

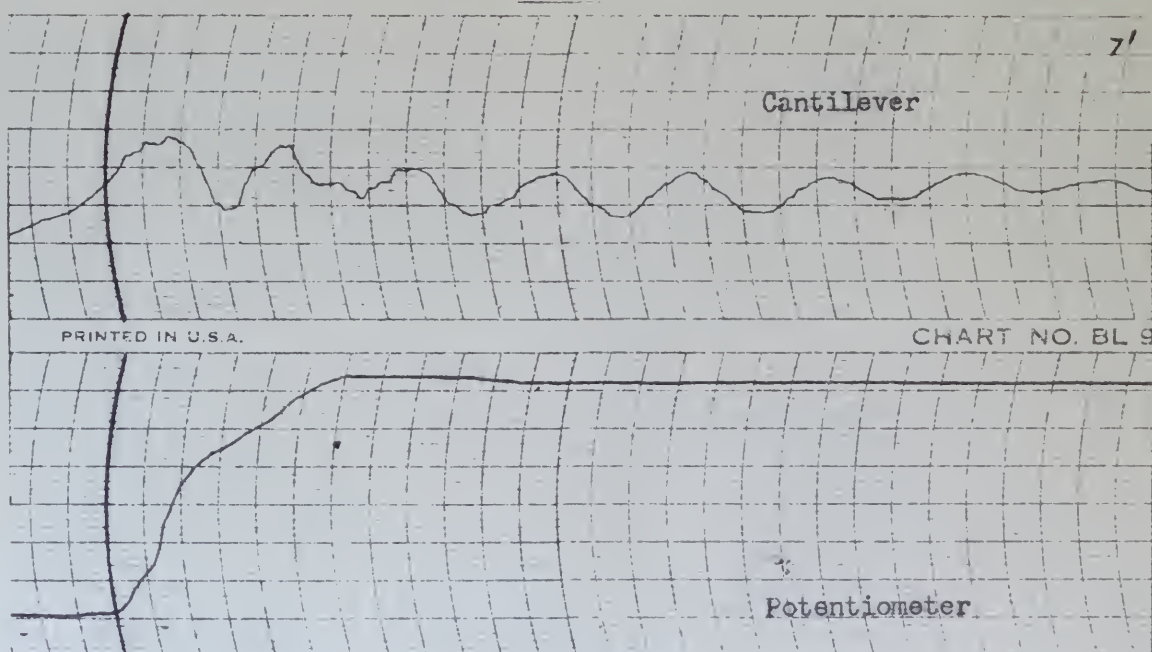
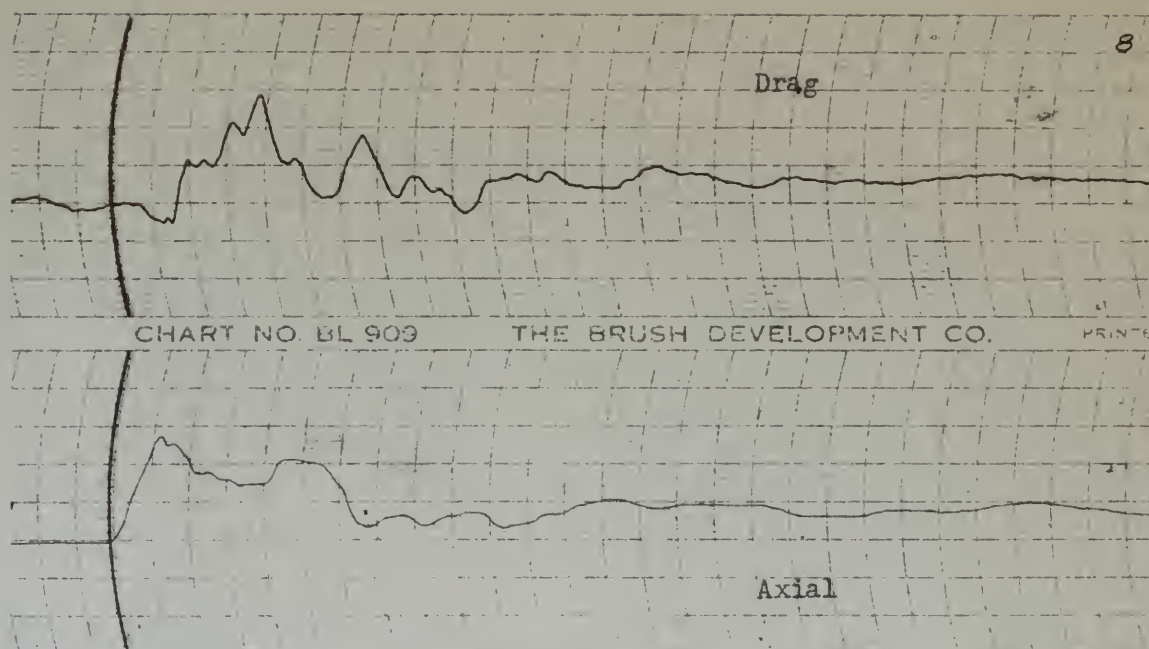


Fig. No. 14

Date: 7/13/49
 Strut Angle - 24°
 Weight - 1060#
 Brush Speed 125 mm/sec.

Tire Pressure - 30#
 Landing Velocity - 55.5 FPS
 Dropping Velocity - 4 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .416"

Potentiometer - Refer to Fig. No. 5.

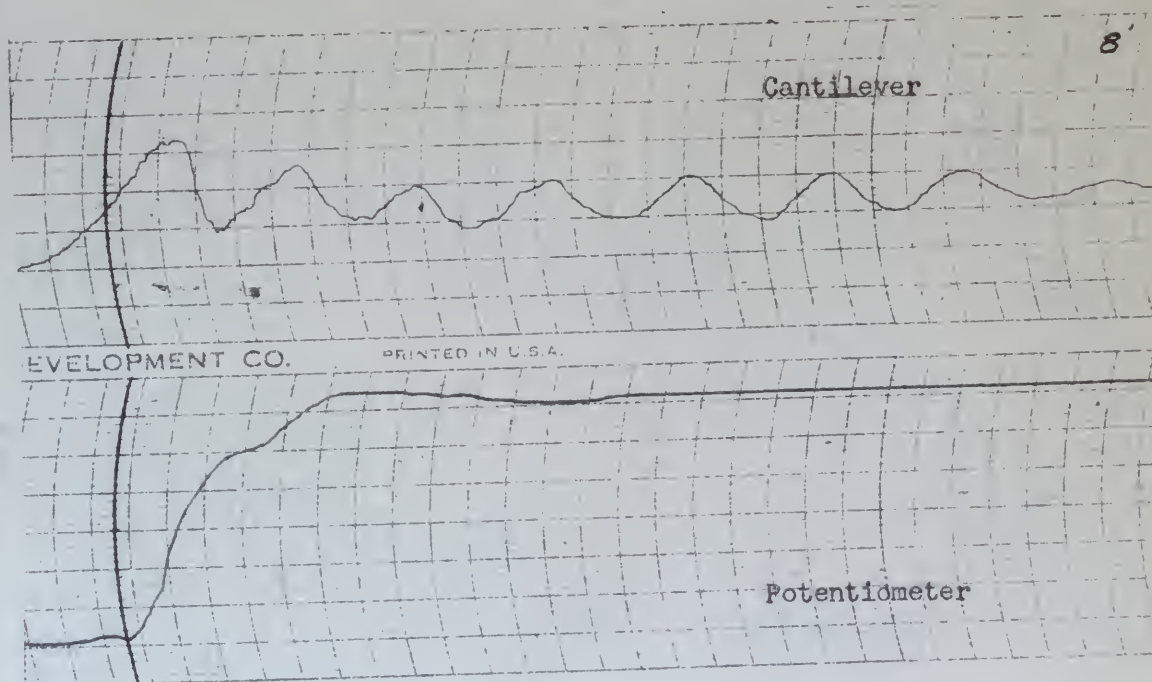


Fig. No. 15

Date: 7/13/49

Strut Angle - 24°

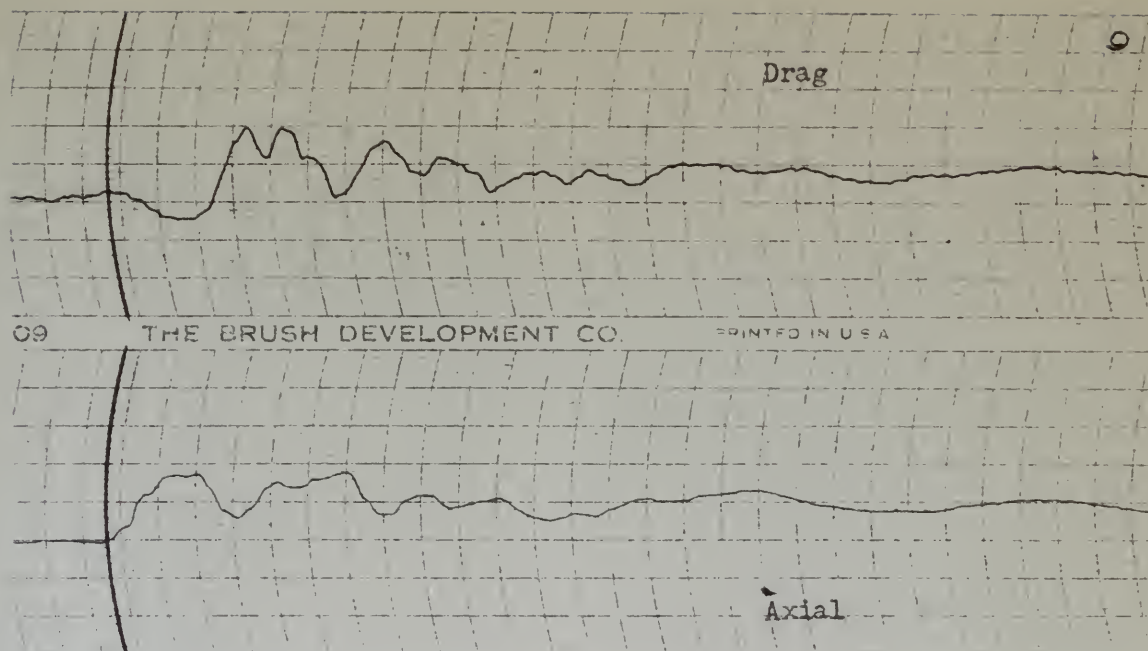
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 30#

Landing Velocity - 55.5 FPS

Dropping Velocity - 5 FPS.



Calibration:

Drag - 1 mm = 110#

Cantilever - 1 mm = .416 "

Axial - 5 mm = 835#

Potentiometer - Refer to Fig. No. 5.

