RESEARCH MEMORANDUM

INVESTIGATION OF POWER EXTRACTION CHARACTERISTICS AND BRAKING REQUIREMENTS OF A WINDMILLING TURBOJET ENGINE

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INVESTIGATION OF POWER EXTRACTION CHARACTERISTICS AND BRAKING

REQUIREMENTS OF A WINDMILLING TURBOJET ENGINE

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SUMMARY

An investigation was conducted in an altitude chamber at the NACA Lewis laboratory to determine the power extraction and braking characteristics of a windmilling single-spool axial-flow turbojet engine of the 5000-pound thrust class over a range of altitudes from 5000 to 50,000 feet and flight Mach numbers from 0.2 to 1.0. The maximum corrected power available for accessory drive with the engine investigated was found to increase from 3 horsepower at a flight Mach number of 0.2 to 178 horsepower at a flight Mach number of 1.0.

The constant applied torque required to stop the rotation of a windmilling engine in 0.2 minute at a simulated altitude of 40,000 feet was found to be 99 foot-pounds at a flight Mach number of 0.2 and 620 foot-pounds at a flight Mach number of 1.0. The torque required to stop the engine in 0.2 minute at a flight Mach number of 0.4 decreased from 280 foot-pounds to 160 foot-pounds as altitude was increased from 5000 to 50,000 feet.

INTRODUCTION

In modern aircraft there are many accessories such as the flight controls and landing-gear mechanisms that must be powered from the engine. In the event of engine flame-out or failure on a single-engine aircraft it is desirable to know the amount of power that would be available from the windmilling engine for these essential accessories. In the case of a multiengine aircraft, it is also desirable to prevent a damaged engine from windmilling. For example, a badly unbalanced engine, if allowed to continue its rotation, could cause failure of the supporting structure. It has been found in a previous investigation (reference 1) that the internal drag of a turbojet engine when allowed to windmill is greater than when rotation is prevented; a knowledge of the torque and time required to brake the engine rotor at various flight conditions is therefore also desirable.
An investigation was accordingly conducted in an altitude test chamber at the NACA Lewis laboratory to determine the power available for accessory drive with a windmilling engine over a range of altitudes from 5000 to 50,000 feet and flight Mach numbers from 0.2 to 1.0. This investigation also included a determination of the time to stop the engine from free windmilling speed when a constant braking torque was applied. A study of speed decay from engine speeds above free windmilling speed has been presented in reference 2 from an investigation of a similar engine.

Data are presented in tabular and graphical form showing the effects of altitude, flight Mach number, and engine speed on the extractable power and the effect of engine speed on the total pressure gradient through the engine. In addition, generalized data are presented permitting prediction of power-extraction data at flight conditions other than those simulated in this investigation. A method of predicting the time to brake the engine from free windmilling speeds with constant applied torque is also presented. Symbols used in this report and methods used in calculations are given in the appendixes A and B, respectively.

APPARATUS

A turbojet engine incorporating an eleven-stage axial-flow compressor and a single-stage turbine was used in this investigation. The polar moment of inertia of the rotating parts was 440 pound-feet². At sea-level static conditions and rated engine speed of 8000 rpm, the engine had an inlet-air flow of 91 pounds per second. The engine was installed in an altitude test chamber 10 feet in diameter and 60 feet long. A sketch of the installation, including pressure and temperature measuring stations, is shown in figure 1. A bulkhead with a labyrinth seal around the front of the engine was used to separate the inlet and exhaust sections of the chamber. The desired conditions of inlet total pressure and temperature and exhaust static pressure were established in the chamber by controlling the flow of air from the laboratory compressors through the engine to the laboratory exhaust system.

