PREDICTION OF WINDAGE POWER LOSS IN ALTERNATORS

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ABSTRACT

The purpose of this report is to develop a method of predicting the windage loss of rotating electrical machines operating in various gases under different pressures and temperatures. An equation was developed for a cylindrical rotor and modified by empirical relations to take into account the effects of the salient poles and shrouds of the homopolar inductor alternator. The effect of the gap length is briefly studied. The windage loss for a shrouded homopolar inductor alternator was calculated by these equations and compared to the experimental results obtained at the NASA Lewis Research Center. The agreement was within ±10 percent for a range of pressure from standard atmospheric to 40 psia (2.75×10^5 N/m^2).

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SUMMARY

The purpose of this report is to develop a method of predicting the windage loss of rotating electrical machines operating in various gases under different pressures and temperatures. An equation was developed for a cylindrical rotor and modified by empirical relations to take into account the effects of the salient poles and shrouds of the homopolar inductor alternator. The effect of the gap length is briefly studied. The windage loss for a shrouded homopolar inductor alternator was calculated by these equations and compared to the experimental results obtained at the NASA Lewis Research Center. The agreement was within ±10 percent for a range of pressure from standard atmospheric to 40 psia (2.75×10^5 N/m^2).

INTRODUCTION

Windage loss in a generator is the power absorbed by the fluid surrounding the rotor as a result of the relative motion between the rotor and the stator. Since this absorbed power must be supplied by the prime mover (some type of motor or turbine) and is not converted into useful energy, the presence of windage loss decreases the overall efficiency of the machine. Another undesirable characteristic of windage loss, and sometimes the most important, is that the power absorbed is converted into heat which increases the temperature of the rotor. Therefore, it would be useful to be able to predict the windage loss of a proposed machine in order to study its feasibility.

In the past, the windage loss of a proposed rotating electrical machine was usually estimated by comparing it to a similar machine with a known windage loss. Since literally millions of motors and generators have been designed and tested for use in air at standard temperature (20° C) and pressure (STP), this method has proven to be adequate for commercial machines. Due to the acceptability of this approach, little work has been done to develop an analytical method of predicting the windage loss of a rotating machine. However, the requirements for rotating machinery for auxiliary space power

has created a need for accurate methods of determining windage losses. Specifically, alternators currently being designed for space are high-speed and high-temperature machines operating in gases different from air and at pressures different from atmospheric. It is difficult to extrapolate the windage loss from commercial machine data unless a sound theoretical knowledge of the dependence of windage loss on these variables is known. The purpose of this investigation was to develop a method of predicting the windage power loss in a type of alternator being developed for space power generating systems.

The method used to determine the windage loss was to first make enough simplifying assumptions to reduce the problem to a solvable mechanics problem. An equation was then developed to predict the windage loss. The next step was to eliminate some assumptions which resulted in a usable equation for the windage loss of a cylindrical rotor.

With the aid of empirical relations, the effect of salient poles was taken into account for a particular type of alternator (homopolar inductor alternator). It will be shown that the equation developed for a cylindrical rotor multiplied by an appropriate constant predicts the windage loss for the type of alternator under consideration. A brief analysis of the effects of air gap length on windage loss follows.

The final step was to consider shrouded salient-pole rotors. This was also done by using the empirical relations in order to determine a constant multiplier for use with the cylindrical-rotor equation.

SYMBOLS

A area

B constant in skin friction coefficient equation

C_d skin friction coefficient

F force

H pole depth

K salient-pole correction factor

L cylinder length

M molecular weight

m mass

n number of moles

P pressure

R radius

R_o universal gas constant

Re   Reynolds number

T   temperature

t   air gap length

V   volume

v   tangential velocity

W   windage power loss

μ viscosity

ν kinematic viscosity

ρ density

τ time

ω angular velocity

GENERAL CONSIDERATION OF A CYLINDRICAL-ROTOR MACHINE

To determine the power loss of a cylinder rotating in a concentric cylinder, the following assumptions will be made:

(1) No axial flow exists.

(2) The gap is small compared to the radius and length.

(3) The fluid in the gap is homogeneous, and no pressure differential exists across the top.

(4) The flow in the air gap is laminar.

These assumptions are necessary to develop a simple theoretical analysis of the windage loss of a rotating cylinder.

The first assumption is reasonable since there is no axial force exerted on the fluid in the gap so there should not be any flow. Because the air gap is small compared to the radius, the difference in pressure across the gap (proportional to the difference in centrifugal force across the gap) is also small. Also, because of mixing, the temperature and the density of the gas should be homogeneous across the gap, justifying the third assumption. Later the loss will be determined for the turbulent flow condition, however, initially the assumption is made that gas flow in the gap is laminar.

Consider a cylindrical rotor of radius R and length L rotating in a stator with a gap clearance of length t shown in figure 1.

