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Fire Control Division - Director Development Section

10 July 1945

MECHANICAL OSCILLATOR WITH SYNCHRO OUTPUT

By Charles F. White

Report R-2582

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NRL Problem O-111R-C

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ABSTRACT

The existing dummy directors are inadequate for the testing and development of automatic tracking apparatus for fire control radar equipment. Specifically, the sinusoidal oscillation amplitude ~~range~~ is too high and the frequency is not continuously variable nor of the proper range. The following report describes a mechanical oscillator providing synchro generator output continuously variable from approximately 0.1 cycles per second to 10 cycles per second. When used in the fine channel of a two-speed (1-speed and 36-speed) fire control system, coarse speed maximum amplitudes of plus and minus 1, 0.5, 0.25, and 0.125 degrees are available. In the development of the mechanical oscillator, the simplest possible mechanical pin-linkage was used with the proportioning of the components such that low harmonic distortion is obtained.

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INTRODUCTION

1. A synchro generator or synchro control transformer output varying sinusoidally at adjustable amplitude and at controllable frequency is useful in the development of automatic tracking apparatus for fire control radar equipment. A mechanical oscillator which provides these characteristics was developed and is the subject of this report. This work was authorized by Reference (a).

2. Due to the frequency range involved, the nature of synchro output voltages, and the desire for easy adjustment to certain definite values of maximum amplitude, the approach used involved direct mechanical oscillation of a synchro generator shaft.

3. The simplest possible pin-linkage was used and a study was made to determine the optimum proportioning of the components to produce an output as free from harmonic content as possible.

4. The initial arrangement of the oscillator is suited for use in the fine channel of a two-speed fire control system (1-speed and 36-speed). When so used the coarse channel amplitudes of plus and minus 1 degree, 0.5 degrees, 0.25 degrees, and 0.125 degrees are obtainable over the frequency range of 0.1 cycle per second to 10 cycles per second. Exact determination of the frequency is obtained by stop-watch timing of cycles indicated on a mechanical counter.

MECHANICAL ARRANGEMENT

5. A sketch of the mechanical arrangement of the generator is shown on Plate 1. An electric motor is geared to the input shaft of a disk type integrator. The location of the ball relative to the center of the disk determines the rotational speed of the integrator output shaft. The control of speed introduced at this point in the system provides a means for varying the oscillation frequency of the synchro generator. The output shaft of the integrator is geared to a mechanical counter and to a driver plate. The gearing ratio is such that the extreme right figure on the counter indicates tenths of a revolution of the driver plate. With the aid of a connecting rod, a crank arm secured to the synchro generator is oscillated once for each revolution of the driver plate. Stop watch timing of the driver plate revolutions permits calibration of the control dial and check on any particular setting. Positioning holes determining crank arm length, connecting rod length, and driver plate radius for each of four amplitudes are provided and a marking on the components indicates the proper ones to be used for each amplitude.

6. Plates 2 and 3 are photographes of the mechanical oscillator. In the top view given by Plate 2, the driver plate is shown at the left and the synchro generator output control unit on the right. The driver plate and the crank arm are interconnected by means of the connecting rod. The pin joints at each end of the connecting rod carry ball bearings. The various additional holes for the smaller amplitudes of oscillation are also visible. In the photograph the proper hole combination has not been used. In the front view given by Plate 3, the mechanical counter used in conjunction with a stop watch to determine exact oscillation frequency (cycles per second) appears at the upper left. The control dial knob is calibrated both in f (frequency cycles per second) and in terms of 2π times cycles per second; that is, values of ω. The drive motor indicator lamp, fuse, switch, and extension cord connection appear to the right.

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ANALYSIS OF THE PIN-LINKAGE SYSTEM

7. For a fixed distance between the center of the rotating shaft and the center of the oscillating shaft it is clear that an oscillating motion of the crank arm will be obtained provided that the length of the connecting rod plus the length of the crank arm is greater than the sum of the distance between centers and the length of the driver plate radius. However, the proper proportioning of these three lengths for the closest approach to a pure sine wave output must be established. The approach used in the study of the geometry of the linkage included the following concepts: (1) the plus and minus amplitudes should be equal, (2) the average value of the two maximum amplitudes should divide the complete cycle in half; that is, the 180 as well as the 0 (and 360) degree points of an output cycle should have zero amplitude, and (3) the maximum amplitudes should occur at the 90 and 270 degree points of a cycle. The geometrical construction of Plate 4 achieves the above enumerated aims with the exception that only one of the maximum amplitudes could be made to occur in exactly the correct phase.

8. The trigonometric functions that represent the design equations are given as follows:

d = distance between centers of rotating driver plate and oscillating crank arm.

c = length of oscillating crank arm.

l = length of connecting rod.

r = length of rotating lever arm of driver plate (driver plate radius).

$\pm \alpha$ = amplitudes of oscillation of crank arm.

Defining a function, z, in terms of maximum amplitude alpha:

$$z = \frac{2 \sin \frac{\alpha}{2}}{1 + \sin \frac{\alpha}{2} - \cos \frac{\alpha}{2}}$$

then,

$$c = d \div \sqrt{1 + 2z \sin \frac{\alpha}{2} \cos \frac{\alpha}{2} + z^2 \cos^2 \frac{\alpha}{2}}$$

$l = c\ z$, and

$$r = c\ z \sin \frac{\alpha}{2}$$

Table 1 gives the values computed for c, l, and r based on a value of d = 10 and α equal to 36,18,9, and 4.5 degrees successively.

