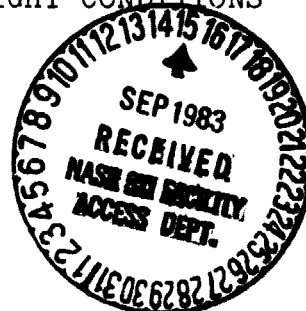# General Disclaimer

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WINDMILLING OF THE ROTOR OF A TURBOJET ENGINE WITH AN AXIAL-FLOW COMPRESSOR UNDER FLIGHT CONDITIONS

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16. Abstract

The concept of rotor windmilling is understood to mean rotation of the rotor caused solely by the energy of the air (not gas) streaming through the apertures between the blades (under conditions of power shut-off) under the action of dynamic pressure. The concept of windmilling is analyzed for an engine with an axial-flow compressor, showing that windmilling must be taken into account in such cases as in-flight reignition of the engine. A graph-analytic method for determining the range of windmilling is proposed.

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WINDMILLING OF THE ROTOR OF A TURBOJET ENGINE
WITH AN AXIAL-FLOW COMPRESSOR UNDER FLIGHT CONDITIONS

Jan Borgon

The article explains the concept of windmilling of the rotor /34*
unit of a turbojet engine. Examples of the occurrence of this
phenomenon and examples and calculation of windmilling ranges
using a graph-analytical method are presented.

The concept of windmilling is also known under different
names (for example, autorotation or autoturning). However, in
practice, the first term is used most frequently (i.e., wind-
milling). Therefore, the author will use this term in the re-
maining part of this article. Engineering encyclopedias do not
define the concept of windmilling of the rotor unit of a turbo-
jet engine. On the other hand, the concept of windmilling of the
rotor of a rotorcraft is defined as the rotation of the propelled
rotorcraft under the effect of oblique aerodynamic flow around it.

Using the definition of the last concept, in the part of the
article which follows, by the windmilling of the rotor unit of a
turbojet engine will be meant rotation of a rotor unit not driven
by combustion gases, acquiring motive power from the energy of the
air stream flowing through the apertures between the blades of the
engine. Thus, a condition for the occurrence of windmilling is
the flow of air streams through the apertures between the blades
of the engine after the latter was shut off. This flow exists
as a result of the dynamic pressure caused by the flight of the
aircraft, notwithstanding the fact that the engine was shut off.

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*Numbers in the margin indicate pagination in the foreign text.

Cases of Occurrence of Windmilling of the Rotor Unit of a Turbojet Engine

Windmilling of the rotor unit of a turbojet engine during flight of the aircraft always occurs after the engine was shut off (except in cases followed by wedging of rotors). During the flight of an aircraft the engine may:

1. be shut off spontaneously without or even in spite of the pilot's intention, which happens frequently during sudden movements of the engine control lever, during fast descent of the aircraft under the effect of a negative g-force, etc.;

2. be shut off intentionally by the pilot for the purpose of realizing a particular task (for example, landing training with shut-off engine, elimination of certain undesirable effects, such as stalling of engine or stalling of air intake, etc.).

The first case differs from the second by the instant at which the inflow of fuel is shut off. Although both in the first and second case, after the engine was shut off, the rotational speed of the rotor decreases rapidly to the stationary windmilling speed under the given conditions, in the first case, until the fuel inflow is shut off, the flow of air through the apertures between the blades of the turbine unit is accompanied by the flow of fuel.

This fact makes a difference as far as the engine is concerned, above all, because of the greater density of the fuel-air mixture compared with the density of air alone. During flow of fuel through apertures between the blades after the engine was shut off during the flight of the aircraft, different cooling conditions of hot parts prevail than those during the flow of air alone. Hence, other temperature gradients and other thermal stresses occur in the walls of elements. When evaporation of fuel does not occur in front of the turbine unit, the fuel-air mixture flowing through this unit cools at a very rapid rate the elements with which it makes contact, for example, the

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blades of the nozzle apparatus, the blades of the turbine rotor, the walls of the propulsion nozzle, or the walls of the afterburner chamber. In this case, the flame tubes of the combustion chamber are also cooled at a very fast rate, since essentially the injected fuel is evaporated.