The power available for accessory drive was absorbed with a 50-horsepower direct-current dynamometer mounted in the inlet section of the chamber and coupled to the main shaft of the engine through the take-off supplied by the manufacturer. The rotor of this dynamometer had a polar moment of inertia of 56 pound-feet². In order to protect the dynamometer from harmful overheating and brush arc caused by the low pressures encountered at high altitudes, it was sealed within a separate chamber vented to the atmosphere and supplied with dry air from the laboratory air system. The dynamometer was mounted on trunion bearings and equipped with an electric strain gage to measure the torque and hence the power transmitted to it from the engine.
PROCEDURE

In order to evaluate its steady-state characteristics, the windmilling engine was operated over a range of altitudes from 5000 to 50,000 feet and flight Mach numbers from 0.2 to 1.0. At each condition, engine speed was decreased by increasing the torque applied by the dynamometer. In this manner, data were obtained showing the effects of altitude, flight Mach number, and engine speed on the power available for accessory drive, and the effect of engine speed on the total pressure gradient through the engine. Furthermore, it was of interest to know the relative work contributed by the compressor and turbine. Therefore, data were obtained of the extractable power available from the windmilling compressor when the turbine was removed from the engine. This brief investigation was conducted at several constant corrected windmilling speeds over a range of compressor pressure ratios, no attempt being made to determine Reynolds number effects.

In order to determine the time required to stop the engine from free windmilling speed, a nearly constant torque was applied to the engine with the dynamometer, and a photographic time history of applied torque and elapsed revolutions of the engine was taken. From these records, plots of elapsed revolutions versus time were made for each run. The slope of these curves plotted as a function of time gave curves of rpm versus time which provided a means of evaluating the time required to change the speed of the engine and dynamometer with a given torque at a given flight condition. To find the time required to stop the engine alone from free windmilling speed at a specified flight condition with a constant applied torque, a graphical computation method was used (see appendix C). The time required to change the speed of the engine and dynamometer combination for several of the flight conditions at which time histories were taken was computed to verify the methods of computation.

RESULTS AND DISCUSSION

Power Extraction

Extractable horsepower from windmilling engine. - The relation of extracted horsepower to windmilling engine speed is shown in figure 2. The extracted horsepower available at altitudes from 5000 to 50,000 feet and a flight Mach number of 0.4 is shown in figure 2(a). As altitude was increased, the horsepower available rapidly decreased because of the decrease in weight flow. Because the dynamometer imposed a windage and friction load even with no electrical load, it was necessary to
extrapolate the data to free windmilling engine speed. At a flight Mach number of 0.4, the free windmilling engine speed was 1800 rpm at an altitude of 5000 feet and decreased to 1420 rpm at 50,000 feet.

As torque was applied to the engine, the speed was reduced; maximum extracted horsepower was obtained at about one-half of free windmilling speed. These curves peak because horsepower is the product of torque and engine speed and, as mentioned previously, windmilling engine speed was decreased by increasing torque. The maximum power extracted at an altitude of 5000 feet was 14.2 horsepower as compared with only 1.9 horsepower at 50,000 feet.

The relation of extracted horsepower to windmilling engine speed for flight Mach numbers from 0.2 to 1.0 at an altitude of 40,000 feet is shown in figure 2(b). As flight Mach number was increased, there was an increase in the pressure drop across the engine and an increase in air flow whereby the horsepower available from the engine was increased. At a flight Mach number of 0.2, only 2.0 horsepower were available as compared to nearly 28 horsepower at a flight Mach number of 0.8.

In order to make the extracted horsepower data more useful, the data have been corrected to static sea-level pressure and temperature in figure 3. These data show a tendency to generalize for altitude but not for Mach number. At a given flight Mach number, the spread in extracted horsepower is primarily a result of changes in the inlet Reynolds number. The corrected power curve for a Mach number of 1.0 at 50,000 feet was extrapolated to zero. In order to permit the use of these data at intermediate flight Mach numbers, the maximum corrected power available for accessory drive at 40,000 feet is presented as a function of flight Mach number in figure 4 which is a cross plot of figure 3. Above a flight Mach number of 0.7 there was apparently a nearly linear increase in maximum corrected extracted horsepower with increasing flight Mach number.