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9. Referring to Plate 1, the zero point for a cycle may be taken as that of the connecting rod location AA' and the direction of rotation of the driver plate as A'B'C'D'A'. Accordingly, angular rotation, ϕ, is indicated clockwise from O'A'. A corresponding oscillation angle, θ, measured from OA and taken positive in the clockwise direction from OA has maximum amplitudes of plus and minus angles equal to alpha. The function relating θ and ϕ is not simply $\theta = \sin\phi$ but is given by the following:

$$\left(1-\frac{1}{2}\sin\alpha-\cos\frac{\alpha}{2}\left(\sin\frac{\alpha}{2}\cos\phi-\cos\frac{\alpha}{2}\sin\phi\right)-\left(\frac{1+\sin\frac{\alpha}{2}-\cos\frac{\alpha}{2}}{2\sin\frac{\alpha}{2}}\right)\sin\theta\right)^2$$

$$-\left(\frac{1}{2}\sin\alpha+\cos\frac{\alpha}{2}\left(\cos\frac{\alpha}{2}\cos\phi+\sin\frac{\alpha}{2}\sin\phi\right)+\left(\frac{1+\sin\frac{\alpha}{2}-\cos\frac{\alpha}{2}}{2\sin\frac{\alpha}{2}}\right)\left(1-\cos\theta\right)\right)^2=1$$

Certain recurring combinations of functions of alpha could be used to define symbols in order to display the above expression in more compact form. No solution has been obtained for the basic problem of separating the variables θ and ϕ. Hence, an explicit expression for their relationship could not be given.

HARMONIC ANALYSIS OF SYSTEM WAVEFORM

10. Another approach to the analysis of the system is that of obtaining a table of values of the functional relationship between θ and ϕ and applying the methods of Fourier analysis to determine the harmonic content of the resulting waveform. This could be done by careful large scale graphical construction but it was decided to let the results include any mechanical imperfections occurring in the construction of the parts of the linkage so that the analysis would represent an overall system performance test of the equipment. The driver plate periphery was divided into 10 degree intervals and a piece of polar graph paper was secured in proper position to permit measurement of the output amplitude. The values of output amplitude as a function of driver plate angular position are given for 36 points in the cycle. As mentioned in paragraph 4, the apparatus is arranged to operate at four particular amplitudes. The nominal values of the amplitudes are plus and minus 36, 18, 9, and 4.5 degrees. Accordingly, Table 2 includes four sets of 36 values. Plots of these waveforms are given on Plates 5, 6, 7, and 8. Records made using a Brush crystal recording oscillograph across R1 and R2 of a synchro control transformer while S1, S2, and S3 were energized from a synchro generator voltage source are reproduced on Plate 9. These curves represent dynamic tests of the system and show the additional fact that a possible slippage in the integrator drive was not present. Note that additional apparent distortion is partly due to the curvilinear ordinate.

11. The harmonic analysis of the waveforms was accomplished with the aid of a mechanical harmonic analyzer developed by Mader. Table 3 shows the coefficients of the Fourier series as obtained by tracing the curves of Plates 5, 6, 7, and 8, with the device. Table 4 shows the computed values of the amplitudes of the harmonics. Table 5 gives these values in terms of percent of the fundamental. The average amplitude in percent of the fundamental and the root-mean-square value for total harmonic content is also given. As expected from an inspection of the functional relationship of θ and ϕ given in paragraph 9, the distortion from a pure sine wave is much smaller for low values of maximum amplitude.

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USE OF APPARATUS

12. As mentioned in the introduction, the apparatus is designed for use in the development of automatic tracking equipment for fire control radar systems. In determining the performance of the drive systems, it is convenient to open the synchro channels controlling the power drive mechanisms and apply a sinusoidally varying synchro signal. The amplitude of oscillation of the unit is then measured for a range of frequencies from essentially zero frequency to an upper frequency well above the usual range of operation. The upper frequency obtainable with the device constructed in accordance with Plate 1 is approximately 10 cycles per second while the lower limit is about 0.1 cycles per second. The first "system" tested with the mechanical oscillator was a synchro motor. The resonant frequency with and without a dial was determined. In this test it was possible to use the lowest amplitude available. In general, the accuracy of the results obtained in system tests is greatest when the amplitude of oscillation is the smallest permitted by the dead space of the system control. Accordingly, a selection of amplitudes was made available in the mechanical oscillator and, when used in the fine channel of a 1-speed and 36-speed synchro drive, the unit under test may be oscillated through the coarse channel equivalent amplitudes of plus and minus 1, $\frac{1}{2}$, $\frac{1}{4}$, and 1/8 degrees.

CONCLUSIONS

13. A mechanical oscillator suitable for use in the testing of fire control apparatus and in the development of automatic tracking radar equipment has been developed. A synchro generator output varying approximately sinusoidally between any of several maximum amplitudes at rates from 0.1 to 10 cycles per second is provided. The simplest possible mechanical linkage is used with the proportioning for minimum distortion from a sine wave output based on an analysis of the linkage system. The analysis of the output waveform shows, for low maximum oscillation amplitudes, a root-mean-square value of approximately one percent for the total harmonic content.

ACKNOWLEDGEMENT

14. Mr. Peter Waterman, Ens. J.W. Titus, and Lt.(jg) L. O. Brown have assisted with constructive comments. Lt. (jg) James A. White and Ens. J. E. Myers have aided in the analysis of the system performance. The above are all members of the Fire Control Division of this laboratory.

REFERENCE

15. a. BuOrd ltr (Re4f) S67 of 9 November 1944 to Director NRL, Problem O-111R-C, Development of Electronic Test Equipment.

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Table 1

Design Dimensions for Components of Mechanical Oscillator. Dimensions based on a distance between centers of 10 inches.

Amplitude in 1-speed channel	Amplitude in 36-speed channel (and in oscillator)	Dimensions in inches		
		Driver Plate Radius r	Crank Arm Length c	Connecting rod length l
$\pm 1^\circ$	$\pm 36^\circ$	2.458	4.607	7.955
$\pm \frac{1}{2}^\circ$	$\pm 18^\circ$	1.307	4.505	8.354
$\pm \frac{1}{4}^\circ$	$\pm 9^\circ$	.677	4.480	8.622
$\pm 1/8^\circ$	$\pm 4.5^\circ$	.345	4.474	8.776

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Table 2

Mechanical Oscillator Input and Output Shaft Relationships.
Data for Harmonic Analysis of Output.

