CHAPTER III

EXPERIMENTAL DETERMINATION

3.1 Introduction. In the chapter II, the method used to determine the equivalent circuit parameters and the motor constants have been mentioned. In this chapter, the given motor has been tested experiment ally and its significant dimensions have been measured. The method of testing and measurements are briefly listed as follows:

3.1.1 The no-load test. The no load test were carried on while the starting winding connected only, and while the main winding connected only.

3.1.2 The locked-rotor test. The motor was subjected to the locked-rotor tests for the same connection as those in the no-load test.

3.1.3 The lowest operating-voltage test. The motor was subjected to the lowest operating-voltage test while the starting winding is disconnected and the motor was initially start by the external torque. The lowest power input to the motor to run at no-load was recorded.

3.1.4 Measurements of the motor dimensions. The motor was deconstructed into parts, and the type of stator windings were studied. The conductor sizes, the stator and the rotor dimensions were measured. The performances of the motor were then determined by calculations from those measurements.

3.1.5 **Measurements of starting torque.** A torque arm pressed on a spring balance was attached to the rotor of the motor. The motor was then supplied at its rated voltage and various values of the starting capacitance were used to obtain various values of the starting torque.

3.2 **Determination of the starting torque from equivalent-circuit parameter of the motor.** The equivalent circuit parameters were determined as follows:-

3.2.1 **The main-winding equivalent circuit.** At rated voltage and with the starting winding disconnected, the test results are obtained as follows:

From the no-load test:

Applied voltage, V_1 = 110 Volts
No load current, I_o = 4.44 Amps.
No load power supply = 95.2 Watts.

The main-winding resistance measured after the test = 1.88 ohms.

From the locked-rotor test:

Applied voltage V_L = 75 Volts
Locked-rotor current I_L = 14.2 Amp.
Locked-rotor power supply = 770 Watts
The main-winding resistance measured after the test = 1.80 ohms.

From full-load test:

Stator main winding resistance measured after the test= 1.95 ohms.

From the lowest operating-Voltage test:

The power supply for the test = 8.0 Watts.

Calculations

After several trials, the value of K_2 is arbitrarily assumed to be 1.04 *

$$\varkappa_m = \frac{V_1}{I_0} \cdot \frac{K_2}{2K_2^2-1}$$

$$= \frac{110}{4.40} \cdot \frac{1.04}{2(1.04)^2-1}$$

$$= 22.2 \text{ ohms.}$$

$$Z_L = \frac{V_L}{I_L} = \frac{75}{14.2} = 5.28 \text{ ohms.}$$

$$R_L = \frac{W_L}{I_L{}^2} = \frac{770}{14.2^2} = 3.82 \text{ ohms.}$$

$$X_L = \sqrt{Z_L{}^2 - R_L{}^2} = \sqrt{5.28^2 - 3.82^2}$$

$$= 3.64 \text{ ohms.}$$

Since $\varkappa_1 \approx 2\varkappa_2' = \frac{X_L}{2}$

then $x_1 = \frac{3.64}{2} = 1.82$ ohms.

and $\varkappa_2' = \frac{1.82}{2} = 0.91$ ohm

Using the values of $\varkappa_2'$ and $\varkappa_m$ obtained above, the value of K_2 is rechecked,

---

* Refer to chapter II, item 2.23

$$K_2 = 1 + \frac{x_2'}{x_m} = 1 + \frac{0.91}{22.2}$$

$$= 1.041$$

which is close to the initially assume value.

$$\text{Then } r_2' = \frac{R_L - r_1}{2} K_2^2$$

$$= \frac{3.82 - 1.8}{2} (1.04)^2$$

$$= 1.09 \text{ ohm.}$$

For performance calculation, the resistance measured immediately after the full load test is used. The increase of the rotor resistance can be assumed to be at the same rate as that of the stator,*

$$\text{therefore } r_2' \text{ (full load)} = 1.09 \left(\frac{1.95}{1.80}\right)$$

$$= 1.18 \text{ ohm.}$$

For copper-loss calculation the resistance measured at the no-load test is used.

$$P_{co,1} = \text{copper loss in stator main winding}$$

$$= I_o^2 \; r_1$$

$$= (4.44)^2 \, 1.88$$

$$= 37 \text{ watt.}$$

By the foregoing assumption the resistance of rotor increases at the same rate as that of the stator, then, at no load,

---

* Chester L.Dawes, Electrical Engineering, Vol I, 4th edition Apprendix H., Mc Graw - hill book company, inc., 1952

$$r_2' \text{ (no load)} = 1.09 \left(\frac{1.88}{1.80}\right)$$

$$= 1.14 \text{ ohms.}$$

$$P_{co,2} = \text{Copper loss in rotor}$$

$$= I_o^2 \ r_2'$$

$$= (4.44)^2 \ 1.14$$

$$= 22.5 \text{ watts.}$$

P_o, the wattage required at the lowest operating-voltage which is equal to friction and windage loss, = 8 watts.

Then, $$P_{rot.iron} + P_{h+e} = Wo - (Po + P_{co,1} + P_{co,2})$$

$$= 95.2-(8+37+22.5)$$

$$= 27.7 \text{ Watts.}$$

$$P_{h+e} \approx \frac{P_{rot.iron} + P_{h+e}}{2}$$

$$\approx \frac{27.7}{2}$$

$$= 14 \text{ watts.}$$

E_1 = Voltage across the forward and the backward branches.

$= Vo - Iox_1$

$= 110-4.44 \times 1.82$

$= 101.9$ Volts.

C = the ratio of voltage across the forward branch to the voltage aross the backward branch

$$= \frac{x_m}{\sqrt{\left(\frac{r_2'}{2}\right)^2 + (x_2')^2}} = \frac{22.2}{\sqrt{(0.507)^2 + (0.91)^2}}$$

$$= 21.3$$

E_{2f}' = Voltage across forward branch

$$= E_1 \frac{C}{C+1} = 101.9 \times \frac{21.3}{21.3+1}$$

$$= 97.3 \text{ volts.}$$

$$g_m = \frac{P_{h+e}}{(E_{2f}')^2} = \frac{14}{(97.3)^2}$$

$$= 0.00148$$

$$r_m = g_m . x_m^2 = 0.00148\,(22.2)^2$$

$$= 0.73 \text{ ohm.}$$

The equivalent circuit parameters are then listed al follows:

r_1 = 1.95 ohms.

r_2' = 1.18 ohms.

r_m = 0.73 ohms.

x_m = 22.2 ohms.

x_1 = 1.82 ohms.

x_2' = 0.91 ohms.

