DISCUSSION OF TWO SPECIALIZED AIRCRAFT PROPELLER PROBLEMS

Thesis

by

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and

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DISCUSSION OF TWO SPECIALIZED AIRCRAFT PROPELLER PROBLEMS

Part I

Governing and Synchronization

Summary

The design and construction of an aircraft propeller governor or synchronizer is a specialized problem concerning Servo-Mechanism Theory. Search developed that adequate theory existed to cover the specific variables involved. The sources used in this report are listed in the extensive bibliography. Short descriptions are presented of the various governing and synchronizing means used to control present day propellers. In this research an airplane engine-propeller system was simulated and a single unit of a synchronizer, suitable for use as a governor for one engine, was invented and constructed. It was demonstrated to meet the United States Army Air Corps tentative specifications for propeller synchronizers. Time and unavailability of material and overworked shop facilities did not permit the construction of a model for full scale multi-motored airplane test. It is contemplated that such a model will later be constructed at the Materiel Division, United States Air Corps, Wright Field, Dayton, Ohio. A detailed description of

this invention is presented in Appendix I. A discussion is presented of the general servo-mechanism theory as applied to airplane propeller governors and synchronizers. In addition, a short discussion is presented of how synchronization of propellers influences the tactical employment of military aircraft. The physiological effect on occupants of aircraft is also shortly discussed.

INTRODUCTION

The primary object of this research problem was to review servo-mechanism theory, fit it to the specialized problem of aircraft propeller governing and synchronization, and to develop, construct, and demonstrate a simplified governor-synchronizer which would be adaptable to the control of the standard types of controllable propellers. Search developed that servo-mechanism theory had only recently been fitted to the problem as stated above. Attention was therefore concentrated on developing a new and simplified synchronizer of <u>controlled</u> accuracy. The accuracy desired was to permit phasing of the propellers within a practical limit of about ± 12 degrees, or about 1/30 of one revolution. This accuracy was obtained. Refinement of the basic design will permit improving this accuracy by several hundred per cent if desired. There are no known propeller types that permit the extremely small associated pitch change to effect such phasing; yet phasing may at some later date be desirable for some experimental work. The control principles are also applicable to many other fields of rpm control where greater accuracy is required than for propeller synchronizing. It is debatable, and later discussed, if an aircraft engine-propeller combination can be controlled within less than the one rpm possible today by solely varying the pitch of the propeller. Nevertheless, the first concept of the governing device hereinafter described permitted the generation of a corrective impulse within the phasing limits above outlined. There is no objection to a governing device being inherently more sensitive than the mechanism it is to govern. Hence, the development continued to completion and the successful testing later described.

DISCUSSION

A change of propeller pitch of one degree will effect a change of about 60 rpm in a direct drive engine in level flight. With the engine reduction gear ratios prevalent today it suffices to consider that a change of one degree in pitch will change the engine speed about 100 rpm. Thus to effect a one rpm change in engine speed a pitch adjustment of 0.01 degree must be made in the propeller. Considering the magnitude of the control forces involved in changing pitch, back-lash of gears in the pitch change mechanism etc., it is doubtful if changes in pitch of less than .01 degree can be made using the present conventional propeller pitch change mechanisms and governing methods. It will later be discussed if it is even desirable to govern or synchronize to less than the one rpm possible today. Means have been suggested to effect phasing under one rpm by other than the present pitch change methods.[1] Using this means the propeller will still make the gross corrections to about one rpm, then some auxiliary means actuated by engine ignition timing or very sensitive synchronizers as here developed must make the smaller corrections. One method of making these small corrections is with the use of electrical alternators mounted on each engine propeller shaft. This method is heavy and inefficient, however, and it is doubtful if the dubious benefits will ever justify their use.

DESCRIPTION OF PRESENT PROPELLER GOVERNING METHODS

Let us consider the present methods of governing propellers to hold aircraft engine speeds constant. There are two standard constant speed type propellers in use in this country. These are the Curtiss and the Hamilton Standard. The former is an electrically actuated type and the latter a hydraulic type. For single-engined installations Curtiss uses a "proportional" type governor.[2] This is of the common flyball type driven by the governor drive shaft in the nose of the engine. Engine speed is varied by the pilot by adjusting the governor spring tension remotely from the cockpit by conventional push-pull rods, cable-pulley-bellcrank, flexible cable, or electric motor governor head adjusting means. The governor spindle operates, whenever the engine speed changes either direction from equilibrium, to close electrical relay contacts in the proper direction to cause the electric pitch change motor to change the propeller pitch to bring the engine speed back to equilibrium. These contacts are so mounted that they are oscillated at a frequency proportional to engine speed through an amplitude such that if the engine speed does not deviate more than about two rpm the contacts will remain open. However, if the deviation is greater than two rpm then the contacts will be closed for a duration of time directly proportional to the magnitude of "off-speed" until about ± 30 rpm "off-speed" is reached when the contacts are 100% closed and the pitch change correction is at a constant, maximum rate. Thus in correcting a disturbance of say 100 rpm "off-speed" the governor contacts will cause the pitch change motor to correct continuously until about 30 rpm "off-speed" is reached. At say 29 rpm "Off-speed" the contacts are then opened for a very short time interval. The <u>duration</u> of "contact closed" time decreases as equilibrium is approached until at just above two rpm the last correction is made for the shortest <u>duration</u> of time during which it is possible to make the smallest pitch change. The "off-speed" rpm selected at which "proportionalizing" commences depends primarily upon the pitch change motor inductance characteristics, the pitch change control forces, reduction gear ratio in pitch change mechanism (rate of pitch change), the combined polar moment of inertia of the propeller and rotating engine parts, and the airplane engine torque characteristics.[3] In general, for a given engine, the larger the propeller and hence its inertia response characteristics, the greater the "off-speed" rpm at which it is necessary to begin "proportionalizing."

The Hamilton Standard propeller governor is also of the flyball type driven in the same manner as described above and controlled from the cockpit in the same manner.[4]

The governor spindle however, operates a hydraulic servo-valve which admits oil under several hundred pounds unit pressure to one side or the other of a piston in the pitch change mechanism. The piston movement is transferred to the blades through cams and gears. In correcting a disturbance in engine speed from the equilibrium or "on-speed" condition, the flyballs move the spindle and valve in the proper direction to effect a corrective change in pitch toward equilibrium. It is inherent in such a servo-valve type of control that as equilibrium is approached the valve is gradually closing. This "throttling" action of the valve serves as a "follow-up" and causes the rate of pitch change to vary with a value "proportional" to the valve opening or magnitude of "off-speed." The governor spring characteristics, friction in the governor parts, viscosity of the oil etc., all affect the governing operation in addition to those pertinent propeller factors mentioned above.[5] Proper design, however, makes the governor action stable for operating conditions for any given propeller-engine combination. Note that in the Curtiss Electric propeller that the rate of pitch change, except when accelerating, is constant and that "proportionalizing" is effected by varying the duration of pitch correction. On the other hand, the Hamilton Standard hydraulic propeller "proportionalizes" by varying the rate of pitch change as described above. This latter method gives quicker response in returning to equilibrium for small disturbances.

DESCRIPTION OF PRESENT PROPELLER SYNCHRONIZING METHODS

Note that synchroscopes are not to be confused with synchronizers. Synchroscopes are merely indicator instruments which serve to visually indicate when propellers are synchronized. Most of these work on the differential galvanometer principle and are connected to the engine ignition timing circuits or to alternators or impulse switches driven by the engine. The Kollsman type differentiates the electric tachometer circuits. Synchronizers, on the other hand, are mechanisms which automatically control the pitch of individual propellers on a multi-engined airplane to keep the engines at the same rpm.

The Curtiss Synchronizer uses a governor controlled direct current motor as a master source of rpm.[6] RPM control of all propellers and hence engines of a multi-engined airplane is effected with only one control by which the pilot or engineer adjusts the governor of the master motor. A small permanent magnet alternator is driven from the governor drive shaft in each engine. The master motor through gearing rotates small synchronous motors, one for each engine, the stator windings of which are supplied with the three-phase alternating current from the engine alternator referred to above. Whenever the frequency of the engine alternator current differs from that of the master motor, the rotor of the small synchronous motor rotates at a speed and direction which is the difference of the field frequencies of engine (alternator) and master motor. A commutator attached to this rotor causes a brush holder assembly to close contacts in one direction or the other to increase or decrease pitch through the propeller pitch change motor to bring the engine back to equilibrium speed. A few shorted, opposed segments of the commutator cause the duration of these corrective impulses to vary "proportional" to the "off-speed" up to a certain selected "off-speed" rpm above which the correction becomes constant. The mechanism contains suitable relays, condensers, adjustable time delays etc., to effect proper propeller operation as before described under Curtiss Governors. This synchronizer has been Government approved at this writing, having successfully passed several hundred hours of operation in at least two different airplane installations over the past two years. A single unit of this synchronizer would suffice adequately as a governor for a single engined installation.

The Hamilton Standard synchronizer works under quite different principles.[7, 8] Here any engine of a multi-engined airplane is selected by the pilot as the master engine. An alternating current synchronous generator is driven from the accessory drive on the rear of each engine. Each generator has to have sufficient power to operate the electric governor head mechanisms of all the remaining engines because any one may be used as the master. The electric governor head for each propeller has a differential motor. When only one winding of these differential motors is energized at the will of the pilot they serve as induction motors only to adjust the governor spring tension. Thus each propeller governor can be remotely electrically adjusted either when the synchronizers is turned off "automatic" to "manual" or on one engine only whichever is selected as the master. Synchronizer operation is as follows:

One engine is selected as the master. Its governor is adjusted by means of toggle switches from the cockpit using the governor head motor as an induction motor. This governor then maintains the rpm of that engine constant. The generator on the back of this master engine then generates a current of a frequency which is a constant function of this master engine rpm. This frequency is fed to the differential motor of each of the remaining governors. As long as the speeds of these remaining engines are identical to the master engine frequency there is no change in the respective governor spring settings. Should any disturbance cause any of these engines to change speed then that differential motor will correct its governor to bring that engine rpm back to "on-speed." This Hamilton Standard synchronizer has the desirable feature that the conventional governor corrects for large disturbances in the speed of individual engines. However, each engine must be brought to within about ± 100 rpm of the master engine or the differential motors will be too far out of synchronism to have sufficient torque to adjust its governor. Another fault is that the failure or hunting for any cause of the selected master engine will cause all the others to slow down or follow the master until switched "off" or to a new master. The weight is excessive because of the duplication of alternating current generators each large enough to carry all the remaining differential governor motors. The wiring for all of this control is very complicated and heavy. Although on test for several years this type of synchronizer has not at this writing been Government approved. It is understood that a new simplified type is undergoing development and test. This latter type holds much more promise for lighter weight, less maintenance, and more positive operation.

An Electronic Synchronizer invented by Mr. E. M. Sorenson, while a civil service employee at Wright Field, Dayton, Ohio deserves mention here. A master frequency, controllable by the pilot, is generated by an electronic (vacuum tube) oscillator. An inexpensive alternator using a "Hammond Organ" tone disk and pickup element is driven by each engine. When the frequency that

that this alternator generates matches the master frequency there is no change in pitch. When it differs, an electric filter circuit trips relays which in turn cause an electric type (Curtiss) propeller to change pitch. On Hamilton Standard installations the governor would normally be adjusted to bring the engine back to equilibrium. A simple and exceedingly clever "anticipatory" (second time derivative of the off-speed displacement) control using neon tubes and condensers was also invented by Mr. Sorenson to "proportionalize" from a selected ±30 rpm in "off-speed" to take care of the propeller inertia effects as earlier described to prevent hunting. A single engine governor unit of this device was constructed and successfully tested in four months at Wright Field. At last report a two-engined synchronizer for an airplane equipped with Hamilton Standard propellers was being constructed. This type of synchronizer is of comparable weight with the Curtiss but it is doubtful if any electronic type can be made as dependable as those based on electrical and mechanical principles.

DISCUSSION OF REFERENCES ON THE THEORY OF SERVO-MECHANISMS

When this research problem was undertaken in July 1940, the authors knew of no papers either published or undergoing preparation in which the general theory of servo-mechanisms had been specifically applied to aircraft propeller control and synchronization. The paper by Hazen,[9] had constituted practically the major reference on the general theory of servo-mechanisms. For instance, it constituted the basis of servo theory as applied to the numerous automatic devices concerning boat and airplane control, bomb sights, fire control apparatus, etc., developed by the Sperry Gyroscope Company. The bibliography[9] lists 32 references, practically all of which deal with descriptions of servo-mechanisms for specific control purposes but none concerning aircraft propellers. Reference 10 was a source of much of the theory used by Hamilton Standard Propellers in the design of their governors. Reference 11 is a more recent paper giving data applicable in general to the subject problem.

It was the original purpose of this research, therefore, to apply the general theory to the subject specialized problem and to develop in addition a simple mechanism adaptable to the governing or synchronizing of standard types of controllable propellers. Search developed that unknown to the authors when the research was undertaken, in July 1940, several papers and reports were in preparation or had recently been completed on this specific subject. Most of these had been undertaken since January 1940, but were not available to the authors until about December 1940. Proof that the application of the general theory to propeller control was pertinent and timely lies in the wealth of data contained in references 12-16 inclusive, all dated since January 1940, and all concerning or directly applicable to propeller control. The Hamilton Standard reports are directly concerned with governor controls for their hydraulic type governors. The Curtiss reports are of a more general nature but of course include data pertinent to their electric type propellers.

References 12 and 3, by Meyer and Draper cover in considerable detail data for governor and synchronization computations applicable in general to any type of controllable propeller. This work was that originally intended to be covered in this research problem. Now that it has been accomplished no purpose would be served in reproducing it in this thesis. However, discussion will later be given of the principles involved.

