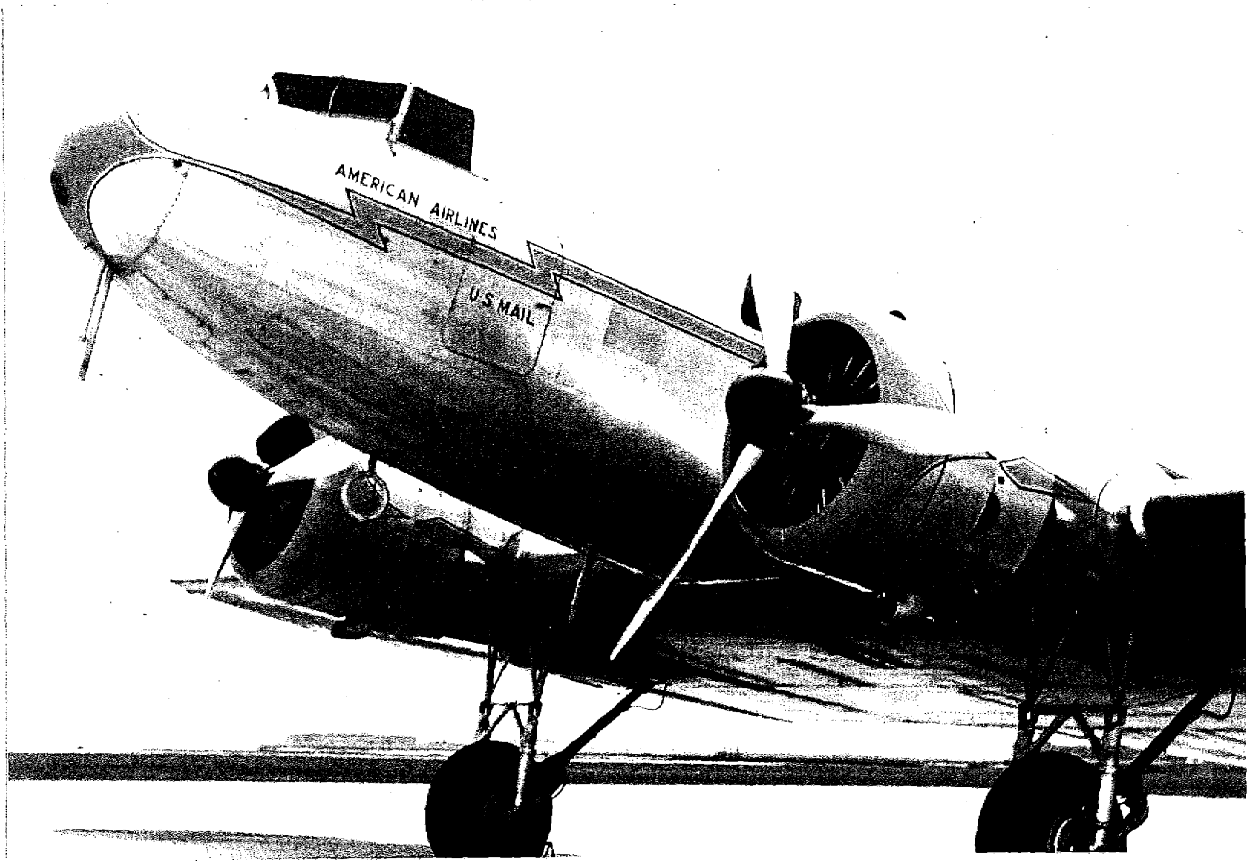


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THE
AUTOMATIC SYNCHRONIZATION OF MULTIPLE AIRCRAFT ENGINES



Professor R.G. Hudson
Thesis advisor

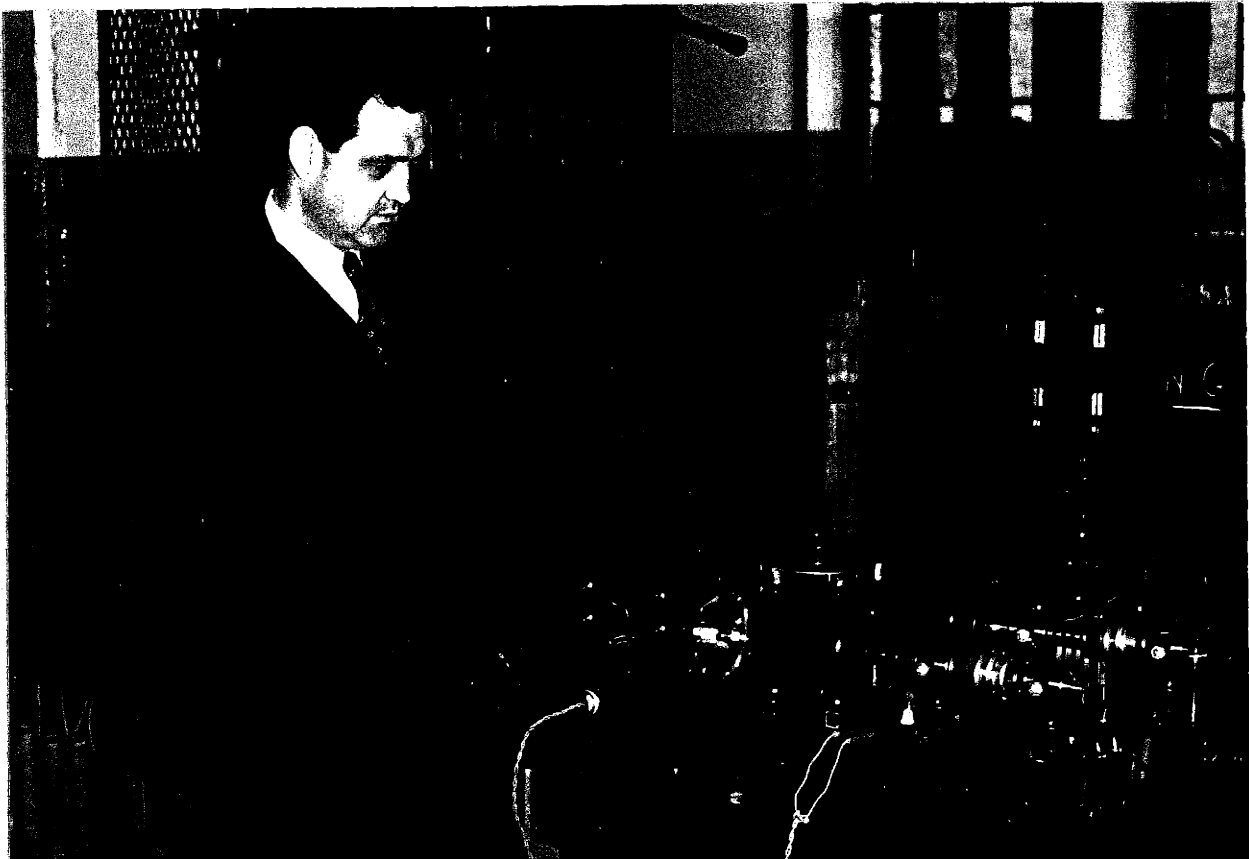
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Professor C.S. Draper

Thesis project

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ACKNOWLEDGMENTS

Of the several professors who have given me help and advice on this project I wish to thank especially Professor E. S. Taylor of the department of Aeronautical Engineering for his suggestion that electric motors be substituted for gasoline engines in the building of this model. Because electric motors were used the project was completed in less time and at less cost than would have been the case had gasoline engines been used. To Professor C. S. Draper of the department of Aeronautical Engineering I am deeply grateful for the loan of the two Pioneer Autosyn motors used in this project and for his interest in this thesis. To Professor R. G. Hudson of the department of Electrical Engineering, my course and thesis advisor, I am especially indebted for his permission to launch on a project of such doubtful future and for his encouragement and direction from the time the first letters of inquiry were sent out until the completed mechanism was successfully operating.