Windmilling of Rotor of Turbojet Engine with an Axial-Flow Compressor

Both in the case of spontaneous as well as intentional engine shutoff, the fuel combustion process is stopped, which entails a breakdown in the normal operation of the engine. Stopping of the combustion process in any operating range of the engine causes a fast decrease in the rotational speed of the rotor to the so-called windmilling rotational speed. The windmilling rotational speed depends on the speed and the flight altitude of the aircraft (Figs. 1 and 2) and the characteristics of the units in a concrete type of turbojet engine.

Considering the problem of windmilling of the rotor of a turbojet engine, we can ask the following question: why does the rotor of this engine continue to rotate (although at a slower speed) after the engine was shut off during flight of the aircraft? Why does the rotor not begin to rotate in the direction opposite to that in normal operation? This phenomenon can be explained very generally as follows. /35

It is generally known that the air flowing through the engine acts on the blades of the compressor and turbine and conversely, the blades act on the air streams. As a result of this interaction, the rotor of a turbojet engine rotates properly during windmilling. This explanation, however, is very general and does not deal with the essentials of the problem. We will try to approach this problem differently.

The turbine of a turbojet engine under rotor windmilling conditions, similarly as during starting on ground, begins to
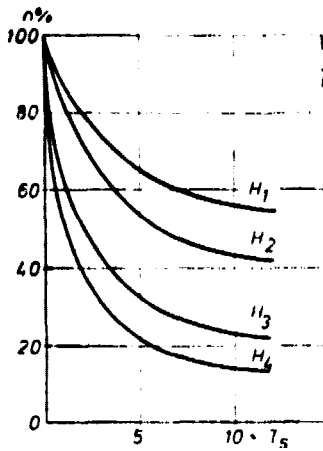
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Fig. 1. Graph of variation of rotary speed of rotor after engine was shut off during flight of aircraft at various altitudes:
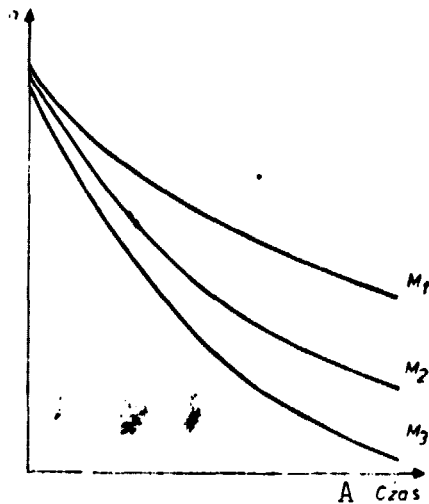$H_1 > H_2 > H_3 > H_4$

Fig. 2. Graph of variation of rotary speed of rotor after engine was shut off during flight of aircraft at various velocities:
$M_1 > M_2 > M_3$
Key: A = time

operate actively only when the pressure above it is adequate and a particular air mass flow exists. Until such conditions are created, the turbine cannot independently drive the rotor of the compressor, and at very low flight velocities may even act as a brake. In such cases, up to a particular instant, the compressor also contributes to driving the rotor, which, as is well known, under normal operating conditions of the engine acts entirely as a brake. How does this happen? In the windmilling range, at low flight velocities, the rotor of the compressor rotates essentially as a result of partially utilized pressure (and hence also energy) generated in front of the compressor and in the first stages of the compressor as a result of dynamic pressure.