Reference 15 was translated in October, 1940, by E. G. Chilton at Pasadena, California. This paper presents a detailed theoretical analysis of and comparison between regulators of pressure, revolution, temperature and directional control. This translation is on file in the G.A.L.C.I.T.[*] library. It is a very valuable reference for general automatic control theory of all types.

Reference 16 is the most exhaustive presentation of the "Behavior and Design of Servo-Mechanisms", wherein the controlled member is to be rotated, that has been published. This paper is "Restricted" and privately printed November, 1940, by the Fire Control Committee of the National Defense Research Committee. It is particularly valuable for the numerous charts it contains which aid materially in the solution of many of the more complicated equations peculiar to this theory involving operational and other tedious mathematical methods. A copy of this paper is in the possession of Dr. Theodore von Kármán at G.A.L.C.I.T. In this paper Professor Brown takes exception to Hazen's[9] <u>ideal</u> treatment of the response of a servo. Professor Brown recognizes that in practice no controller can be ideal. Specifically he derives equations which take into account that the maximum torque of a controller must physically be limited, and that a finite torque applied to a mechanism member for zero time cannot cause a change in that member's angular position or velocity.

The following section includes comments on the application of the theory of Brown[16] to the mechanism invented by one of the authors, H .M. McCoy, and on its

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development and test by both authors. The Appendix I describes in detail the physical operation of the mechanism. This is placed in an Appendix to facilitate the use of the description for patent purposes.

THE SUBJECT AIRCRAFT PROPELLER SYNCHRONIZER AS A SERVO-MECHANISM

It is suggested that the description of Appendix I be read at this point to familiarize the reader with the nomenclature hereinafter used. This synchronizer comes under the general classification of a "continuous-control servo-mechanism" as defined by Hazen[9]. Here the "indicating element continuously controls the restoring force acting on the output element in both magnitude and direction." Brown[16] calls this type a "closed-cycle continuous-control system" wherein a control element, here the pitch change motor, is actuated by a function of the difference between the source of master rpm and the airplane engine speed. In this mechanism the control impulses are intermittent up to a certain selected "off-speed" and the duration of these impulses is proportional to the "off-speed" while their magnitude is constant. Appendix I describes how the control impulses can readily be made continous instead of intermittent and the magnitude of the corrections be made proportional to the "off-speed" rather than constant. Time-lag is the only difference between these two means of control, the overall result is the same.

The tentative United States Air Corps requirements for automatic synchronizers are listed and discussed in reference 17. Those items concerning precision of control can be considered very lenient in view of the performance of the subject synchronizer. One requirement is that the difference in angular velocity between any two engines should not exceed 15 rpm when averaged over one second. Naturally, this item could not be physically checked in the subject mechanism because only one governing unit was constructed. It is obvious however, that as only one master source of rpm is used and as all separate propeller pinion nuts are driven from the same master elongated pinion, that this requirement is readily met so far as control impulses are concerned. The only variable that could cause the rpm of two or more propellers to vary one from another at any instant, provided the disturbance was the same for all propellers, would be due to differences in production tolerances to cause one propeller to change pitch at a different rate from another propeller for a given control impulse. In fact the mechanism is capable of keeping the difference to one rpm, and less if desired, provided that all propeller pitch change mechanisms respond at the same rate to the control impulses. This requirement therefore, is a function of the transient and steady state rate of pitch change for the type of propeller being governed and should properly be changed to some function dependent on the characteristics of the particular propeller. The other requirement is that the angular difference when averaged over one minute shall not exceed 2 rpm. It has been demonstrated that this is an easy requirement to meet but is also dependent on the maximum rate of pitch change of the particular propeller being considered. Assuming that a particular type of propeller can be controlled to one rpm and using the normal rates of pitch change of present day propellers it should not take longer than 20 seconds to make the changes in propeller pitch to bring any one or all propellers back to equilibrium within one rpm of the master rpm. This time response is also dependent on the magnitude of the "off-speed" disturbance and should properly be expressed as some function of that disturbance rather than an arbitrary time.

The other requirements were outside the scope of the subject experiment because of limitations of experimental funds and shop facilities. However, they only concern details of physical design such as elimination of radio interference, interchangeability of parts, etc., which can easily be met using standard design procedures for typical aircraft mechanisms. All requirements concerning operation and precision of control were demonstrated to have been met and exceeded to an extent warranting rewriting those requirements making them more severe.

The background of Air Corps synchronizer requirements was presented above as necessary in order to acquaint the reader with the nature of this problem. The solution progressed in the manner now presented. It was desired to construct a simple mechanism that could be universally used to govern or synchronize propellers regardless of their number or type. It was further desired to have a pilot operated sensitivity control for smooth or bumpy weather. Such a control should have sufficient range to provide adaption to various propeller types depending on their pitch change characteristics. It would also provide adaption to a specific propeller type to cover the entire inertia response range of all such propeller-engine combinations. The design was to be such as to permit any desired accuracy by merely interchanging gears or screw machine parts. Remote rpm indications were to be made by using standard "autosyn" or "selsyn" transmitters and receivers. If the above conditions could be met a synchronizer would be available that had qualities no other possessed. Before continuing with the discussion of the operation of the mechanism let us see how it fits Brown's definition of a servo-mechanism.[16]

Reference 16, made available to the authors on December 9, 1940, deals exhaustively with the theoretical treatment of "maintaining the angular position of a shaft operating at a high-power level automatically in synchronism (or in step) with the angular position of a shaft as established by a low-power mechanism." This fits exactly the case of the aircraft propeller synchronizer. Reproduction of the data contained in this reference would serve no useful purpose. Fig. I of reference 16 is reproduced below, however, to allow identification of the major parts of the general servo-mechanism with those of the propeller synchronizer described in Appendix I.

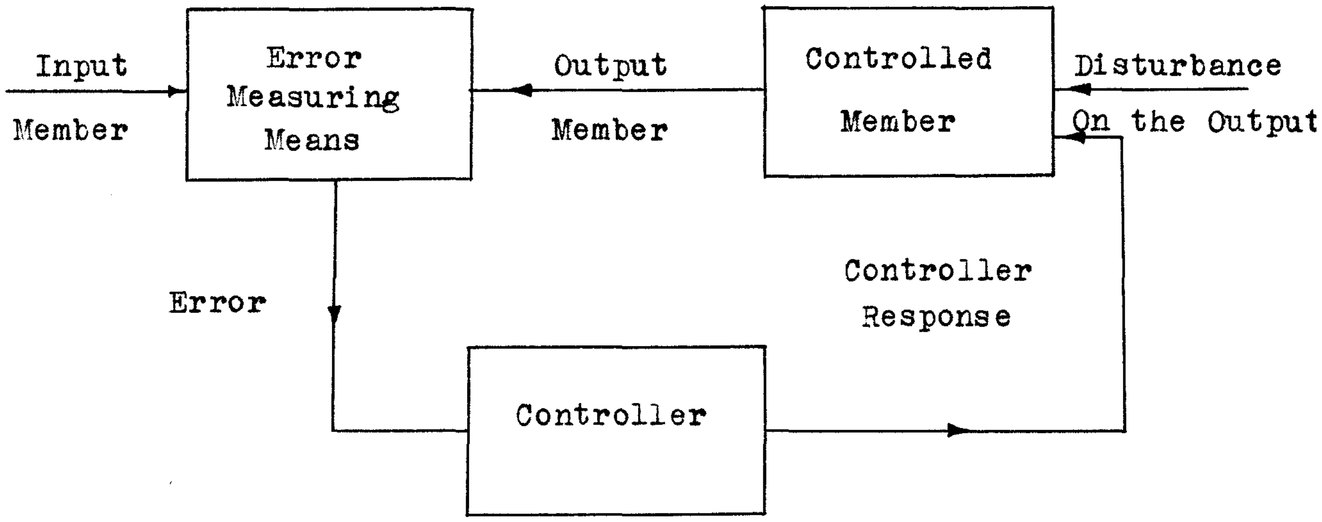

Fig. 1 Block diagram for a Servomechanism

Referring to Fig. I the"Input Member" corresponds to the elongated pinion driven by the master motor. The "Error Measuring Means" is composed of the lead screw and pinion nut. The "Error" is the off-center position of the pinion nut. Said position is a function of the "off-speed" rpm in magnitude and direction. The "Controller" is the pitch change motor. The "Controller Response" is the rate of pitch change. The "Controlled Member" is the aircraft engine. The "Output Member" is the selsyn (autosyn) or flexible shaft drive which transmits engine rpm to the lead screw through the follow-up differential. "Disturbance on the Output" is the temporary slowing down or speeding up of the airplane engine by any means. In the analysis of a servo-mechanism of the above type equations are written for each of the elements of Fig I. Values peculiar to the mechanism involved are then assigned to each element.

DESIGN CONSIDERATIONS AND OPERATION

The principles of the subject mechanism were to be demonstrated as inexpensively as possible. It was decided to use an auxiliary motor with controllable governed speed as the master source of rpm, rather than one of the engines, for the reasons earlier discussed when the operation of the present Hamilton Standard Synchronizer [7, 8] was reviewed. Several sources of direct current governor controlled motors are available. The General Electric Company has so refined their design for the Curtiss Synchronizer that its accuracy is comparable to normal house lighting current constancy. Actually an alternating current synchronous motor was used in this experiment to furnish a constant master rpm because, had it been necessary, the G.A.L.C.I.T. variable frequency laboratory current could have been used for control purposes. The control principles can be demonstrated just as well however, by disturbing the equilibrium of the simulated airplane engine by changing the load on it by means of the variable resistances provided or by friction means.

Analysis of the mechanism followed the procedure of Brown[16] and showed that a positive check of the time response would be very difficult and would involve an expensive experimental test setup which was outside the scope of the very limited funds available for this problem. Mainly for that reason a careful analysis was made to insure that the general principles of operation were correct and that the mechanism would function as conceived, not only over the relatively narrow range of present propellers but over as wide limits, ie., boundary conditions, over which it appears aircraft propellers will ever be called upon to operate in the future.

Assume a particular engine-propeller combination. The engine torque versus rpm curve is plotted for a given fixed throttle setting. The propeller torque versus rpm curve is superimposed. Where the two curves cross the torques are balanced and the combination is said to be in equilibrium. Inspection of typical curves will show that for our synchronization purposes that for an "off-speed" of about 100 rpm on either side of this equilibrium point that both curves may be considered straight lines.[3] Inspection shows that the difference in torque for a given "off-speed" is that torque available to accelerate or decelerate the propeller. Meyer[12] calls this the "restoring torque". The polar moment of inertia of the propeller and rotating engine parts is enormous considering servo-mechanism controlled members in general. The inertia torque is equal to the moment of inertia times the first time derivative of the "off-speed", ie., the rate of change of propeller speed. For equilibrium the sum of all the torques must equal zero. Coulomb and viscous friction torque can be neglected without introducing an appreciable error. We thus see that the propeller inertia and the engine torque characteristics are the principle variables which influence synchronizer behaviour. Time lag due to motor windings and magnetic clutch coil inductances can also influence operation if not carefully considered. Due to the disproportionate inertia of the propeller and rotating engine parts such a considerable time lag is present in all representative combinations that on the average no appreciable response to a control impulse is evident for a second or more. The higher the rate of pitch change of the propeller, however, the quicker the response and hence the lesser the time lag. Draper[3] calculates and checks experimentally a steady state lag of about 36 rpm on a typical engine-propeller combination with a Curtiss propeller. This propeller has a relatively low maximum rate of pitch change on the order of about 1.5 degrees per second. On the other hand the Hamilton Standard propeller has a maximum rate of about 4 degrees per second. In this investigation the gear ratio of the motor that simulated the pitch change motor was so varied from 100:1 to 30,000:1 that the equivalent rates of pitch change varied from about 30 degrees per second to 0.1 degree per second. Thus we see that the rates varied from more than seven times the normal maximum of the Hamilton Standard to about one fifteenth of that of the relatively slow Curtiss propeller. Assuming an average "characteristic time" [12, 3] of one second a disk mass was placed on the shaft of the controlled motor that simulated the engine, so as to give the combined rotating parts the same inertia response as a conventional engine-propeller combination. The torque versus rpm characteristics of the motor were determined by means of a friction brake and sensitive postal scales in the manner detailed by Marks. See Fig. 24, page 2051.[18] For the entire range of rates of pitch change, propeller masses varying from zero to about ten times the inertia value of the conventional propeller were tested. For a given rate of pitch change it was found that the corrective response to control impulses increased as propeller inertia was reduced. The fact that the mechanism worked successfully for even extreme (boundary) conditions with only slight variations in rate of response and time lag is proof of its sound principles.

The brains of this synchronizer is the "follow-up" mechanism. In propeller parlance a "follow-up" is a device that takes a correction off just as fast as it is made. Inspection of the description and figures of Appendix I will show how this "follow-up" functions. "Proportionalizing" was effected by varying the duration of the corrective impulses proportional to the first time derivative of the "off-speed". Brown[16] clearly and simply illustrates how effective this means of damping really is. In the absence of viscous and coulomb damping one must go to at least the first derivative control. It is not really damping in the physical sense but appears the same mathematically in the control equations. To obtain aperiodic control for any combination of rate of pitch change and propeller inertia for an imposed disturbance it was only necessary to increase the speed of the "follow-up" motor by means of the sensitivity control rheostat. This increased the total time necessary to reach equilibrium by decreasing the duration and increasing the number of corrective impulses. For very slow speeds of the "follow-up" motor the duration of corrective impulses was relatively long and the number few so that a divergent or damped oscillation was obtained in approaching equilibrium after imposing a disturbance. The sensitivity control rheostat to control the "follow-up" motor speed would permit aperiodic "proportionalizing" when set for a high rpm. This would give very sensitive adjustment but would take longer to reach equilibrium. This is the condition for flight in smooth air. In rough air where there are frequent disturbances of considerable magnitude, the rheostat would be set for a low "follow-up" motor speed to permit more rapid approach to equilibrium conditions although such approach would not be aperiodic.