Maximum Amplitude	$\alpha = \pm 36^\circ$		$\alpha = \pm 18^\circ$		$\alpha = \pm 9^\circ$		$\alpha = \pm 4.5^\circ$	
Input angle in 10° intervals	0 to 180	350 to 190	0 to 180	350 to 190	0 to 180	350 to 190	0 to 180	350 to 190
0	0		0		0		0	
1	6.2	-6.3	3.0	-3.0	1.55	-1.65	.75	-.85
2	12.5	-12.3	5.8	-6.0	3.0	-3.15	1.45	-1.50
3	18.8	-18.0	8.6	-8.7	4.35	-4.50	2.10	-2.15
4	25.1	-23.0	11.1	-11.2	5.55	-5.70	2.80	-2.80
5	30.9	-27.5	13.2	-13.3	6.75	-6.95	3.40	-3.30
6	34.8	-31.2	14.9	-15.0	7.65	-7.75	3.75	-3.80
7	36.3	-34.1	16.2	-16.3	8.30	-8.35	4.00	-4.10
8	35.5	-36.0	16.9	-17.1	8.65	-8.75	4.20	-4.30
9	33.5	-36.6	17.2	-17.2	8.85	-8.85	4.40	-4.35
10	30.7	-36.0	16.9	-16.7	8.80	-8.65	4.30	-4.30
11	27.8	-34.3	16.3	-15.6	8.45	-8.25	4.05	-4.10
12	24.3	-31.3	15.1	-14.0	7.90	-7.45	3.85	-3.70
13	20.8	-27.2	13.6	-12.0	6.35	-6.50	3.45	-3.20
14	17.0	-22.2	11.8	-9.5	7.00	-5.05	2.90	-2.80
15	12.9	-17.1	9.8	-6.8	4.85	-3.75	2.20	-2.10
16	8.5	-11.6	7.2	-4.0	3.45	-2.45	1.60	-1.35
17	3.9	-6.1	4.6	-1.1	2.15	-1.0	.85	-.65
18	-1.0		1.8		.55		0	

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Table 3

Harmonic Analysis of the Mechanical Oscillator Output. The coefficients of the following equation as obtained by the Mechanical Harmonic Analyzer developed by Mader are given in the Table.

$$\theta = S_1 \sin\phi + S_2 \sin 2\phi + S_3 \sin 3\phi + \ldots$$
$$+ D + C_1 \cos\phi + C_2 \cos 2\phi + C_3 \cos 3\phi + \ldots$$

Maximum Amplitude	$\alpha = \pm 36^\circ$	$\alpha = \pm 18^\circ$	$\alpha = \pm 9^\circ$	$\alpha = \pm 4.5^\circ$
S1	35.1	17.5	8.90	4.35
C1	1.8	-.7	-.30	-.03
S2	2.7	.4	-.16	.03
C2	.3	.6	.10	.00
S3	-.5	-.3	.00	.00
C3	-1.5	-.2	.00	.03
S4	-.3	-.1	.02	.02
C4	.0	-.1	.00	.00
S5	.0	-.2	.00	.00
C5	.4	-.2	.00	.00
S6	.2	-.1	-.02	.01
C6	.1	-.1	-.02	.00
S7	.1	-.3	.00	.00
C7	0	-.2	-.02	.00
S8	.1	.0	.02	.00
C8	0	-.1	.00	.00

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Table 4

Combination of the Coefficients of the Sine and Cosine Terms of the Harmonic Analysis of the Mechanical Oscillator Output. Values for S_n and C_n from Table 3 are used to calculate A_n in the expression:

$$\Theta = A_0 + A_1 \sin\left(\phi + \phi_1\right) + A_2 \sin\left(2\phi + \phi_2\right) + \dots + A_n \sin\left(n\phi + \phi_n\right) + \dots$$

$$\text{where } A_n = \sqrt{S_n^2 + C_n^2} \qquad A_0 = 0$$

Maximum Amplitude		$\alpha = \pm 36^\circ$	$\alpha = \pm 18^\circ$	$\alpha = \pm 9^\circ$	$\alpha = \pm 4.5^\circ$
	Average Maximum Amplitude	36.45	17.2	8.85	4.37
A1	Fundamental	35.14	17.6	8.91	4.35
A2	2nd harmonic	2.72	1.0	.19	.04
A3	3rd harmonic	1.58	.36	0	.03
A4	4th harmonic	.3	.14	.02	.02
A5	5th harmonic	.4	.28	0	0
A6	6th harmonic	.22	.14	.03	.01
A7	7th harmonic	.1	.36	.02	0
A8	8th harmonic	.1	.1	.02	0
R-M-S of all harmonics to 8th		3.20	1.18	.195	.017

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Table 5

Summary of Results of the Harmonic Analysis of the Mechanical Oscillator Output. Values include the effects of inaccuracies of construction of the unit.