The equivalent circuit for main winding can then be constructed as shown in Fig 3.1

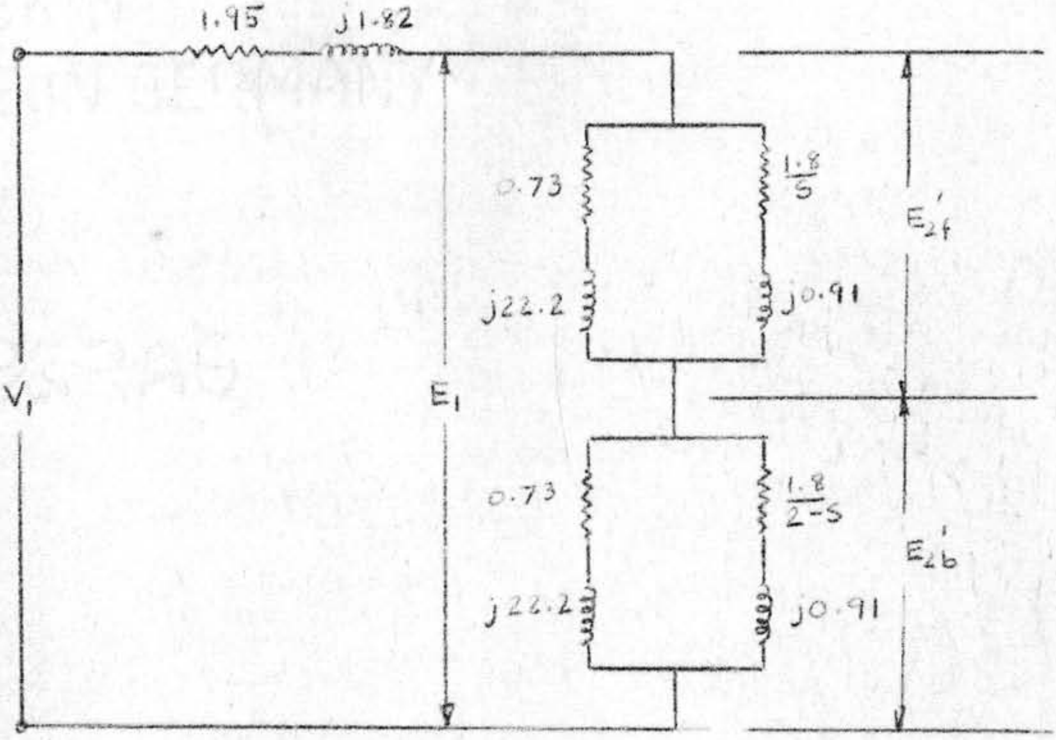

Fig. 3.1 The Equivalent Circuit for Main Winding.

3.2.2 <u>The starting- winding equivalent circuit.</u> At rated voltage and with the main winding disconnected, the test results are obtained as follows:

<u>From the no load test:</u>

Applied voltage V_1 = 110 Volts.

No load current I_o = 2.20 Amp.

No load power supply W_o = 85 Watts.

Starting-winding resistance measured after the test = 7.65 ohms.

<u>From the locked-rotor test.</u>

Applied voltage V_L = 80 Watts.

Locked-rotor current I_L = 5.2 Amp.

Locked-rotor power supply $W_L = 345$ watts.

Starting winding resistance measured after the test = 7.53 ohm.

From full load test.

Starting winding resistance measured after the test = 7.82 ohm.

Calculation By the same procedures and assumptions used in calculation of the main-winding equivalent circuit, the calculations in this part are made as follows:

K_2 is assumed arbitrarily to be 1.05

$$x_m = \frac{110}{2} \times \frac{1.05}{2(1.05)^2 - 1}$$

$$= 43.5 \text{ ohms.}$$

$$Z_L = \frac{V_L}{I_L} = \frac{80}{5.2} = 15.4 \text{ ohms.}$$

$$R_L = \frac{W_L}{I_L^2} = \frac{345}{5.2^2} = 12.8 \text{ ohms.}$$

$$X_L = \sqrt{Z_L^2 - R_L^2} = \sqrt{(15.4)^2 - (12.8)^2}$$

$$= 8.54 \text{ ohms.}$$

Since $x_1 \approx 2x_2' = \frac{X_L}{2}$

then, $x_1 = \frac{8.54}{2} = 4.27$ ohms.

$x_2' = \frac{4.27}{2} = 2.14$ ohms.

Using the values of x_2' and x_m obtained above, the value of K_2 is rechecked,

$$K_2 = 1 + \frac{x_2'}{x_m} = 1 + \frac{2.14}{43.5}$$

$= 1.0492$ which is close to the initially assumed value.

Then, $$r_2' = \frac{R_L - r_1}{2} \cdot K_2^2$$

$$= \frac{12.8 - 7.53}{2} (1.05)^2$$

$= 2.90$ ohms.

r_2' (full load) $= 2.9 \left(\frac{7.82}{7.53} \right) = 3.02$ ohms.

$P_{co,1} = 2.2^2 (7.65) = 37$ watts.

r_2' (no load) $= 2.90 \left(\frac{7.65}{7.53} \right) = 2.95$ ohms.

$P_{co,2} = 2.2^2 (2.95) = 14.3$ watts.

The friction and windage loss = 8 watts.

Prot.iron + $P_{h+e} = 85 - (8 + 37 + 14.3)$

$= 25.7$ watts.

$P_{h+e} = 13$ watts.

$E_1 = 110 - 2.2 \times 4.27$

$= 100.6$ Volts.

$$C = \frac{x_m}{\sqrt{\left(\frac{r_2'}{2}\right)^2 + (x_2')^2}} = \frac{43.5}{\sqrt{\left(\frac{2.95}{2}\right)^2 + (2.14)^2}}$$

$= 16.9$ volts.

$$E'_{2f} = 100.6 \times \frac{16.9}{16.9+1}$$

$$= 94.6 \text{ volts.}$$

$$g_m = \frac{13}{(94.6)^2} = 0.00145$$

$$r_m = 0.00145\,(43.5)^2$$

$$= 2.74 \text{ ohms.}$$

The equivalent circuit parameters are then list as follows:

r_1 = 7.82 ohms.

r_2' = 3.02 ohms.

r_m = 2.74 ohms.

x_m = 43.5 ohms.

x_1 = 4.27 ohms.

x_2' = 2.14 ohms.