The above described tests covering all conceivable extremes of propeller operation successfully demonstrated the efficacy of this mechanism to govern and synchronize aircraft propellers. It should be noted here that this device would control a Curtiss type propeller directly but would have to be used to control the governor of a Hamilton Standard type unless means were devised to directly control the servo governor valve without using the governor mechanism. No further mention has here of late been made concerning controlling propellers under one rpm. It is obvious that this type of mechanism if refined is of sufficient accuracy to permit the generation of control impulses within a practical lower limit of about one degree out-of-phase (synchronization). Actually with the crude mechanism above, control impulses were generated down as low as 10-12 degrees out-of-phase. To increase this accuracy it is only necessary to steepen the pitch of the lead screw and provide more sensitive switches. However, the following discussion will provide data permitting conclusions that control under one rpm is not justified, at least in the immediate future.

DISCUSSION OF PROPELLER SOUND EFFECTS

The uninitiated often ask, "Why bother to synchronize propellers so accurately?" The answer to this question is obvious to the pilot or air traveler in a multi-engined airplane who has normal hearing and sensibilities. If the three bladed propellers of a two-engined airplane are out of synchronism two rpm there will be produced six "beats" per minute or one every ten seconds. This is about the lowest beat frequency that can be detected audibly. A beat frequency above six per minute is very objectionable to occupants of an airplane and is physiologically and for some temperaments even psychologically undesirable. From the military standpoint it is mainly this out-of-synchronism beat that hastens the detection and recognition of aircraft at considerable distances by means of sound locators.

The intensity of the noise emanating from a propeller is primarily a function of the tip speed. Those components of noise due to blade angle, ie. power absorbed for a given rpm, blade planform, vortex losses, etc., can be neglected in this discussion. The fundamental note of a propeller, sometimes slightly influenced by the first few harmonics, is that one most audible to both occupants of an airplane and ground observers. Due to the approximately logarithmic response of the human ear to sound pressures the audible measure of sound is called the "loudness level". This level is generally less than the sound "intensity level" measured by instruments, but for the relatively low frequencies (propeller rpm times number of blades) with which we are here concerned this difference is slight and may be neglected. We shall henceforth speak of sound <u>intensity</u> only.

Sound intensity at a point varies inversely as the square of the distance from the source. This is true under ideal laboratory conditions only. Even then great care must be taken to avoid reflections and interference from surrounding bodies. In the free atmosphere terrain reflections, wind velocity and direction (including stratification), temperature, humidity, inversion, and clouds, to name a few, all affect this law.[19] In this discussion, however, it can be considered as holding in general in connection with the operation of anti-aircraft sound locators. It therefore follows that to make the detection of aircraft from the ground as difficult as possible, aircraft should approach an objective at as great a height as practicable and stay above or in cloud formations when such exist.

Reference 20 shows that there is a reduction of 95% in the intensity of sound when the tip speed of a propeller is reduced from that of the velocity of sound

(1118 fps.) to 800 fps. No worthwhile further reduction is obtained in going below 800 fps. It is interesting to note that about 1.6% of the total engine power is dissipated in sound energy at 1118 fps and about .35% at 800 fps.

References 21, 22, and 23 contain data concerning aircraft engine silencers. Although this subject is a bit out of place in a discussion of propellers it is revelant to airplane noise in general and contributes to the conclusions at the end of this discussion. Over the operating range, the energy intensity of exhaust noise is proportional to the square of the engine power. It is therefore apparent that low power is a prerequisite operating condition for aircraft wishing to avoid detection. This low power is consistent with low propeller rpm as discussed above. Silencers are effective in reducing exhaust noise. Exhaust location is an important factor which influences the direction at which exhaust noise is emitted. All the above variables can be made to act favorably to reduce exhaust noise, which if unrestrained may approach equal intensity to propeller noise at low rpm. Aerodynamic noises are of too low intensity on modern clean airplanes to affect the conclusions drawn from the above discussion.

Everything that serves to reduce airplane noise from the ground observer's standpoint also influences the airplane occupant in the same order. However, a high propeller sound intensity level with accurately synchronized propellers is not as objectionable from the comfort standpoint as a considerably lower level with a beat frequency over 6 cpm due to poorly synchronized propellers. Reference 1 outlines in detail a mathematical presentation of the possibility of reduction of the noise emanating from the propellers of a four-engined airplane by using acoustic interference produced by accurate and controllable angular phasing of each of the propellers relative to each other. Under ideal conditions where the propellers are isolated from sound interference and reflections by parts of the airplane structure such as wings, engine nacelles, etc.; which condition would be approached if the propellers were on long extension shafts; it appears that considerable reduction in sound intensity could be effected. As previously discussed, the mechanical solution of this problem of effecting such phasing would necessitate heavy, complicated and expensive mechanisms, and would not be justified for either air transport or military airplanes. The solution[1] moreover, is only for propellers in line and in one plane and with constant spacing. In most four-engined airplanes, due to dihedral and sweepback, the propellers are neither in line laterally nor in the same plane. In addition the thrust line of individual propellers is often yawed and the spacing, while symmetrical, is not constant along the span. When one also considers the shielding effect of the fuselage and engine nacelles the problem becomes of such complexity that a theoretical or practical solution appears hopeless. It is the opinion of the authors that the benefits theoretically possible even under ideal conditions are of not sufficient magnitude to warrent further investigation. It is concluded that as long as an audible out-of-synchronism beat is avoided and the rotation intensity level limited by not exceeding tip speeds of 800 fps for normal operating conditions, the resulting noise level will be tolerable. Empirical means of calculating noise levels for a given airplane are contained in reference 23. Additional valuable propeller noise data are contained in references 24, 25, 26.

The above discussion on synchronization, from the military standpoint, applies only to one airplane. When a formation of airplanes is involved there appears to be no practical means nor need of synchronizing the propellers of all airplanes in the formation. If there are three or more airplanes each with synchronized propellers in a formation the propeller noises will be all mixed up and no regular beats should occur.

It is interesting to note that in the current German air attacks on the British Isles that British ground observers can readily distinguish German multi-engined airplanes from their own by the "rumm-rumm" out-of-synchronism beat of the German planes.[27] This is explained by the fact that the standard German propellers are of the V. D. M. electrical type and are not equipped with governors.[28] The pitch adjustment is made manually by means of toggle switches. The overall gear reduction of this propeller is so low that fine enough adjustments in pitch cannot be readily made to permit accurate synchronization. Because the engines used have fuel injection they run with much better regularity than those with carburetion. Hence the out-of-synchronism beat is quite regular.[29] The British planes are equipped for the most part with governed propellers of types which can readily be synchronized by the pilot. Due to hunting of the carburetion engines any beat that develops is irregular. Hence the ground observer's distinction between airplane nationality types is readily made by audible means whether the airplane is visible or not. American military observers who have been abroad and to whom the authors have talked confirm the above remarks.

CONCLUSIONS

1. Adequate servo-mechanism theory now exists to cover its adaptation to any phase of the problem of synchronizing aircraft propellers.
2. Tests of the subject synchronizer mechanism demonstrated that the present tentative United States Air Corps requirements for propeller synchronizers can very easily be met. The requirements were exceeded to an extent which now warrant amending the requirements and making them more severe.
3. Reduction in the overall noise level of an airplane, especially by the use of automatic synchronizers, aids in improving airplane pilot and passenger comfort and makes more difficult the detection of aircraft by ground anti-aircraft sound locators.
4. In order to make as difficult as possible the detection from the ground of aircraft in flight the following rules should be followed:-
   - (a) Propellers should be automatically synchronized within one rpm of each other. Present propellers should permit this if proper synchronizing means are used.
   - (b) Propeller tip speeds should not exceed 800 fps.
   - (c) As low a cruising engine power as is practicable should be used consistent with tactical considerations.

(d) Flight should preferably be above or in cloud formations when they exist, and when tactical and aircraft flight safety considerations permit.

(e) Engine exhaust silencers should be used. If back pressure is prohibitive with silencers then exhaust outlet location should be carefully chosen for maximum silencing qualities.

5. The controlled angular phasing of propellers of a multi-engined airplane under one rpm is not at present practical nor justified.

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APPENDIX I

Introduction

This appendix includes a complete detailed description of the servo-mechanism constructed at G.A.L.C.I.T.* to demonstrate the working principles of an aircraft engine-propeller synchronizer invented by H. M. McCoy, Captain, United States Air Corps and designed and tested by the authors. The operation of the actual mechanism is described. Because the aircraft engine-controllable propeller combination, Selsyn torque transmitters and other aircraft parts had to be simulated, there is also presented a discussion of how this synchronizer would actually function on an airplane. Discussion is also presented of alternate arrangements of the control system for hydraulic and substitute electrical control methods other than shown, making the general mechanism applicable to rpm control of machinery other than aircraft propellers.

Description

Fig. 1 is a photograph of the mechanism showing the final test arrangement. Other arrangements only differed in reduction gear ratios and sizes of the follow-up and pitch change motors, impressed voltages, motor mounting means, types of resistances, etc., none of which changed the

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physical arrangement of elements or principles of operation.

Fig. 2 shows schematically the mechanism as developed and tested and including a schematic wiring diagram. (1) is a synchronous motor running constantly at 1800 rpm from the laboratory lighting circuit and driving elongated pinion wire (2) at that speed. It is the master source of rpm. Pinion nut (3) is of the same number of teeth and pitch diameter as (2) and is internally threaded to run easily along lead screw (4). (4) is driven at an rpm which is the algebraic sum of rpm of the governed D.C. motor (5) and reversible D.C. clutch motor (6) as affected by gearing. (7) is a fly wheel disk that represents the mass of the aircraft propeller. This mass (7) was calculated from the torque-versus-rpm characteristics of motor (5) to give a moment of inertia and time response representative of the rotating parts of an actual aircraft propeller-engine combination. (8) is a slip clutch drive of brass-on-wood, spring loaded to transmit the same torque as an autosyn (selsyn) aircraft tachometer system. (10) is a differential gear arrangement. The rpm of motor (5) is transmitted through slip-clutch (8) and shaft (9) into differential (10). The direction is reversed due to the idler gears in the differential (10) and then is transmitted to pinion nut (3) through lead screw (4). The cage of differential (10) has a gear wheel attached to it which meshes with worm wheel (11) driven by clutch motor (6). Clutch motor (6) has an annular solenoid clutch incorporated in it. The driven disk of this motor is held by a spring against brake material when not energized. When energized the solenoid pulls the driven disk away from the brake material and against the driving disk integral with the rotor of the motor. Suitable gearing (12) is interposed between the clutch motor (6) and worm gear (11). The cage of differential (10) is mounted in suitable bearings to be rotable whenever clutch motor (6) is energized, but is normally held against rotation by the brake in corporated in (6) whenever (6) is not energized. "Micro-switches" (13) are normally "open" and are of the "lever-and-roller" type spring loaded. Variable resistance (14) controls the speed of clutch motor (6) and hence the sensitivity of the entire mechanism as later explained. This motor (6) is called the "follow-up" motor. Motor (5) represents the aircraft engine. The speed of an aircraft engine is normally controlled automatically by the pitch of the propeller. Here an automatically operated variable resistance is used. (15) is this variable resistance consisting of suitable size resistance wire laid in a groove around the periphery of a micarta disk (16). This disk is mounted on a rotable shaft and is driven through wheel and worm gearing by reversible D.C. clutch motor (17), called the "pitch change" motor and which is identical in operation to "follow-up" motor (6). One end of variable resistance (15) is grounded to the frame as indicated. Spring loaded brush contact (18) is in contact with resistance wire (15). A manually operated variable resistance (19) is in series with (15) and provides means of imposing speed disturbances on motor (5). Mechanical stops (20) on the micarta disk (16) operate limit switches (21) to prevent damage to the mechanism. The various motors and switches are wired as shown. The operation is as follows:-

Pinion wire (2) is continuously rotated at 1800 rpm. As long as motor (5) is running at exactly 1800 rpm then pinion nut (3) is stationary and both switches (13) are open. The torque of motor (1) is greater than that transmitted through the lead-screw (4). It is of course assumed that the direction of rotation of the various motors and shaft concerned are in the proper direction to effect the above and following operations. Once the speed of motor (5) slows down or exceeds 1800 rpm by manually changing resistance (19) the pinion nut (3) will traverse in one direction or the other closing one or the other of switches (13). As soon as contact is made both pitch change motor (17) and "follow-up" motor (6) will begin to rotate because they are connected in parallel to switches (13). The "follow-up" motor (6) will rotate in a direction to superimpose sufficient rpm on the lead screw (4) to cause pinion nut (3) to go back to the neutral or equilibrium position. Pitch change motor (17) will rotate in a direction to cause the variable resistance (15) to change in a direction to change the speed of motor (5) to bring it back towards 1800 rpm. When the "off-speed" is of such magnitude to cause the pinion nut (3) to hit the stops at either end of the lead screw (4) travel, then slippage will occur at slip clutch (8). Of course the contacts (13) are closed at all times pinion nut (3) is off the equilibrium position so that the speed of motor (5) is continuously changing toward equilibrium.