INTRODUCTION

A problem non-existent in the era of single engine airplanes rose to significance during the present era of bi-motored transport planes and promises extreme importance in the period quadrimotored transports will dominate the air, the period that we are this moment ushering in. This problem is the lack of synchronism between the several motors powering a ship in the air. This thesis is one attempt to solve this problem; it makes use of a device herein described, conceived by the author to synchronize automatically multiple aircraft engines in flight. Beating and yawing are the results of non-synchronism.

Before starting this project a general canvass of the field was made in the form of letters to five companies directly connected with Aviation, and to the General Electric Company. These letters asked for the readers' opinions on the importance of the proposed project, synchronization of multiple motors; it further asked for any information on present devices already in use to achieve this synchronization, it being feared that a device similar to that proposed might already be in use. I quote from some of the answers.

Pan American Airways, Inc.: "There is no question of the worth of an efficient device for synchronizing the engines in multiple engined aircraft."

Wright Aeronautical Corporation: "In our opinion, in the final analysis the passenger comfort will depend upon the r.p.m. synchronization of the engines and not the power synchronization."

American Airlines, Inc.: "...fully automatic synchronizing device...would be very desirable in our opinion."

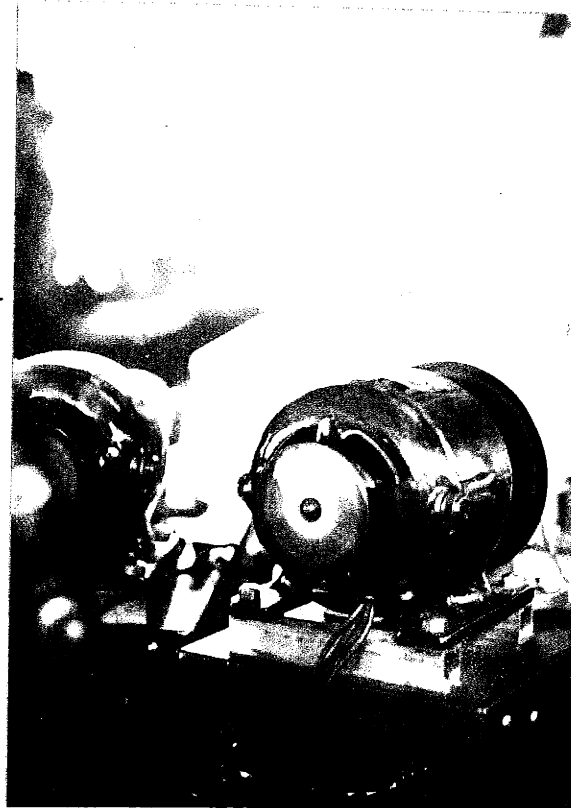
From these and other letters it was seen that the problem of synchronism was important and that no devices of the type proposed in this thesis were in commercial use. This device differs from those in use in two respects. First, most of the present arrangements depend upon manual adjustment and are not fully automatic; secondly, most devices attempt to achieve synchronization through variation of the propeller pitch. The device herein proposed is fully automatic and proposes to achieve synchronism through throttle variation. The synchronizer as constructed departs from the installation as it would have to be in an actual airplane, in three respects. One, electric instead of gasoline engines are the engines synchronized. Two, a centrifugal fan instead of a propeller is used for the load. Three, the field resistances of the D.C. Shunt motors take the place of carburetors. These departures should in no way detract from the validity of the project in the opinion of Professor E. S. Taylor of the department of Aeronautical Engineering.

OBJECT AND RESULTS OF THESIS

The object of this thesis was to synchronize in rpm the two 20th horsepower D.C. Shunt motors. This objective was attained in three steps: first, the synchronizing of the two motors without any load; secondly, the synchronizing with the fan attached as a load and lastly reducing drift angle to as small a value as possible. The drift angle is the angular difference between two corresponding points on the two engines which were originally together. Two arrows pasted on the backs of two brass disks in turn connected to the shafts of the two motors give a constant indication (under stroboscopic light) of the phase difference between the two motors. Below is a picture illustrating just what this drift is. The disk shown is connected to the shaft of the "follower" motor.

On the left out of sight is the "master". The master motor drives a contactor which flashes a stab of light onto the disk and arrow as shown on the right.

Close scrutiny will show eight arrows which are the locus of the real arrows phase drift over a period of ten minutes. Eight pictures were taken in a period of ten minutes all on the same negative to make this picture.



A revolution counter would show the same number of revolutions turned out in a period of any number of hours this means that beat and

yawing would not occur in an airplane powered with an apparatus that permitted drift not exceeding 360 degrees. The sole reason for attempting to reduce drift to a very small angle is to permit the neutralization of unbalanced harmonics in the engines themselves through phase differences of the correct angle usually of 180 degrees.

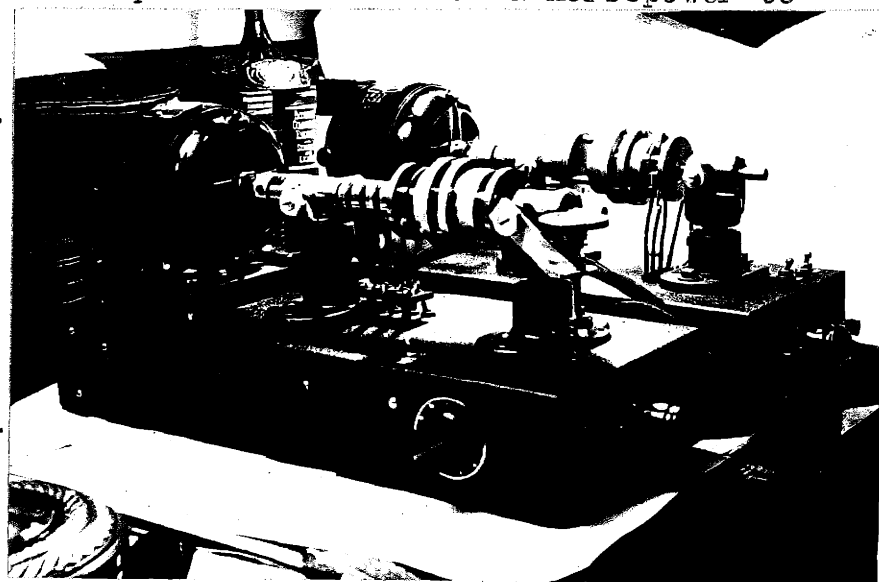
Before going into the results of this thesis it might be well to state here the reason throttle variation was selected as the variable to compensate for the other variables changes. Engine rpm is principally dependent upon the square root; the first power or the square of the following variables: fuel air ratio, air density, volumetric efficiency, mechanical efficiency, oil viscosity, manifold pressure and load. All of these variables break down into further variables but to follow this further would be to confuse the issue unnecessarily. It is at once apparent that as rpm varies with these quantities it also could be held constant if one variable moved to oppose another. This thesis proposes to compensate for the effect of all variables by the control of one, namely, the volumetric efficiency or really the throttle. For very small changes in rpm the throttle only changes the volumetric efficiency for the first instant and this is the instant that is of particular importance in synchronization. The fact that the throttle in succeeding instants does more than change the volumetric efficiency does not confuse the issue for the net result is still an increase or decrease in rpm which is the desired effect. Most devices in present use increase or decrease the load to keep the rpm constant; this as has been pointed out before does act to prevent beating, but sets