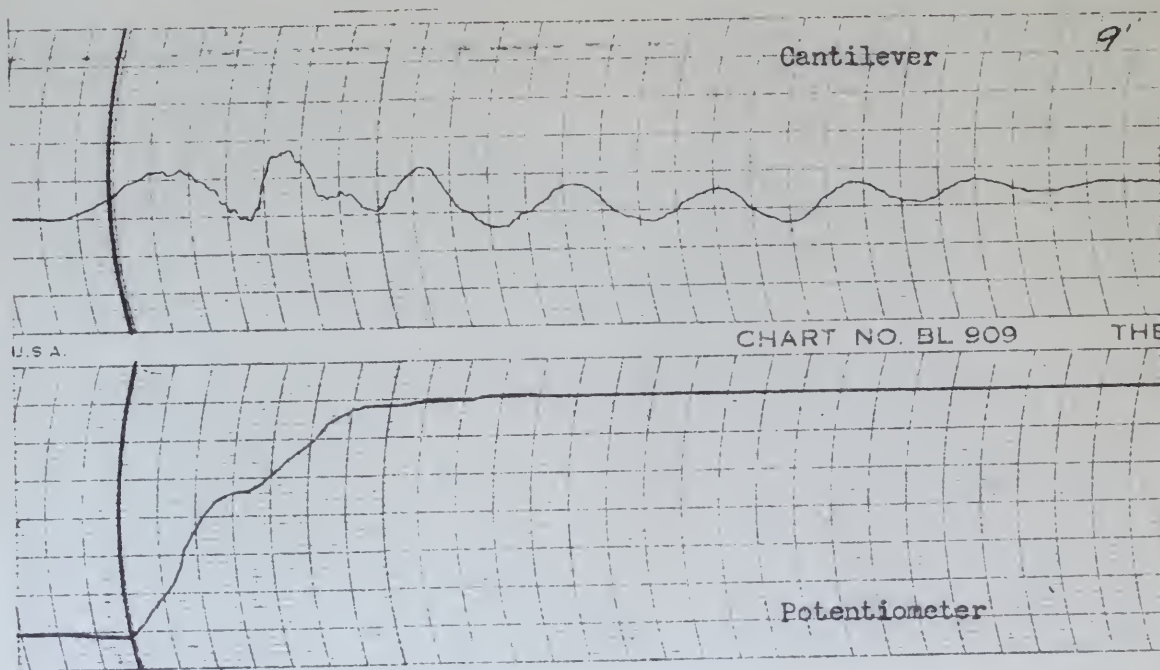


Fig. No. 16

Date: 7/13/49

Strut Angle - 24°

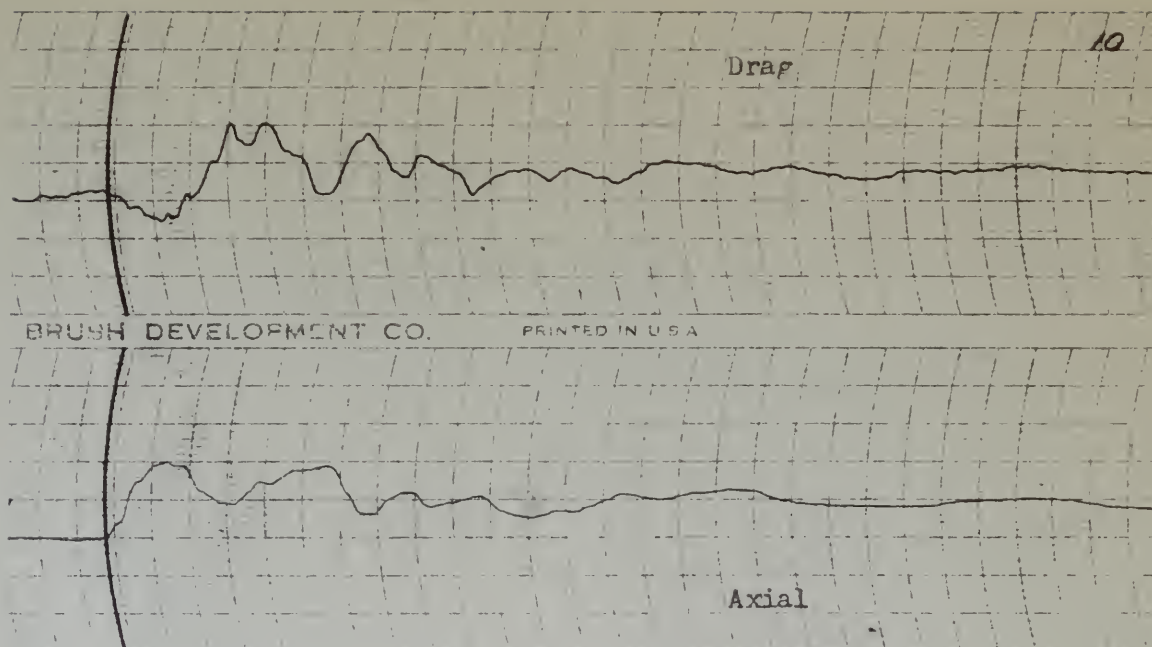
Weight - 1060#

Brush Speed 125 mm/sec

Tire Pressure 35#

Landing Velocity - 56 FPS

Dropping Velocity - 2 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .416"

Potentiometer - Refer to Fig. No. 5.

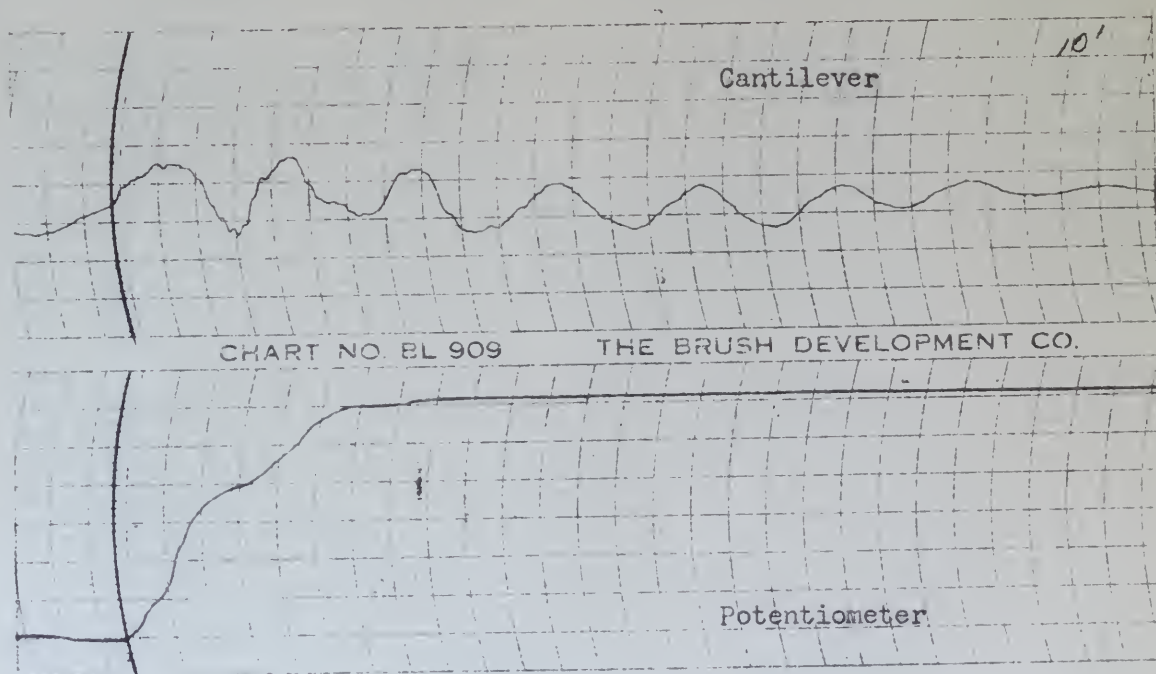


Fig. No. 17

Date: 7/13/49

Strut Angle - 24°

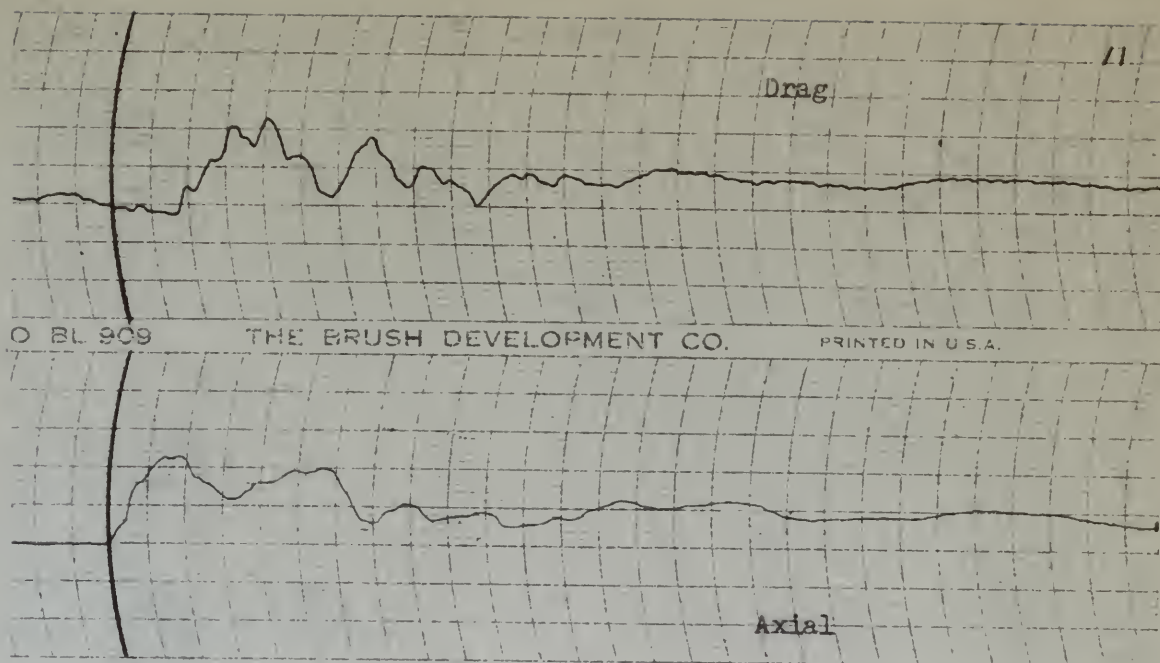
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure 35#

Landing Velocity - 56 FPS

Dropping Velocity - 3 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .416"

Potentiometer - Refer to Fig. No. 5.

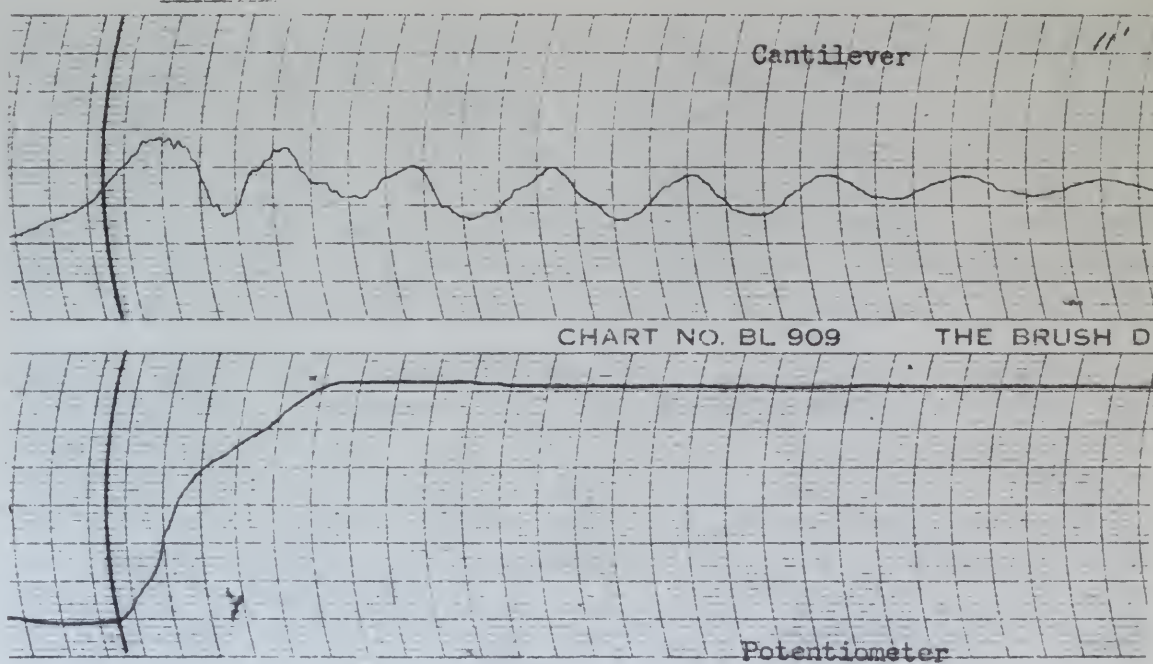


Fig. No. 18

Date: 7/13/49

Strut Angle -24°

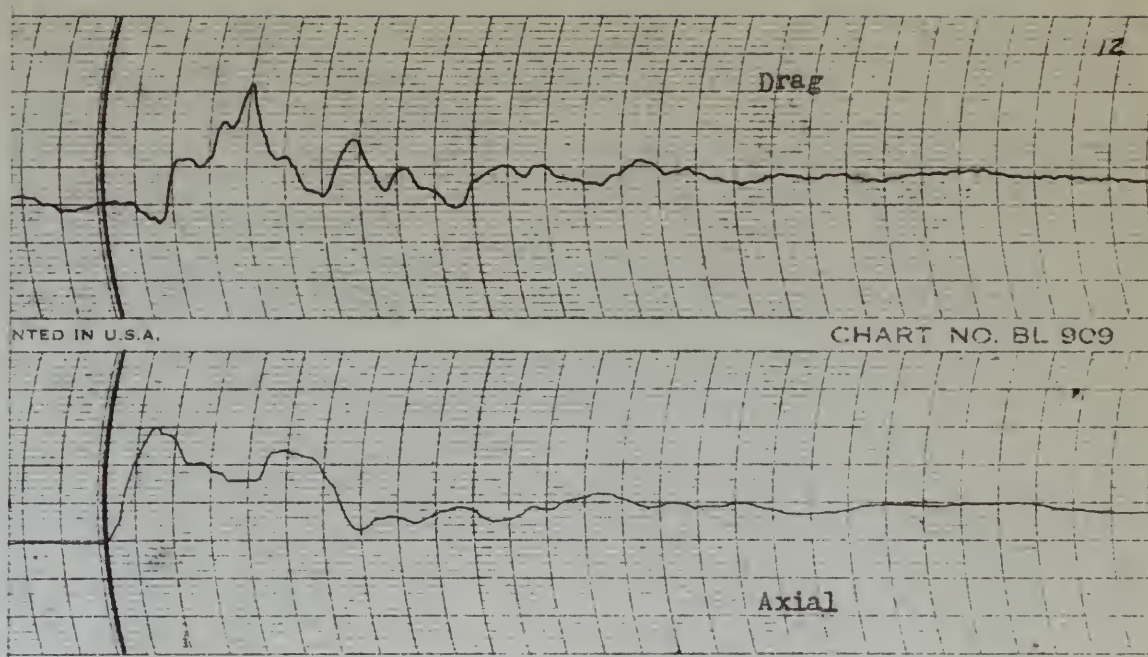
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 35#

Landing Velocity - 56 FPS

Dropping Velocity - 4 FPS.