Let us assume that the steady state speed of the "follow-up" motor (6) is such through its gearing as to superimpose 100 rpm upon lead screw (4). Lead screw (4) has 24 threads per inch. Hence at the instant when the speed of motor (5) is (1800 ± 124) rpm the pinion nut (3) will be traveling linearly to or fro at a velocity of one inch per minute. At the instant the speed of the governed motor (5) is exactly at (1800 ± 100) rpm, the velocity of the pinion nut (3) will be zero at whatever "off equilibrium" position it may be at that instant. Hence as the speed of motor (5) approaches (1800), from less than 100 rpm off-speed, the pinion nut (3) will be returned to the equilibrium position by the follow-up motor. It is apparent therefore, that under 100 rpm "off-speed" in either direction there will be a "proportionalizing" governing action with the duration of "contact-closed" time proportional to the off-speed. Correction will be constant above 100 rpm off-speed but proportional to the off-speed below 100 rpm. Due to the relatively high mass polar moment of inertia of the disk (7) and rotating motor (5) parts approximately one second passes before there is an appreciable change in motor (5) speed to a disturbance imposed by manually changing the resistance (18). This disturbance simulates changing the throttle setting of an actual airplane engine for a given propeller governor speed setting or of changing the load on the engine by climbing or diving the airplane. The larger the inertia of the governed rotating mass the greater the time lag for response either to a disturbance or a governing control impulse.

The variable resistance (14) is placed in the common lead circuit of the "follow-up" motor (6) to allow adjustment of its speed to give the proper "proportionalizing" control to the mechanism. Aperiodic response can be obtained by advancing the follow-up speed to sufficiently high enough values. The action of the "follow-up" serves the same purpose as heavy Coulomb or viscous damping. It is seen that without the "follow-up" action which counteracts or corrects for small disturbances (up to the limit of "follow-up" speed) that the system is of the inherently divergent oscillating type, because a given disturbance would otherwise displace the pinion nut (3) a certain distance, then to get it returned to equilibrium position the control would have to cause an overspeed equal to the initial disturbance but in the opposite direction. Because there is considerable time lag in this system and no measurable damping (without the "follow-up") there must result a serious divergent oscillation. This was easily demonstrated by disconnecting the common (ground) lead of the "follow-up" motor (6) and then imposing even a small disturbance.

For this mechanism to operate successfully it is imperative that the friction torque of friction clutch (8) drive be greater than that necessary to turn lead screw (4), cause pinion nut (3) to be traversed along the lead screw and pinion wire (2), and operate the switches. Otherwise the superimposed "follow-up" rpm of motor (6) would feed back through clutch (8) causing slippage which would prevent proper proportionalizing.

In the test of this mechanism follow-up speeds from 20-2000 rpm were used. Pitch change speeds equivalent to .1 degree per second to 30 degrees per second were used for all follow-up speeds. Present day propellers have rates of pitch change varying from 1.5 to about 4 degrees per second. Inertia disks varying from none at all to a size approximately 10 times that of an equivalent aircraft propeller were used in combination with all of the above combinations. The only variation in control with all combinations of all variables was in time response to get back to equilibrium for a given disturbance. Response varied from several minutes with aperiodic control to but a few seconds with over controlling but always positively damped oscillations.

The means used here to measure the error between the master rpm and that of the governed motor is a novel differential gear system comprised of the elongated pinion, the pinion nut, and lead screw. These parts measure the rpm difference between the two motors and convert an angular difference into a linear motion. This permits simpler arrangement of switches, "follow-up", etc., than a conventional differential arrangement. The conventional (such as a bevel gear) differential could be used here alternately, however, if desired. This mechanism is unique in that the control impulses (except for their transient conditions) are constant in magnitude and "proportionalizing" is effected by varying the duration of these control impulses. It is apparent that this "proportionalizing" action is a function of the first time derivative of the "off-speed". For any "off-speed" displacement a control impulse is generated which is constant regardless of the magnitude of the "off-speed."

Alternate arrangements are, however, possible and their discussion follows.

Let us assume that the movement of pinion nut (3) in either direction from equilibrium closes an electrical circuit as before by actuating a potentiometer (variable resistance) so that the resistance will decrease the greater the "off-speed". As the resistance decreases the speed of both the "follow-up" and pitch change motors will increase. Hence "proportionalizing will vary not only as any desired function of the first time derivative (ie. velocity of the "off-speed") but additionally as a direct function of the magnitude of the "off-speed". By using switches and separate potentiometers for each of the "follow-up" and pitch change motors, and by varying the winding of these potentiometers (such as logarithmically) practically any desired shape of time response and control curve can be obtained to fit any given set of conditions and variables.

The movement of pinion nut (3) could also actuate means for tapping in a series of resistances instead of varying a potentiometer. Reference (1) of this appendix presents several means, particularly by use of a "Silverstat", of controlling voltages and varying resistances. Means such as indicated could be used in combination with the subject mechanism to automatically control or govern any type of machinery requiring rpm control.

The movement of pinion nut (3) could alternately actuate hydraulic or pneumatic motors to effect "follow-up" or pitch change action. In addition mechanical clutches and mechanical variable drives could be actuated to effect the necessary "follow-up" and governing action. For some control installations Ward-Leonard and similar systems could be controlled by the pinion nut (3) movement.

To prevent any possibility of the pinion nut (3) from jamming at the end of its travel on "lead-screw" (4) it is possible to have it when near the end of its travel actuate a switch or valve or mechanism to drive the "follow-up" motor at a speed greater than the master motor. This permits "follow-up" actuated return of the pinion nut (3) toward equilibrium even when the governed motor (5) is stopped. This is the worse condition.

The accuracy of control obtained with the relatively crude mechanism actually built permitted control impulses to be generated when only 10-12 degrees out of phase. Steepening the pitch of the lead screw and using more sensitive switches should permit increasing this accuracy to less than one degree out of phase if desired.

The next step in a control of this kind is to get "anticipatory" control. To do this it is necessary to work with the second time derivative (the acceleration) of the "off-speed". This measures the rate of change of velocity and permits accurate control with practically no time delay of mechanisms possessing tremendous moments of inertia exceeding those of propellers as here described. Such anticipatory action permits the generation of control impulses <u>before</u> an equivalent corrective force could be generated due to speed changes only. Reference 2 to this Appendix adequately discusses the variables involved in adding "anticipatory" control to the subject mechanism. This synchronizer operates satisfactorily to control aircraft propeller-engine combinations. To use its principles to control other systems would make desirable the addition of "anticipatory" control. This could be accomplished in the subject mechanism by having a slidable yoke or carriage surrounding the pinion nut (3). In this carriage a mass could be restrained in a neutral position by springs or a magnetic field in such a manner as to be unaffected for steady velocities of translation but which would operate auxiliary switch contacts when undergoing acceleration. Reference (2) discusses electrical means for measuring rates of changes of voltages and currents proportional to the regulated speed. These effect "anticipatory" control as desired for any given condition and many arrangements could be incorporated in this mechanism.

Angularity of control without slippage and without provision for slippage can be effected by the subject mechanism if the control forces are of sufficient magnitude and response is quick enough to prevent large time delays throughout the system. The movement of pinion nut (3) could actuate a second or any multiple stage of control forces at any desired "off-speed" to take care of large disturbances.

It should be noted at this time that one master source of rpm can be used to control any desired number of motors, engines, or machines by simply adding pinion nut and lead screw drives (one complete set for each controlled motor) in a rosette fashion about the master pinion wire or by extending the pinion wire or having a cascaded series driven by one master source of rpm.

In closing let us see how this synchronizer would function on an airplane. Refer to Fig. 3. (1) is the master source of rpm and is a D.C. governed motor similar to one used in the Curtiss Propeller synchronizer. The switch contacts (2) are actuated by the "off-speed" movement of pinion nut carriage (3). The system differs but slightly from that of Fig. 2. A variable resistance (4) permits adjustment of the speed of "follow-up" motor (5) to fit the "proportionalizing" control to individual propeller-engine combinations and to permit a <u>sensitivity</u> control for smooth and rough air to be varied at the pilot's will. For smooth air the "proportionalizing" speed of motor (5) would be high. It will take longer to correct for a given disturbance but synchronization will be finer. For rough air where disturbances are greater in magnitude and more frequent than in smooth, the speed of motor (5) would be cut down. This permits larger corrective impulses and lessens the time for correction back to equilibrium for a given disturbance but decreases the sensitivity.

(6) is an autosyn (selsyn) generator driven from the engine and (7) is the autosyn receiver. This arrangement permits magnetic slippage when the pinion nut carriage (3) is against the stops for any reason, such as if the airplane engine (8) was stopped for any reason such by a feathered propeller. The switches (2) control both the "follow-up" motor (5) and the propeller (9) by adjusting the pitch of (9), if an electrical propeller such as the Curtiss, or adjusting the propeller governor if a hydraulic propeller such as the Hamilton Standard. The propeller pitch controls the speed of the airplane engine (8). Duplication of the pinion nut, carriage, and lead screw drive, etc., (one complete drive for each engine being governed), thus provides synchronization of all engines because all systems are driven and controlled by the one pinion wire driven at the selected master rpm.

In conclusion it may be stated that the subject mechanism in its present form is directly applicable to the control and synchronization of aircraft-engine-propeller combinations or other systems wherein rigid angularity or phasing is not required, where the controlled elements have relatively large inertia and the control forces are relatively small. The principles of operation of this mechanism may, however, be used by varying certain elements to control any system wherein the angularity of a controlled number is required to be synchronized with the angular variation of some master input member.

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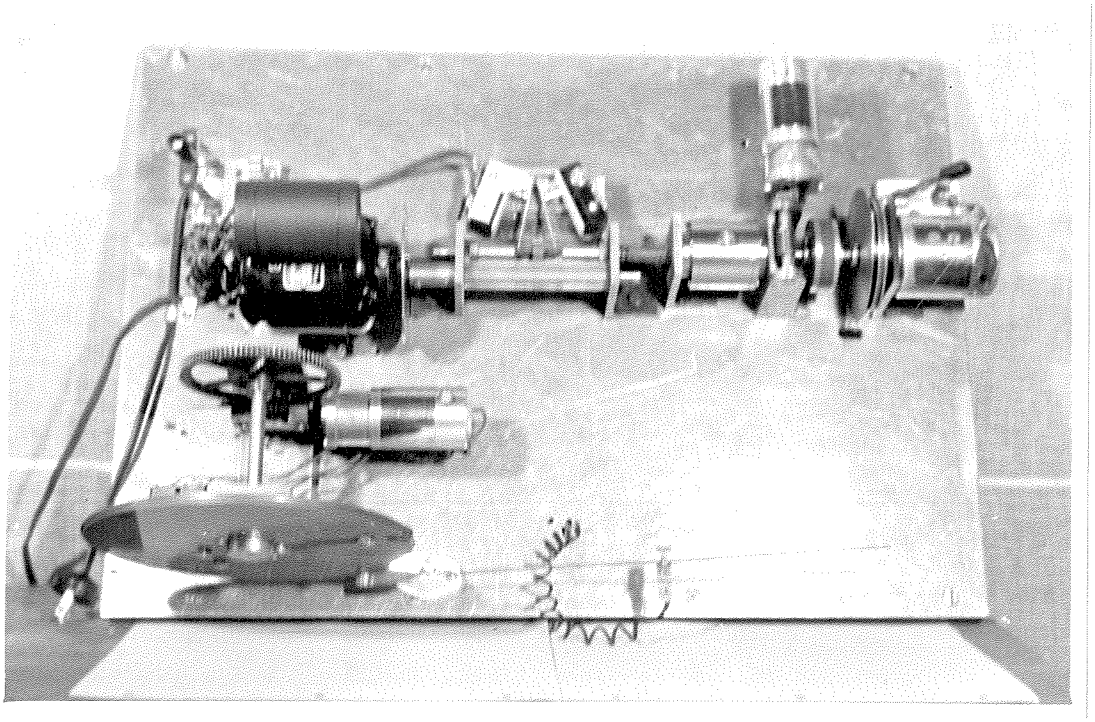

Figure 1 - Photograph of Model Synchronizer

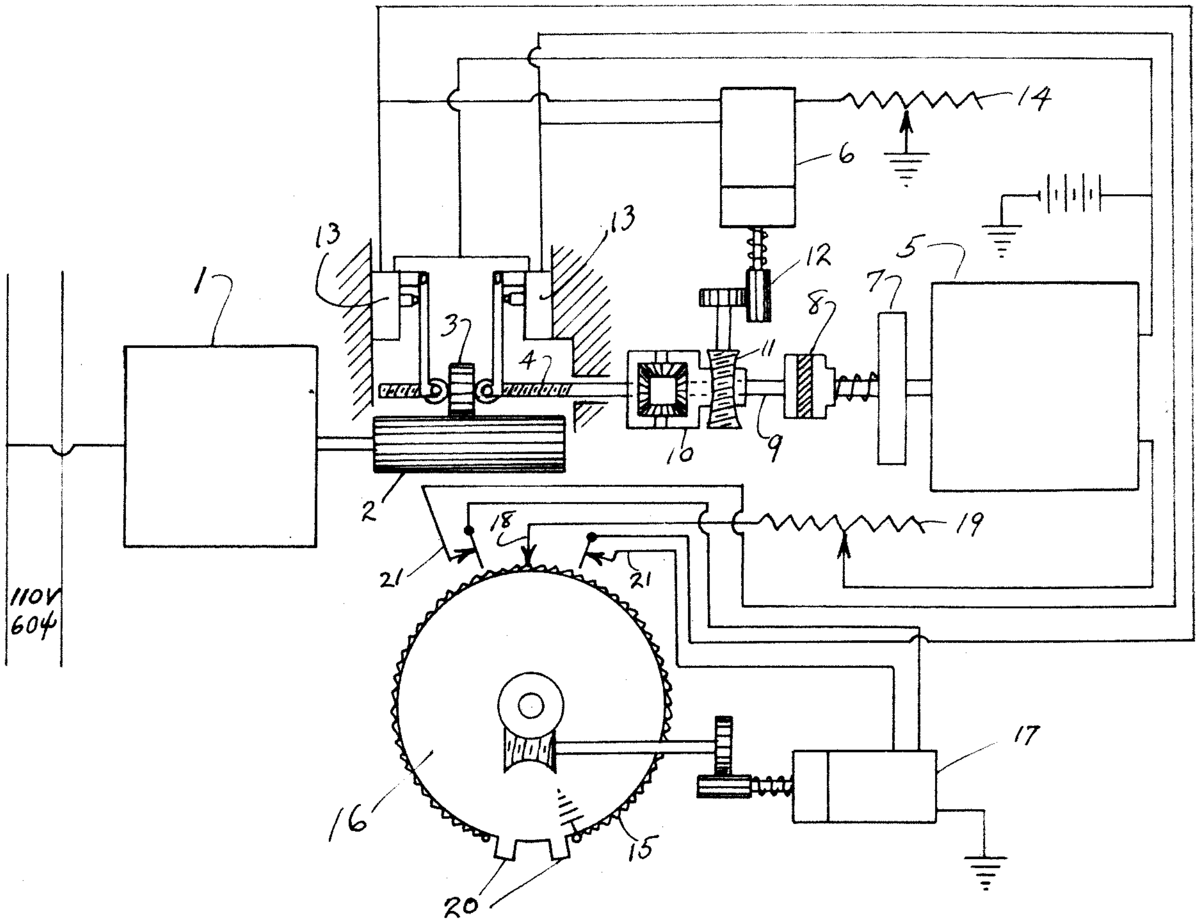

FIG. 2.