All values in percent of the fundamental				
Maximum Amplitude	$\alpha = \pm 36^\circ$	$\alpha = \pm 18^\circ$	$\alpha = \pm 9^\circ$	$\alpha = \pm 4.5^\circ$
Average Maximum Amplitude	104	98	99	100
Fundamental	100	100	100	100
2nd harmonic	7.8	5.7	2.1	.9
3rd harmonic	4.5	2.0	0	.7
4th harmonic	.9	.8	.2	.5
5th harmonic	1.1	1.6	0	0
6th harmonic	.6	.8	.3	.2
7th harmonic	.3	2.0	.2	0
8th harmonic	.3	.6	.2	0
Total harmonic content (up to 8th)	9.1	6.7	2.2	1.26

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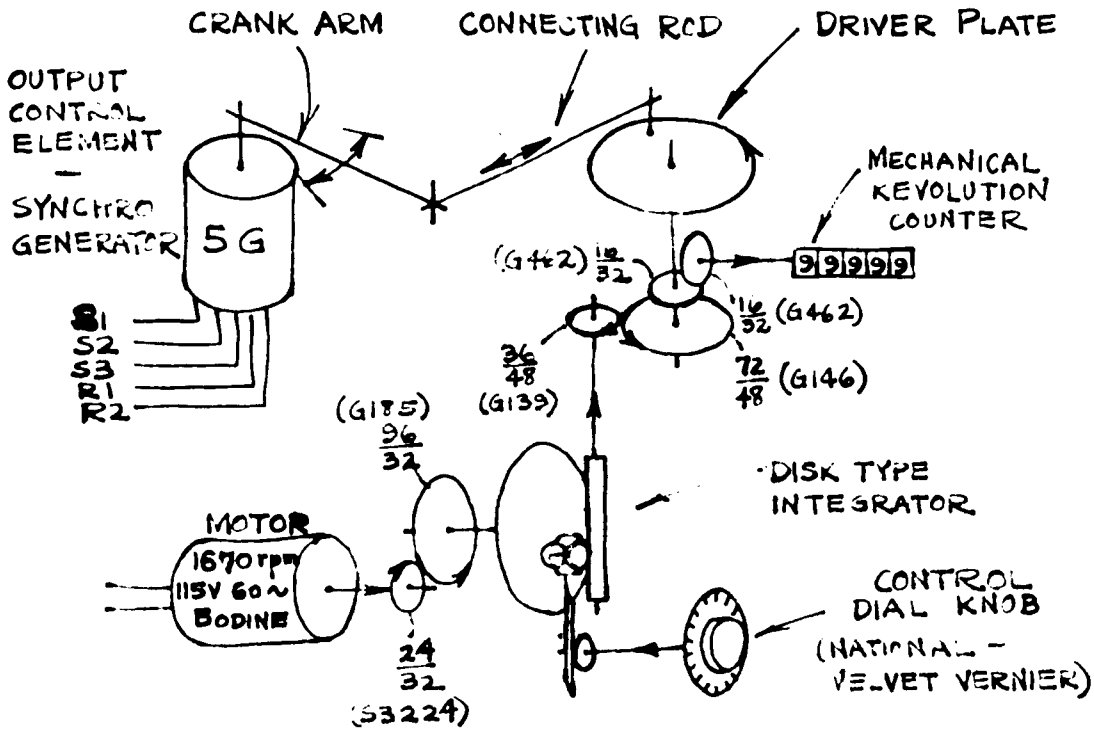
SKETCH SHOWING MECHANICAL LAYOUT OF THE
MECHANICAL OSCILLATOR



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	14 JUNE '45 E.J.H. R-2582	

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[redacted]	NRL - FIRE CONTROL DIVISION 18 JULY '45 [redacted] R-2582	PLATE 2

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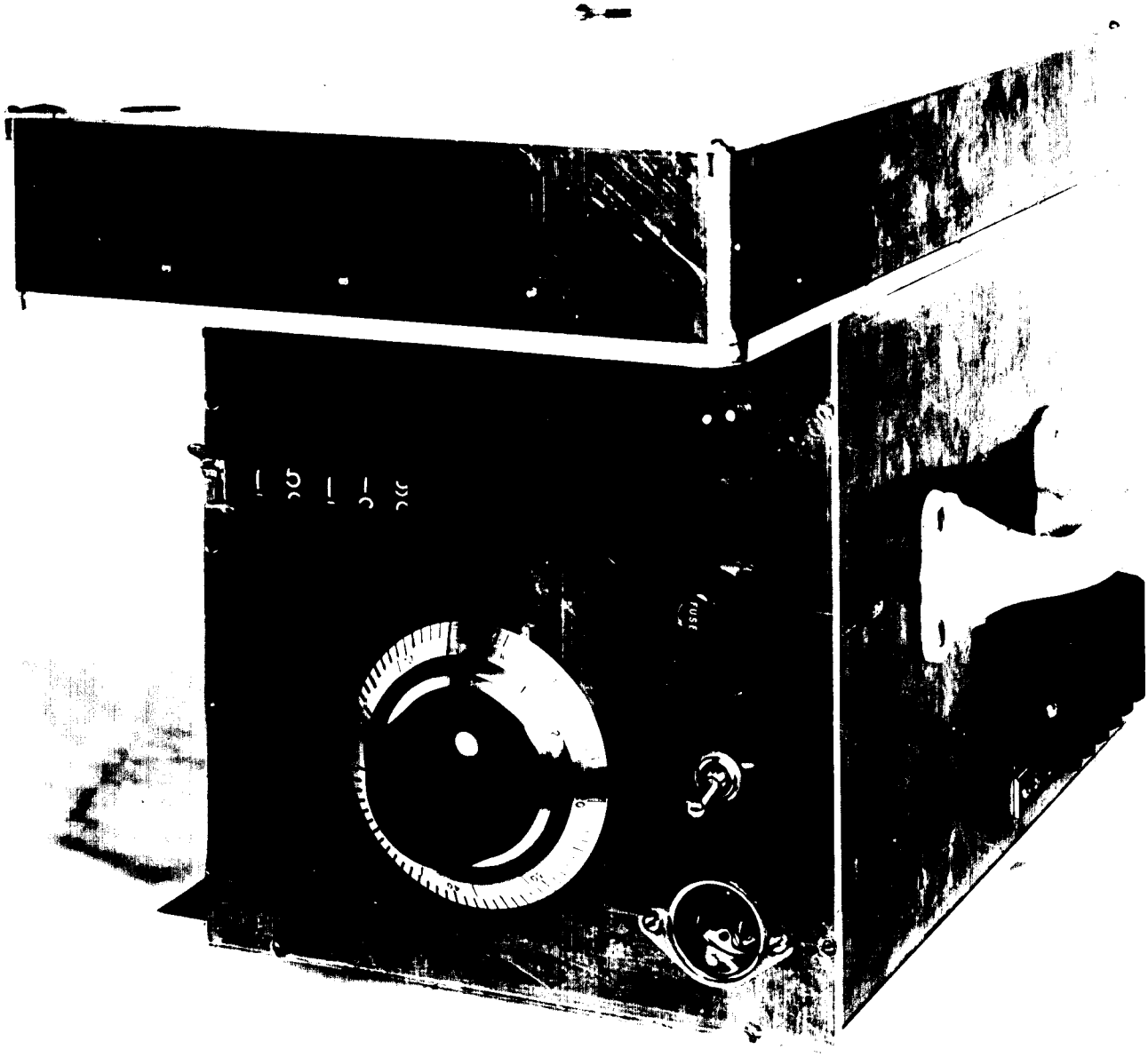