up a tendency for yawing. To date complete success of this method has not been achieved, even with respect to preventing beating of the two engines.

The result of this thesis was to synchronize two 20th horsepower D.C. Shunt motors exactly in rpm and to hold the follower's drift down to within 40 degrees. When the apparatus is extremely well greased so that gear backlash can be reduced to a minimum it has been possible to hold the phase angular difference within ten degrees. As will be explained in Conclusions, a Selsyn of four times more strength should be used in the actual case so that the carburetor gearing mechanism can be tightened up enough to eliminate all backlash, it is then theoretically possible to hold the drift to three electrical degrees. Gearing up the Selsyns could further reduce this drift by the gear ratio used. For example, if the Selsyns were geared up three to one the theoretical drift at the carburetor would be reduced from three degrees to one. The synchronization in this set-up operated at any point from 1950 to 2200 rpm. The response of the device was fast enough to take a change of ten revolutions in the space of one minute, experiencing the lag mentioned above. The "follower" motor was equipped with a centrifugal fan that required one 200th of a horsepower to

operate (at 2000 rpm) approximately.

The two units are connected by an eight-wire cable to emphasize their mechanical independence. Similarly



the only connection between synchronizing units on an actual airplane would be the eight-wire cable strung from motor to motor inside the wing.

It was also found possible to set the phase angle to any desired value by jazzing an auxiliary throttle (resistance) or by rotating the master Selsyn through the necessary degrees. This latter method would be the most desirable way to affect phase control, but its action is complicated by the fact that the synchronizing attachment has to make a phase change by means of a speed change which it automatically cuts down when the correct phase position is reached.

PRINCIPLE OF OPERATION OF THE SYNCHRONIZER

The operation of this synchronizing device makes use of the principle that if two or more Selsyns are connected electrically the motion of any one will be duplicated by the others unless the sum of the loads of the several be greater than the force applied to the one or greater than the breakdown torque of the Selsyns themselves.

In this device two Selsyns are connected to two independent motors of the same size making finally two separate units. A cable connects the two Selsyns electrically and also serves to bring in the power to run the D.C. Shunt motors which are to be synchronized. When the two shunt motors are running exactly at the same speed the fields of the two Selsyns will be running at the same speed and no restoring torques will exist. If either Shunt motor should speed up or slow down the two Selsyn fields would not rotate at the same speed would no longer be in opposition and a restoring torque would be set up to oppose the speed difference of the two Shunt motors. The Selsyns can only develop a half inch ounce of torque so the speed of the twentieth horsepower Shunt motors is not affected by this restoring torque. However, if the case of one Selsyn be mounted like a dynamometer so it is free to swing, its restoring torque will move it until there is no longer any phase difference between its field and the other Selsyn's field. If there is a constant difference in rpm between the two d-c motors, then the Selsyn free to move will revolve at a speed equal to the difference in rpm of the Shunt motors. It must be kept in mind that this speed of rotation is in no wise affected by the load on the Selsyn providing always that the load is always below the breakdown of the Selsyn. Here is

motion that is a function of the speed difference of two non-synchronous motors; here too is motion that is absolutely positive. It is absolutely positive because the smallest imaginable difference of rpm is bound to result in an ever widening phase difference between the two fields of the Selsyns. As soon as the phase difference is greater than a degree and a half with these Selsyns, the case starts to move following the angular breach. The displacement of the case then can be made to actuate suitable throttling mechanism to return the two units to synchronism. It is obvious that there cannot be any speed difference with a device of this type; there cannot be any "slip"; the units are locked in step as soon as the Selsyn field switch is closed.

The response of the device was calculated to be in the neighborhood of a three thousandth of a second; this calculation is included on a later page. A close examination of the control mechanism shows its response to be well above the response of the human eye.

In actual practice the "follower" Selsyn had its case rotated instead of its rotor because the inertia of the case was approximately 2000 times larger than the inertia of the rotor. If the case controlled the carburetor the response time would lengthen out to several seconds and severe "hunting" would result. Response as the word is used here refers to the time lag between an actual phase difference in the Shunt motor and the time the Selsyn has displaced itself through that angle and is "caught up". A worm gear of the correct ratio connects the rotor (which moves very little in this case) to the resistance in the field of the D.C. Shunt motor that is the follower. Any change in rpm of either motor is directly reflected into a change

in value of this field resistance of the correct magnitude to bring the speeds together again. The master motor is allowed to run free and it runs up and down about 10 rpm from where it is set. The follower running the fan follows these speed changes varying its rpm up and down in synchronism.

This, then, is the principle of this synchronizing device; how it was made will be related upon succeeding pages.

At right is shown the "follower" unit. Numbered below the picture is the key to the various components of the unit.

1. 16 bladed centrifugal fan.
2. 4 ring commutator which brings in the connections to the rotating Selsyn case.
3. The "follower" Selsyn.
4. The carburetor shaft which connects directly to the field resistance under the subpanel. The worm gear assembly can be seen at the top of the shaft.



Left behind the fan can be seen the 20th horsepower engine

running about 2000 rpm. The knob between 3 and 4 is an auxiliary throttle (resistance). Just to the right of the Selsyn can be seen the rotor shaft (look for small vertical bolt) which is almost standing still, it never moves more than a few degrees unless the master Selsyn's speed is changed manually a hundred rpm or so.