The equivalent circuit for starting winding can then be constructed as shown in Fig 3.2

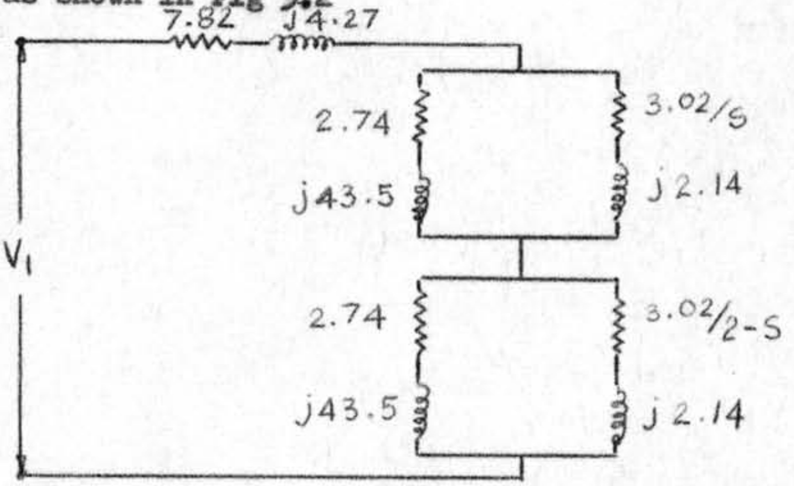

Fig. 3.2 The equivalent Circuit for Starting Winding.

3.2.3 Starting Torque Calculation from the equivalent-circuit parameters

From the equivalent - circuit parameters of the starting winding and the main winding the starting torque of the motor can be calculated as follows:

For Main Winding

The equivalent circuit parameters obtained are,

$r_{1m} = 1.95$ ohm.

$r_m = 0.73$ ohm.

$r_2' = 1.18$ ohm.

$x_{1m} = 1.82$ ohm.

$x_m = 22.2$ ohm.

$x_2' = 0.91$ ohm.

at starting, $S = 1$

$$a = r_m (r_2'/S) - x_2' x_m$$

$$= 0.73 (1.18) - 0.91 (22.2)$$

$$= -19.44$$

$$b = (\frac{r_2'}{S}) x_m + x_2' r_m$$

$$= 1.18 (22.2) + 0.91 (0.73)$$

$$= 26.864$$

$$K_2 = 1 + \frac{x_2'}{x_m} = 1 + \frac{0.91}{22.2} = 1.0405$$

$$R_f = R_b = \frac{a\,(r_m + r_2'/S) + bk_2\,x_m}{(r_m + r_2'/S)^2 + (k_2\,x_m)^2}$$

$$= \frac{-19.44\,(0.73 + 1.18\,) + 26.864 \times 1.0405 \times 22.2}{(0.73 + 1.18)^2\,(1.0405 \times 22.2)^2}$$

$$= 1.09$$

$$X_f = X_b = \frac{b\,(r_m + r_2'/S) - a\,K_2 x_m}{(r_m + r_2'/S)^2 + (K_2\,x_m)^2}$$

$$= \frac{26.864\,(0.73 + 1.18) + 19.44 \times 1.0405 \times 22.2}{(0.73 + 1.18)^2 + (1.0405 \times 22.2)^2}$$

$$= 0.935$$

$$l_m = r_{1m} + R_f + R_b = 1.95 + 1.09 + 1.09 = 4.13$$

$$m_m = x_{1m} + X_f + X_b = 1.82 + 0.935 + 0.935 = 3.690$$

$$\dot{Z}_m = l_m + jm_m = 4.13 + j\,3.690$$

$$A = \frac{N_s,\text{eff}}{N_n,\text{eff}} = \sqrt{\frac{x_{1s}}{x_{1m}}} \;*$$

$$= \sqrt{\frac{4.27}{1.82}} = \sqrt{2.35} = 1.53$$

<u>For starting winding.</u>

The equivalent circuit parameters obtained are,

r_{1s} = 7.82 ohms

r_m = 2.74 ohms

---

* Alternating Current Machines, A.F.Puchstein, T.C Lloyd, A.G. Conrad, third edition, John Wiley & Sons, inc. New York.

$r_2' = 3.02$ ohms.

$x_{1s} = 4.27$ ohms.

$x_m = 43.5$ ohms.

$x_2' = 2.14$ ohms.

at starting, $S = 1$

$$a = r_m (r_2'/S) - x_2' \, x_m$$

$$= 2.74 \, (3.02) - 2.14 \, (43.2)$$

$$= -84.9$$

$$b = (r_2'/S) \, x_m + x_2' \, r_m$$

$$= 3.02 \, (43.5) + 2.14 \, (2.74)$$

$$= 136.86$$

$$K_2 = 1 + \frac{x_2'}{x_m}$$

$$= 1 + \frac{2.14}{43.5}$$

$$= 1.0492$$

$$R_f = \frac{a(r_m + r_2'/S) + b \, (K_2 \, x_m)}{(r_m + r_2'/S)^2 + (K_2 x_m)^2}$$

$$= \frac{(-84.9)\,(2.74+3.02) + 136.86 \, (1.0492 \times 43.5)}{(2.74+3.02)^2 + (1.0492 \times 43.5)^2}$$

$$= 2.73$$

$$X_f = \frac{b\,(r_m + r'_{2/S}) - a\,K_2\,x_m}{(r_m + r'_{2/S})^2 + (K_2\,x_m)^2}$$

$$= \frac{136.86\,(\,2.74 + 3.02\,) - (-84.9)\,(1.0492 \times 43.5)}{(\,2.74 + 3.02)^2 + (1.0492 \times 43.5)^2}$$

$$= 2.2$$

$$l_s = r_c + A^2\,(r_{1s} + R_f + R_b)$$

$$= 0 + 2.35\,(7.82 + 2.73 + 2.73)$$

$$= 30.6$$

$$m_s = x_c + a^2\,(x_{1s} + X_f + X_b)$$

For example, assume

$$C = 180\ \mu F$$

= capacitance installed by manufacturer.