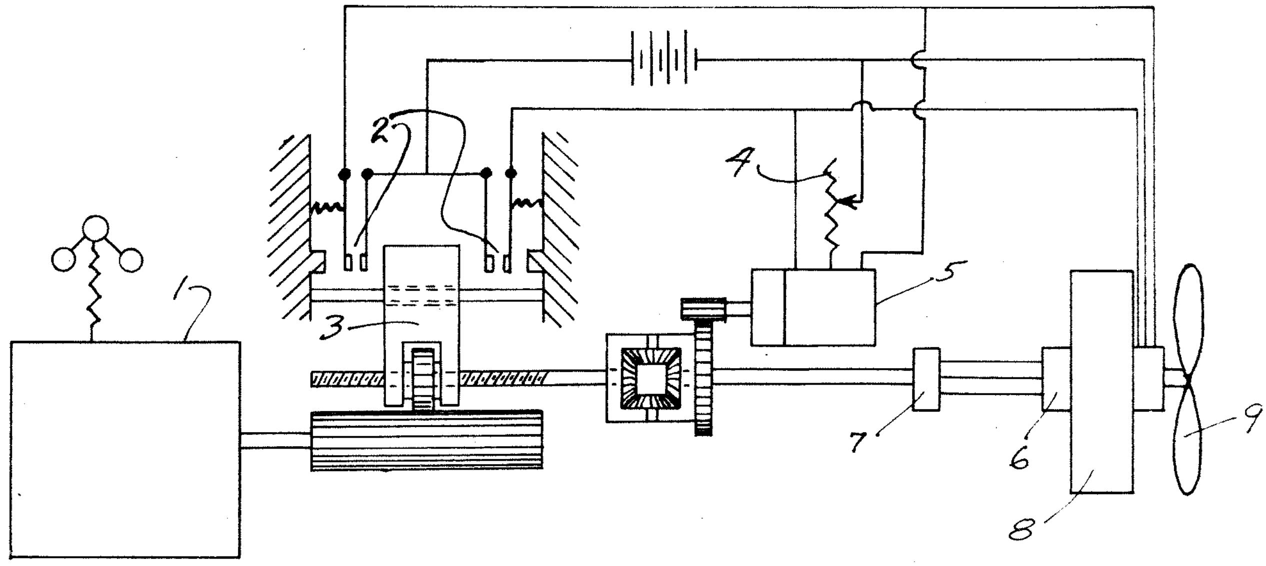

FIG. 3.

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Part II

Effect of Variable Engine Reduction Gearing on Aircraft Performance

DISCUSSION OF TWO SPECIALIZED AIRCRAFT PROPELLER PROBLEMS

Part II

Effect of Variable Engine Reduction Gearing on Aircraft Performance

Summary

The demand for improved performance in aircraft has led through the years to the development of more efficient propulsive systems, starting with the fixed pitch propeller directly driven from the engine and progressing to the modern geared constant speed variable pitch propeller. This development and the reasons for it are briefly described. The continued increase in performance leads to the two speed reduction gear and finally to the continuously variable reduction gear combined with the constant speed variable pitch propeller. The possible advantages of such an installation and the reasons for these advantages are described. Two examples of modern military airplanes are used to illustrate in detail the gains in performance that may be obtained. The extension to probable developments in airplanes to be built in the near future is considered. Mechanical difficulties and control problems are briefly discussed.

INTRODUCTION AND RESUME OF PROPELLER DEVELOPMENT

From the time of the first airplanes to within the last decade the fixed pitch propeller directly driven from the engine was used by practically all aircraft and was taken as the most advantageous means available of transforming the power of the engine into thrust for propulsion of the airplane. As long as the maximum speeds of aircraft were limited to 120 to 140 miles per hour there was no great incentive for the development and use of more complicated propulsive systems, for it was felt, and rightly so, that the advantages to be obtained would not warrant the additional complexity, weight, and expense.

Within recent years increased performance demands led to the development and production of airplanes with top speeds of 200 to 250 miles per hour and designed for much higher wing loadings than had been used previously. At this point serious difficulties arose in the use of fixed pitch propellers on such aircraft. The pitch of the propeller was usually chosen for the maximum level flight speed at design altitude and in this condition the propeller was permitted to rotate at the maximum allowable engine rpm which corresponded to maximum engine brake horsepower. This led to rather high pitch settings. The larger airplanes of this period when equipped with fixed pitch propellers required such a long takeoff run that they could not be taken off fully loaded from the majority of existing airfields. The high pitch of the propeller did not permit full rated rpm so the full power of the engine could not be developed at a time when it was most needed. In addition the propeller blades, pitched for high speed at altitude, were partially stalled during the take-off run and initial climb. Under these conditions the take-off of heavily loaded fast aircraft became extremely critical. The pitch of the propeller did not allow maximum rpm during climbing flight and therefore the maximum power of the engine could not be developed. In addition, the propeller was not operating at maximum efficiency. This loss in rate of climb was of great importance in both military and commercial aircraft.

In range, a similar penalty was exacted for the use of the fixed pitch propeller. With a fixed pitch propeller operating at a given level flight speed only one value of the specific fuel consumption and of propeller efficiency was possible. The propeller efficiency was not maximum for a propeller designed for high speed and the fuel consumption was not the minimum, for the specific fuel consumption increases under the throttled conditions necessary in range with this type of propeller. The net result was lessened range.

Under these conditions, investigations into other propulsive possibilities were greatly accelerated and many alternate systems to the fixed pitch propeller were considered. The most important of these possibilities were as follows:

1. Fixed pitch propeller with two speed reduction gear.
2. Fixed pitch propeller with variable speed reduction gear.
3. Two position variable pitch propeller with fixed reduction gear.
4. Two position variable pitch propeller with two speed reduction gear.
5. Continuously variable pitch propeller, manually controlled, with fixed reduction gear.
6. Constant speed variable pitch propeller with fixed reduction gear.
7. Variable pitch propeller with variable diameter.
8. Constant speed variable pitch propeller with two speed reduction gear.
9. Constant speed variable pitch propeller with infinitely variable reduction gear.

The considerations involving each of these propositions from the standpoint of application to aircraft operating in the medium speed range are now briefly discussed. This discussion is due in part to investigations carried out by Dr. H. C. Watts of the Airscrew Company, Limited,[2] whose paper is listed in the bibliography at the end of this section. This bibliography lists all material covered in reading for this problem.

When it became apparent that fixed pitch propellers were inadequate, a suggested solution, at least for the take-off problem, was the use of two speed or variable speed reduction gears between the engine and the fixed pitch propeller. This would allow the motor to "rev up" to maximum rpm while the propeller ran more slowly. This did increase the power available but only aggravated the stalling of the propeller blades. The increase in power does result in a small increase in thrust but also makes the blades stall even further so that the net increase is certainly not sufficient to show a clear advantage over the fixed pitch fixed gear. The additional weight and complexity of the two speed or variable speed reduction gear are not warranted. With the failure of any type of reduction gear to eliminate the stalling of the fixed pitch propeller on take-off it became obvious that the solution must involve changing the pitch of the propeller in flight. The first practical solution to this was the two pitch propeller with fixed gear. This propeller permits the use of a low pitch angle for take-off and climb and the shift to a high pitch angle for high speed. This device permits the engine to rotate at maximum rpm and thus to develop full power at take-off and, most important, the pitch is reduced so that the blades are removed almost completely from the stall region. This improves the propeller efficiency and satisfactory take-off and climb performance result. Most of the gains that the variable pitch propellers make over the fixed pitch propellers may be obtained with the two pitch propeller. However, when the high pitch is chosen for high speed at altitude it is not suitable for level flight at sea level as it will not permit sufficient rpm to produce full engine power and the low pitch is not suitable as it would overspeed the engine and also be operating at poor propeller efficiencies. For this reason,it may be seen that a two pitch propeller combined with a two speed reduction gear would furnish an improvement in performance. With this arrangement the engine and propeller speeds may be kept within the proper limits in the various regimes of flight and thus provide full engine power and high propulsive efficiencies under most conditions.

The probable weight of such an arrangement, the difficulties in synchronizing gears so that the shift may be made, the reluctance of the engine manufacturer to make the number of sets of reduction gears required for various installations, and lastly the perfection of the constant speed variable pitch propeller with its almost equivalent advantages resulted in the decision not to continue the development of the two pitch propeller equipped with two speed reduction gear.

A more flexible arrangement is obviously one providing a continuous series of pitch settings so that the pilot may choose the setting to suit the particular flight condition. This is provided in the variable pitch propeller with manual control such as the Curtiss, Lycoming-Smith, and the German V. D. M. types where the pitch setting of the propeller is changed at will by the pilot from the cockpit by means of electrical switches. The only difficulty with this arrangement is that it requires practically continuous adjustment by the pilot in order to maintain constant speed. This requirement becomes difficult during take-off, climbing flight, or maneuvering flight, particularly for single seater airplanes where the pilot is already fully occupied by the other complexities of flight control.

For this reason the constant speed variable pitch propeller was developed and is now almost universally used.

In this type the pilot sets a governor to the speed at which he desires the propeller to operate. The governor will then maintain constant speed by automatically varying the pitch angle to meet the load on the propeller. For the airplanes in the speed range considered this type of propeller is very satisfactory from the performance standpoint and is fairly simple in construction and has shown excellent dependability. By proper setting of his governor control the pilot is able to develop maximum power under all conditions and is operating close to maximum efficiency under most flight conditions. This latter is due in part to the fact that the efficiency curves for this propeller are fairly flat in the normal operating range and it requires a considerable departure from the conditions for maximum efficiency before the efficiency falls off seriously.

The ideal propeller is one that would travel on the envelope of the efficiency curves. That is at any speed it would operate at the maximum possible efficiency for that speed. This may be achieved in two ways. The first is a combination of a variable pitch and a variable diameter propeller and the second is to combine a variable pitch propeller with an infinitely variable reduction gear.

The tremendous structural and mechanical difficulties of the first method eliminate it from practical consideration . The second arrangement, or its near equivalent of a variable pitch propeller with two speed reduction gear, does have certain performance advantages over the constant speed variable pitch propeller with fixed gear. But, in airplanes designed for the speed range of 200 to 250 mph that we are considering, these advantages are not sufficient to warrant the extra weight, complexity, and expense.

From the preceding discussion it may be observed that choice of the constant speed variable pitch propeller as the means of propulsion of most of the airplanes flying today was quite logical. The following discussion concerns the optimum arrangement of propeller and reduction gear for higher flight velocities.

DISCUSSION

The present armament race between the nations of the world has greatly accelerated the demand for and the development of high performance airplanes. Maximum level flight speeds are now in the region of 400 miles per hour, ranges are over 4000 miles, rates of climb exceed 3000 feet per minute, and wing loadings have gone up to 50 pounds per square foot. All these values have been attained by aircraft now in production. Airplanes now being designed exceed these values considerably. Up to the present the constant speed variable pitch propeller has proven capable of covering the entire range of flight conditions of modern airplanes with satisfactory efficiency variation. However, in the very latest types of airplanes, there may be discerned an increasing inability of this type of propeller to maintain satisfactory performance over the extreme range of speed and power conditions now required. It seems possible that it will prove necessary in the near future to supplement the constant speed variable pitch propeller with a two speed or infinitely variable reduction gear in order to maintain propulsive efficiency over the flight range. The possibilities of improvement in the four basic divisions of performance, i.e., maximum speed, rate of climb, take-off, and range, must be considered in detail.

The present study was conducted on the basis of the use of a continuously variable reduction gear as opposed to the two speed reduction gear. This was done for two reasons. First, this arrangement shows the maximum advantages to be obtained by varying the reduction gearing between a constant speed variable pitch propeller and the engine. Second, the use of a two speed reduction gear necessitates the manufacture of a different set of two gears for each particular airplane-engine-propeller combination and creates a considerable manufacturing problem. This latter reason will probably lead to the use of a continuously variable gear which could be used in any installation . Thus, in the ensuing discussion the continuously variable gear will be considered although the two speed gear possesses most of its performance advantages.