BUILDING THE SYNCHRONIZER

First in order to see what theoretical response was possible with the Pioneer Autosyns model 769C which were available the inertias of the case and rotor were calculated. The case was calculated assuming it possessed all of the weight of the unit and that its radius of gyration was equal to its diameter divided by the square root of 2. The rotor's inertia was calculated in the physics laboratory with more accuracy by measuring a small amount of work put into it, the rpm produced and the number of revolutions to deaccelerate. From this data friction torque (assumed constant) and inertia were calculated.

$$W = \frac{10}{16 \times 32} = 0.0195 \text{ SLUGS} ; R = \frac{2.375}{2 \times 12} = 0.099 \text{ FT.}$$

$$K = \frac{9.9 \times 10^{-2}}{\sqrt{2}} = 0.07 \text{ FT.} ; I_p = MK^2 = 1.95 \times 10^{-2} \times 49 \times 10^{-4} = 95.5 \times 10^{-6}$$

$$I_p = 0.000095 \text{ FT-IB-SEC}^2 = \text{INERTIA OF CASE}$$

$$N = 5.16 = 100 \text{ cm} ; \dot{N} = 19.35 \text{ cm/sec.}$$

$$\frac{2\pi \times 1 \times 2.54}{32} = S = 0.5 \text{ cm} ; R.R.S. = 38.7 ; \omega = 243.5 \text{ RAD./SEC.}$$

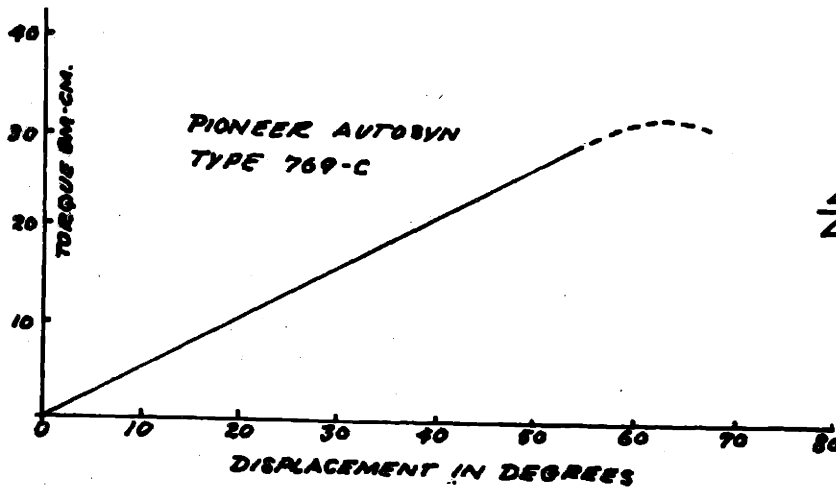
$$T = I_p \alpha ; \alpha = \frac{d\omega}{dt} ; \omega = \frac{d\theta}{dt} ; K.E. = \frac{I\omega^2}{2} ; \tau_f = 5 \times 2\pi = I \times (243.5)^2$$

$$\tau_f = 1.5 \times \frac{1}{32} \times 2.54 = 0.1199 \text{ gm-cm} = \frac{.119 \times 16}{2.54 \times 453.6} = 1.65 \times 10^{-3} \text{ IN-OZ}$$

$$I = 6.32 \times 10^{-5} \text{ gm-cm-sec}^2 = \frac{6.32 \times 10^{-5}}{2.54 \times 12 \times 453.6} = 4.56 \times 10^{-9} \text{ FT-IB-SEC}^2$$

ROTOR I_p ↗

After finding the inertias of the two principle parts of the Selsyn, a relationship between its torque output and its angular displacement was obtained from the graph below.



$$\frac{\Delta T}{\Delta \theta} = \frac{.435 \times 57}{80 \times 12 \times 16} = \frac{.001615}{\frac{\text{FT-LB}}{\text{IN}^2} \text{ / DEG}}$$

With this relationship it is now possible to set up a mathematical relationship that will express the ^{follower} Selsyn's position in relation to the master Selsyn's position both in time and in space.

$$I = .0001 \text{ FT-LB-SEC}^2 ; \text{ LET } \theta = \text{DISPLACEMENT RADIANS}$$

$$\text{LET } T = \text{TORQUE IN OZ.} = T$$

$$\text{THEN } \frac{dT}{d\theta} = .001615 ; T = .001615 \theta + C ; C = 0 ; T = .001615 \theta$$

$$T = I\alpha = I\frac{d^2\theta}{dt^2} = .0016\theta ; I\frac{d^2\theta}{dt^2} - .0016\theta = 0 ; P = \frac{d\theta}{dt}$$

$$I\frac{d^2\theta}{dt^2} - .0016\theta = 0 ; I\frac{dP}{dt} - .0016(\theta P + \theta) = 0$$

$$\frac{I dP}{dt} = .0016\theta P ; \frac{dP}{P} = \frac{.0016 \theta dt}{I} = 16.15 dt$$

$$\int_{\omega_0}^{\omega} \frac{dP}{P} = \frac{16.15 t^2}{2} + (C=0) ; \text{ LET ONE MOTOR SPEED UP AT RATE OF 60 REVS IN ONE MINUTE}$$

(CONTINUED)

$\omega_0 \text{ THEN } = 2\pi = P_0 ; a = 3.54 \times 10^5 \text{ (ROTOR)} ; a = 8.07 \text{ (CASE)}$

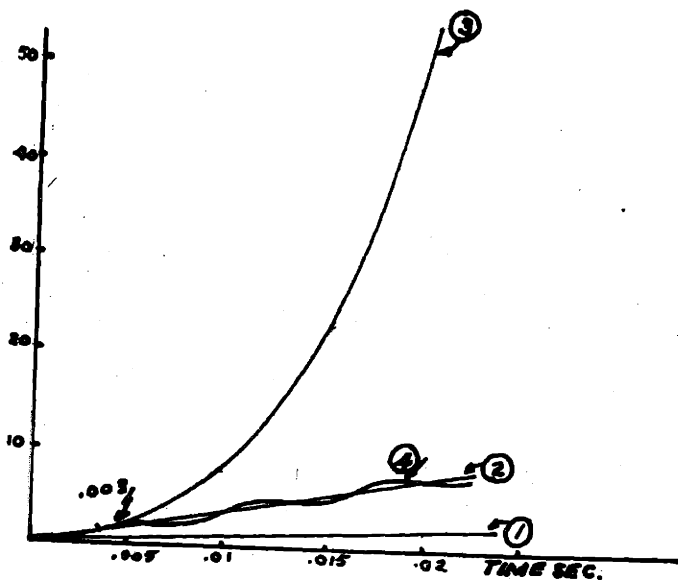
$\ln P = at^2 = \frac{16.15}{2} + (C=0) ; P = \frac{d\theta}{dt} = e^{at^2} \text{ THIS WAS}$

BELIEVED IMPOSSIBLE TO SOLVE SO IT WAS PLOTTED BY SERIES. LET $at^2 = u$ THEN $\frac{d\theta}{dt} = e^u$

$e^u = 1 + u + \frac{u^2}{2!} + \frac{u^3}{3!} + \frac{u^4}{4!} \dots$

$e^{at^2} = 1 + at^2 + \frac{a^2t^4}{2} + \frac{a^3t^6}{3!} + \frac{a^4t^8}{4!} \dots$

$\int e^{at^2} dt = \theta = t + \frac{at^3}{3} + \frac{a^2t^5}{10} + \frac{a^3t^7}{42} \dots ; a_1 = 3.54 \times 10^5$
 $a_0 = 8.07$