$$X_c = \frac{10^6}{2\pi 50 \times 180} = 17.7 \quad \text{ohm.}$$

$$m_s = -\,17.7 + 2.35\,(4.27 + 2.2 + 2.2)$$

$$= +\,2.7 \quad \text{ohms.}$$

$$I_m = \frac{V_m}{Z_m} = \frac{V_m}{lm + jm_m}$$

$$= \frac{110}{4.13 + j\,3.69}$$

$$= 19.9\ \underline{/\,-41.5^\circ}$$

$$I_s = \frac{V_s}{Z_s} = \frac{V_s}{l_s + jm_s}$$

$$= \frac{110}{30.6 + j\,2.7}$$

$$= 3.57 \angle{-5^\circ}$$

$$T_{s=1} = \frac{7.04}{n_s} \times 4\, I_m I_s\, aR_f \sin\varphi \quad \text{lb-ft.}$$

$$= \frac{7.04}{1500} \times 4 \times 19.9 \times 3.57 \times 1.53 \times 2.73 \times \sin(41.5-5)^\circ$$

$$= 3.31 \text{ lb-ft.}$$

$$= 53.0 \text{ oz-ft.}$$

For various values of capacitance, the starting torque has been calculated and listed below:

Table 3.1

C μF	X_c ohms	I_s Amps	φ_s degrees	$T_{s=1}$ oz-ft.
0	00	0	-	0
20	159.0	0.78	77.5	17.1
40	79.6	1.65	63.0	40.0
60	53.0	2.46	47.0	61.6
80	39.9	3.03	32.5	72.5
100	31.8	3.37	20.0	74.0
120	26.9	3.50	12.0	70.3
140	22.7	3.57	4.5	64.2

C μF	X_c ohms	I_s Amps	φ_s degrees	$T_{s=1}$ oz- ft.
160	19.9	3.58	1.0	60.5
180	17.7	3.57	-5.0	53.0
200	15.95	3.55	-8.0	49.0
220	14.45	3.52	-11.0	44.7
240	13.3	3.50	-12.5	42.4
260	12.2	3.46	-15.0	38.6
280	11.4	3.42	-16.5	36.2
300	10.6	3.41	-18.0	34.0
320	9.96	3.40	-19.0	32.6
340	9.36	3.37	20.0	30.8
360	8.85	3.36	20.5	30.1
380	8.37	3.34	-21.5	28.6
400	7.96	3.33	-22.0	27.8
420	7.58	3.31	-22.5	27.6
440	7.25	3.30	-23.0	26.2

3.3 **Determination of starting torque from physical dimensions of the motor** The given motor has been deconstructed into parts, the method of winding is studied, the conductor size, the stator dimension and the rotor dimension are measured and recorded as follow:

3.3.1 Main Winding

The main winding is of the concentric type.

The gauge 20 A.W.G. of enamel copper wire of which its cross sectional area is 0.000804 square inches has been used. The concentric-type winding has been would in the following slot orders :

Slot 5 to slot 32 - 34 turns
4 to slot 33 - 60 turns
3 to slot 34 - 42 turns
2 to slot 35 - 34 turns

The winding has been arranged into two circuits connected in paralled.

C_{wm} = Winding Constant in Main winding

$$= \frac{(f_c \text{ coil } 5\text{-}32)(t\ 5\text{-}32) + (f_c \text{coil } 4\text{-}33)(t\ 4\text{-}33) + (f_c \text{ coil } 3\text{-}34)(t\ 3\text{-}34) + (f_c \text{ coil } 2\text{-}35)(t\ 2\text{-}35)}{t_{5-32} + t_{4-33} + t_{3-34} + t_{2-35}}$$

$$f_c \text{ coil } 5\text{-}32 = \sin\left(\frac{9}{9} \times 90\right) = 1.0$$

$$\text{"} \quad 4\text{-}33 = \sin\left(\frac{7}{9} \times 90\right) = 0.94$$

$$\text{"} \quad 3\text{-}34 = \sin\left(\frac{5}{9} \times 90\right) = 0.766$$

$$\text{"} \quad 2\text{-}35 = \sin\left(\frac{3}{9} \times 90\right) = 0.50$$

$$C_{wm} = \frac{1 \times 34 + .94 \times 60 + .766 \times 42 + .50 \times 34}{34 + 60 + 42 + 34}$$

$$= 0.82$$

The number of series conductors in main winding,

$$N_m = \frac{t_p \text{ X } 2 \text{ X } p}{a}$$

$$= \frac{170 \text{ X } 2 \text{ X } 4}{2}$$

$$= 680$$

The length of the half mean turn of each coil of the stator main winding, l_{smm}

$$l_{smm} = \frac{4.2\ (D + d_s)}{S_s} \text{ X slot spanned} + 1$$

$$l_{smm} \text{ for } 1^{st} \text{ coil group} = \frac{4.2\ (3.90 + .638)}{36}\ 3 + 1.725$$

$$= 3.315 \text{ inch.}$$

$$l_{smm} \text{ for } 2^{nd} \text{ coil group} = \frac{4.2(3.90 + .638)}{36}\ 5 + 1.725$$

$$= 4.375 \text{ inch.}$$

$$l_{smm} \text{ for } 3^{rd} \text{ coil group} = \frac{4.2\ (3.90 + .638)}{36}\ 7 + 1.725$$

$$= 5.435 \text{ inch.}$$

$$l_{smm} \text{ for } 4^{th} \text{ coil group} = \frac{4.2\ (3.90 + .638)}{36}\ 9 + 1.725$$

$$= 6.495 \text{ inch.}$$

L_{sm} = length of half mean turn of stator main winding

$$= \frac{3.315 \text{ X } 34 + 4.375 \text{ X } 42 + 5.435 \text{ X } 60 + 6.495 \text{ X } 34}{34 + 42 + 60 + 34}$$

$$= 4.95 \text{ inch.}$$

The resistance of the main winding, R_{sm}

$$R_{sm} = \frac{L_{sm} \times N_m \; 0.692}{a \cdot S_{sm} 10^6}$$

$$= \frac{4.95 \times 680 \times 0.692}{2 \times 0.000804 \times 10^6}$$

$$= 1.45 \quad \text{ohms at } 25\,^\circ C$$

$$= 1.73 \quad \text{ohms at } 75^\circ C$$

3.32 The Starting Winding

The winding is also of the concentric type The starting-winding conductor is of gauge 21 A.W.G., enamel copper wire.