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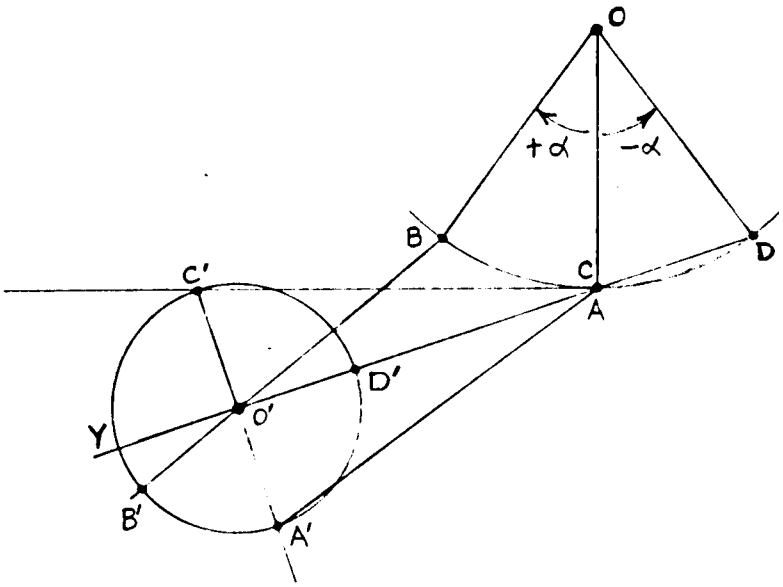
BASIS FOR PROPORTIONING OF PIN-LINKAGE COMPONENTS IN SINE WAVE MECHANICAL OSCILLATOR



O′ is center of rotating driver

O is center of oscillating crank arm (CA, OB, OC, OD)

A′A, B′B, C′C, D′D are successive positions of connecting rod

C′A is ⊥ to OA

$\angle C'AD' = \frac{\alpha}{2}$

O′C′ is ⊥ to O′A and is driver radius

ABOVE CONSTRUCTION INSURES CORRECT AMPLITUDE AND PHASE AT 0° (& 360°), 180°, & 270° AND CORRECT AMPLITUDE FOR THE SHIFTED 90° PEAK — MAGNITUDE OF SHIFT INCREASES WITH INCREASE OF α.

[redacted]	NRL – FIRE CONTROL DIVISION 16 JUNE 45 ~~6.5%~~ R-2582	PLATE 4

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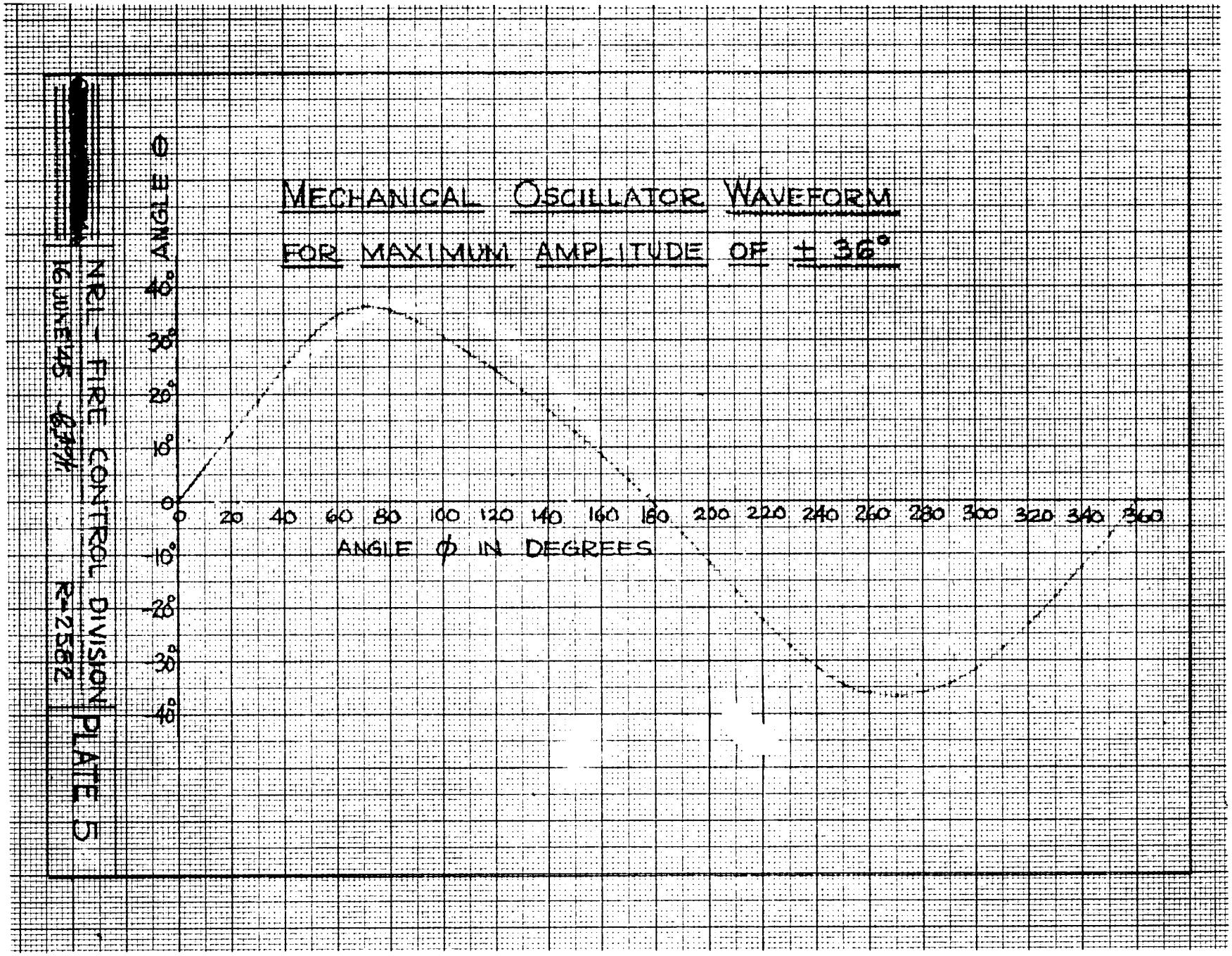