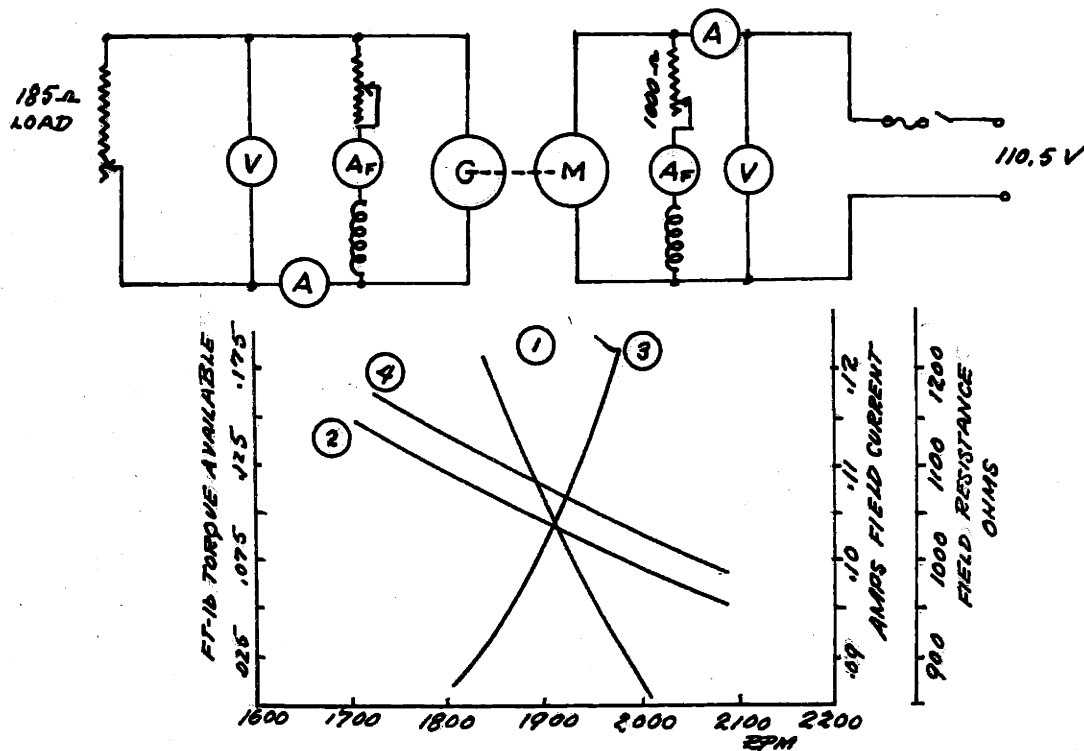
θ_0°	t sec	θ_1°
.57	.01	7.3
.656	.015	23.6
1.14	.02	55.0

This chart shows the speed with which the "follower" Selsyn will displace its rotor as the master engine goes out of phase. For the sake of example this graph is made showing the results of solving the series derived at the middle of the page. On this graph ② represents the master motor going out of step at the

rate of 60 revolutions in one minute. (1) shows the rate of displacement the Selsyn would undergo if it swung the case; (3) shows the theoretical displacement of the rotor if the series derived on the previous page held continuously. The series is only approximately accurate until the phase angular difference between "master" and "follower" is reduced to zero then the series should reverse in sign as the torque becomes negative. (4) shows the true displacement of the Selsyn swinging the rotor when it is connected to the synchronizing resistance. It can at once be seen that with the small torque that is available (half an inch ounce) from the Selsyn a case hung device would be hopeless. This can also be seen from an inspection of the graph on page 16 where (1) shows that the case would take about three seconds to "catch" the master and, of course, it would have absorbed so much energy by that time that it would far overshoot and cause severe hunting. Any attempts to make this set-up critically damped would result in still further loss in response. The case then had to be rotated which allowed the rotor to be hung, a condition that gave very fast response (one three thousandth of a second) but offered a difficult problem of construction. A differential Selsyn would be the happy solution to all of these difficulties but as far as could be learned, none are made small enough at present, although one could be made if time permitted. Therefore, one Selsyn had to be commutated and as it has five connections and had to be turned at 2000 rpm without binding the rotor and its half inch ounce of torque a very neat problem of design was presented.

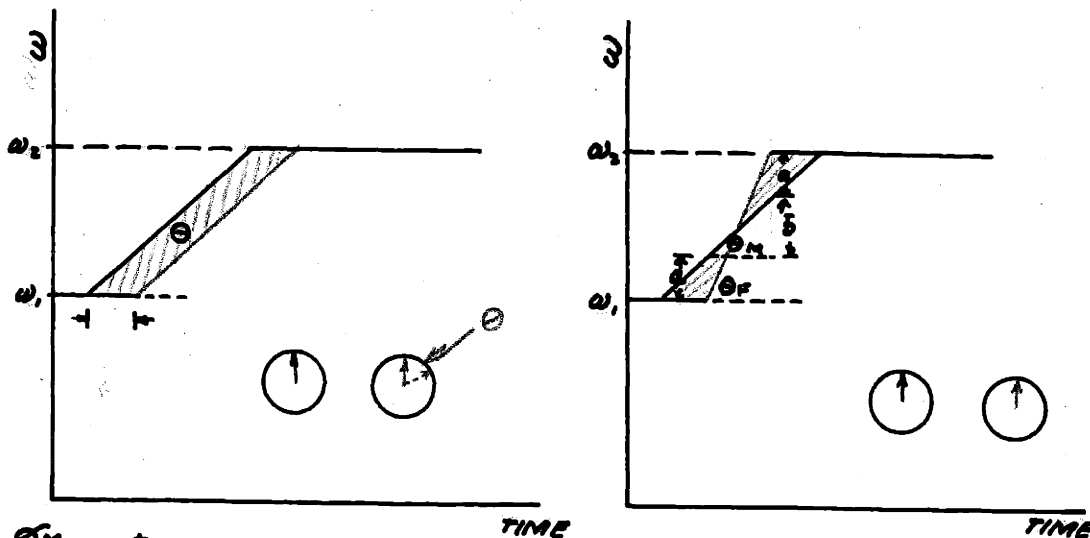
The next thing to determine was the amount of field resistance to be turned out per degree displacement of the Selsyn's

rotor. In order to determine this factor the two D.C. Shunt motors were connected together one as a motor and the other as a generator. Readings were taken at various rpms and at various torque levels, achieved by varying the motor's field.



The above graph shows the result of the test. (1) is a curve of field current against motor rpm. (2) is the available torque at a field current of .122 amps. against rpm. (4) is the available torque against rpm at a field current of .11 amps. (3) is a curve of field resistance against rpm; it is from this curve that the theoretical value of delta ohms per delta revolution was calculated. The above field resistance curve was made at a load of constant resistance that absorbed 57 watts at 1834 rpm and 76 watts at 2020 rpm. The delta ohms per delta revolution was seen to be almost independent of load, as the resistance rpm curve is simply shifted up or down with an increase or decrease in load. It was seen that in order to hold speed constant a change of 2 ohms should be made for every Selsyn rotation of 360 deg.