Calibration:

Drag - 1 mm = 110#
 Axial - 5 mm = 835#

Cantilever - 1 mm = .416"
 Potentiometer - Refer to Fig. No. 5.

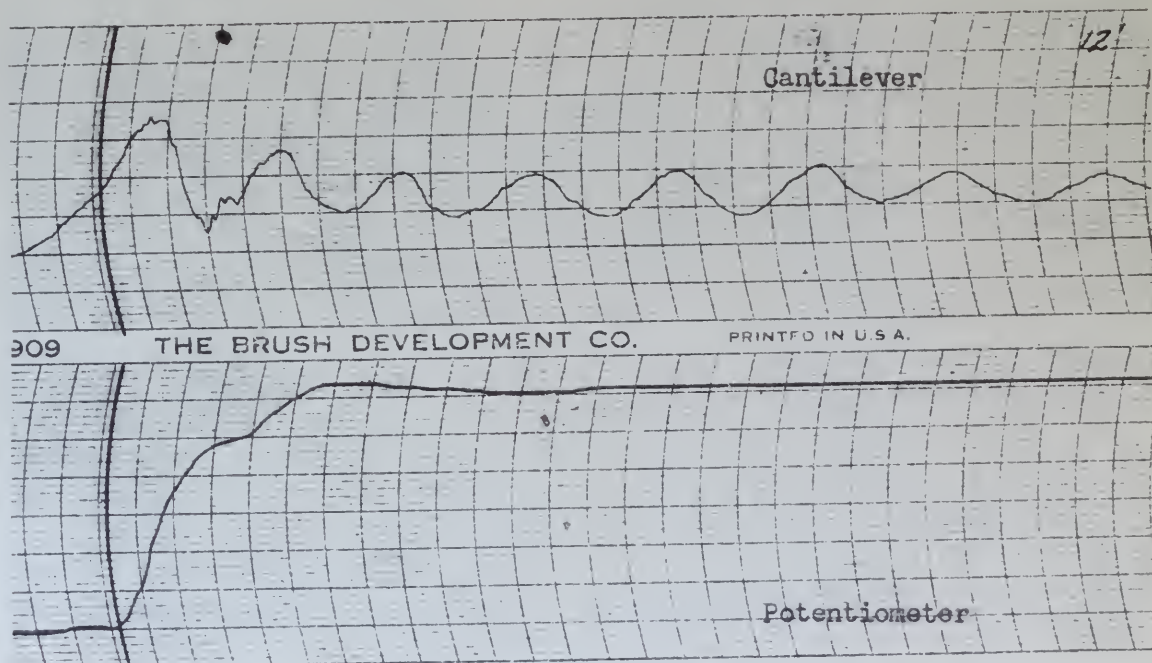
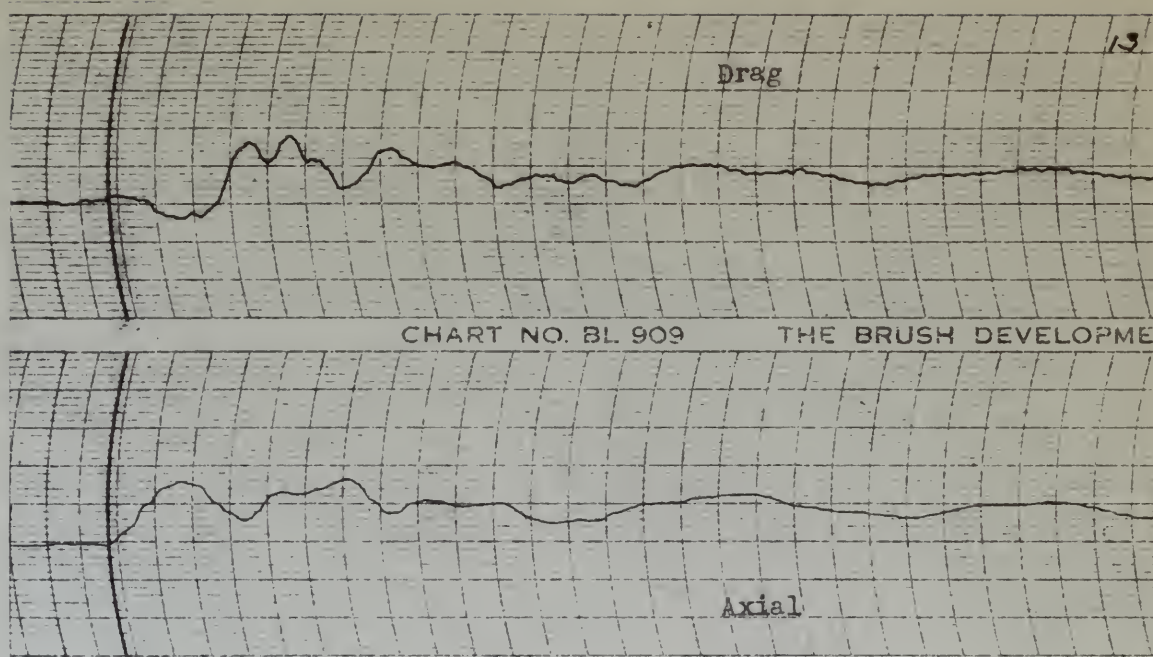


Fig. No. 19

Date: 7/13/49
 Strut Angle - 24°
 Weight - 1060#
 Brush Speed 125 mm/sec.

Tire Pressure - 35#
 Landing Velocity - 56 FPS
 Dropping Velocity - 5 FPS.



Calibration:

Drag - 1 mm = 110#
Axial - 5 mm = 835#

Cantilever-1 mm = .208"
Potentiometer - Refer to Fig. No. 5

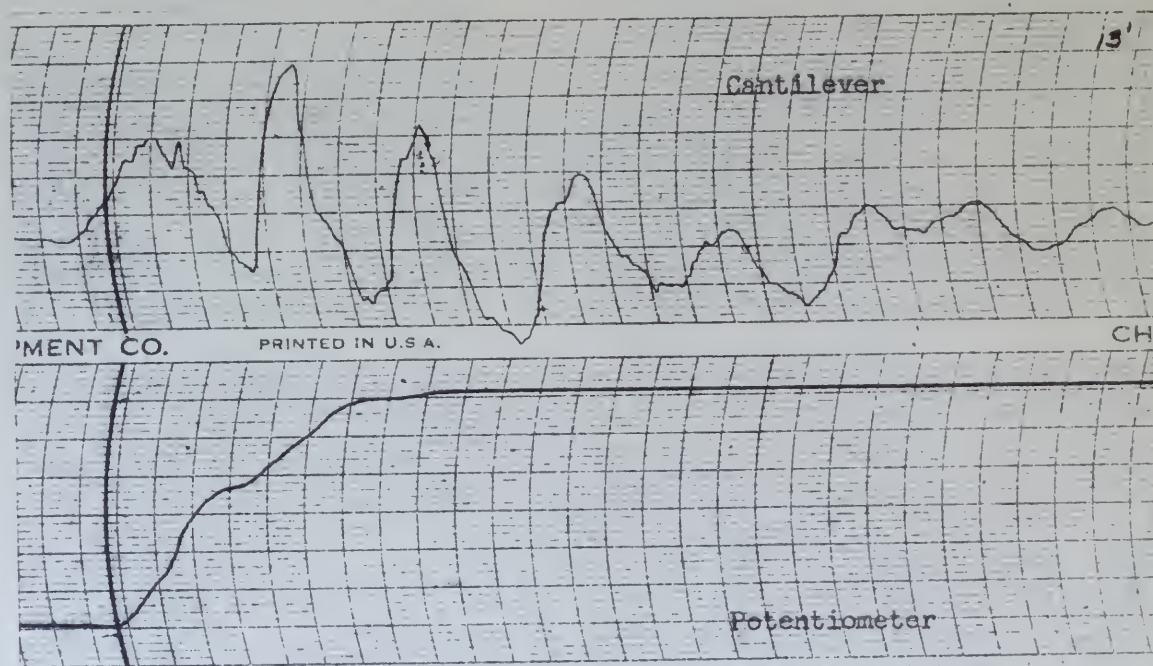
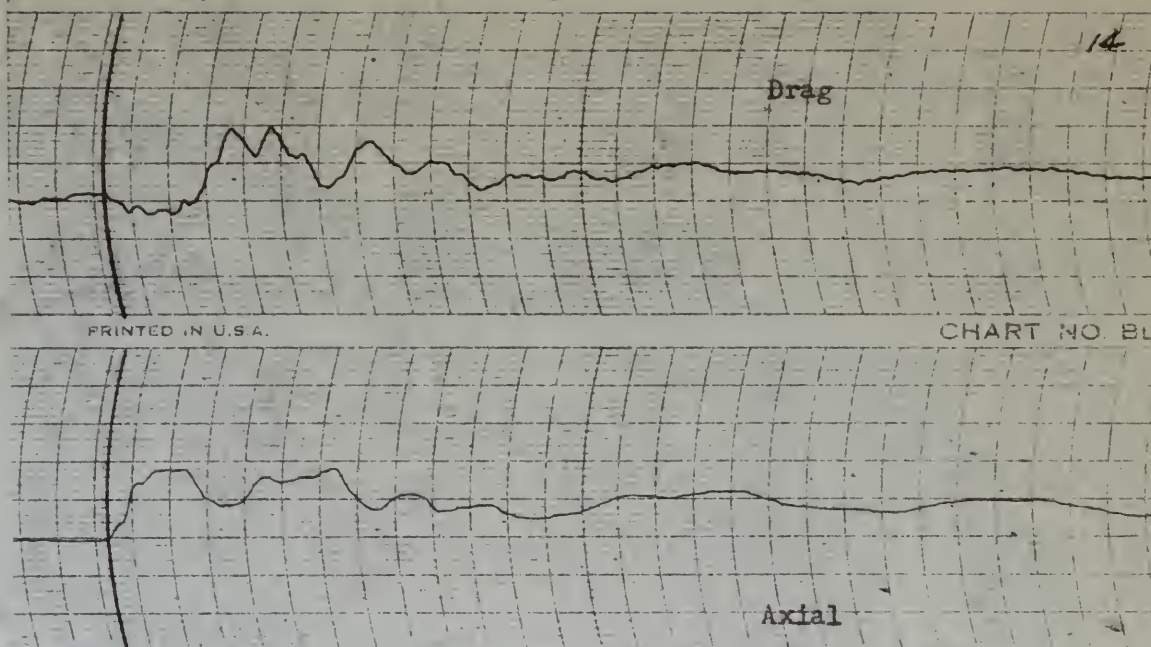


Fig. No. 20

Date: 7/13/49
Strut Angle - 24°
Weight - 1060#
Brush Speed 125 mm/sec.

Tire Pressure - 40#
Landing Velocity - 56 FPS.
Dropping Velocity - 2 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .208"

Potentiometer - Refer to Fig. No. 5.