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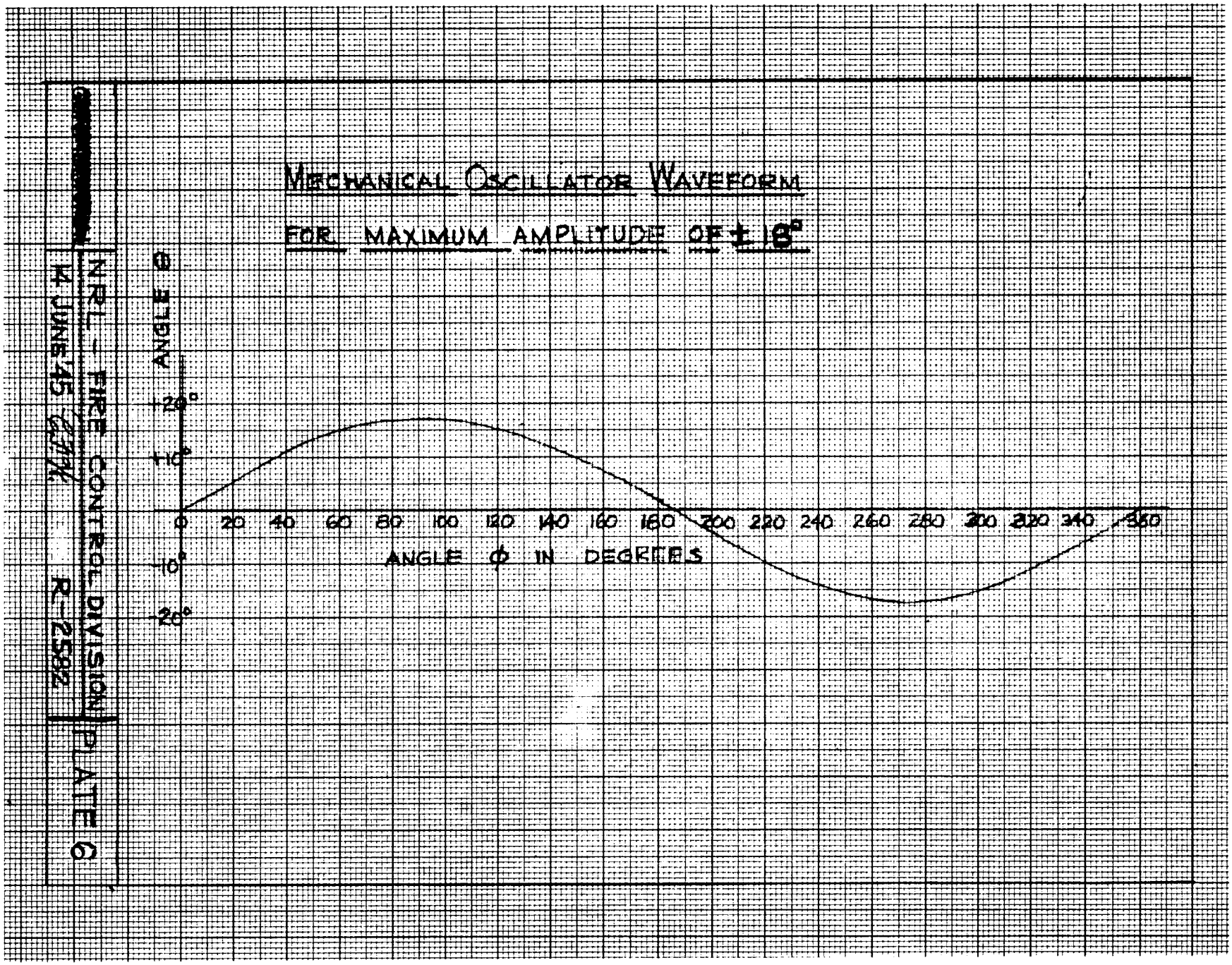