Changes in the air pressure along the engine for various flight velocities are presented in Fig. 3. From the diagram it is evident that the air pressure at the outlet from the compressor at particular flight velocities and absence of combustion in the chambers is lower than at the intake, which indicates that the last stages of the compressor operate in the turbine range, since the pressure drop in the last stages of the compressor causes an increase in the rate of flow and thus

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a change in the angles of incidence of the streams α from normally
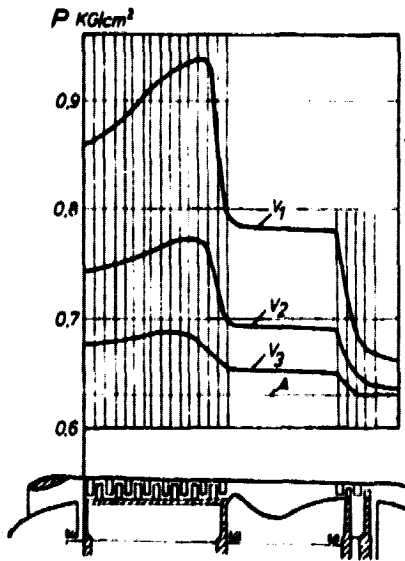positive values to negative values (Figs. 4 and 5).

Fig. 3. Graph of variation in
air pressure along engine in
windmilling range at various
flight velocities:
$V_1 > V_2 > V_3$; A is the line
corresponding to magnitude of
pressure in surrounding medium

During normal operation of a
compressor, in all stages of the
compressor during windmilling of
the rotor in the first stages of
the compressor, positive angles
of incidence of the streams α oc-
cur; hence, peripheral forces Pu
braking the rotation of the rotor
are generated on the blades
(Fig. 6).

In the case when negative
angles of incidence of the air
streams α occur (as is the case
at low flight velocities in the
windmilling range in the last
stages of the compressor), peri-
pheral forces Pu driving the rotor
unit of the engine are generated
on the blades (Fig. 7).

Calculation of windmilling ranges shows, however, that essen-
tially in the entire windmilling range, the compressor taps the
power generated by the turbine as a result of dynamic pressure.
The latter follows from the fact that, although at low flight
velocities the last stages of the compressor operating in the
turbine range may produce a certain amount of work, in the gen-
eral balance, as a result of low efficiency of compressor stages
operating in the turbine range, compressor work and friction
work are dominant in the first stages. An analysis of the curves
of the changes in air pressure along the engine for various flight
velocities (Fig. 3) allows one to draw the following theoretical
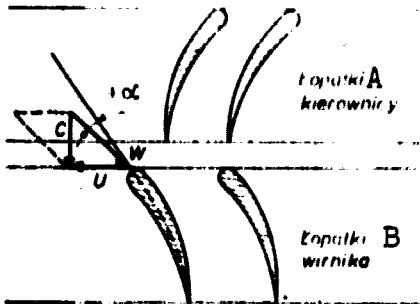conclusion: if, during windmilling of the rotor, compression of

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Fig. 4. Angles of incidence of
air streams in apertures between
blades of rotor during normal
operation of compressor: C = ab-
solute velocity, W = relative
velocity, U = peripheral velo-
city, and α = angle of incidence
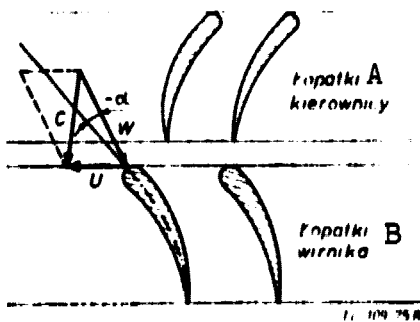KEY: A = vane blades
     B = rotor blades

Fig. 5. Angles of incidence of
air streams in apertures between
blades of rotor of compressor
operating in turbine range (same
notation as in Fig. 4)
Key: A = vane blades
     B = rotor blades

air occurred only in front of
the compressor, while only ex-
pansion occurred in the com-
pressor (which is possible at
very low flight velocities),
then one cannot exclude the
possibility that the compressor
may completely take over the
role played by the turbine.
However, with an increase in
the flight velocity the pres-
sure drop in the turbine in-
creases and hence, also its
contribution to driving the
rotor of the engine.