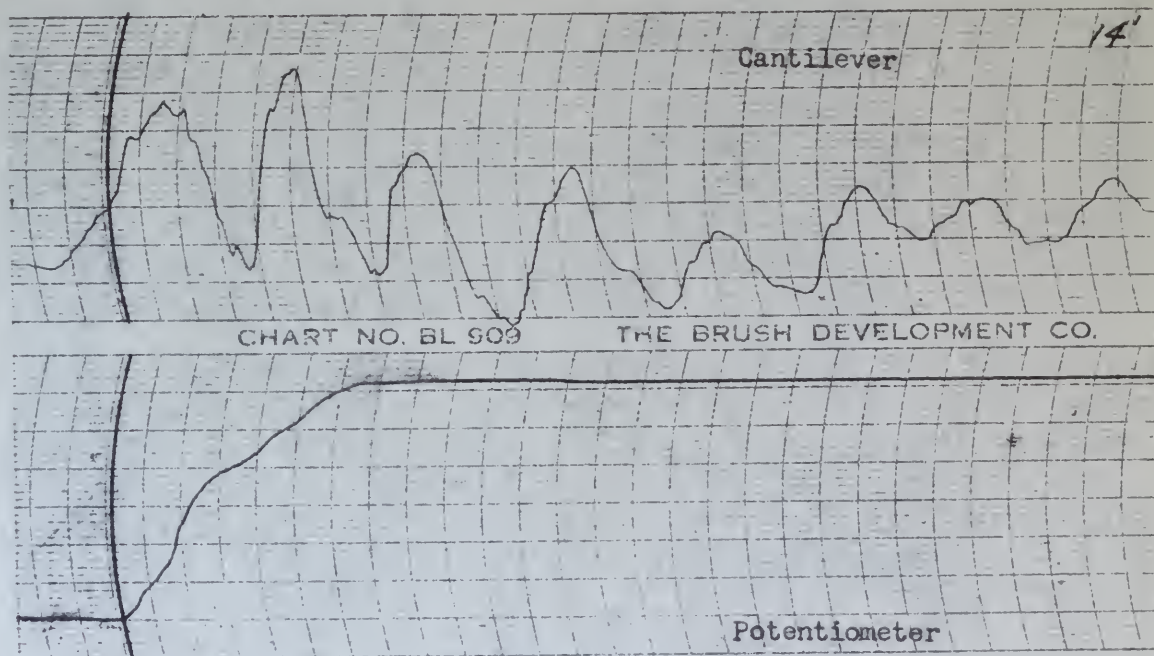


Fig. No. 21

Date: 7/13/49

Strut Angle - 24°

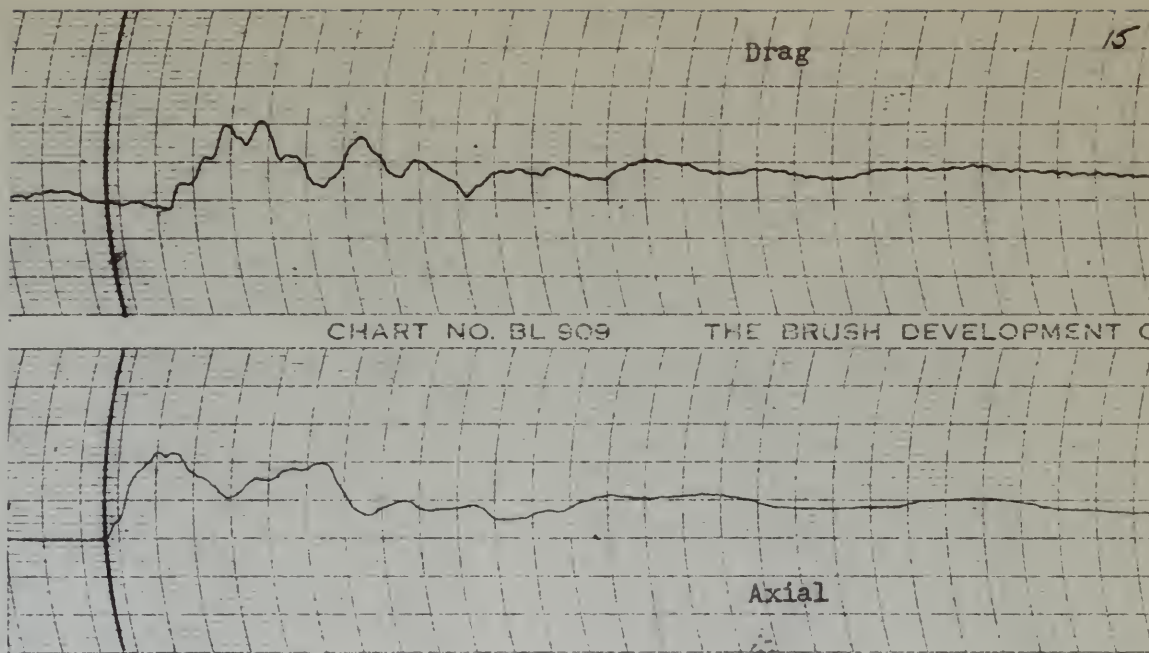
Weight - 1060#

Brush Speed 125 mm/sec

Tire Pressure - 40#

Landing Velocity - 56 FPS.

Dropping Velocity - 3 FPS.



Calibration:

Drag - 1 mm = 110#
Axial - 5 mm = 835#

Cantilever - 1 mm = .208"

Potentiometer - Refer to Fig. No. 5.

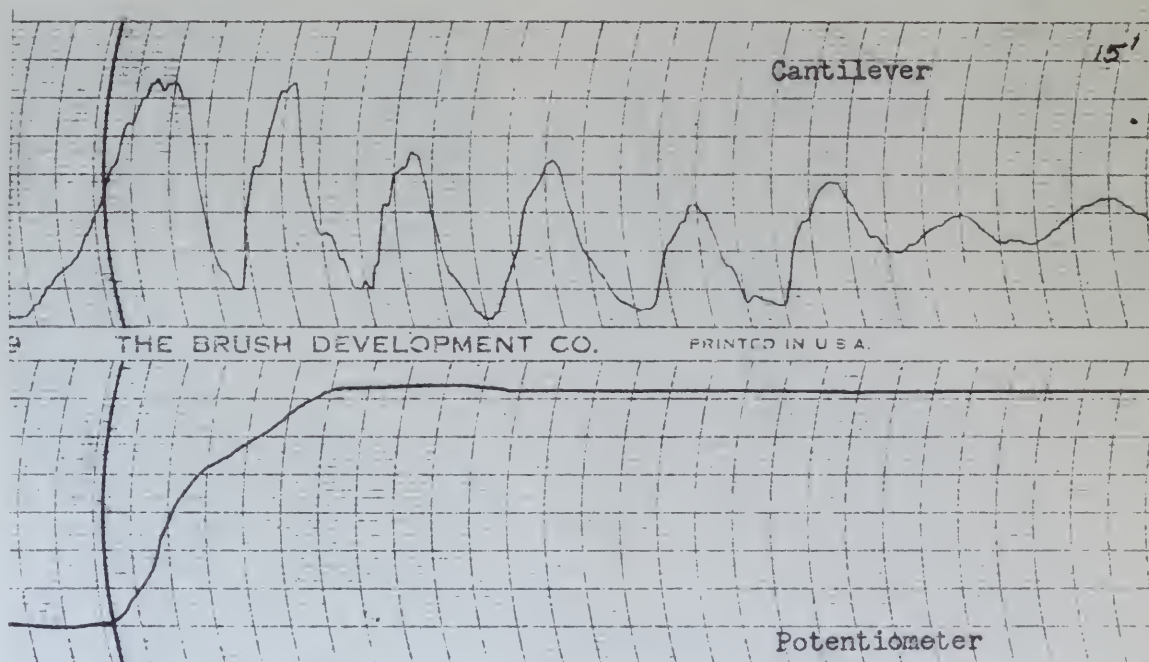


Fig. No. 22

Date: 7/13/49

Strut Angle - 24°

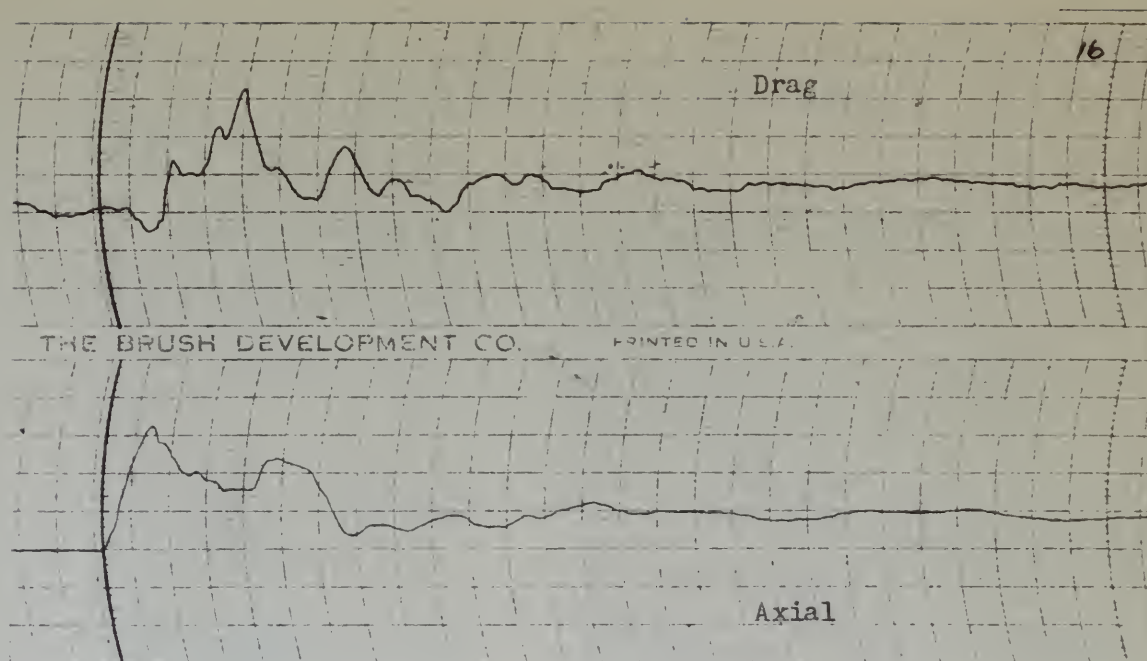
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 40#

Landing Velocity - 56 FPS.

Dropping Velocity - 4 FPS.



Calibration:

Drag - 1 mm = 110#
Axial - 5 mm = 835#

Cantilever - 1 mm = .208"
Potentiometer - Refer to Fig. No. 5.

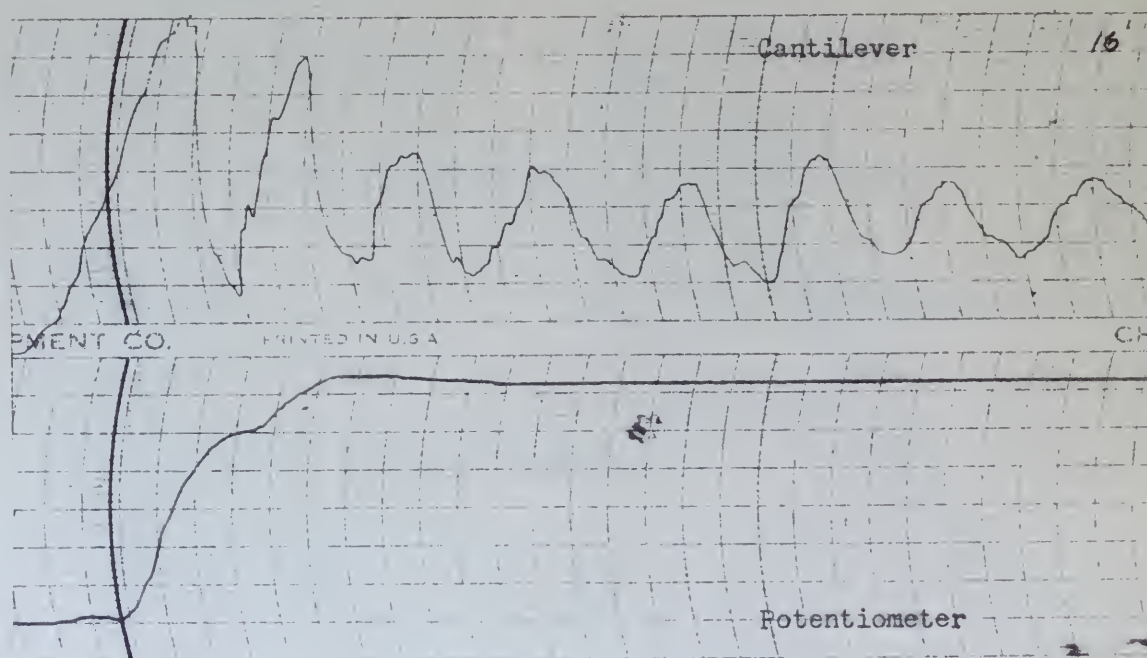


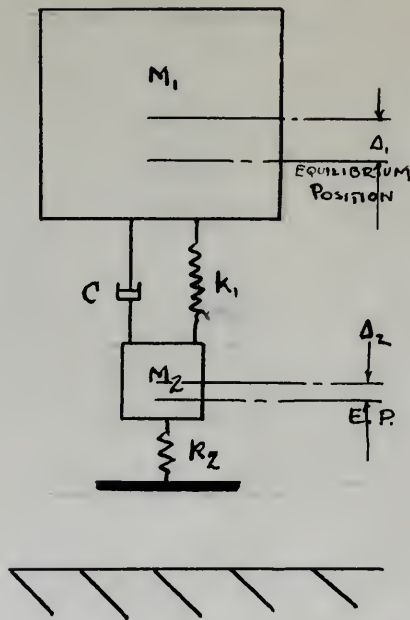
Fig. No. 23

Date: 7/13/49
Strut Angle - 24°
Weight - 1060#
Brush Speed 125 mm/sec.

Tire Pressure - 40#
Landing Velocity - 56 FPS.
Dropping Velocity - 5 FPS.