This theoretical value was found to be insufficient in practice and was changed to 4 ohms per revolution as will be explained below. A gear ratio of 50 to 1 was originally chosen to keep the Selsyn from stalling. Later it was discovered that the machine work was good enough to permit a gear ratio of 30 to 1 which was desirable in that it reduced the effect of backlash in the mechanism.



$$\frac{\alpha_M}{\alpha_F} = \frac{b}{2a+b}$$

α_M = angular acceleration of master motor.

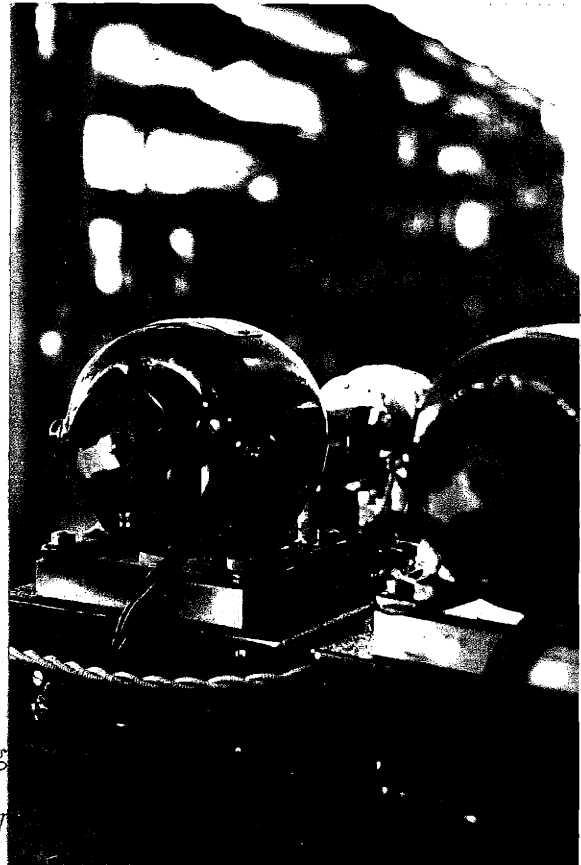
α_F = angular acceleration of follower motor.

Above is pictured the reason why the theoretical value of two ohms per revolution had to be changed to a value of four ohms per Selsyn revolution. The left-hand graph shows both master and follower revolving at a uniform speed ω_1 . The master changes velocity at a rate α_M until it reaches a new velocity ω_2 . The follower, however, has continued along at the first speed ω_1 until the backlash in the throttle mechanism has been taken up; at this point it accelerated (ideally) at the same rate as the master until it reaches ω_2 where it again is in step with the master motor. It was noticed in practice that if the master motor were sped up, the follower would soon reach the same speed,

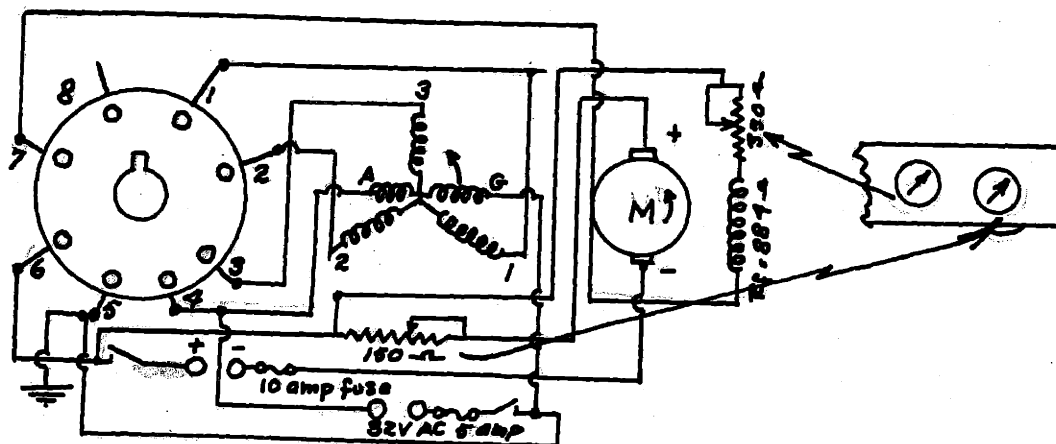
but the new position of its arrow showed that it had lost an angle θ . The positions of the arrows, as shown in stroboscopic light, are drawn in the circles on the charts on page 19 just as they appeared on the backs of the motors. It was also noted in practice that the greater the rate of change of angular velocity of the master motor, the greater the displacement angle θ which the follower suffered. At this stage of the project's development the backlash was about 90 degrees; so using this figure, since reduced to about 20 degrees, as the amount of backlash and using a base figure of 60 rpm per min. rate of change, it was calculated by the formula on page 19 that four ohms, not two, should be ground out per one revolution of the follower Selsyn. The right-hand graph on page 19 shows why this is true. The only way to overcome the loss θ is to make the follower's rate of acceleration great enough to climb steep enough (see graph) so that the amount of degrees it lost due to backlash it will gain back by shooting ahead of the master for the same length of time it hung back. For 60 rpm per min. it was found a value of 4 ohms per rev. was necessary; for a 300 rpm per min. rate of change it was calculated that 32 ohms per rev. must be turned out. If the backlash could be reduced to 30 deg. 10 ohms per revolution would be sufficient. The importance of minimizing the backlash can be seen from the above experiment. Due to the low torque output of the Selsyns available, $\frac{1}{2}$ inch ounce, it was impossible to reduce the backlash to a value less than 20 deg. This did not result in the theoretical response of 4 rpm per sec. either because the rheostat used, although theoretically turning out 4 ohms per Selsyn rev., turned out far less due to its slider's covering several turns of resistance resulting

in a parallel-series addition instead of a straight series addition of resistance. To duplicate this effect in a carburetor would mean the opening of a second throttle as the main throttle was closed, the action of the second partially overcoming the effect of the closing of the main throttle. This is one problem given by the electric motors that would not have to be overcome in the case of the gasoline engines. This effect, of course, could be overcome in two ways, neither of which was practical in view of the satisfactory enough operation of the device. The first plan was to make the resistor itself so big that in spite of its paralleling action 4 ohms instead of 2 would be turned out per revolution. This was impractical because a small blade at the base of each resistance made it necessary to put the movable arm at a position of about 20% full-in of resistance, in order to secure easy mechanical motion of the arm. This blade could not be removed as it was most securely fixed in position. To run at a position of 20% full-in meant that the slowest the motors could run with the 500 ohm (2 actual ohms per rev.) resistor, was 1900 rpm. As the motors were designed to run at 1725 rpm and as the slight unbalance of the rotating Selsyn caused vibration proportional to the square of the rotational velocity the speed was held to as low a base as possible. The second method of getting 4 ohms per rev. from the 500 ohm resistance was to cut down the shoe of the movable resistance arm so it only touched one wire at a time; this would have caused excessive arcing and stresses so it was not attempted. More work was not done on this aspect as it was relatively unimportant as long as its cause was fully understood. Since the apparatus responded up to a change of 30 rpm per min. without loss of