The over-all efficiency of the windmilling engine is defined as the ratio of the measured extractable horsepower to the ideal horsepower available from adiabatic expansion of the measured weight flow. This over-all efficiency is presented in figure 5 as a function of corrected windmilling engine speed for various flight conditions. These data show a reduction in efficiency with increasing altitude at a constant flight Mach number, and the highest efficiency obtained in this investigation was 0.36 at a flight Mach number of 0.2 and an altitude of 5000 feet. As flight Mach number was increased at a constant altitude, peak efficiency showed a tendency to increase. This increase may be attributed to higher component efficiencies encountered as the components approach their design condition at higher speeds.
The scatter in these data at the low Mach numbers is primarily due to the inability to accurately measure the low-power output of the windmilling engine and the low ram-pressure ratios encountered at these flight conditions.

Total pressure gradient through a windmilling engine. - The effect of windmilling engine speed on the total pressure gradient throughout the engine is illustrated in figure 6. At the 0.8 flight Mach number conditions (figs. 6(a) and 6(b)), a continuous drop in total pressure through the engine occurred at all windmilling engine speeds. However, at rotative speeds near free windmilling speed and a flight Mach number of 1.0, there was a pressure rise across the compressor (station 2 to 3) as shown in figure 6(c) and 6(d). Unpublished data from a previous investigation of the pressure from stage to stage in a similar compressor has shown that under windmilling conditions the first stages produce a pressure rise and the last stages produce a pressure drop. The net result can be a compressor pressure ratio greater than unity at the high windmilling engine speeds.

Contribution of compressor to extracted horsepower. - In order to determine the contribution of the compressor to extracted horsepower, an investigation was conducted with the turbine removed. The variation of corrected compressor horsepower with corrected windmilling engine speed is shown in figure 7 for various compressor pressure ratios. These data were obtained with the turbine removed from the engine and no attempt was made to determine the Reynolds number effects. Negative horsepower on this curve was obtained with the dynamometer driving the compressor. A comparison of corrected extracted horsepower from the windmilling engine with the corrected power of the compressor is presented in figure 8. These values of compressor power (solid lines) were obtained from figure 7 with the compressor pressure ratio and corrected windmilling speed from windmilling engine data. The dashed lines of corrected extracted power from the windmilling engine were taken from figure 3 at 0.4 Mach number for all altitudes investigated and at 0.8 Mach number for 30,000 and 40,000 feet. At a flight Mach number of 0.4, the compressor power was nearly equal to the total power of the engine, which means that at this condition the turbine was contributing very little power. At a flight Mach number of 0.8, the compressor power increased as corrected windmilling speed was increased from 0 to 1400 rpm. Maximum extracted power from the engine was obtained at a corrected windmilling speed of about 1700 rpm, at which point the compressor was supplying approximately half of the power available from the windmilling engine. As windmilling speed was increased beyond this point, the rapid decrease in compressor power caused the turbine to supply all of the extractable power plus the power required to drive the compressor above a corrected windmilling speed of 2170 rpm.
Braking of the Windmilling Engine

The investigation of the braking requirements of the windmilling engine provided time-history data that included the torque required to decelerate both the engine rotor and the rotor of the dynamometer. Furthermore, it was found that when the dynamometer was used, constant torque during deceleration generally could not be maintained. Because of these two difficulties, it was impossible to use the experimental data directly to determine the time history of the braking of the windmilling engine alone at a constant torque. Therefore, a graphical method of computing deceleration time using experimental steady-state data was developed and is presented in appendix C.

The method is based on the two factors affecting the time required to change rotative speed: moment of inertia of the rotating mass and the steady-state windmilling torque of the engine. The steady-state windmilling torque of the engine must be obtained from an engine calibration such as that shown in figure 9. Figure 9(a) presents the torque-speed characteristics of this windmilling turbojet engine at a flight Mach number of 0.8 for altitudes from 5000 to 50,000 feet. At any constant engine speed, windmilling torque decreased with increasing altitude. For example, at 2400 rpm an increase in altitude from 30,000 to 50,000 feet decreased the windmilling torque from 67.5 to 19 foot pounds.