COMPARISON OF THE TEST AND THEORY

The following problem incorporates the constants computed into the theory developed.



$$w_1 = 939 \#$$

$$w_2 = 121 \#$$

$$M_1 = 29.16 \# \text{sec.}^2/\text{ft.}$$

$$M_2 = 3.76 \# \text{sec.}^2/\text{ft.}$$

$$k_{\text{effective}} = k_{\text{measured}} \cos 24^\circ$$

$$k_1 = 1584 \#/\text{ft.}$$

$$k_2 = 11280 \#/\text{ft.}$$

$$-\Delta_1 = -.094 \text{ ft.}$$

$$k_2 = 12300 \#/\text{ft.}$$

$$-\Delta_2 = -.636 \text{ ft.}$$

DETERMINATION OF (C) DAMPING CONSTANT

Example:

From Fig. No. 14

$$\dot{x} = \frac{dx}{dt} = \frac{1.07}{.04} = 26.8 \text{ ft./sec.}$$

at $t = .04 \text{ sec.}$

$$R_1 = 69 \#/\text{in.}$$

$$F = \frac{9.5}{5} \times 835 \# = 1615 \#$$

Oleo Deflection = 1.07 inches

$$F = C\dot{x} + k_1 x$$

$$1615 = C26.8 + 69 \times 1.07$$

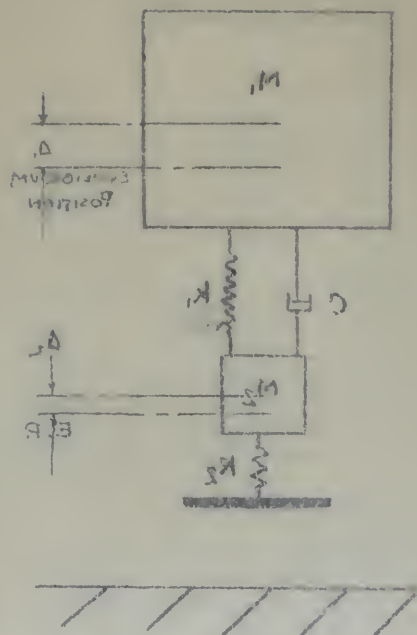
$$C = \frac{1549}{26.8} = 57.5 \# \text{sec./in.}$$

$$C = 688 \# \text{sec./ft.}$$

IDENTIFICATION OF THE TEST AND THEORY

The following problem incorporates the elements

computed into the theory developed.



$$M_1 = 100 \text{ lb}$$

$$M_2 = 10 \text{ lb}$$

$$K_1 = 20.16 \text{ lb/in.}$$

$$K_2 = 1.76 \text{ lb/in.}$$

$$C = 1.76 \text{ lb-sec/in.}$$

$$\Delta_1 = 1.571 \text{ in.}$$

$$\Delta_2 = 1.571 \text{ in.}$$

$$\Delta_1 = -1.571 \text{ in.}$$

$$\Delta_2 = 1.571 \text{ in.}$$

$$\Delta_1 = -1.571 \text{ in.}$$

IDENTIFICATION OF THE THEORY

Example:

$$M = \frac{100}{32} = 3.125 \text{ lb-sec}^2/\text{in.}$$

$$K = 20.16 \text{ lb/in.}$$

$$C = 1.76 \text{ lb-sec/in.}$$

$$M = 3.125 \text{ lb-sec}^2/\text{in.}$$

$$K = 20.16 \text{ lb/in.}$$

$$C = 1.76 \text{ lb-sec/in.}$$

$$M = 3.125 \text{ lb-sec}^2/\text{in.}$$

$$K = 20.16 \text{ lb/in.}$$

$$C = 1.76 \text{ lb-sec/in.}$$

$$M = 3.125 \text{ lb-sec}^2/\text{in.}$$

$$C_{ave.} = \underline{\underline{653}}$$

Equations of Motion

$$-M_1 \ddot{x}_1 - C(\dot{x}_1 - \dot{x}_2) - k_1(x_1 - x_2) = 0$$

$$-M_2 \ddot{x}_2 - k_2 x_2 + k_1(x_1 - x_2) + C(\dot{x}_1 - \dot{x}_2) = 0$$

Or

$$s^4 + 196s^3 + 3,475.65s^2 + 67,182.05s + 162,965.34 = 0$$

By Synthetic Division

$$s_1 = -2.759$$

$$s_2 = 178.62$$

$$s_3 = -7.31 - i 16.65$$

$$s_4 = -7.31 + i 16.65$$

$$A = \phi_1 A'$$

$$A = -50.03A'$$

$$B = \phi_2 B'$$

$$B = -.141B'$$

$$C = \phi_3 C'$$

$$C = .663 + i .862$$

$$D = \phi_4 D'$$

$$D = .663 - i .862$$

$$A' = \frac{E_1}{E}; B' = \frac{E_2}{E}; C' = \frac{E_3}{E}; D' = \frac{E_4}{E}$$

$$E = 1 286,359.82;$$

$$A' = .00745;$$

$$E_1 = 1 2133.98;$$

$$B' = -.01699;$$

$$E_2 = -1 4866.03;$$

$$C' = -.052 + i .112;$$

$$E_3 = -32.145 - i 14.91$$

$$D' = -.052 - i .112;$$

$$E_4 = +32.145 - i 14.91$$

$$A = -.373$$

$$B = .0024;$$

48

$$\frac{d^2 \theta}{dt^2} = \frac{1}{I} \sum \tau_i$$

Equation of motion

$$0 = (x_2 - x_1) \ddot{\theta} - (\dot{x}_2 - \dot{x}_1) \dot{\theta} - \ddot{x}_2 \theta - \ddot{x}_1 \theta$$

$$0 = (\ddot{x}_2 - \ddot{x}_1) \theta + (x_2 - x_1) \ddot{\theta} + \ddot{x}_2 \theta - \ddot{x}_1 \theta$$

or

$$18.20 \ddot{x}_2 \theta + 18.20 \ddot{x}_1 \theta + 18.20 \ddot{\theta} (x_2 - x_1) + 18.20 \ddot{\theta} = 0$$

$$0 =$$

or Equations of motion

$$\ddot{x}_2 = -1.73 \ddot{\theta}$$

$$\ddot{x}_1 = 1.73 \ddot{\theta}$$

$$\ddot{x}_2 = -1.73 \ddot{\theta} = -1.73 \ddot{\theta}$$

$$\ddot{x}_1 = 1.73 \ddot{\theta} = 1.73 \ddot{\theta}$$

$$18.20 \ddot{x}_2 = 0$$

$$18.20 \ddot{x}_1 = 0$$

$$18.20 \ddot{\theta} = 0$$

$$18.20 \ddot{\theta} = 0$$

$$\ddot{x}_2 = 0$$

$$\ddot{x}_1 = 0$$

$$\ddot{\theta} = 0$$

$$\ddot{\theta} = 0$$

$$\ddot{x}_2 = 0, \ddot{x}_1 = 0, \ddot{\theta} = 0, \ddot{\theta} = 0$$

$$\ddot{x}_2 = 0$$

$$\ddot{x}_1 = 0$$

$$\ddot{\theta} = 0$$

$$\ddot{\theta} = 0$$

$$\ddot{\theta} = 0$$

$$\ddot{\theta} = 0$$

$$\ddot{x}_2 = 0$$

$$\ddot{x}_1 = 0$$

$$\ddot{\theta} = 0$$

$$\ddot{\theta} = 0$$

$$\ddot{\theta} = 0$$

$$\ddot{\theta} = 0$$

$$C = -.131 + i .029;$$

$$D = -.131 - i .029;$$

$$x_1 = -.373e^{-2.759t} + .0024e^{-178.62t} + e^{-7.31t} (-.262 \cos. 16.65t + .058 \sin 16.65t)$$

$$x_2 = .00745e^{-2759t} - .01699e^{-178.62t} + e^{-7.31t} (-.104 \cos. 16.65t + .224 \sin 16.65t)$$

Frequency,

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \sqrt{16.65} = \frac{4.09}{2\pi} = .651 \text{ CPS}$$

Period of Vibration,

$$T = \frac{2\pi}{\omega} = \frac{6.28}{16.65} = .377 \text{ sec.}$$

$\lim_{t \rightarrow \infty} \|x(t)\| = 0$

19501. $\bar{z} = \frac{1}{N} \sum_{i=1}^N z_i = 0.00$

$$123.456789 + 987.654321 + 210.987654 + 345.678901 = 1667.777661$$

$$(21.-) 18.7\% + 400,000 - 400,000 = 5\%$$

$$\text{RMS} = \frac{V_m}{\sqrt{2}} = 21.31 \sqrt{\frac{1}{2}} = \frac{21.31}{\sqrt{2}} = 15.14 \text{ V}$$

$$\cos \varphi = \frac{R_2 \cdot \omega}{R_1 \cdot \omega} = \frac{\pi}{\omega} = \pi$$

There is a close agreement between the test data and the theory. The computed period of vibration is .377 seconds whereas the experimental period is .388 seconds. The theory is within 2.8 per cent of the experimental values. The theoretical maximum force for the landing gear's dropping velocity of four feet per second shows an axial force of 2440 pounds. An experimental force, 1910 pounds, was indicated on the Brush recorder. The association between these two values is not as close as that of the period previously mentioned. The affinity between the maximum theoretical force is 22 per cent greater than in the experimental axial load.

From Fig. Nos. 6 & 7 are chosen the values of spring constant used in the illustrated problem. These values are not true constants, but are assumed to be in order to simplify computations. For example, as the air compressed in the oleo, the force versus distance curve was not of a linear relation. This was also true for the tire. In other words, these "spring constants" are not in reality, constant. Had they been a true constant the agreement between the theoretical and experimental would have been closer.

There is a close agreement between the test data and the theory. The computed period of vibration is .377 seconds whereas the experimental period is .368 seconds. The theory is within 2.5 per cent of the experimental values. The theoretical values for the leading member's flexing velocity of 100 feet per second shows an axial force of 12,500 pounds. An experimental force, 12,000 pounds, was indicated on the strain transducer. The correlation between these two values is not as close as that of the tested previously mentioned. The difference between the various calculated force is 20 per cent greater than in the experimental value.

From Fig. 20, it is shown the values of spring constant used in the illustrated problem. These values are not true constants, but are assumed to be in order to simplify calculations. For example, as the air pressure in the pipe, the force versus distance curve was not of a linear relation. This was also true for the pipe. In other words, these "spring constants" are not in reality, constants. The fact that a true constant the agreement between the theoretical and experimental would have been closer.

$x_2 = .007 e^{-2.759t} - .017 e^{-178.62t} + e^{-7.13t} (-.104 \cos 16.65t + .224 \sin 16.65t)$									
t	(c)		(E)		(F)		(E+F)		x ₂
	cos ω	sin ω	e ^{-7.13t}	-104C	+224D				
.0	1	0	1	-.1040	0		-.1040		-.1040
.01	.986	.165	.929	-.1036	.0370		-.0666		-.0656
.02	.945	.326	.863	-.0982	.0730		-.0252		-.0218
.03	.878	.479	.802	-.0912	.1072		+.0160		+.0128
.04	.786	.617	.747	-.0818	.1382		+.0564		+.0422
.05	.675	.738	.695	-.0702	.1654		+.0952		+.0661
.06	.540	.841	.644	-.0561	.1886		+.1322		+.0852
.07	.390	.921	.600	-.0406	.2062		+.1652		+.0992
.08	.239	.971	.557	-.0205	.2180		+.1875		+.1043
.09	.071	.997	.516	-.0073	.2235		+.2162		+.1118
.10	-.091	.996	.481	+.0095	.2235		+.2320		+.1117
.11	-.257	.967	.447	+.0278	.2170		+.2448		+.1095
.12	-.416	.909	.416	+.0432	.2035		+.2467		+.1025
.13	-.555	.830	.387	+.0576	.1860		+.2436		+.0941
.14	-.690	.725	.360	+.0716	.1625		+.2341		+.0844
.15	-.801	.598	.336	+.0833	.1340		+.2173		+.0731
.16	-.887	.468	.310	+.0922	.1050		+.1972		+.0611
.17	-.925	.302	.289	+.0990	.0681		+.1671		+.0483
.18	-.990	.140	.268	+.1030	.0314		+.1344		+.0347
.19	-.999	-.018	.249	+.1039	-.0040		+.0999		+.0249
.20	-.984	-.190	.232	+.1024	-.0425		+.0599		+.0139
.21	-.936	-.345	.215	+.0972	-.0786		+.0186		+.0043
.22	-.862	-.494	.200	+.0900	-.1110		-.0210		-.0042