Cross-sectional area of the copper = 0.000638 in^2

Bare diameter = 0.0285 in^2

The winding is of one circuit winding and is wound in the following orders.

slot 1 to slot 9 - 60 turns
slot 2 to slot 8 - 32 turns
slot 3 to slot 7 - 30 turns

$$t_p = 122$$

$$N_a = \frac{122 \times 2 \times 4}{1} = 976$$

The winding constant for starting winding, C_{wa}

$$= \frac{(\sin \frac{8}{9} X 90^\circ)(60) + (\sin \frac{6}{9} X 90)(32) + (\sin \frac{4}{9} X 90)(30)}{60 + 32 + 30}$$

$$= 0.87$$

The length of the half-mean-turn of each coil of the starting winding, l_{sma}

$$l_{sma} = \frac{4.2(D + d_s)}{S_s} X \text{ slot spanned} + l$$

$$l_{sma} \text{ for } 1^{st} \text{ coil group} = \frac{4.2(3.90 + .638)}{36} 4 + 1.725$$

$$= 3.845 \quad \text{inch.}$$

$$l_{sma} \text{ for } 2^{nd} \text{ coil group} = \frac{4.2(3.90 + .638)}{36} \quad 6 + 1.725$$

$$= 4.895 \quad \text{inch.}$$

$$l_{sma} \text{ for } 3^{rd} \text{ coil group} = \frac{4.2(3.9 + .638)}{36} \quad 8 + 1.725$$

$$= 5.97 \quad \text{inch.}$$

The length of half-mean-turn of the starting winding,

$$L_{sa} = \frac{3.845 X 30 + 4.895 X 32 + 5.97 X 60}{30 + 32 + 60}$$

$$= 5.15 \quad \text{inch.}$$

Resistance of the starting winding,

$$R_{sa} = \frac{L_{sa} X N_a X .692}{a X S_{sa} X 10^6}$$

$$= \frac{5.15 X 976 X .692}{1 X .000638 X 10^6}$$

$$= 5.46 \quad \text{ohm.}$$

3.3.3 The Rotor

The end ring and the rotor conductor are made of cast alluminum alloy.

Inside diameter of the end ring = 2.25 inch

Out side diameter of the end ring = 3.812 inch

Thickness of the end ring = 0.145 inch

From Fig 2.10 K_{ring} = 1.04

The rotor resistance in term of the stator main winding

$$R_{rm} = \frac{N_m^2 \, C_{\omega m}^2 \, m \, r}{} \left(\frac{l_b}{S_b N_b} + \frac{0.64 \, D_{er}}{p^2 \, S_{er}} \cdot K_{ring} \right)$$

$$= \frac{680^2 \times 0.82^2 \times 2 \times .692}{10^6} \left(\frac{1.69}{.0525 \times 44} + \right.$$

$$\left. + \frac{0.64 \times 3.812}{4^2 \times .781 \times .145} \times 1.04 \right) 2$$

$= 1.83$ ohm at 25 ° C

$= 1.83 \times 1.15$

$= 2.1$ ohms at 65° C

The constant term for the various reactance,

$$= 2 \pi f \, N_m^2 \, C_{wm}^2 \, 10^{-8}$$

$$= 0.973$$

For stator slots

$$\frac{W_{s2}}{W_{s3}} = \frac{.175}{.305} = .574$$

From Fig 2.9 $\phi = .55$

$$F_{ss} = \phi \frac{d_1}{W_{s3}} + \frac{d_4}{W_{s4}} + 2\frac{d_3}{W_{s1} + W_{s2}}$$

$$= .55 \times \frac{.593}{.305} + \frac{.030}{.09} + \frac{2 \times .015}{.094\ .175}$$

$$= 1.516$$

For rotor slot,

$$F_{sr} = 0.62 + \frac{d_4}{W_{s1}}$$

$$= 0.62 + \frac{.05}{.06}$$

$$= 1.453$$

$$X_s = 2\pi f N_m^2 \; C_{wm}^2 \times 10^{-8} \left[\frac{6.38\ l}{S_s}\right]\left[F_{ss} + \frac{S_s}{S_r} \; F_{sr}\right]$$

$$= .973 \left[\frac{6.38 \times 1.725}{36}\right]\left[1.516 + \frac{36}{34} \times 1.453\right]$$

$$= .776$$

The zigzag leakage reactance for the stator and the rotor refereed to main winding.

$$X_z = 2\pi f N_m^2 C_{wm}^2 \times 10^{-8}\left[\frac{2.13\ l}{S_s}\right]\left[\frac{(W_{ts1} + W_{tr1})^2}{4(t_{1s} + t_{1r})}\right]$$

$$= .973 \left[\frac{2.13 \times 1.725}{36 \times .011}\right]\left[\frac{(.25 + .216)^2}{4\ (.34 + .276)}\right]$$

$$= .793$$

The end - connection leakage reactance,

$$X_e = 2\pi f N_m^2 C_{wm}^2 \times 10^{-8} \left[\frac{\pi(D+d_s)\ (\text{ave.coil span})}{S_s \times p}\right]$$

$$= .973 \left[\frac{\pi(3.90 + .638)\ (6)}{36 \times 4}\right]$$

$= .579$ ohms.

The ratio of stator slot opening to air gap length $= \frac{.09}{.011} = 8.18$

from fig. 2.11 $\quad y = 3$

The ratio of rotor slot opening to air gap length $= \frac{.06}{.011} = 5.45$

from fig. 2.11 $\quad y = 2.45$

Let K_s be air gap coefficient for stator

K_r be air gap coefficient for rotor

$$K_s = \frac{t_{1s}}{W_{ts1} + (y\delta)} = \frac{.34}{.25 + 3 \times .011}$$

$$\simeq 1.2$$

$$K_r = \frac{t_{1r}}{W_{tr1} + (y\delta)} = \frac{.276}{.216 + 2.45 \times .011}$$

$$= 1.135$$

$$K = K_s . K_r$$

$$= 1.2 \times 1.135$$

$$= 1.36$$

X_m = magnetizing reactance

$$2\pi f \; N_m^2 \; C_{wm}^2 \times 10^{-8} \; \frac{0.645 \times 1 \times \tau}{\delta . K . p . F_s}$$

F_s = saturation factor usually use 1.2

$$X_m = \frac{.973 \times .645 \times 1.725 \times 3.06}{.011 \times 1.36 \times 4 \times 1.2}$$

$$= 46 \text{ ohm.}$$

The skew leakage reactance,

$$X_{sk} = X_m \frac{\theta_{s_k}^{\ 2}}{12} K_p$$

K_p = stator leakage flux factor usually

= 0.95

$$X_{sk} = \frac{46\left(\frac{2}{44/4}\right)^2}{12} \times 0.95$$

$= 1.19$ ohm.