The effect of flight Mach number on the torque-speed characteristics of the windmilling engine is shown in figure 9(b) for a constant altitude of 40,000 feet. At a given speed, an increase in flight Mach number requires an increase in brake torque to maintain that speed. At 1200 rpm an increase in flight Mach number from 0.4 to 0.8 raised the torque requirement from 9 to 111 foot-pounds. The torque-speed characteristics were generalized for altitude by use of the conventional factors $\delta$ and $\theta$ to provide a means of computing time-to-stop for flight conditions other than those investigated (see fig. 10). The curves of figure 10 were extrapolated both to locked rotor torque and to free windmilling speed because these conditions were not obtainable with the dynamometer.

After the necessary torque-speed characteristics had been obtained, a check of the validity of the graphical method was made by use of experimentally determined speed-decay curves. In this verification, the moment of inertia used in the graphical method included the moment of inertia of the dynamometer. The computational method appeared reliable and the times required to stop the rotation of the engine alone for several applied torques and flight conditions were computed and are presented in figure 11. The applied torque is presented in figure 11(a) as a function of time-to-stop from free windmilling speed at a flight
Mach number of 0.4 over a range of altitudes from 5000 to 50,000 feet. This relation is also presented in figure 11(b) for an altitude of 40,000 feet over a range of flight Mach numbers from 0.2 to 1.0.

In order to provide a means of determining the torque required to stop the engine in shorter lengths of time than those presented in figures 11(a) and 11(b), these data were replotted on logarithmic coordinates and are presented in figures 11(c) and 11(d). The relation between applied torque and time-to-stop for a constant altitude of 40,000 feet (fig. 11(c)) shows that the applied torque required to stop the engine in 0.2 minute increased from 99 foot-pounds to 620 foot-pounds as flight Mach number was increased from 0.2 to 1.0. At a constant flight Mach number of 0.4 (fig. 11(d)), the applied torque required to stop the engine in 0.2 minute increased from 160 foot-pounds at an altitude of 50,000 feet to 290 foot-pounds at 5000 feet. The primary advantage of plotting braking data on logarithmic coordinates is that the computed data become asymptotic to a straight line (dashed) which relates applied torque and time-to-stop from free windmilling speed if only the inertia of the rotating masses is considered. Because it is physically impossible to stop the engine with an applied torque less than locked rotor torque, these curves also become asymptotic to a value equal to locked rotor torque. These relations provide a simple means of estimating the time-to-stop curve for any engine when the following three characteristics are known: the locked rotor torque and the free windmilling speed at the desired flight condition, and the polar moment of inertia of the engine. While locked rotor torque and free windmilling speed must be obtained experimentally, these quantities are more easily determined than the relation between steady-state windmilling torque and windmilling engine speed.

CONCLUDING REMARKS

From a steady-state power-extraction investigation of a single-spool axial-flow turbojet engine of the 5000-pound thrust class, it was found that the windmilling turbojet engine is an available but inefficient source of power for accessory drive. At a flight Mach number of 0.4, only 1.9 horsepower could be extracted at an altitude of 50,000 feet, whereas at 5000 feet, 14.2 horsepower were available for accessory drive. At an altitude of 40,000 feet, the maximum extractable power increased from about 1.0 to 20.7 horsepower at flight Mach numbers of 0.2 and 0.8, respectively. The maximum power available for accessory drive at flight conditions closely approximating landing conditions, 5000 feet and 0.2 flight Mach number, was found to be about 2.6 horsepower.
The steady-state windmilling power-extraction data were found to generalize rather well for altitude but not for flight Mach number variation. The maximum corrected horsepower obtainable from the turbojet engine used in this investigation increased from 1.5 to 178 horsepower as flight Mach number was raised from 0.2 to 1.0.

The maximum over-all efficiency of the windmilling engine as a power source was found to be about 0.36 for a flight Mach number of 0.2 at an altitude of 5000 feet and tended to decrease with increasing altitude at constant flight Mach number. As flight Mach number was increased at a constant altitude, efficiency showed a tendency to increase.