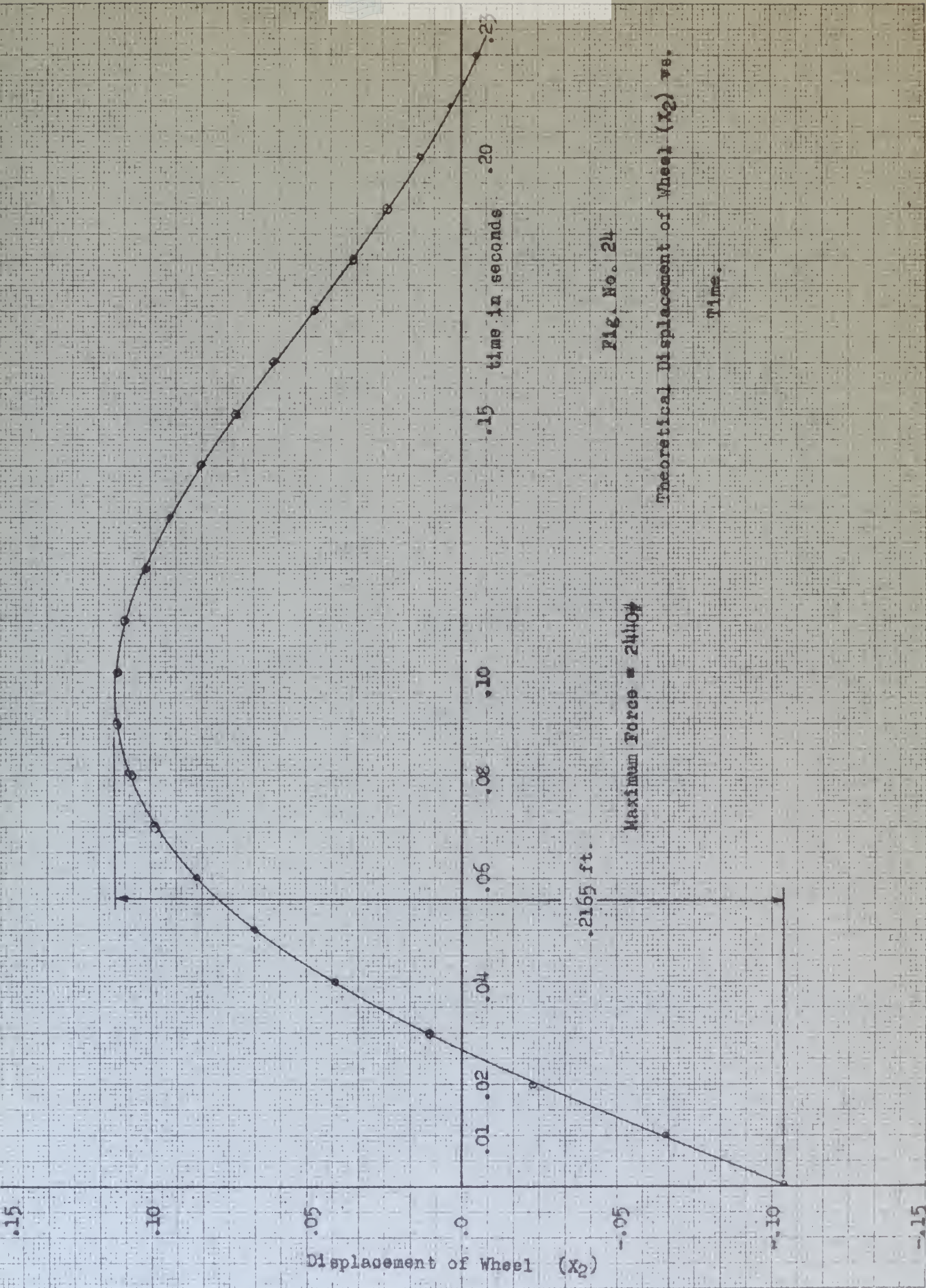


Fig. No. 25.

Maximum Initial Axial Force vs. Tire Pressure
 For Different Dropping Velocity

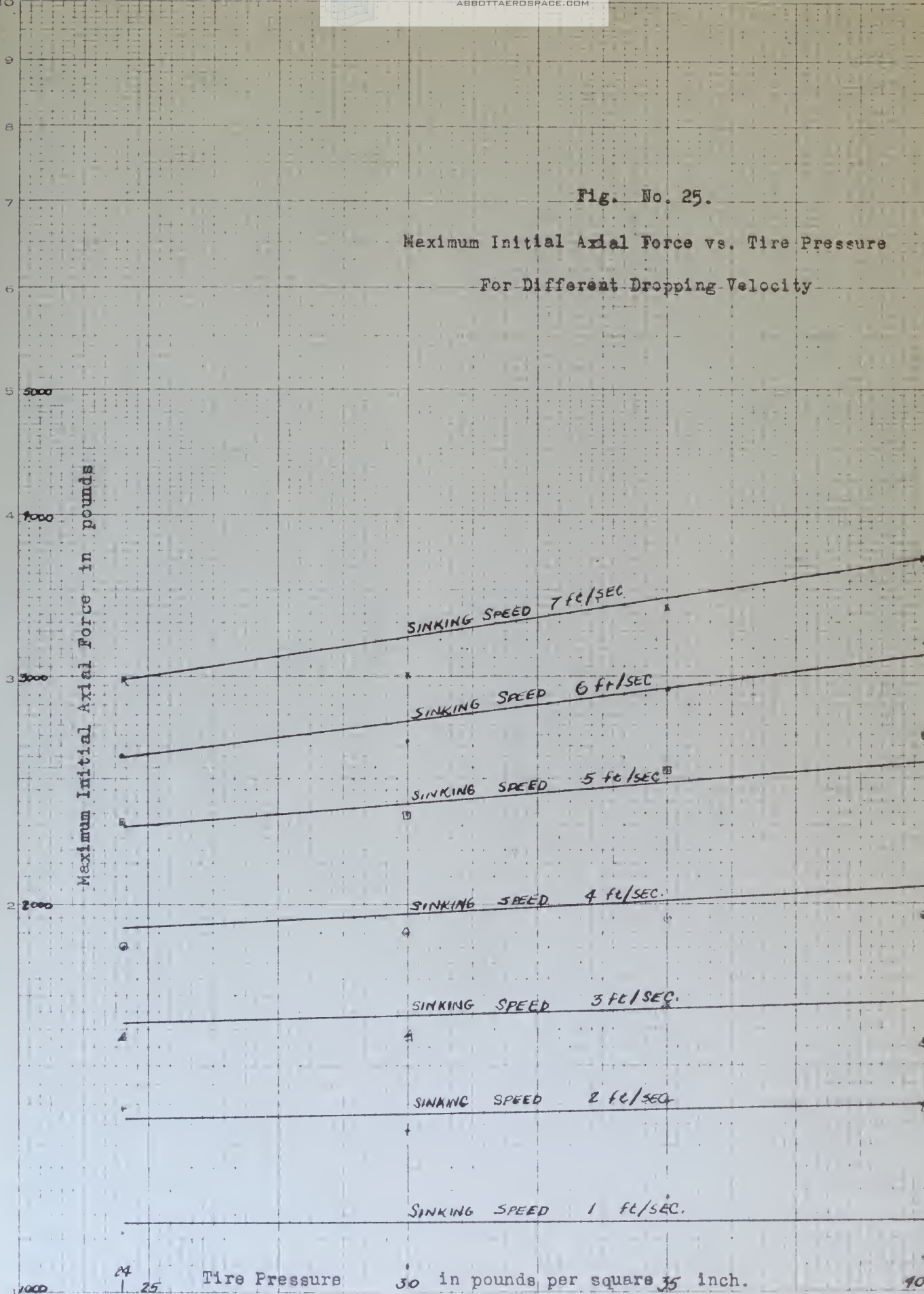
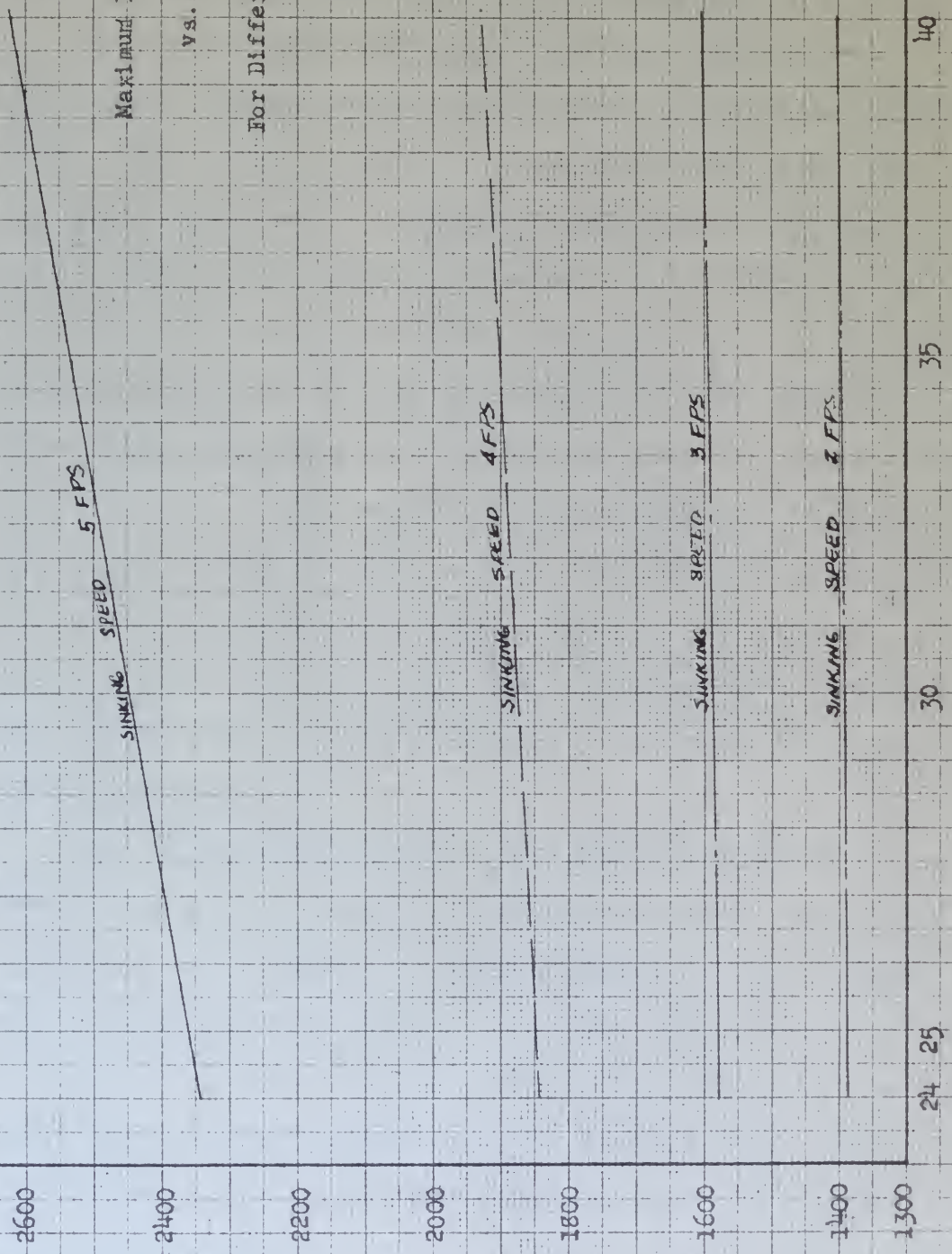


Fig. No. 26

Maximum Initial Axial Force
vs. Tire Pressure

For Different Dropping Velocity.



Maximum Initial Axial Force in pounds

Tire Pressure in pounds per square inch.

CONCLUSION

The data of this experiment indicates that the theory and the experimental results agree quite closely.

As the tire pressure increases the axial force increases. At the slower striking velocities the effect of the tire pressure is not as noticeable as when the vertical forces are of a greater magnitude. In Fig. No. 25 there is an indication that the axial force increases by the square as the dropping velocity increases linearly. On log paper (Fig. No. 25) the graph shows equal distances between the curves at constant tire pressure. These equal distances increase between the curves as the pressure of the tire becomes greater. This gives an increasing slope. Fig. No. 26 shows a better picture of this slope and indicates more clearly that as the tire pressure increases the force along the strut increases.

Both the Brush Recorder and motion picture show that a temporary frequency is introduced into the system during the first phase of landing impact of the landing gear. This frequency results from the drag forces imposed on the strut, and the vertical vibrations of the tire. The film indicates that the landing gear, after its initial contact with the flywheel, does not leave the landing surface.

CONCLUSIONS

The data of this experiment indicates that the theory and the experimental results agree quite closely. In the first pressure measurement the axial force increased. At the lowest striking velocities the effect of the fire pressure is not as noticeable as when the vertical forces are of a greater magnitude. In Fig. No. 32 there is an indication that the axial force increased by the amount as the striking velocity increased linearly. On the basis of Fig. No. 32 the graph shows equal distances between the curves at constant fire pressures. These equal distances increase between the curves as the pressure of the fire becomes greater. This gives an increasing slope. Fig. No. 33 shows a better picture of this phenomenon and indicates more clearly that as the fire pressure increases the force along the axial increases.

Both the strain gauges and section lines show that a frequency tendency is introduced into the system during the first phase of loading. It is of the nature of a beat. This frequency varies from the first force in phase on the steel, and the vertical vibrations of the steel. The film indicates that the loading beam, after its initial contact with the specimen, does not have the loading surface.