Total leakage reactance of the stator main winding plus rotor interms of the main winding of the stator

$$\begin{aligned} X_{1m} &= X_s + X_z + X_e + X_{sk} \\ &= .776 + .793 + .579 + 1.19 \\ &= 3.338 \end{aligned}$$

3.3.4 Calculations of the starting torque.

For starting torque calculations, the d.c. rotor resistance referred to main winding is increased by 10 %, and the effective locked rotor resistance

$$\begin{aligned} R_{rm} &= 1.10 \times 1.83 \\ &= 1.99 \text{ ohm.} \end{aligned}$$

The total resistance in the main winding,

$$\begin{aligned} R_m &= R_{sm} + R_{rm} \\ &= 1.45 + 1.99 \\ &= 3.44 \text{ ohms at } 25^\circ \text{C} \end{aligned}$$

The ratio of effective conductor

$$K = \frac{N_a \cdot C_{wa}}{N_m \cdot C_{wm}}$$

$$= \frac{976 \text{ X } .87}{680 \text{ X } .82}$$

$$= 1.52$$

The rotor resistance in term of auxiliary winding.

$$R_{ra} = 1.52^2 \text{ X } 1.99$$

$$= 4.6 \text{ ohm at } 25^{\circ} \text{ C}$$

Total resistance the starting winding

$$R_a = R_{sa} + R_{ra}$$

$$= 5.46 + 4.6$$

$$= 10.06 \text{ ohm.}$$

The total leakage reactance in term of auxiliary winding

$$X_{1a} = K.^2 \text{ X } 1_m$$

$$= 1.52^2 \text{ X } 3.338$$

$$= 7.72 \text{ ohms}$$

The main winding locked rotor impedance

$$Z_m = \sqrt{X_{1m}^2 + (R_{sm} + R_{rm})^2}$$

$$= \sqrt{3.338^2 + 3.34^2}$$

$$= 4.82 \text{ ohm at } 25^{\circ} \text{ C}$$

The locked rotor current in the main winding

$$I_{sm} = \frac{110}{4.82}$$

$$= 22.8 \text{ Amp.}$$

The capacitance required for maximum starting torque

$$X_c = X_{1a} + \frac{R_a}{R_m} \, (Z_m - X_{1m})$$

$$= 7.72 + \frac{10.06}{3.44} (4.82 - 3.338)$$

$$= 12.05 \quad \text{ohm.}$$

Capacitance in micro-farads

$$C = \frac{10^6}{2 \pi f X_c}$$

$$= \frac{10^6}{2 \pi 50} \times 12.05$$

$$= 264 \quad \mu F.$$

Starting torque

$$T_s = \frac{1.88 \, p \, E^2 K \, R_{rm}}{f} \; \frac{R_a X_{1m} - R_m(X_{1a} - X_c)}{[R_m^2 + X_{1m}^2][R_a^2 + (X_{1a} - X_c)^2]}^2 \; K_r$$

$$= \frac{0.92 \times 1.88 \times 4 \times 110^2 \times 1.52}{50} \times$$

$$\times \frac{10.06 \times 3.338 - 3.44(7.72 - 12.05)}{[3.44^2 + 3.338^2][10.06^2 + (7.72 - 12.05)^2]}^2 \text{ oz-ft.}$$

$$= 92.0 \quad \text{oz - ft.}$$

The value of the starting capacitance is varied and the theoritical starting torque is calculated and tabulated below.

Table 3.2.

Starting Capacitance C (μF)	Starting torque T_s (oz.-ft)
0	0
10	2.54
20	5.42
30	8.50
40	11.90
50	15.70
60	19.70
70	24.00
80	28.00
90	33.40
100	38.40
110	43.20
120	48.50
130	53.70
140	58.80
150	63.70
160	68.20
170	72.40

Starting Capacitance C (μF)	Starting torque T_s (oz-ft)
180	76.30
190	79.80
200	83.20
210	85.50
220	87.60
230	89.30
240	90.60
250	90.80
260	91.00
270	92.00
280	92.00
290	92.00
300	90.40
310	89.80
320	88.60
330	87.80
340	87.20
350	85.00
360	84.2

3.4 Measurement of the Starting torque. The torque developed is obtained by multiplying the reading on the balance to the torque arm length. The starting torque for a starting capacitance is calculated, and the average values are tabulated below:-

Table 3.3

Starting Capacitance C (μF)	Starting torque T_s (oz -ft)
0	0
10	0
20	0.27
30	3.05
40	6.08
50	9.88
60	13.4
70	13.65
80	17.4
90	17.8
100	21.9
110	26.6
120	30.6
130	35.2

Starting Capacitance C (μF)	Starting torque T_s (oz-ft)
140	39.2
150	43.4
160	47.4
170	50.2
180	54.0
190	56.0
200	57.3
210	59.3
220	61.4
230	61.2
240	62.1
250	62.1
260	61.4
270	61.0
280	60.2
290	59.5
300	58.7
310	57.8
320	57.0