The propellers of high speed aircraft, with almost no exceptions, are chosen for best efficiency and maximum speed in level flight at altitude. This means that the propeller diameter and the reduction gear ratio are chosen for this condition. Obviously, we can accomplish no improvement at the design altitude in maximum speed by adding a variable reduction gear. At other altitudes almost the same situation exists through the effect of tip speed. The propeller is operating in the high V/nD region and to obtain higher efficiencies the rpm of the propeller must be increased so as to get a lower value of V/nD. When this is done the propeller exceeds the critical tip speed and the loss of efficiency approximately counterbalances any gain from the overspeeding. It does not seem likely that any airplane with a propeller chosen for high speed at altitude can obtain gains of more than a few miles per hour in high speed at altitude. These gains will not be sufficient to warrant by themselves the use of a variable reduction gear. This opinion is substantiated by Mr. Frank Caldwell who has previously investigated this possibility.[8]

In climbing flight it appears that some improvement in propeller efficiency might be achieved and the rate of climb improved. The propeller is usually not operating at maximum efficiency and improvement may be had. However, the factor of tip speed enters here to prevent any considerable amount of overspeeding. If the climbing is done in the region of .4 - .6 of maximum speed the propeller efficiency is already near the maximum for that region and improvements in propeller efficiency of up to 5% are all that may be expected even if tip speed losses do not enter. Thus, we may not expect any phenomenal improvements in rate of climb by use of variable reduction gears. It should be remembered that velocity varies as the cube root of the propeller efficiency thus a gain or loss of three per cent propulsive efficiency only represents ± one per cent in velocity.

The propeller of a high speed airplane operates at very high pitch angles of the order of 50 to 55° at the maximum speed condition. When the propeller is turned at maximum revolutions in take-off the blade angles are still very high being about 25°. This leads to very poor propeller efficiencies in the take-off range. If we introduce the variable reduction gear we may overspeed the propeller and reduce the blade angle. By this procedure we may improve the propeller efficiency and the thrust by a considerable amount. The limit to the overspeeding, as always, being provided by the tip speed which determines the point at which it is no longer advantageous to overspeed. For modern high speed airplanes we might expect reductions in take-off distance of from 5 to 10%. For future airplanes of advanced high speeds even greater improvements should result. Since the take-off of high speed airplanes is critical, this improvement is an important factor in the case for variable reduction gears.

In the calculation of the maximum range possible for an airplane the established method is to determine the power and speed conditions such that the value of the propulsive efficiency divided by the specific fuel consumption is a maximum. For range only about 40 to 50% of rated power is used. Best engine efficiency for these powers is obtained with about 50% of normal rpm but this rpm will cause the propeller to operate at values of V/nD higher than those for maximum propulsive efficiency. To improve propulsive efficiency the propeller must be operated at higher rpms but these rpms reduce the engines' efficiency and increase the specific fuel consumption. Therefore, in the conventional airplane we compromise and define our conditions for maximum range as mentioned above by the maximum value of (η/c). However, with the use of the continuously variable reduction gear we may choose our propeller speed independently of the engine speed. Therefore, we may operate our engine at the speed corresponding to minimum specific fuel consumption, and operate the propeller at conditions corresponding to maximum propeller efficiency. In this way we obtain the maximum range possible with a given airplane. In the case of a pursuit it is not likely that this improvement will be of great interest due to the prime importance attached to the other factors of performance, but in a very long range airplane any appreciable improvement makes the installation of the variable gear not only advantageous but a necessity.

To summarize this discussion, slight or no improvement may be expected in maximum speed and in rate of climb, but appreciable and important improvements in take-off and range may be anticipated in the application of the continuously variable gear to modern high speed aircraft.

Examples showing the results to be obtained with two production military airplanes are now presented.

Example I

High Speed Military Pursuit Airplane

This example deals with a modern high speed pursuit airplane of a type now in production. It represents one of the latest developments in single seat pursuits now in use. The constants of the aircraft are as follows:

Airplane

Normal Gross Weight = 7810 pounds
(includes 105 gallons of fuel and 7.5 gallons oil)
Wing Area = 233.42 squarefeet
Wing Span = 37.025 feet
Aspect Ratio = 5.88
Airplane Efficiency Factor = 0.801

Propeller

Curtiss 614, 3 blades, Clark Y section, $(h/b)_{.75} = 0.085$

Diameter = 10.5 feet, Gear ratio = 0.500

The propeller was chosen for high speed at 16,500 foot altitude.

The propeller chart used was for a three-bladed #5868-9 propeller with spinner and a liquid cooled engine nacelle.

Engine

The engine used is the Allison Model F3R. All engine performance data was taken from data furnished by the Allison Company.

Ratings are as follows:

Take-off: 1150 B.H.P. at 3000 rpm at sea level.

High Speed: 1150 B.H.P. at 3000 rpm at 16,500 feet.

Specific Fuel Consumption = .452 at 400 B.H.P. at 1600rpm (At conditions for maximum range) at 10,000 feet

Parasite Drag

High Speed, Range, and Climb $C_{D_P} = 0.0145$

Take-off $C_{D_P} = 0.0385$

Tip Speed Corrections

Effective tip speed of the propeller was determined by means of Fig. I of Appendix II which is taken from the Hamilton Standard Propeller Manual.[5] This effective tip speed was used in Fig. 2 of Appendix II to determine the loss in propeller efficiency. Fig. 2 is taken from the Curtiss Propeller Performance Handbook.[7]

Calculation Procedure and Results for Example I

The detailed steps in the calculations and the formulas used are given on pages(90-96) of Appendix II. In this section only the general scheme of calculation will be presented.

The power required versus velocity curves of the airplane were computed for altitudes of sea level, 5000 feet, 10,000 feet, and 16,500 feet. The curve for each altitude was plotted on a separate sheet. At each altitude the power available versus velocity curves for various gear ratios were determined and plotted. The intersection of each of the power available curves with the power required curve gave the maximum level flight velocity for that gear ratio. At any velocity the difference in ordinate between the power available curves and the power required curve gave the excess thrust horsepower from which rate of climbs were computed. A typical plot showing this method is given in Fig. 3.

The results show that no improvement is possible in maximum level flight velocity at sea level and that small improvements ranging up to three or four miles per hour can be made at altitude. In maximum rate of climb no improvement was possible at any altitude. The rates of climb at speeds less than that of maximum climb could be improved up to 6% and at speeds greater than maximum climb improvements up to 10% were noticed. However, as stated above, the maximum rate of climb was always achieved with the original airplane.

In the calculation of take-off a short approximate method was used rather than the exact step by step integration method in order to reduce the length of calculation. This method, which is given by E. P. Hartman in T.N. 557,[9] calculates the take-off run by computation of the thrust and resistance of the airplane at one representative velocity during the take-off run. This method has been found to have an absolute accuracy of about ± 2% and for the present purpose of comparison of take-off distances for various gear ratios it is adequate. The take-off distances for gear ratios varying from 0.333 to 0.667 were calculated and are plotted in Figure 4 in Appendix II. This figure shows the shortest take-off distance, equal to 95.4% of the original distance, to be accomplished at a gear ratio of .533.

The conditions for maximum range of the original airplane were known. The same engine power and rpm but with varying propeller rpms constituted the other cases calculated. The engine power and rpm were held constant as they already represented the condition of minimum specific fuel consumption and no advantage could be obtained by varying them. The various ranges were calculated by means of an approximate range formula which is adequate for purposes of comparison. The maximum range obtained was five per cent greater than the maximum range of the original airplane. This occurred at a gear ratio of 0.875.

Discussion of Example I

As the choice of the propeller was for high speed, the inappreciable gains in maximum level flight velocity were anticipated. However, it was expected that the maximum rate of climb could be bettered by at least several per cent. The apparent reason why this did not occur is that in the original airplane at the speed for maximum climb the propeller was working close to the maximum efficiency. Any attempts to obtain a better propulsive efficiency by increasing the propeller rpm were negated by tip speed losses. The reduction in take-off distance of approximately five per cent is of primary importance. Maintaining the original take-off distance a four per cent greater gross weight can be used. This additional weight could be in ammunition, bombs, or fuel. If it were in fuel, then 50 % more fuel could be carried because the original fuel load was only 8% of the total. This makes it possible to extend the maximum range about 50%, which combined with the increase of 5% from the use of the continuously variable gear gives a maximum range approximately 55% greater than that of the original airplane. The gear ratio to cover all the flight conditions would have to vary from 0.500 to 0.875.

The advisability of installation of the continuously variable gear on this airplane is problematical. The advantages in high speed and climb do not warrant the adoption. The improvement in range by use of the continuously variable gear plus overloading with fuel and keeping the take-off distance constant seems of considerable importance because this increase in range would enable this short range pursuit to be used as a medium range convoy fighter. It must be noted, however, that this analysis did <u>not</u> penalize the airplane with additional weight due to the weight of the continuously variable gear as no accurate estimate seemed possible. In an airplane of this size the weight of the variable gear would be an appreciable percentage and would reduce this gain in range considerably. The decision as to whether this improvement in range, which is a secondary factor in pursuit performance, would warrant the adoption of the continuously variable gear must be based on the weight of such a gear and its attendant controls, and therefore must pend actual production of the gear.

It is noted that 50% of the 55% improvement in range is due to improved take-off with the .533 gear while only 5% gain is obtained at maximum cruise with the .875 gear ratio. It is apparent that for this airplane a two-speed reduction gear with ratios of .5 and .533 would be desired over the continuously variable gear from .500 to .875 unless the latter were a standard reduction gearing which added no weight nor loss in reliability over the two-speed gearing.

Example II

Long Range Four Engine Bomber

This example deals with a modern long range bomber of a type now in production. It is the latest four engine type to be put into service. The constants of the aircraft are as follows:

Airplane

Normal Gross Weight = 46,000 pounds

(includes 1800 gallons of fuel)

Wing Area = 1048.0 square feet

Wing Span = 110.0 feet

Aspect Ratio = 11.55

Airplane Efficiency Factor = 0.853

Propeller

Hamilton Standard 6153A-12, 3 blades, $(h/b)_{.75} = 0.0735$

Diameter = 12.0 feet, Gear ratio = 0.500

The propeller was chosen for high speed at the 15,000 foot altitude.

The propeller chart used was for a three-bladed #5868-9 with radial engine nacelle.

Engine

The four engines used are the Pratt and Whitney Twin Wasps R-1830 S3C4-G. All engine performance data was taken from data furnished by the Pratt and Whitney Engine Company.

Ratings are as follows:

Take-off: 1200 B.H.P. at 2700 rpm at sea level.

High Speed: 1100 B.H.P. at 2550 rpm at 6100 feet.

High Speed: 1000 B.H.P. at 2700 rpm at 1500 feet.

Specific Fuel Consumption = 0.4385 at 500 HP at 1600 rpm

(At conditions for maximum range) at 15,000 feet

Parasite Drag

High Speed, Range, and Climb $C_{D_P} = 0.0280$

Take-off $C_{D_P} = 0.0390$

Tip Speed Corrections

The same method is used as explained in Example I.

Calculation Procedure and Results for Example II

The calculation procedure used to compute maximum velocity, rate of climb, and take-off is exactly equivalent to the procedure of Example 1. In range the conditions for maximum range of this original airplane were not the conditions for minimum specific fuel consumption. Therefore, in calculating the cases for the continuously variable reduction gear the conditions of minimum fuel consumption were assumed for the engine and then the propeller rpm was varied as in Example I.

The results show that no appreciable improvement in maximum level flight velocity is possible at sea level or at altitude. In maximum rate of climb no improvement was possible at any altitude.

The variance of take-off distance with gear ratio is shown in Figure 5. The shortest take-off distance obtained was 93.5% of the standard distance and occurred at a gear ratio of 0.537.

The maximum range possible was found to be 1.05 as great as the maximum range of the original airplane. This occurred at a gear ratio of 0.656.

Discussion of Example II

The propeller of this example was chosen for high speed so the lack of improvement in this branch of performance was expected. The inability to improve maximum rate of climb is due to the same reasoning as in Example I. The reduction in take-off distance assumes considerable importance in this case. If, as before, the take-off distance is kept constant and the airplane overloaded with fuel, the total increase in range resulting from the overload and from the use of the continuously variable gear amounts to approximately 25%. In a long range bomber of this type, this would be of great importance. It would appear that if the weight of the continuously variable gear were not excessive, the use of the gear would be of considerable advantage and warrant its adoption. It is noted that no allowance has been made in these two examples for added structural weight for tankage to accommodate the overload in gasoline. Nor has allowance been made for the decrease in structural load factors that would be imposed during take-off and cruising until the overload of fuel were consumed. It was the purpose of this study merely to evaluate the absolute percentage improvement possible. Each individual airplane would have to be carefully analyzed to determine what net gains could be obtained by the use of two or continuously variable gearing.

MECHANICAL DIFFICULTIES AND CONTROL PROBLEMS

It appears that variable reduction gears will first appear in the two-speed types using optimum gear ratios for a particular airplane-engine-propeller combination. The problems of effecting gear shift at high power outputs are difficult, but existing methods used in two-speed supercharger drives present several combined mechanical and hydraulic methods or solutions to these problems. Propeller governing and synchronization methods should be no different than those used at present. Because of the unlimited number of gear ratios that will be needed it appears safe to predict that continuously variable reduction gears will be used in the future which will possess a wide enough range to cover all desirable ratios. Caldwell[3] discusses possible means of control of the continuously variable gear to limit both propeller speed and engine speed to whatever arbitrary maximums are necessary. Chilton[13] also thoroughly discusses the problems associated with the development, manufacture and control of variable reduction gears.