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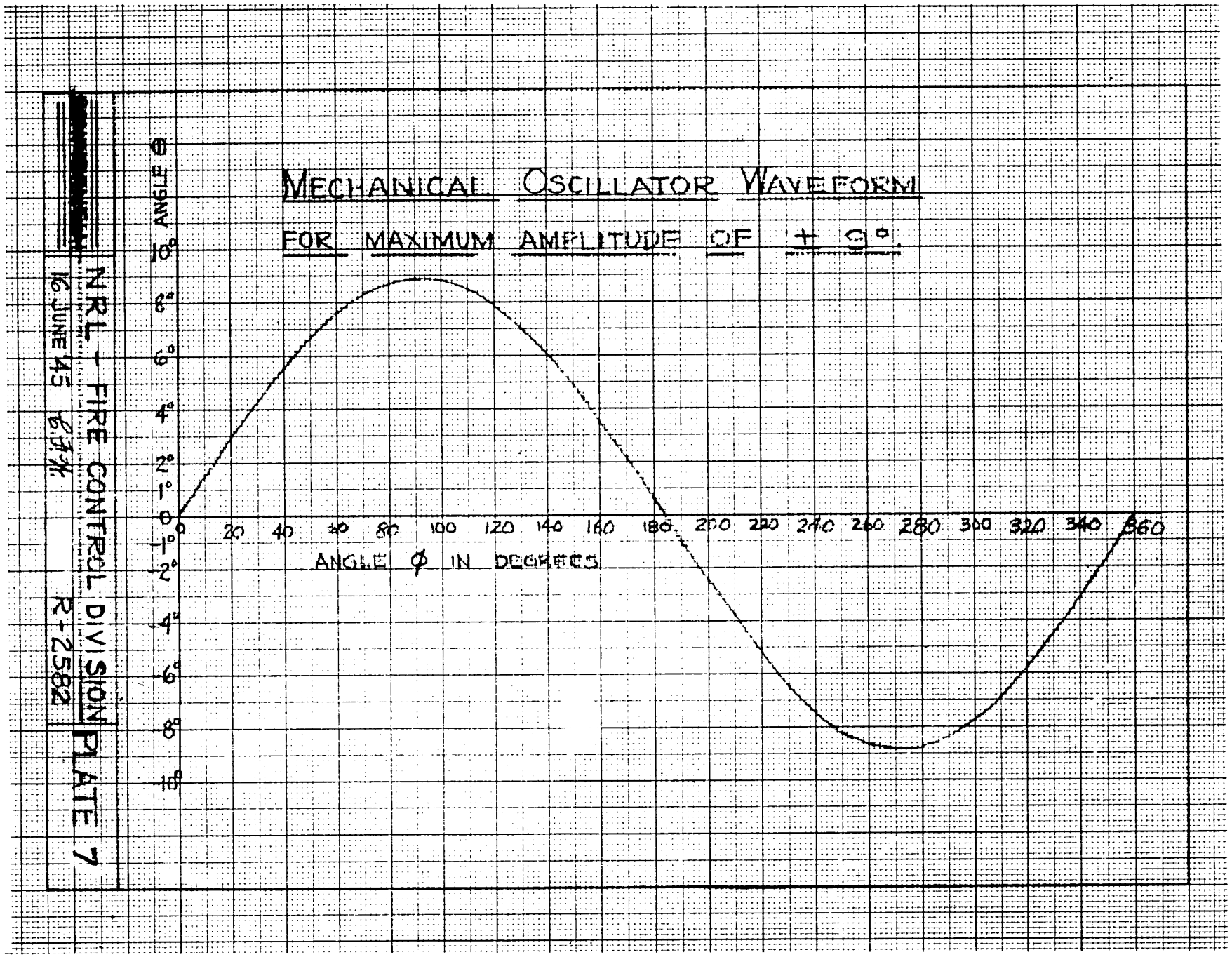

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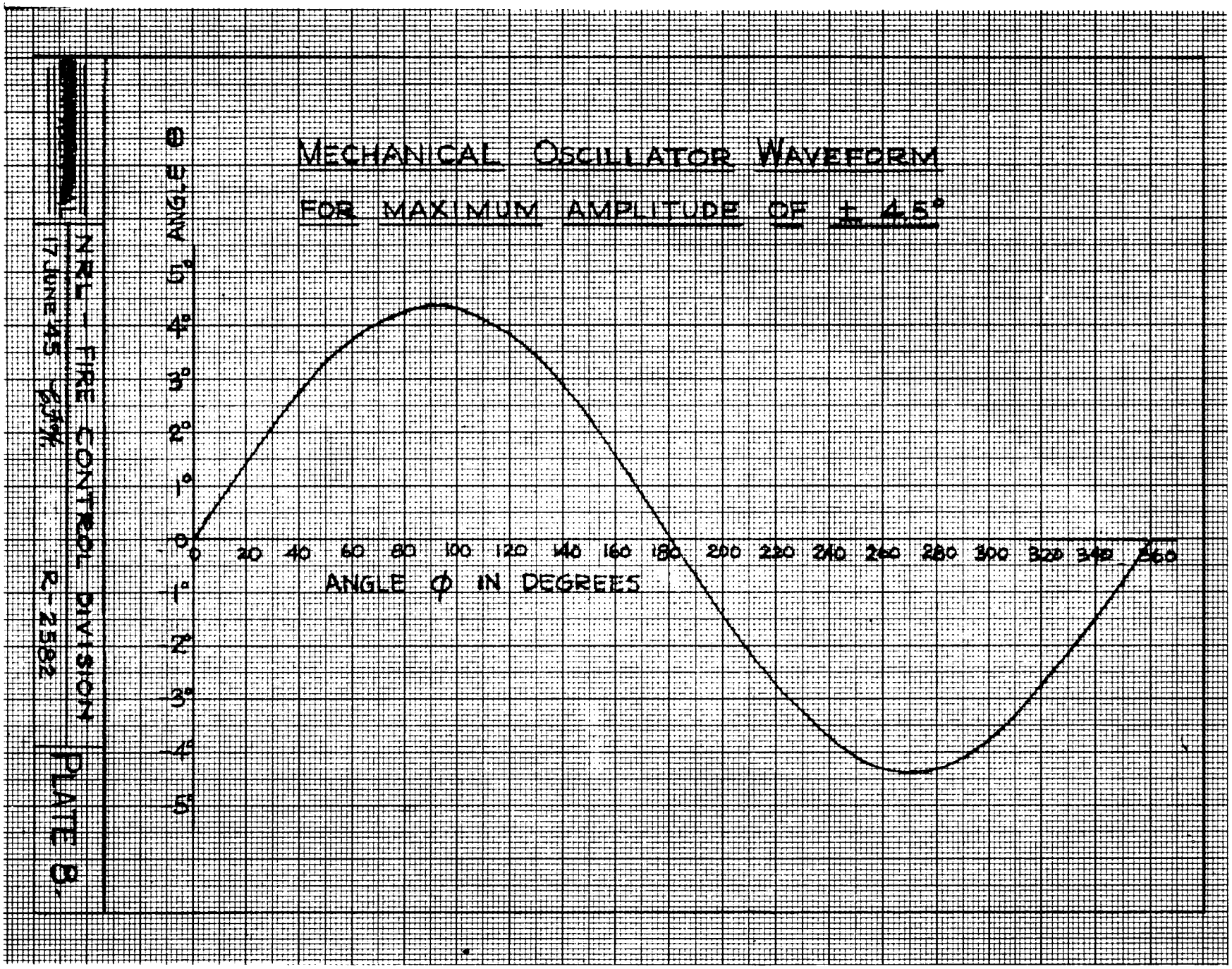
MECHANICAL OSCILLATOR WAVEFORM
FOR MAXIMUM AMPLITUDE OF ± 4.5°
ANGLE θ
5°
4°
3°
2°
1°
0
-1°
-2°
-3°
-4°
-5°
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360
ANGLE φ IN DEGREES
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PLATE B.