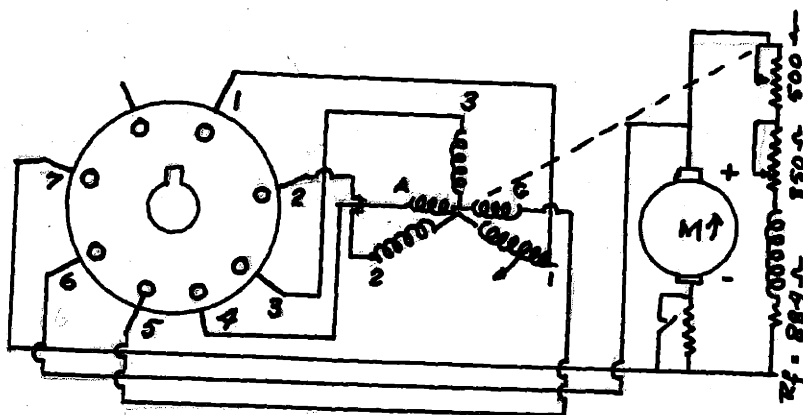
angle the arrows stayed in their relative position for the ordinary wanderings of the master motor. As has been stated before, the master Selsyn was equipped with a contactor which actuated the Strobosc; hence no matter what speed changes the master underwent, its arrow's position remained unchanged. Thus if the follower did not follow its arrow would appear as a white blur on a time exposure, the blur covering whatever arc it had traversed. At the right are shown the two units turning up about 2000 rpm as attested by the continuous blur on the disk, made by the illumination of the room falling on the arrows as they whirl. Standing out from their blurred background are the arrows "stopped" by the Strobosc; at the left is the arrow on the master motor; at the right slightly blurred is the arrow of the follower motor. The blurring is due partly to movement and partly to the short depth of focus as is attested by the background. This exposure was a half second at f 3.5 with a portrait lense attachment to secure a larger image. The handles shown are for ease in carrying the units. The white twisted pair is the contactor conduit coming from the master motor.



CIRCUIT DIAGRAM



Master



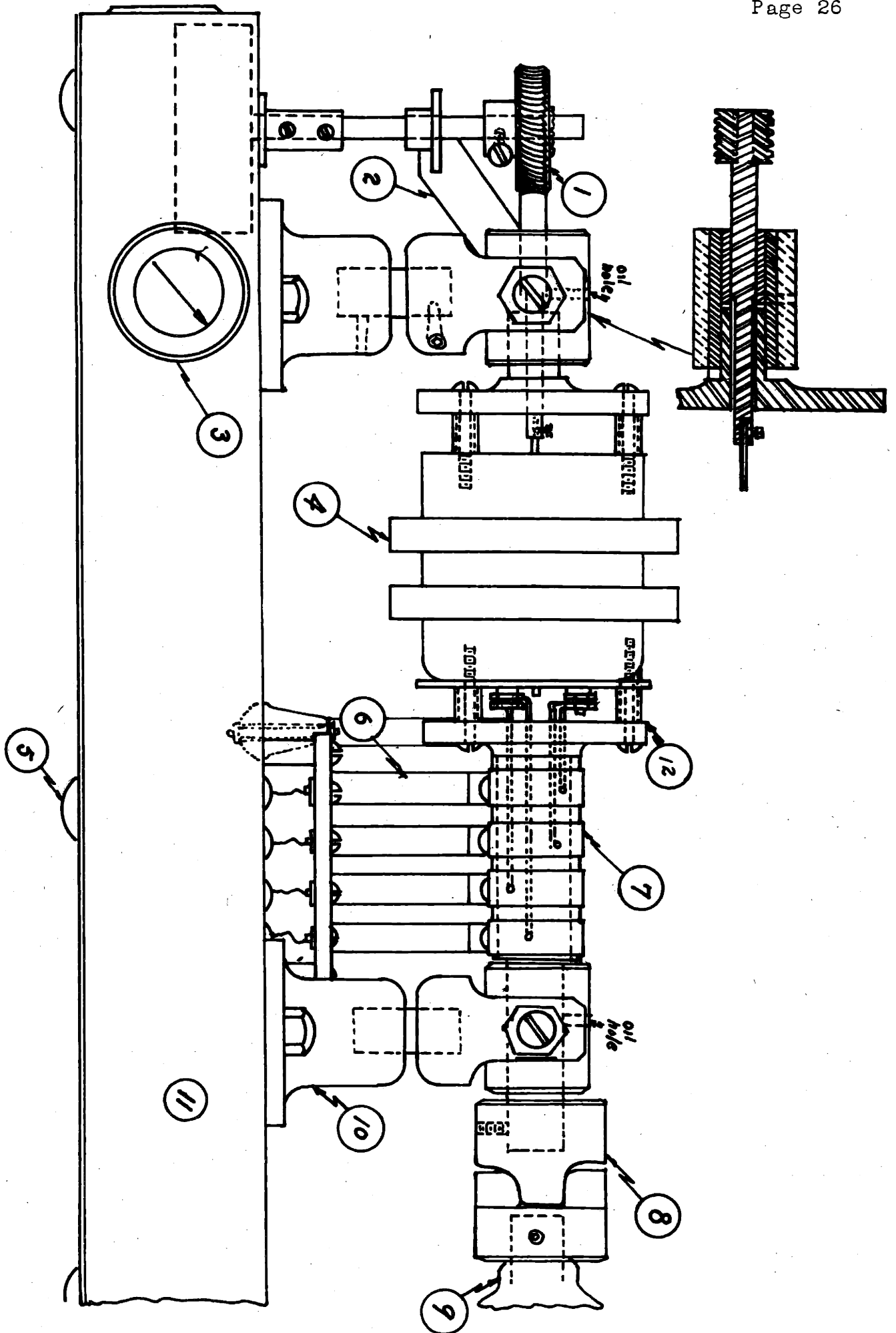
Follower

The above is the circuit diagram of the two synchronizing units. The two large circles represent the bases of the cable connections looking at the bottom of the plugs. It can be seen that when the d.c. is thrown on the motors a protective resistance is in series with the armatures while the fields are allowed to draw full current. This system reduces acceleration stresses on the delicate Selsyns. In the case of the master where the .06 inch shaft is connected directly to the 20th horsepower motor the problem of reducing driving and accelerating torques becomes acute. As will be shown in a drawing on a following page the Selsyn shafts were isolated from all stresses except torque.

One interesting point to notice on this diagram is that although the master Selsyn has its rotor revolving and the follower has its case rotating the two fields still go in the same direction because the follower is driven from the back/end thus no changes in three phase connections had to be made. When the device was first tried out it was noticed that the compensating device tended to make the speed difference between the two units worse instead of better. Investigation showed the rotor to be going in the wrong direction as it had been hooked up to run with a reversed field. As related above, the field did not reverse so the movable arm on the carburetor was made to run in the opposite direction changing this corrected the difficulty. All data as to impedances of the Selsyns and motors was obtained by experiment in the laboratory. The inertia and friction torque of the two Shunt motors was also taken but was found to be so small in proportion to the torque developed it was never used in anything calculated. The two inlets for d-c and a-c are shown on page 23. The a-c is 32 volts and was obtained from a 2 ampere Variac. Both circuits were fused to protect the units. The figure at the top right hand of page 23 represents the appearance of the auxiliary throttle and starting resistance as seen on the side of the master panel. See page 13 for a pictorial view of the follower's throttles. Connections 1 2 3 A and G of the follower are all made through carbon brushes to slip rings; see page 13 for photograph. The seven connections are brought out to eight place sockets in the subpanel where an eight wire double plug cable connects the units.