There is a positive displacement type of hydraulic remote drive being developed for military aircraft powers. This drive is about 95% efficient over the entire operating range because it is positive displacement. It provides a continuously variable reduction drive between any desired limits between the engine and propeller permitting both to be operated at their maximum efficiency speeds for any given flight condition. One of the secondary objects of this study was to determine the rpm limits for such a reduction drive. The results from study of the pursuit and long range bombardment examples above presented should quite accurately indicate the general range which may be expected to be needed. Detailed discussion of the numerous possible control methods for such a drive to safely limit the propeller and engine rpms and to provide rpm and torque synchronization is beyond the scope of this paper. It will suffice to say that existing automatic synchronization methods combined with torque and pitch indicators furnish several means of automatic control to limit the operational pilot controls to a minimum. The conclusions listed below present the results of this study to determine the required gear reduction limits.

CONCLUSION

The use of the continuously variable reduction gear on the latest types of airplanes seems to depend on the successful development and production of this gear in a compact unit, without excessive weight, and with adequate controls, as evidenced by the examples the weight and complexity must be balanced against the apparent aerodynamical advantages. In the airplanes that will be built in the near future, we may expect speeds up to 500 miles per hour at altitudes up to 30,000 feet. Wing loadings will probably attain 75 pounds per square foot and ranges will be lengthened to exceed 5,000 miles. It is felt that in airplanes subject to these performance requirements the constant speed propeller with fixed reduction gear will become increasingly unable to satisfactorily cover the range of flight conditions. Under these conditions the use of the two-speed reduction gear or the superior system, from the engine manufacturers standardization and airplane manufacturers performance standpoints, of a continuously variable reduction gear in combination with the constant speed propeller will be required.

As mentioned previously, their study was also to determine the probable necessary range of gear ratios for most types of aircraft. As the examples varied from a pursuit to a long range heavy bomber they should cover the range. They showed that a range of from 0.450 to 0.875 would be needed for present day airplanes. As the gear ratios depend on both the propeller diameter and engine rpm characteristics, it appears that for future airplanes a range from about .333 to .900 would be desired. This wide range would no doubt prove too inefficient as regards weight and reliability. It is suggested that a range from .333 to .677 would prove practicable and would cover most of the desirable range.

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APPENDIX II

Details of Performance Calculations

I. High Speed and Climb

A. Calculation of Power Required Curves

Various values of velocity were assumed ranging from 75 to 400 miles per hour. For each velocity the corresponding value of the lift coefficient, C_L, was calculated by the following:

$$C_L = \frac{2L}{\rho_0 V^2 S}$$

where L = lift = gross weight of airplane, pounds

ρ_0 = density of air at sea level, slugs per cubic foot

V = forward velocity, feet per second

S = wing area, square feet

For each value of the lift coefficient the corresponding value of the induced drag was found by:

$$C_{D_i} = \frac{C_L^{\,2}}{\pi AR_e}$$

where AR_e = effective aspect ratio = aspect ratio times airplane efficiency factor

The total drag coefficient, C_D, was found by:

$$C_D = C_{D_P} + C_{D_i}$$

where C_{D_P} = parasite drag = constant

C_{D_i} = as above

From the drag coefficient the drag in pounds was obtained by:

$$D = C_D \frac{\rho_o}{2} V^2 S$$

where ρ_o, V, S = as before

From the drags the corresponding powers required for flight at each velocity were determined by:

$$HP_{required} = \frac{D\,V}{550}$$

at altitude the horsepowers required were found by:

$$HP_{altitude} = \frac{HP_{sea\ level}}{\sqrt{\rho/\rho_o}}$$

and the corresponding velocities at altitude by:

$$V_{altitude} = \frac{V_{sea\ level}}{\sqrt{\rho/\rho_o}}$$

where ρ = density of air at given altitude

B. Calculation of Power Available Curves

Various values of velocity were assumed ranging from 75 to 400 miles per hour. For each velocity the corresponding value of the propeller advance ratio, J. was calculated by the following:

$$J = \frac{88V}{N\ D}$$

where V = forward velocity, miles per hour

N = propeller revolutions per minute

D = propeller diameter, feet

The power coefficient, C_P, was found by:

$$C_P = \frac{5 \times 10^{10}\ bhp}{\sigma\ N^3\ D^5}$$

where N and D are as above

bhp = brake horsepower absorbed by propeller

σ = ratio of density of air at altitude to density at sea level = ρ/ρ_0

For each value of J and for the value of C_P a value of the propeller efficiency, η, was obtained from the propeller chart. The effective tip speed of the propeller was found from Figure 1 and the tip speed loss factor from Figure 2. This factor, F_T, was used to obtain the corrected efficiency by:

$$\eta_{corrected} = \eta_{chart} \times F_T$$

The corrected efficiencies multiplied by the brake horsepower gave the thrust horsepower available at each velocity.

This procedure was repeated at each altitude for a number of gear ratios.

C. Determination of High Speed and Climb

For each altitude the power required curve and the power available curves for various gear ratios were plotted as in the sample given in Figure 3. The intersection of the power required curve with the power available curve gave the maximum level flight velocity. The difference between the two curves at each velocity was the excess thrust horsepower and was used to determine the climb by:

$$\text{rate of climb (ft./min.)} = \frac{550 \times \text{Excess thrust power}}{\text{Gross weight}}$$

The maximum rate of climb was found by determining the maximum difference between the power available and power required curves as indicated in Figure 3.

II. Take-off

An approximate method given by Hartman in N.A.C.A. Technical Note No. 557 was used.

First the propeller thrust and total resistance of the airplane were calculated for <u>one representative velocity</u> equal to 0.707 times the take-off velocity, V_T.

The values of J and C_P were calculated from formulas given previously. These were used in the propeller chart to find the propeller efficiency which was corrected for tip speed losses as before. Then the thrust coefficient, C_T, was found by:

$$C_T = \frac{\eta C_P}{J}$$

where η , C_P, J, are as defined previously.

Then the thrust in pounds equaled

$$T = C_T \rho_o n^2 D^4$$

where C_T , ρ_o, n, D, are as defined previously.

The resistance was calculated from the following formula from Hartman:

$$R = uW - uC_L qS + qf + \frac{C_L^2 qS}{\pi A_e}$$

where u = coefficient of ground friction = 0.03

W = weight of airplane, pounds

C_L = lift coefficient

q = dynamic pressure, $\frac{1}{2}\rho_o V^2 \frac{\text{in pounds}}{\text{sq. ft.}}$

S = wing area, square feet

A_e = effective aspect ratio including ground effect

f = equivalent parasite area in square feet

The excess thrust at the velocity $0.707V_T$ was equal to the difference between the propeller thrust and the airplane resistance each calculated at this velocity.

$$T_e = T_{.707V_T} - R_{.707V_T}$$

Then the take-off distance in feet, S, was found from:

$$S = \frac{V_T^2 W}{64.4\ T_e}$$

where V_T, W, T_e, are as defined previously. This was repeated for numerous gear ratios. The results are given in Figures 4 and 5.

III. Range

From dimensional analysis the following approximate formula for range is developed.

$$R = \frac{V \times W_F}{C \times BHP}$$

where R = range in miles

V = average velocity in miles per hour

W_F = weight of fuel in pounds

C = specific fuel consumption in pounds per brake horsepower per hour

BHP = brake horsepower

For the cases of the various gear ratios C, BHP, and W_F were constant. The values of V were obtained from the calculation of new power available curves calculated as before but this time for the power conditions of range. The power available curve for each gear ratio combined with the power required curve of the airplane gave the cruising velocity for that gear ratio. These values were then inserted with the constant values of C, W_F, and BHP in the range formula to give the range for each gear ratio.

[redacted]

FIG. 1

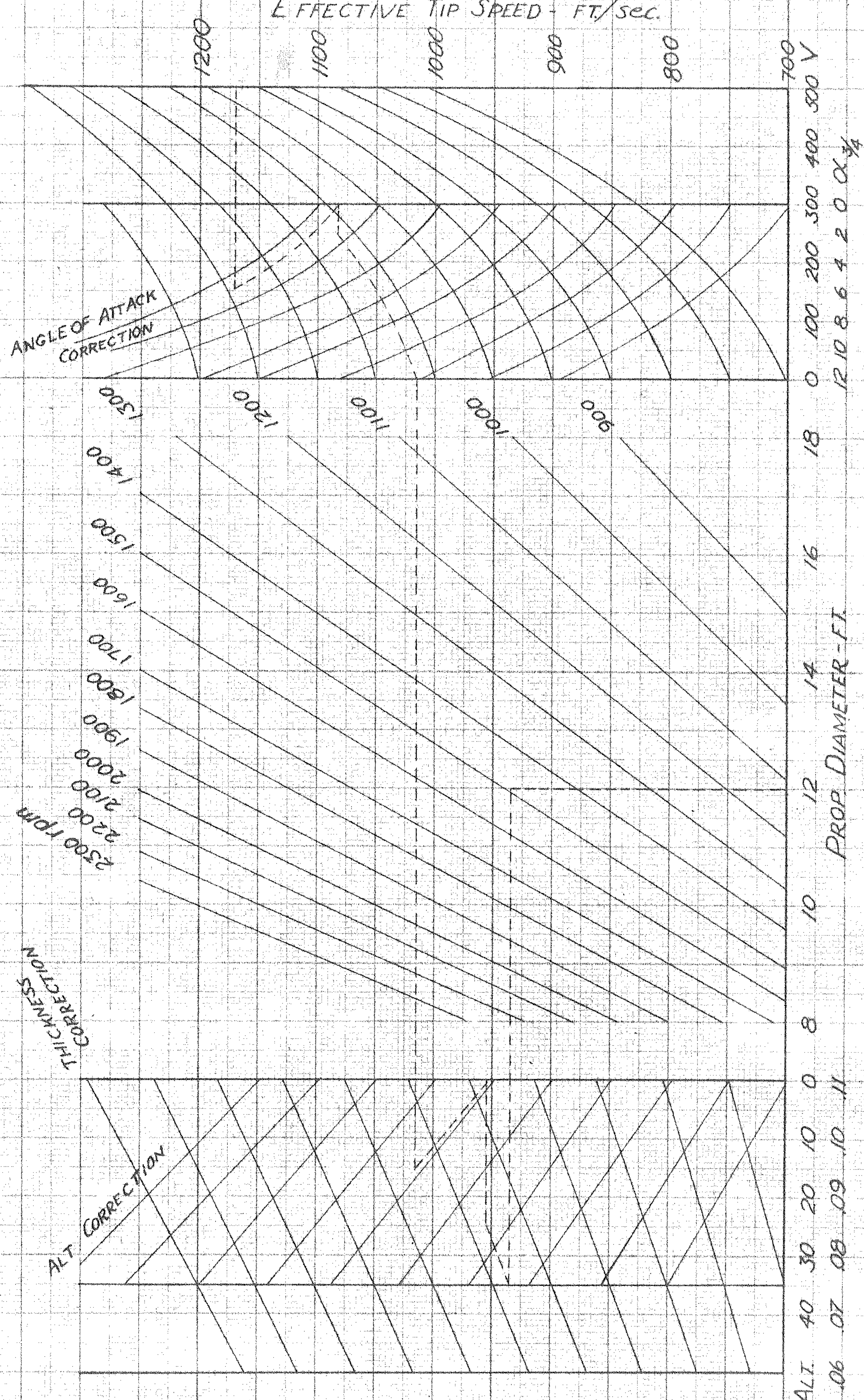
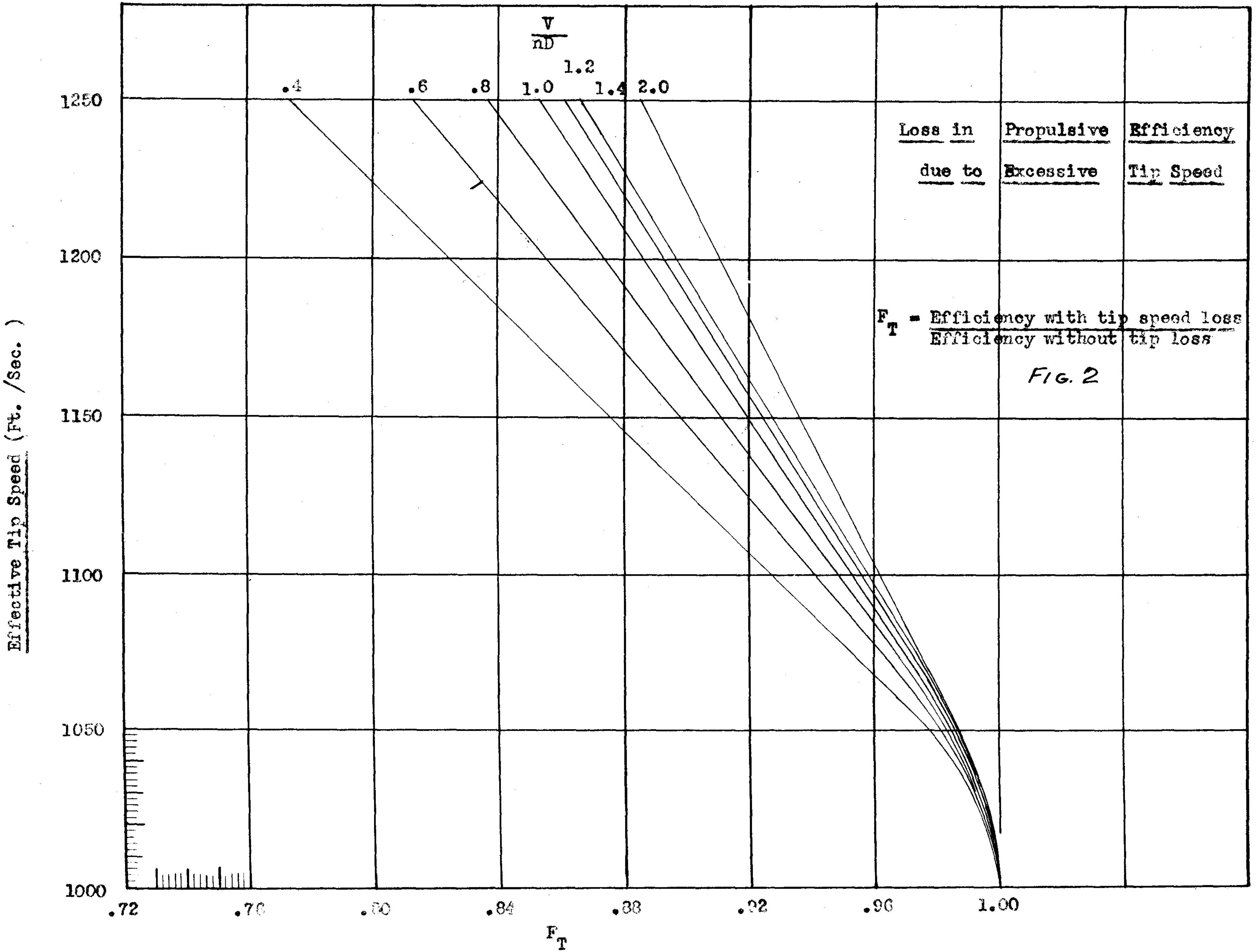