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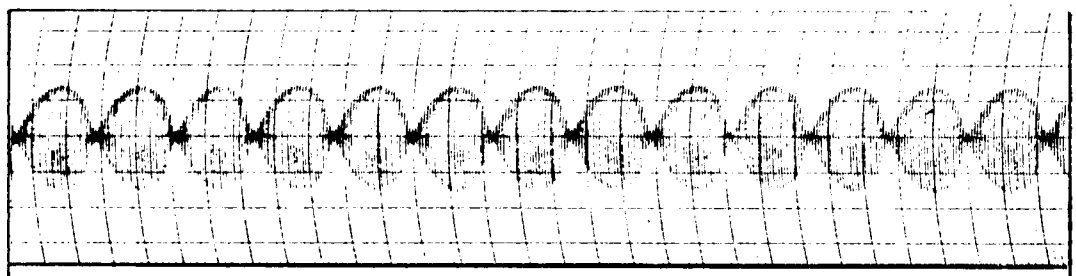
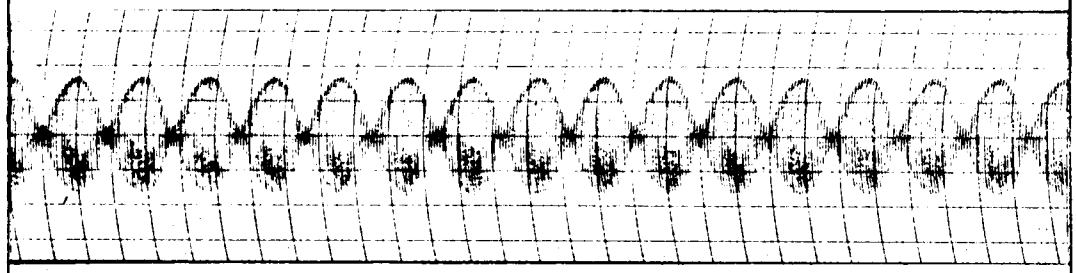
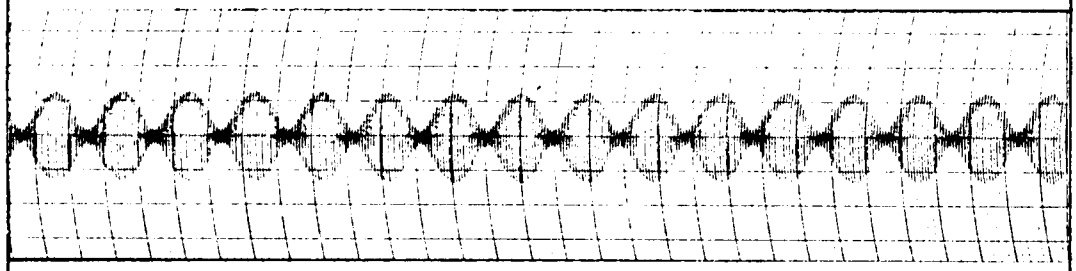


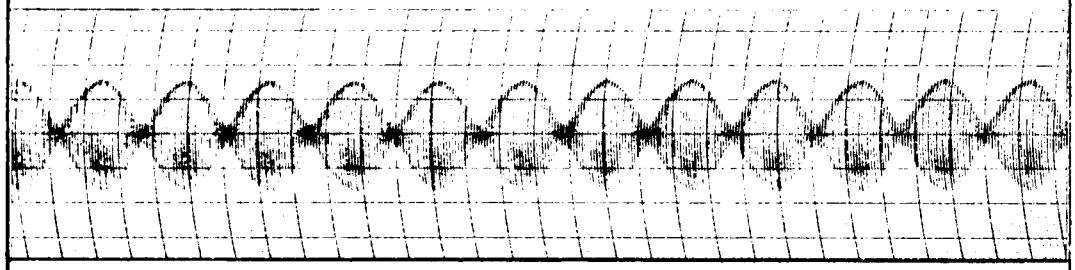
MAXIMUM AMPLITUDE ±36°



MAXIMUM AMPLITUDE ±18°



MAXIMUM AMPLITUDE ±9°



MAXIMUM AMPLITUDE ±4.5°

OUTPUT WAVEFORM OF MECHANICAL OSCILLATOR FOR FOUR VALUES OF MAXIMUM AMPLITUDE.
RECORDS MADE USING A BRUSH CRYSTAL INKING RECORDER.

[redacted]	NRL – FIRE CONTROL DIVISION 27 June '45 E.F.M. R-2582	PLATE 9

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