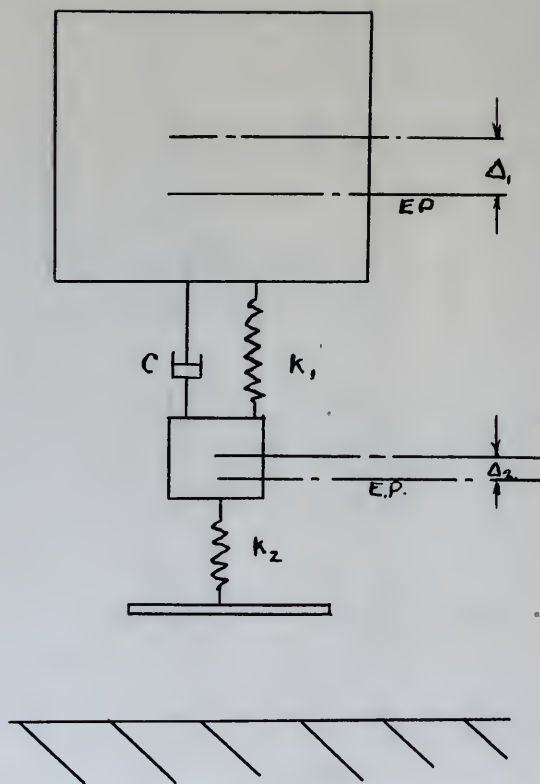
The theoretical and experimental development points out that critical damping for the oleo had been reached.

It is recommended that a more complete study be made of the "spring constants", damping characteristics, and dynamic friction involved in the problem of landing gear.

The theoretical and experimental development of the
and the critical thinking for the also had been reached.

It is recommended that a more complete study be made of the "Applied Economics" section, and that the study be continued in the future.

APPENDIX



k_1 = spring constant of Oleo strut

k_2 = spring constant of tire

C = damping constant of oleo strut

W_1 = weight of airplane

W_2 = weight of wheel and lower half of strut

M = mass

$A, B, C, D, A', B', C', D'$ = constants

i = imaginary unit

s = complex frequency

From the forces acting on this diagram the equation of motion can be written.

$$(1) -m_1 \ddot{x}_1 - c(\dot{x}_1 - \dot{x}_2) - k_1(x_1 - x_2) = 0$$

$$(2) -m_2 \ddot{x}_2 - k_2 x_2 + k_1(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) = 0$$

$$\begin{aligned} \text{Let: } x_1 &= A e^{st} & \dot{x}_1 &= s A e^{st} & \ddot{x}_1 &= s^2 A e^{st} \\ x_2 &= B e^{st} & \dot{x}_2 &= s B e^{st} & \ddot{x}_2 &= s^2 B e^{st} \end{aligned}$$

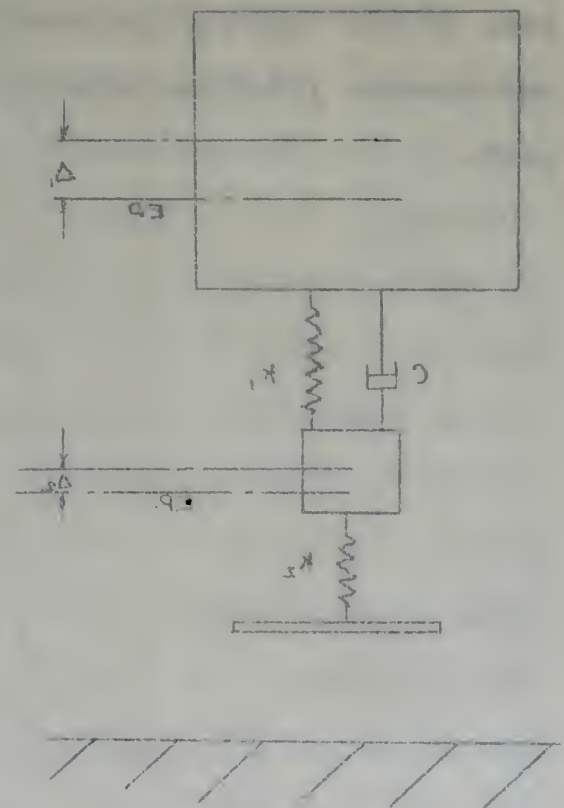
Subs. in (1) and (2) the following results

$$(3) (-m_1 s^2 - cs - k_1) A e^{st} + B e^{st} (cs + k_1) = 0$$

$$(4) (-m_2 s^2 - cs - k_1 - k_2) B e^{st} + A e^{st} (cs + k_1) = 0$$

PROBLEM

Δ_1 = static deflection of spring
 Δ_2 = static deflection of spring
 Δ_3 = static deflection of spring
 Δ_4 = static deflection of spring
 Δ_5 = static deflection of spring
 Δ_6 = static deflection of spring
 Δ_7 = static deflection of spring
 Δ_8 = static deflection of spring
 Δ_9 = static deflection of spring
 Δ_{10} = static deflection of spring
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 Δ_{97} = static deflection of spring
 Δ_{98} = static deflection of spring
 Δ_{99} = static deflection of spring
 Δ_{100} = static deflection of spring



From the above we can write the equation of motion as follows:

$$m_1 \ddot{x}_1 + k_1 x_1 = 0 \quad (1)$$

$$m_2 \ddot{x}_2 + k_2 x_2 + c \dot{x}_2 = 0 \quad (2)$$

$$m_3 \ddot{x}_3 + k_3 x_3 = 0 \quad (3)$$
 where x_1, x_2, x_3 are the displacements of the blocks from their static equilibrium positions.

Substituting the values of $m_1, m_2, m_3, k_1, k_2, k_3, c$ in the above equations, we get:

(1) $10 \ddot{x}_1 + 100 x_1 = 0$
 (2) $5 \ddot{x}_2 + 20 x_2 + 10 \dot{x}_2 = 0$
 (3) $10 \ddot{x}_3 + 100 x_3 = 0$

Solving the above equations, we get the following results:

(1) $x_1 = A_1 \cos(\omega_1 t + \phi_1)$
 (2) $x_2 = A_2 e^{-\gamma t} \cos(\omega_d t + \phi_2)$
 (3) $x_3 = A_3 \cos(\omega_3 t + \phi_3)$

where $\omega_1 = \sqrt{10}, \omega_2 = \sqrt{4}, \omega_3 = \sqrt{10}, \gamma = 2, \omega_d = \sqrt{3}$.

The total displacement of the blocks is given by:

$$x = x_1 + x_2 + x_3$$

The initial conditions are:

$x(0) = 0, \dot{x}(0) = 0$

Substituting the initial conditions in the above equations, we get:

$$A_1 = 0, A_2 = 0, A_3 = 0$$

Therefore, the displacement of the blocks is zero.

The cs cancels--Then putting into determinant form and solve for s (which is the freq.)

$$(5) \begin{vmatrix} -m_1 s^2 - cs - k_1 & cs + k_1 \\ cs + k_1 & -m_2 s^2 - cs - k_1 - k_2 \end{vmatrix} = 0$$

Solve the resultant equation

$$(7) m_1 m_2 s^4 + (m_1 + m_2) cs^3 + (k_1 m_1 + k_1 m_2 + k_2 m_1) s^2 + k_2 cs + k_1 k_2 = 0$$

$$\text{Letting } a = \frac{(m_1 + m_2) c}{m_1 m_2}$$

$$b = \frac{k_1 m_1 + k_1 m_2 + k_2 m_1}{m_1 m_2}$$

$$c = \frac{k_2 c}{m_1 m_2}$$

$$d = \frac{k_1 k_2}{m_1 m_2}$$

$$(8) s^4 + as^3 + bs^2 + cs + d = 0$$

Brots "approximate factorization" gives a relative close solution for this equation under certain conditions:

$$f(s) \approx (s^2 + as + b) (s^2 + \frac{c}{b}s + \frac{d}{b}) = 0$$

$$(9) s_{1,2} \approx \frac{-a \pm \sqrt{a^2 - 4b}}{2}$$

$$(10) s_{3,4} \approx \frac{-\frac{c}{b} \pm \sqrt{(\frac{c}{b})^2 - 4\frac{d}{b}}}{2}$$

The above-mentioned partial differential equation
 is solved for ϕ (which is the free)

$$\phi = \begin{vmatrix} x^2 + y^2 & x^2 - y^2 - 2xy \\ y^2 + x^2 & x^2 + y^2 \end{vmatrix} \quad (2)$$

$$\phi = \begin{vmatrix} x^2 + y^2 & x^2 - y^2 - 2xy \\ y^2 + x^2 & x^2 + y^2 \end{vmatrix} \quad (3)$$

Before the partial differential

$$(1) \quad \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0$$

$$\phi = x^2 + y^2 + 2xy$$

$$\phi = \frac{(x^2 + y^2)}{2}$$

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0$$

$$\frac{\partial^2 \phi}{\partial x^2} = 0$$

$$\frac{\partial^2 \phi}{\partial y^2} = 0$$

$$\phi = x^2 + y^2 + 2xy$$

These "approximate" solutions, given a definite shape
 selected for the section under certain conditions

$$\phi = \frac{x^2}{2} + \frac{y^2}{2} + xy$$

$$(1) \quad \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0$$

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0$$

Synthetic division give better results. With this, the following can be written:

$$(11) \quad x_1 = Ae^{s_1 t} + Be^{s_2 t} + Ce^{s_3 t} + De^{s_4 t}$$

$$(12) \quad x_2 = A'e^{s_1 t} + B'e^{s_2 t} + C'e^{s_3 t} + D'e^{s_4 t}$$

Then put A in terms of A'

$$\begin{vmatrix} (-m_1 s^2 - cs - k_1)A + (Cs + k_1)A' \\ (cs + k_1)A + (-m_2 s^2 - cs - k_1 - k_2)A' \end{vmatrix} = 0$$

or

$$(13) \quad A = \frac{cs_1 + k_1}{m_1 s_1^2 + cs_1 + k_1} A' = \phi_1 A'$$

$$(14) \quad B = \frac{cs_2 + k_1}{m_1 s_2^2 + cs_2 + k_1} B' = \phi_2 B'$$

$$(15) \quad C = \frac{cs_3 + k_1}{m_1 s_3^2 + cs_3 + k_1} C' = \phi_3 C'$$

$$(16) \quad D = \frac{cs_4 + k_1}{m_1 s_4^2 + cs_4 + k_1} D' = \phi_4 D'$$

Now set up boundary conditions

$$\begin{array}{lll} \text{at } t = 0 & x_1 = -\Delta_1 & x_2 = -\Delta_2 \\ & \dot{x}_1 = v_0 & \dot{x}_2 = v_0 \end{array}$$

where $-\Delta_1$ and $-\Delta_2$ equal the distance from center of mass to equilibrium position

$$-1 = \frac{(m_1 - m_2)g}{K_1} + \frac{(m_1 + m_2)g}{K_2}$$

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Quadratic division gives positive remainder. After this, the

following can be written:

$$(11) \quad x_1 = 2x_2^2 + 2x_3^2 + 2x_4^2 + 2x_5^2$$

$$(12) \quad x_2 = 2x_3^2 + 2x_4^2 + 2x_5^2 + 2x_6^2$$

Then put A in terms of x

$$0 = \begin{vmatrix} (2x_1^2 + 2x_2^2) + (2x_3^2 + 2x_4^2) - 2x_5^2 & (2x_1^2 + 2x_2^2) \\ (2x_1^2 + 2x_2^2) - 2x_3^2 - 2x_4^2 - 2x_5^2 & (2x_1^2 + 2x_2^2) \end{vmatrix}$$

or

$$(13) \quad x_1 = \frac{2x_2^2 + 2x_3^2}{2x_1^2 + 2x_2^2 + 2x_3^2 + 2x_4^2} = 1 \quad (13)$$

$$(14) \quad x_2 = \frac{2x_3^2 + 2x_4^2}{2x_1^2 + 2x_2^2 + 2x_3^2 + 2x_4^2} = 0 \quad (14)$$

$$(15) \quad x_3 = \frac{2x_4^2 + 2x_5^2}{2x_1^2 + 2x_2^2 + 2x_3^2 + 2x_4^2} = 0 \quad (15)$$

$$(16) \quad x_4 = \frac{2x_5^2}{2x_1^2 + 2x_2^2 + 2x_3^2 + 2x_4^2} = 0 \quad (16)$$

Now put in boundary conditions

$$\begin{aligned} x_1 &= 1 & x_2 &= 0 & x_3 &= 0 & x_4 &= 0 & x_5 &= 0 \\ x_2 &= 0 & x_3 &= 0 & x_4 &= 0 & x_5 &= 0 & x_6 &= 0 \end{aligned}$$

where $x_1 = 1$ and $x_2 = 0$ equal the distance from origin of

axis to position of origin

$$\frac{1}{R^2} = \frac{1}{x_1^2} + \frac{1}{x_2^2} + \frac{1}{x_3^2} + \frac{1}{x_4^2} + \frac{1}{x_5^2}$$

$$-A_2 = \frac{(m_1 + m_2) g}{K_2}$$

$$(17) -A_1 = A e^{s_1 t} + B e^{s_2 t} + C e^{s_3 t} + D e^{s_4 t}$$

$$(18) -A_2 = A' e^{s_1 t} + B' e^{s_2 t} + C' e^{s_3 t} + D' e^{s_4 t}$$

Let V_0 = The dropping velocity of the landing gear
 and taking derivative, gives

$$(19) V_0 = s_1 A e^{s_1 t} + s_2 B e^{s_2 t} + s_3 C e^{s_3 t} + s_4 D e^{s_4 t}$$

$$(20) V_0 = s_1 A' e^{s_1 t} + s_2 B' e^{s_2 t} + s_3 C' e^{s_3 t} + s_4 D' e^{s_4 t}$$