CHART FOR DETERMINING EFFECTIVE TIP SPEED
(FROM HAM. STAND. PROP. MANUAL, FIG. 21a, PAGE 83)

FIG. 2



Loss in Propulsive Efficiency due to Excessive Tip Speed

$F_T = \dfrac{\text{Efficiency with tip speed loss}}{\text{Efficiency without tip loss}}$

FIG. 2

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FIG. 3

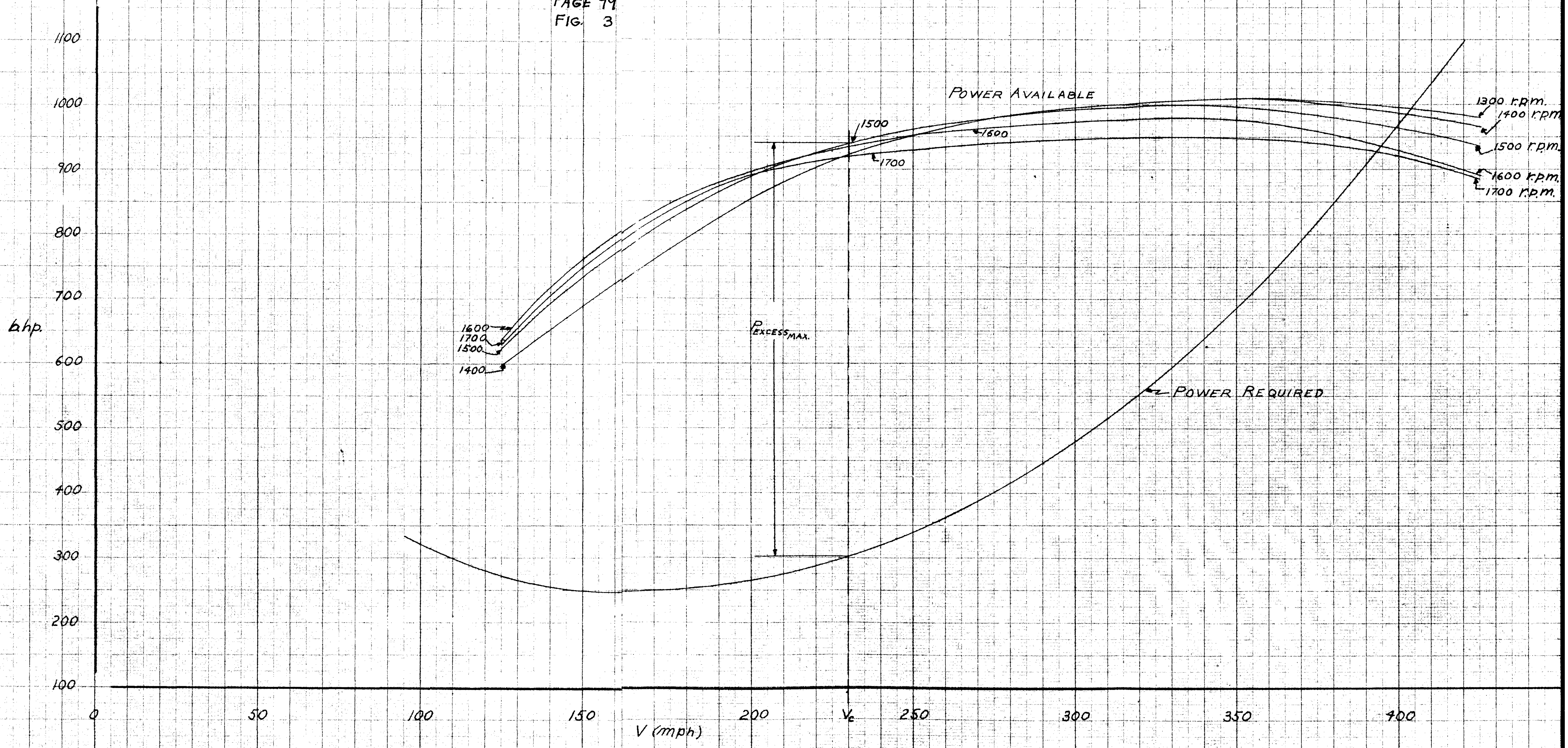

FIG. 3

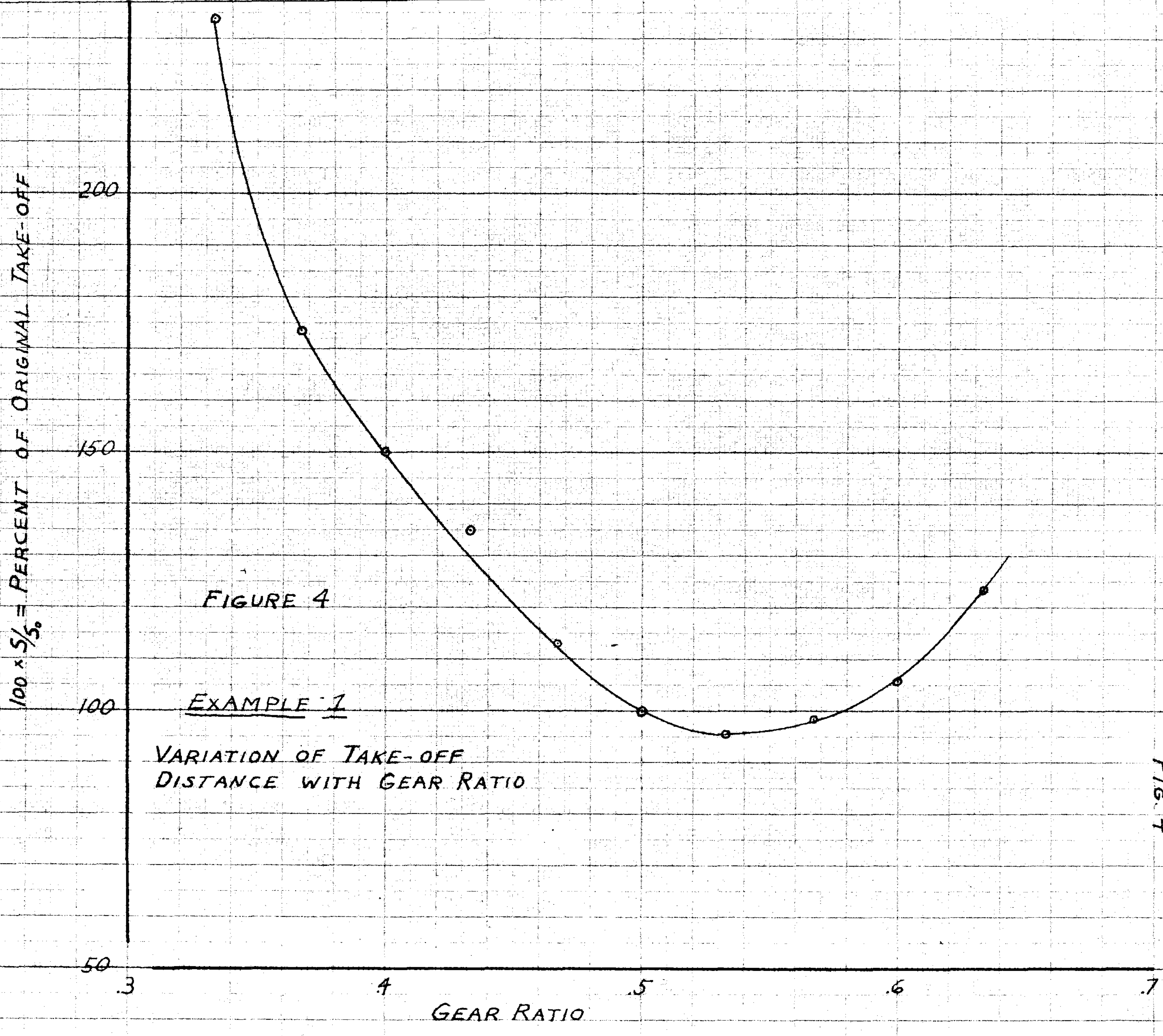

FIGURE 4

EXAMPLE 1

VARIATION OF TAKE-OFF
DISTANCE WITH GEAR RATIO

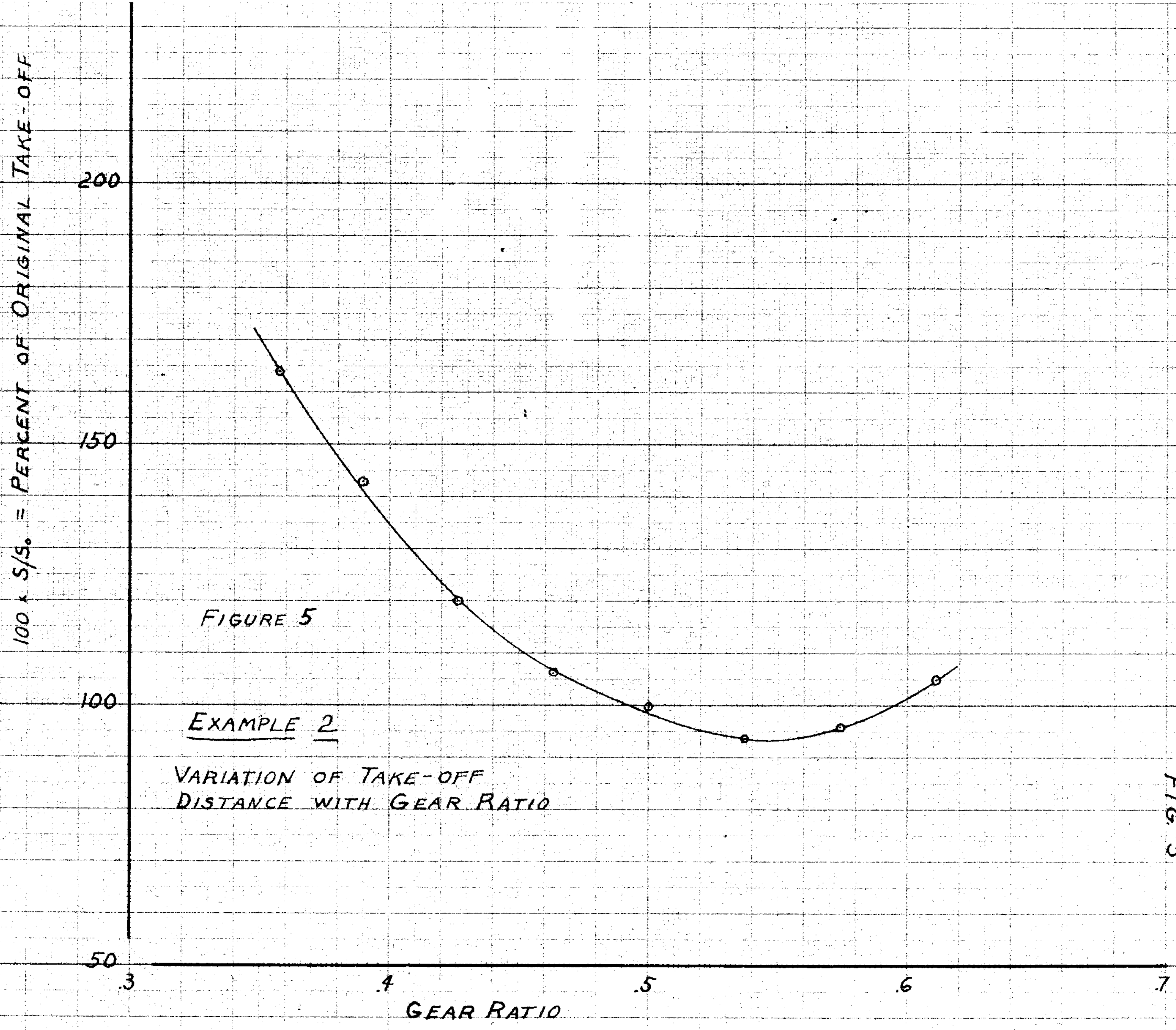

FIGURE 5

EXAMPLE 2

VARIATION OF TAKE-OFF
DISTANCE WITH GEAR RATIO