LIST OF MATERIALS

- 2 Type 769-C Pioneer Autosyn motors.
- 2 G.E. 20th Hy d-c shunt motors.
- 1 6 in. brass tube 1 in. in diameter.
- 1 Bakelite rod 6 in. long $1\frac{1}{2}$ in. diameter.
- 12 small brass tubes for mounting Autosyns on bearings.
- 6 steel machined parts. (see next page for drawing).
- 1 50 to 1 worm gear set.
- 1 30 to 1 worm gear set.
- 4 pillow blocks adjustable. Equipped with $\frac{1}{2}$ " bronze bushings.
- 4 $\frac{3}{8}$ bronze bushings for pillow blocks.
- 1 $\frac{1}{4}$ bronze bushing for pillow blocks. (Sawed in half to make 2).
- Two feet of $\frac{3}{4}$ inch brass square girders for motor mounts.
- Doz. $\frac{3}{8}$ " steel semi-round head cap screws $\frac{3}{4}$ inch long.
- Doz. iron stove bolts 1 inch long.
- Two doz. nuts for above bolts.
- 10 feet of spaghetti wire and bus.
- 5 feet of 8 wire cable.
- 2 eight place plugs and sockets for cable.
- 4 doz. solder lugs.
- 2 7x17x3 steel black subpanels with bases to match.
- 2 doz. $\frac{3}{8}$ " metal screws for securing base of subpanels.
- 1 doz. rubber tacks to be soldered to subpanel base plate.
- 1 doz. $\frac{3}{4}$ inch rubber washers to support d-c motors on the brass beams to isolate vibration.
- 2 rubber type universal joints for coupling d-c motors to the Autosyn motors.
- 2 350 ohm starting resistances one variable 5 watt.
- 2 300 ohm field resistances variable 2 watt.
- 3 toggle switches with name plates.
- 4 small dials with name plates.
- 2 doz. $\frac{1}{4}$ inch rubber inset type washers to prevent chafing of wires coming through the subpanels.
- 1 6 inch long $\frac{1}{4}$ inch diameter steel shaft for throttle arm.
- 1 steel $\frac{1}{4}$ inch shaft coupler.
- 1 foot of $\frac{3}{16}$ square carbon for brushes of slip-rings.
- 3 twin binding post members bakelite inset type.
- 1 $\frac{1}{4}$ inch Birnbach porcelain insulator.
- 2 small fuses with fuse blocks.
- 2 handles for carrying.
- 2 $2\frac{1}{2}$ inch brass disks for indicator arrows.
- 1 5 inch brass $\frac{3}{32}$ " inch brass disk for centrifugal fan.
- Miscellaneous brass for fan blades shaft stiffener, etc.
- Miscellaneous: paint, oil, vaseline (gear lubricant) washers, bolts, nuts, wire and solder.



A pictorial drawing of the "follower" unit is shown on page 26. The various important parts of this unit are denoted by circled arrows.

1. Worm gears connecting to throttle.
2. Stiffener bracing throttle shaft.
3. Auxiliary field resistance.
4. Pioneer Autosyn type 769-C.
5. One of five rubber-headed nails for cushioning.
6. One of the five commutator brushes.
7. One of the four insulated slip-rings.
8. Rubber type universal joint.
9. D-C Shunt motor.
10. One of two pillow-blocks.
11. Subpanel chassis.
12. Steel part to suspend and rotate Autosyn.

Above the left-hand pillow-block is shown a detailed cross-section of the method of carrying through the throttle mechanism to the "follower" Autosyn.

The commutator was made by first cutting a half inch hole in a piece of hard rubber, machining down its outer surface until the slip-rings (cut from a brass tube) would just slip on. Piece 12 was then pressed into the hole and the expansion of the hard rubber fixed on the rings permanently. Holes were then drilled in the rings and rubber base following which wires were pulled through and soldered to make the finished commutator.

Originally only a four unit commutator was designed because it was intended to carry one connection, a ground, through the bearings. The oil film existing in the bearings caused a mean voltage drop of about 10 volts to ground and as soon as this was discovered another outside friction connection to remove the resistance was made to ground through piece 12. The oil film resistance caused some hunting due to the changing impedance angle superimposed upon the rotor.

The master unit resembles the follower in the way it is mounted; as it did not have to be rotated no commutator was

necessary. In place of the worm gear the driving motor is connected to its rotor.

The small part of the worm gear shown in cross-section on page 26 is a force fit; its further end connects to the Autosyn rotor through a sliding connection made fixed by a small bolt moving in threads tapped in the shaft.

Some experimentation was done with a d-c actuated rotor; this system was extremely unstable and unsatisfactory. The rotor current was varied from 2% of rated a-c current to 20% overload without any gain in stability. This instability was probably due to a very unsymmetrical rotating field which tended to allow the rotor to seize at pole points. The foregoing statement is speculation but as no better explanation has come forward it is offered as the author's opinion. With proper design small Synchronous Condensers might prove to be better in operation than the Autosyns or Selsyns, although the experimentation done on this in this thesis resulted in negative results.

At about the same time that the d-c experimentation was done the regular Autosyn set-up was tested and found to lag about 10 electrical degrees in the worst case of lag. This test for lag was done by getting a curve of rotor current versus angular displacement, then taking readings of rotor current at a time when the follower was attempting to make up a difference of one or two hundred rpm between the two units. In normal operation the apparatus ran at an electrical angle of displacement of less than 5 degrees as far as could be interpreted from the data.

SUGGESTIONS

The success of this model synchronizer indicates the possible success of a gasoline engine synchronizer if attempted. As the functioning of the model built for this thesis was made as close to the functioning of a similar apparatus on a gasoline aircraft engine as an imaginative comparison could produce.

Due to the bad practical features of the present model, namely, rotating the entire follower Autosyn, it is believed that any adaptation of this principle to aircraft motors would utilize the Differential Selsyn. The Differential Selsyn would have the advantage of the high torque inertia ratio that the present model possesses without the disadvantages of the severe mounting, commutating and vibrational problems present in the model made for this thesis.

At this writing an investigation is being made to determine the possibilities of patenting the principle of the Synchronizing apparatus set forth in this thesis.

Before concluding the discussion of this project it might be well to mention another device that very possibly might achieve the results of this thesis in a simpler manner. This device would consist of an arrangement of contactors such that any difference in speed of the various motors would be reflected through the contactors to an electrical circuit that would automatically adjust the carburetor to act in the direction opposite to the recorded speed change. This suggestion was advanced by both Professor R. G. Hudson and Professor H. E. Edgerton.