The curve in Fig. 8 indi-
cates that with increasing Mach
number, compression is the com-
pressor first decreases to a cer-
tain value, after which it in-
creases. From the instant com-
pression behind the compressor
begins to increase, the last
stages of the compressor no
longer operate in the turbine
range for all practical purposes.
The velocity of the air behind
the compressor (at the intake
of the combustion chamber)
varies according to the flight
Mach number. The velocity in
the windmilling range increases
until the flight Mach number at-
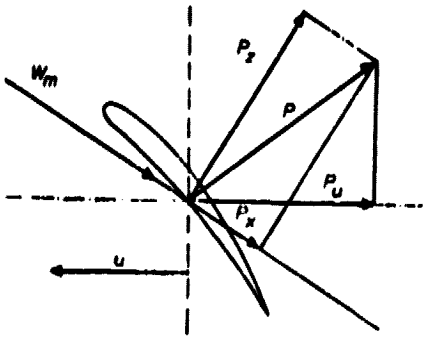tains a value at which critical

Fig. 6. Distribution of forces on blade profile of rotor of compressor at positive angle of incidence α; W_m = relative velocity vector equal to arithmetic mean of velocity vectors W_1 (at intake to aperture between blades of rotor of compressor) and W_2 (at outlet from aperture between blades of rotor of compressor); u = peripheral velocity; P = resultant aerodynamic force on blade profile, P_z = aerodynamic force of blade profile, P_x = blade profile drag, P_u = component peripheral force of blade profile

flow of the air through the nozzle apparatus of the first stage of the turbine occurs. From this instant (from this flight Mach number) the velocity of the air at the intake to the combustion chamber increases proportionally with the square root of the ram effect temperature of the inflowing air, i.e., it varies similarly to the velocity of sound. Critical flow in the nozzle apparatus of the turbine at low flight velocities occurs during windmilling in engines characterized by high compression.

Conclusions

Windmilling of the set of turbines of a turbojet engine is not a phenomenon occurring every day in aeronautical practice. Nevertheless, it is a phenomenon which should be taken into account in considering the efficiency of starting equipment and the possibility of restarting the engine under flight conditions. Successful or unsuccessful restarting of the engine during flight with a properly operating starting installation depends, above all, on the flight altitude and velocity, which have a direct effect on the rotational windmilling velocity of the rotor.

Analytical calculations of the windmilling range are difficult because of the nonuniform shapes of air streams in the compressor and turbine (secondary flows, flow separation zones, etc.) and the occurrence of subcritical air flows, essentially, along the entire engine (at low flight Mach numbers). Therefore, graph-analytical methods are used to calculate windmilling ranges while simultaneously taking advantage of experimentally obtained characteristics of the elements of a specific type of engine.
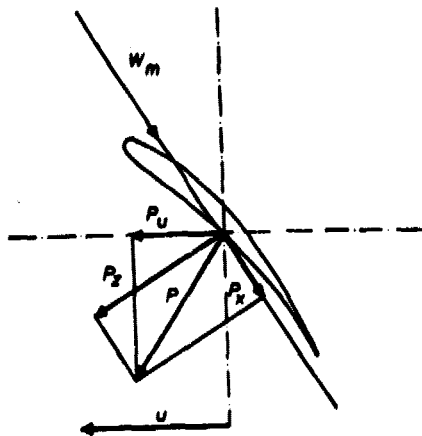
Fig. 7. Distribution of forces on blade profile of rotor of compressor at negative angle of incidence α (same notation as in Fig. 6)
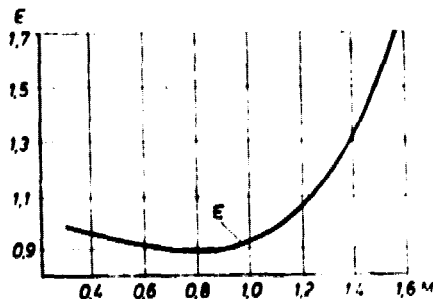
Fig. 8. Graph of variations of compression in compressor versus Mach number

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