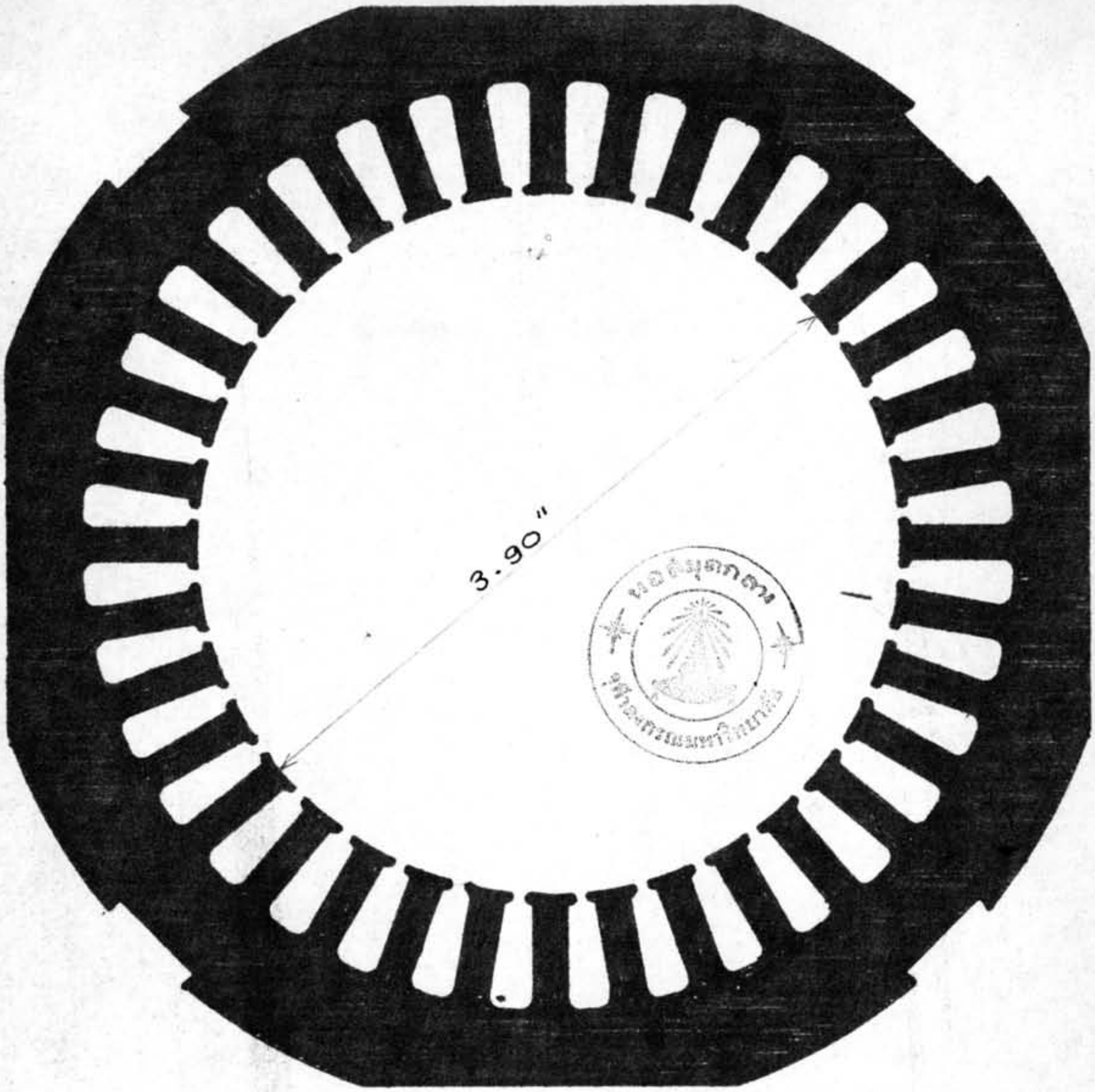

Fig. 3.3

Stator punching, 1/4 H.P capacitor start motor.

$D = 3.90''$

$\ell = 1.725''$

$T = 3.06''$

$S_s = 36$

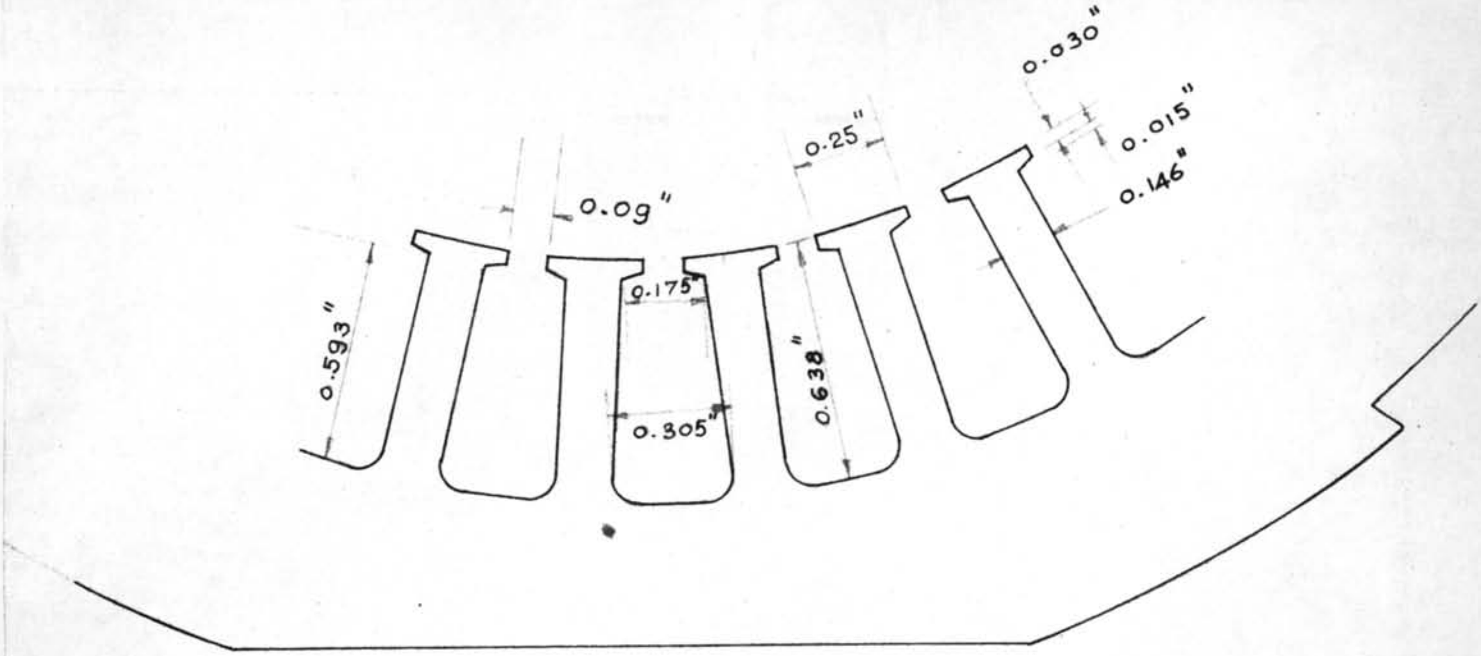

Fig. 3.4 Enlarged view of stator teeth.