Rewriting (17) and (19)

$$(21) -A_1 = \phi_1 A' e^{s_1 t} + \phi_2 B' e^{s_2 t} + \phi_3 C' e^{s_3 t} + \phi_4 D' e^{s_4 t}$$

$$(22) V_0 = s_1 \phi_1 A' e^{s_1 t} + s_2 \phi_2 B' e^{s_2 t} + s_3 \phi_3 C' e^{s_3 t} + s_4 \phi_4 D' e^{s_4 t}$$

Here are four equations, four unknowns putting in determinant form:

$$\text{Let } E = \begin{vmatrix} 1 & 1 & 1 & 1 \\ \phi_1 & \phi_2 & \phi_3 & \phi_4 \\ s_1 & s_2 & s_3 & s_4 \\ s_1 \phi_1 & s_2 \phi_2 & s_3 \phi_3 & s_4 \phi_4 \end{vmatrix}$$

$$E_1 = \begin{vmatrix} -A_2 & 1 & 1 & 1 \\ -A_1 & \phi_2 & \phi_3 & \phi_4 \\ V_0 & s_2 & s_3 & s_4 \\ V_0 & s_2 \phi_2 & s_3 \phi_3 & s_4 \phi_4 \end{vmatrix}; E_2 = \begin{vmatrix} 1 & -A_2 & 1 & 1 \\ \phi_1 & -A_2 & \phi_3 & \phi_4 \\ s_1 & V_0 & s_3 & s_4 \\ s_1 \phi_1 & V_0 & s_3 \phi_3 & s_4 \phi_4 \end{vmatrix}$$

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$$\frac{1}{2} (\dot{x}_1 + \dot{x}_2) = \dot{\Delta} -$$

$$\frac{1}{2} \dot{x}_{11} + \frac{1}{2} \dot{x}_{12} + \frac{1}{2} \dot{x}_{13} + \frac{1}{2} \dot{x}_{14} = \dot{\Delta} - (17)$$

$$\frac{1}{2} \dot{x}_{21} + \frac{1}{2} \dot{x}_{22} + \frac{1}{2} \dot{x}_{23} + \frac{1}{2} \dot{x}_{24} = \dot{\Delta} - (18)$$

Let $\dot{\Delta}$ be the average velocity of the leading edge
 and taking derivative, gives

$$\frac{1}{2} \ddot{x}_{11} + \frac{1}{2} \ddot{x}_{12} + \frac{1}{2} \ddot{x}_{13} + \frac{1}{2} \ddot{x}_{14} = \ddot{\Delta} - (19)$$

$$\frac{1}{2} \ddot{x}_{21} + \frac{1}{2} \ddot{x}_{22} + \frac{1}{2} \ddot{x}_{23} + \frac{1}{2} \ddot{x}_{24} = \ddot{\Delta} - (20)$$

Adding (17) and (19)

$$\frac{1}{2} \ddot{x}_{11} + \frac{1}{2} \ddot{x}_{12} + \frac{1}{2} \ddot{x}_{13} + \frac{1}{2} \ddot{x}_{14} = \ddot{\Delta} - (21)$$

$$\frac{1}{2} \ddot{x}_{21} + \frac{1}{2} \ddot{x}_{22} + \frac{1}{2} \ddot{x}_{23} + \frac{1}{2} \ddot{x}_{24} = \ddot{\Delta} - (22)$$

Now we can separate the average velocity of the
 leading edge

$$\begin{bmatrix} \ddot{x}_{11} & \ddot{x}_{12} & \ddot{x}_{13} & \ddot{x}_{14} \\ \ddot{x}_{21} & \ddot{x}_{22} & \ddot{x}_{23} & \ddot{x}_{24} \end{bmatrix} = \ddot{\Delta} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \ddot{x}_{11} & \ddot{x}_{12} & \ddot{x}_{13} & \ddot{x}_{14} \\ \ddot{x}_{21} & \ddot{x}_{22} & \ddot{x}_{23} & \ddot{x}_{24} \end{bmatrix} = \ddot{\Delta} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

$$E_3 = \begin{vmatrix} 1 & 1 & -\Delta_2 & 1 \\ \phi_1 & \phi_2 & -\Delta_1 & \phi_4 \\ s_1 & s_2 & v_0 & s_4 \\ s_1\phi_1 & s_2\phi_2 & v_0 & s_4\phi_4 \end{vmatrix}; E_4 = \begin{vmatrix} 1 & 1 & 1 & -\Delta_2 \\ \phi_1 & \phi_2 & \phi_3 & -\Delta_1 \\ s_1 & s_2 & s_3 & v_0 \\ s_1\phi_1 & s_2\phi_2 & s_3\phi_3 & v_0 \end{vmatrix}$$

Therefore:

$$A' = \frac{E_1}{E}; B' = \frac{E_2}{E}; C' = \frac{E_3}{E}; D' = \frac{E_4}{E}$$

Substituting in (11) and (12) the equation of motion result.

$$(23) \quad x_1 = \frac{E_1}{E} \phi_1 e^{s_1 t} + \frac{E_2}{E} \phi_2 e^{s_2 t} + \frac{E_3}{E} \phi_3 e^{s_3 t} + \frac{E_4}{E} \phi_4 e^{s_4 t}$$

$$(24) \quad x_2 = \frac{E_1}{E} e^{s_1 t} + \frac{E_2}{E} e^{s_2 t} + \frac{E_3}{E} e^{s_3 t} + \frac{E_4}{E} e^{s_4 t}$$

Let s_1, s_2, s_3 , and s_4 be complex roots,

Or,

$$s_1 = a_1 + i\omega_1$$

$$s_3 = a_2 + i\omega_2$$

$$s_2 = a_1 - i\omega_1$$

$$s_4 = a_2 - i\omega_2$$

Again (11) and (12) can be written

$$(25) \quad x_1 = A e^{(a_1 + i\omega_1)t} + B e^{(a_1 - i\omega_1)t} + C e^{(a_2 + i\omega_2)t} + D e^{(a_2 - i\omega_2)t}$$

$$(26) \quad x_2 = A' e^{(a_1 + i\omega_1)t} + B' e^{(a_1 - i\omega_1)t} + C' e^{(a_2 + i\omega_2)t} + D' e^{(a_2 - i\omega_2)t}$$

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$$\begin{vmatrix} s\Delta & 1 & 1 & 1 \\ 1\Delta & s^2 & s^2 & 1 \\ s^2 & s^2 & s^2 & 1 \\ s^2 & s^2 & s^2 & 1 \end{vmatrix} = 0 \quad \begin{vmatrix} s\Delta & 1 & 1 & 1 \\ 1\Delta & s^2 & s^2 & 1 \\ s^2 & s^2 & s^2 & 1 \\ s^2 & s^2 & s^2 & 1 \end{vmatrix} = 0$$

Therefore

$$\frac{d}{dt} = 0; \quad \frac{d}{dt} = 0; \quad \frac{d}{dt} = 0; \quad \frac{d}{dt} = 0$$

Substituting in (11) and (12) the solution of system

we get

$$+ \frac{1}{2} \omega_1^2 \frac{d}{dt} + \frac{1}{2} \omega_2^2 \frac{d}{dt} + \frac{1}{2} \omega_3^2 \frac{d}{dt} = 0 \quad (13)$$

$$\frac{d}{dt} = 0$$

$$\frac{1}{2} \omega_1^2 \frac{d}{dt} + \frac{1}{2} \omega_2^2 \frac{d}{dt} + \frac{1}{2} \omega_3^2 \frac{d}{dt} = 0 \quad (14)$$

Substituting in (11) and (12) the solution of system

we get

$$\omega_1^2 + \omega_2^2 = 0$$

$$\omega_1^2 + \omega_2^2 = 0$$

$$\omega_1^2 - \omega_2^2 = 0$$

$$\omega_1^2 - \omega_2^2 = 0$$

Substituting in (11) and (12) the solution of system

$$\frac{1}{2} \omega_1^2 \frac{d}{dt} + \frac{1}{2} \omega_2^2 \frac{d}{dt} + \frac{1}{2} \omega_3^2 \frac{d}{dt} = 0 \quad (15)$$

$$\frac{d}{dt} = 0$$

$$\frac{1}{2} \omega_1^2 \frac{d}{dt} + \frac{1}{2} \omega_2^2 \frac{d}{dt} + \frac{1}{2} \omega_3^2 \frac{d}{dt} = 0 \quad (16)$$

$$\frac{d}{dt} = 0$$

DeMoivre's Theorem:

$$e^{i\omega t} = \cos \omega t + i \sin \omega t$$

$$e^{-i\omega t} = \cos \omega t - i \sin \omega t$$

(25) and (26) are written:

$$(27) \quad x_1 = A e^{a_1 t} e^{i\omega_1 t} + B e^{a_1 t} e^{-i\omega_1 t} + C e^{a_2 t} e^{i\omega_2 t} \\ + D e^{a_2 t} e^{-i\omega_2 t}$$

$$(28) \quad x_2 = A' e^{a_1 t} e^{i\omega_1 t} + B' e^{a_1 t} e^{-i\omega_1 t} + C' e^{a_2 t} \\ e^{i\omega_2 t} + D' e^{a_2 t} e^{-i\omega_2 t}$$

$$(29) \quad x_1 = (A \cos \omega_1 t + A i \sin \omega_1 t) e^{a_1 t} + e^{a_2 t} \\ (B \cos \omega_1 t - B i \sin \omega_1 t) + e^{a_2 t} (C \cos \omega_2 t + C i \sin \omega_2 t) + e^{a_2 t} (D \cos \omega_2 t - \\ D i \sin \omega_2 t)$$

$$(30) \quad x_2 = (A' \cos \omega_1 t + A' i \sin \omega_1 t) e^{a_1 t} + e^{a_1 t} \\ (B' \cos \omega_1 t - B' i \sin \omega_1 t) + e^{a_2 t} (C' \cos \omega_2 t + C' i \sin \omega_2 t) + e^{a_2 t} (D' \cos \omega_2 t - D' i \sin \omega_2 t)$$

Combining (29) and (30) using De Moivre's Theorem

$$(31) \quad x_1 = e^{a_1 t} (C_1 \cos \omega_1 t + C_2 \sin \omega_1 t) + e^{a_2 t} \\ (C_3 \cos \omega_2 t + C_4 \sin \omega_2 t)$$

Continuity's Equation

$$\rho_0 \omega_0 = \rho_1 \omega_1 + \rho_2 \omega_2$$

$$-\rho_1 \omega_1 = \rho_2 \omega_2 - \rho_0 \omega_0$$

Substituting into (22)

$$\rho_0 \omega_0 + \rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0 + \rho_1 \omega_1 + \rho_2 \omega_2 \quad (23)$$

$$\rho_1 \omega_1 - \rho_2 \omega_2 = 0$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0 \quad (24)$$

$$\rho_1 \omega_1 - \rho_2 \omega_2 = 0$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0 \quad (25)$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0 \quad (26)$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0$$

Combining (23) and (24) using the continuity equation

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0 \quad (27)$$

$$\rho_1 \omega_1 + \rho_2 \omega_2 = \rho_0 \omega_0$$

$$(32) \quad x_2 = e^{s_1 t} (C_1' \cos \omega_1 t + C_2' \sin \omega_1 t) + \\ e^{s_2 t} (C_3' \cos \omega_2 t - C_4' \sin \omega_2 t)$$

where

$$C_1 = (A + B)$$

$$C_2 = (A - B)i$$

$$C_3 = (C + D)$$

$$C_4 = (C - D)i$$

$$C_1' = (A' + B')$$

$$C_2' = (A' - B')i$$

$$C_3' = (C' + D')$$

$$C_4' = (C' - D')i$$

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$$+ (1/2) \omega \sin \theta \cos \theta + (1/2) \omega \sin \theta \cos \theta \sin \theta = 0 \quad (11)$$

$$[1/2 \omega \sin \theta \cos \theta + 1/2 \omega \sin \theta \cos \theta \sin \theta]$$

boundary

$$(1 + 1) = 10$$

$$1(1 - 1) = 0$$

$$(1 + 1) = 10$$

$$1(1 - 1) = 0$$

$$(1 + 1) = 10$$

$$1(1 - 1) = 0$$

$$(1 + 1) = 10$$

$$1(1 - 1) = 0$$

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