From an evaluation of the time required to stop the engine from free windmilling speed at a given flight condition with a constant applied torque, it was found that to stop the engine in 0.2 minute at an altitude of 40,000 feet required an increase in applied torque from 99 foot-pounds at 0.2 Mach number to 620 foot-pounds at a flight Mach number of 1.0. At a flight Mach number of 0.4, the applied torque required to stop the engine from free windmilling speed in 0.2 minute increased from 160 to 290 foot-pounds as altitude was decreased from 50,000 to 5000 feet. It is possible to estimate with reasonably good accuracy the time-to-stop curve for any engine if the locked rotor torque and free windmilling speed for the desired flight condition and the polar moment of inertia of the rotor are known.

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APPENDIX A

SYMBOLS

The following symbols are used in this report:

A  area, sq ft

$q_p$  specific heat of air at constant pressure = 0.24 Btu/lb-°F

$g$  gravitational constant = 32.2 ft/sec²

$h_{pa}$  extracted horsepower or horsepower available for accessory drive

$h_{pi}$  ideal horsepower available with isentropic expansion assumed

$I$  polar moment of inertia, lb-ft²

$J$  mechanical equivalent of heat, 778 ft-lb/Btu

$M$  flight Mach number

$N$  engine speed, rpm

$P$  total pressure, lb/sq ft abs

$p$  static pressure, lb/sq ft abs

$R$  gas constant

$Q_a$  constant applied torque for braking the engine, ft-lb

$Q_d$  decelerating torque, $Q_d = Q_a - Q_s$, ft-lb

$Q_s$  steady-state windmilling torque of the engine, ft-lb

$T$  total temperature, °R

$t$  time, min

$W_a$  air flow, lb/sec

$\gamma$  ratio of specific heats for air, 1.4

$\delta$  compressor-inlet total pressure divided by NACA standard sea-level static pressure of 2116 lb/sq ft
\( \eta \) over-all windmilling engine efficiency, \( \text{hp}_a / \text{hp}_I \)

\( \theta \) compressor-inlet total temperature divided by NACA standard sea-level static temperature, 519° R

Subscripts:
- \( f \) final conditions
- \( i \) initial conditions
- \( o \) ambient conditions
- \( v \) venturi throat
- \( c \) compressor inlet
- \( c \) compressor outlet
- \( t \) turbine inlet
- \( e \) exhaust-nozzle inlet
APPENDIX B

METHODS OF CALCULATION

Flight Mach number. - In the calculation of flight Mach number, complete ram pressure recovery at the engine inlet was assumed and the following formula was used:

\[ M = \sqrt{\frac{2}{\gamma-1} \left[ \frac{\gamma-1}{\gamma} \left( \frac{P_2}{P_0} \right)^\gamma - 1 \right]} \]  \hspace{1cm} (1)

Extracted horsepower. - The horsepower available for accessory drive was computed from the measured steady-state torque and engine speed.

\[ h_{Pa} = \frac{2\pi Q_s N}{33,000} \]  \hspace{1cm} (2)

Ideal horsepower and efficiency. - The ideal horsepower available was calculated from the isentropic relation:

\[ h_{P_{II}} = \frac{Jc_p T_2}{550} \left[ 1 - \left( \frac{P_0}{P_2} \right)^\gamma \right] W_a \]  \hspace{1cm} (3)

and the weight flow \( W_a \) from the relation:

\[ W_{a,1} = \frac{A_1 P_1}{\sqrt{RT}} \sqrt{2g \frac{\gamma}{\gamma-1} \left[ \left( \frac{P_1}{P_1} \right)^\gamma - 1 \right]} \left( \frac{P_1}{P_1} \right)^\gamma \]  \hspace{1cm} (4)

The over-all efficiency of the windmilling engine \( \eta \) is defined as:

\[ \eta = \frac{h_{Pa}}{h_{P_{II}}} \]  \hspace{1cm} (5)
APPENDIX C

GRAPHICAL METHOD FOR CALCULATING BRAKING REQUIREMENTS OF A WINDMILLING TURBOJET ENGINE

At a given flight condition and applied torque greater than locked rotor torque, there are two factors, moment of inertia and steady-state windmilling torque, which affect the time required to stop the engine. The moment of inertia of the system is related to decelerating torque, engine speed, and time by Newton's second law:

$$Q_d = -\frac{2\pi I}{g \times 3600} \frac{\Delta N}{\Delta t}$$  \hspace{1cm} (6)

where \(\Delta t = t_f - t_i\) is the time required to make the speed change \(\Delta N = N_f - N_i\) with a constant decelerating torque \(Q_d\) available to overcome the inertia forces of the rotating masses. However, the steady-state windmilling torque of the engine \(Q_s\) is a function of engine speed and acts in a direction opposing the applied torque \(Q_a\). Thus, equation (6) becomes:

$$Q_a - Q_s = -\frac{2\pi I}{g \times 3600} \frac{(N_f - N_i)}{(t_f - t_i)}$$  \hspace{1cm} (7)

A mathematical solution of this expression is impossible unless the equation of the steady-state windmilling torque-versus-engine-speed curve (similar to fig. 9) for the flight condition in question is known. However, a graphical solution is possible and is believed to be sufficiently accurate.

Arbitrary values were chosen for \(\Delta N\) over the engine-speed range from free windmilling speed to zero speed. An average steady-state windmilling torque \(Q_s\) was then obtained from a curve such as figure 9 each value of \(\Delta N\). For a constant applied torque \(Q_a\) a value of \(\Delta t\) was obtained from equation (7) for each \(\Delta N\). The sum of these values of \(\Delta t\) yields the time-to-stop from free windmilling speed at the given flight condition and applied torque.

The accuracy of the results obtained by this graphical solution will, of course, depend upon the number of speed increments used. Equation (7) was solved mathematically by writing equations for the steady-state windmilling torque-versus-speed characteristic of the engine and integrating \(\frac{1}{Q_d} dN\) for Mach numbers of 0.8 and 1.0 at
40,000 feet. From these equations, which were tedious to derive, it was found that the graphical method was accurate to within 2 percent when speed increments of 6 percent of free windmilling speed were used.

In order to compute the time required to brake the engine at flight conditions other than those included in this investigation, the uncorrected torque-speed characteristic of the engine can be obtained from the corrected torque-speed curves of figure 10.

REFERENCES


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Note: The table continues with more rows and columns, but the above are examples of the format and content.
Figure 1. - Schematic drawing of engine and dynamometer installation in altitude test chamber.
(a) Effect of altitude. Flight Mach number, 0.4.

Figure 2. - Extracted power from windmilling turbojet engine.
Figure 2. - Concluded. Extracted power from windmilling turbojet engine.

(b) Effect of flight Mach number. Altitude, 40,000 feet.
Figure 5. Generalization of windmilling power-extraction data.
Figure 4. - Effect of flight Mach number on maximum corrected horsepower extractable from windmilling turbojet engine. Altitude, 40,000 feet.
Figure 5. - Over-all efficiency of windmilling turbojet engine used as power source.
Figure 6. - Effect of windmilling engine speed on total pressure gradient through engine.
Figure 6. - Continued. Effect of windmilling engine speed on total pressure gradient through engine.

(c) Altitude, 30,000 feet; flight Mach number, 1.0.
(d) Altitude, 40,000 feet; flight Mach number, 1.0.

Figure 6. - Concluded. Effect of windmilling engine speed on total pressure gradient through engine.
Figure 7. - Variation of corrected compressor horsepower with corrected windmilling engine speed at various compressor pressure ratios.
Figure 8. - Comparison of corrected horsepower output from engine and compressor.
(a) Effect of altitude. Flight Mach number, 0.8.

Figure 9. - Steady-state torque as a function of windmilling engine speed.
Figure 9. - Concluded. Steady-state torque as a function of windmilling engine speed.
Figure 10. Corrected steady-state torque as a function of corrected windmilling engine speed.
Figure 11. - Variation of constant applied torque with time required to stop engine from free windmilling speed.
(c) Effect of flight Mach number. Altitude, 40,000 feet; logarithmic scale.

Figure 11. - Continued. Variation of constant applied torque with time required to stop engine from free windmilling speed.
(a) Effect of altitude. Flight Mach number, 0.4; logarithmic scale.

Figure 11. - Concluded. Variation of constant applied torque with time required to stop engine from free windmilling speed.