$W_{ts1} = 0.25''$

$t_{1s} = 0.34''$

$d_s = 0.638''$

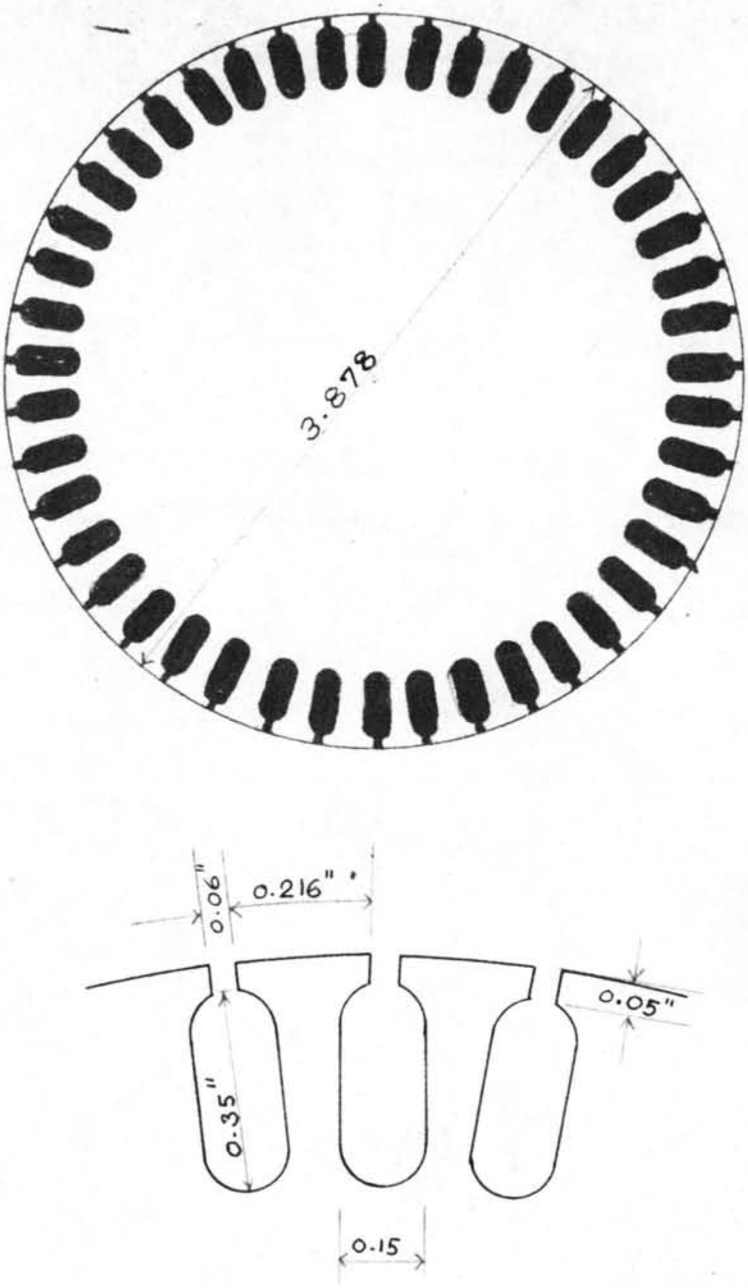

Fig. 3.5 Rotor punching, 1/4 h.p. capacitor start motor

$D_r = 3.878''$
$l_b = 1.75''$
$\delta = 0.011''$
$W_{tr_1} = 0.216''$
$t_{1r} = 0.276''$

$N_b = 44$
Cast alluminum rotor bar and end ring.
Inside dia. of end ring = 2.25"
Outside " " " = 3.812"
Thickness " " = 0.145"

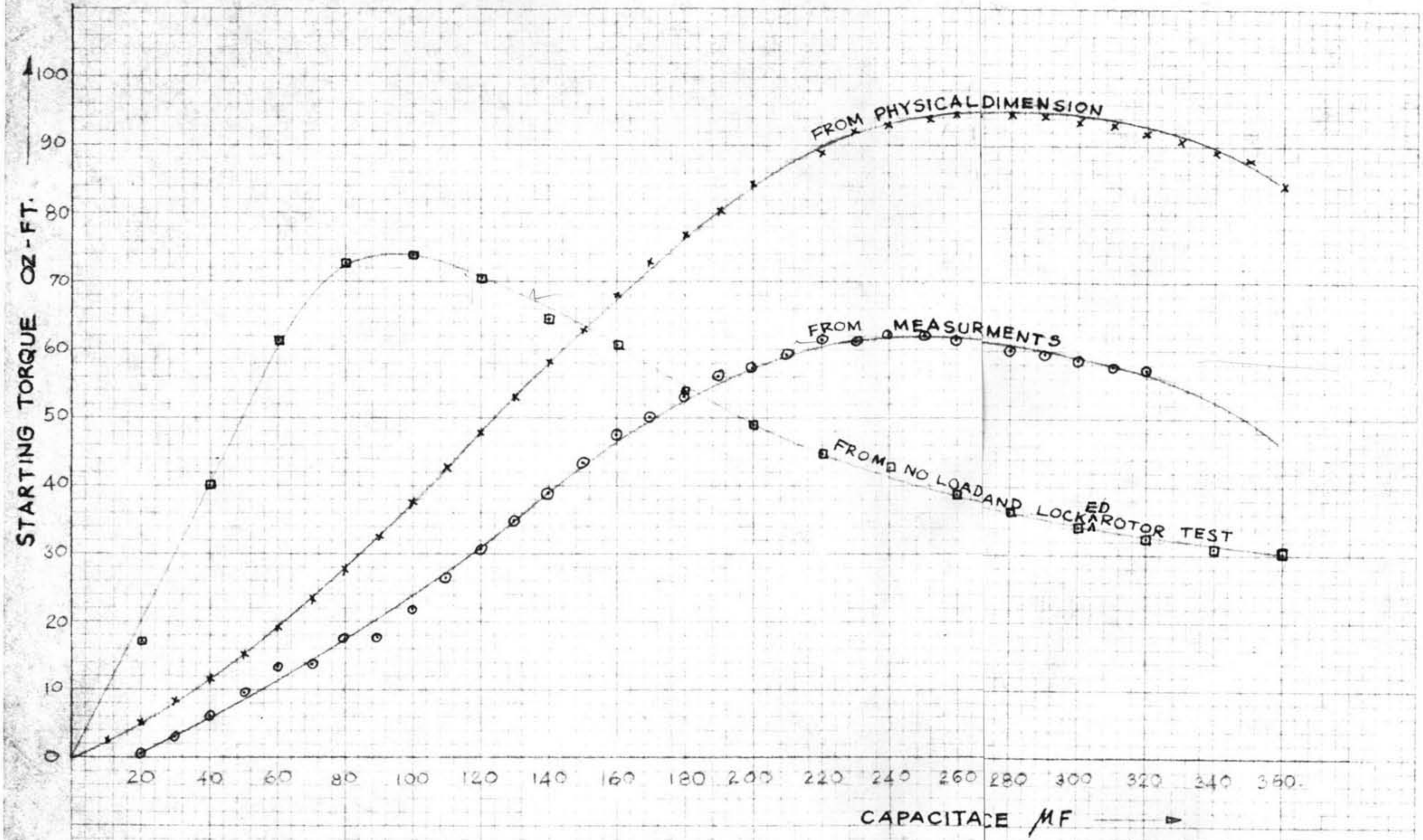

FIG. 3.6

STARTING TORQUE V. S. STARTIG CAPACITANCE