Looking toward the gap from the end of the rotor, if the flow is laminar, the velocity
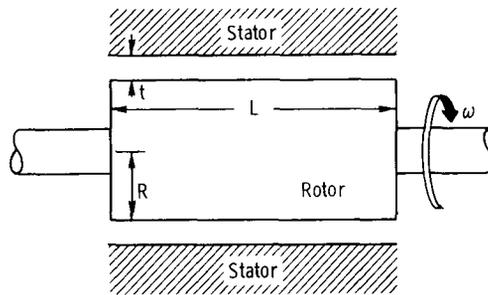
Figure 1. - Side view of rotor in stator.
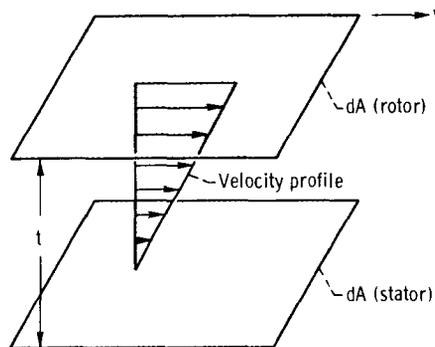
Figure 2. - Increments of rotor and stator surface
areas as viewed from end of rotor.

profile of the fluid between incremental areas of the rotor and stator is as shown in figure 2.

In figure 2, assume the rotor has a force F on it such that it moves with respect to the stator with a velocity v, the rotor peripheral velocity. An equal and opposite force must be applied to the stator to keep it from moving because of the shearing stress of the fluid.

The shearing stress is defined as the force per unit area dF/dA and the shearing strain is defined as the ratio of the displacement due to the stress to the transverse dimension t. In a solid, the stress is proportional to the strain, but in a fluid having Laminar flow, shear stress is proportional to the rate of change of shear strain (ref. 1). The strain is equal to $v\tau/t$, and its rate of change is

$$\frac{d}{d\tau} \frac{v\tau}{t} = \frac{v}{t}$$

Therefore,

4

$$\frac{dF}{dA} \propto \frac{v}{t} = \mu \frac{v}{t} \tag{1}$$

where μ is the constant of proportionality and is defined as the viscosity. Integration results in

$$F = \mu \frac{vA}{t}$$

where $A = 2\pi RL$ and $v = R\omega$ or

$$F = \frac{2\pi \mu R^2 \omega L}{t} \tag{2}$$

(For a more detailed solution of the previous problem, see ref. 1). Since power is

$$W = FR\omega$$

$$= \frac{2\pi \mu R^3 \omega^2 L}{t} \tag{3}$$

If the Reynolds number is defined as $Re = Rt\omega/\nu$ (see ref. 2) where $\nu = \mu/\rho$, then

$$W = \frac{2\pi \rho R^4 \omega^3 L}{Re} \tag{4}$$

and if $2/Re$ is set equal to C_d where C_d is defined as the skin friction coefficient, then

$$W = \pi C_d \rho R^4 \omega^3 L \tag{5}$$

A more detailed derivation of this equation can be found in reference 3.

EFFECT OF TURBULENCE

To develop equation (5), laminar flow in the air gap was initially assumed. However, as the Reynolds number is increased, turbulence will occur and the relation between C_d and Re as defined previously is no longer valid. Also, the presence of teeth in the stator of a cylindrical-rotor machine will promote turbulence. The presence of turbulence will affect the value of the skin friction coefficient but the general
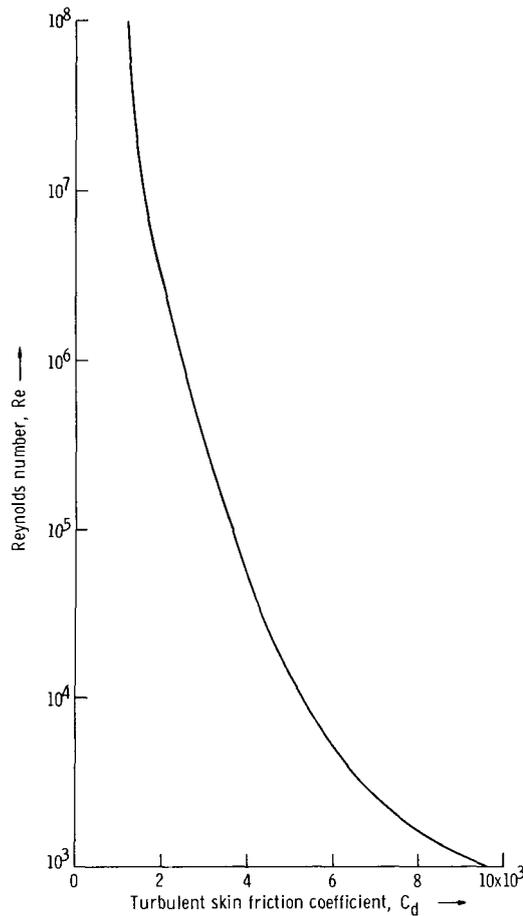
Figure 3. - Calculated skin friction coefficient C_d as function of Reynolds number Re. Curve calculated from equation (6), that is, $1/\sqrt{C_d} = 2.04 + 1.768 \ln (Re\sqrt{C_d})$.

power loss equation will have the same form.

There is no satisfactory theoretical analysis of turbulent flow between two rotating cylinders but as a first approximation the theory of turbulent flow between two parallel plates can be used. This involves assuming that the air gap is small compared with the radius and that the effect of centrifugal force is negligible. Both were previous assumptions and were shown to be valid. The theoretical skin friction coefficient for turbulent flow between two parallel plates is determined by (refs. 2 and 4)

$$\frac{1}{\sqrt{C_d}} = B + 1.768 \ln (Re \sqrt{C_d}) \tag{6}$$

The experimental value of B is 2.04 (see ref. 2).

Since the skin friction coefficient equation (eq. 6)) cannot be solved explicitly for C_d as a function of the Reynolds number, and therefore the effect of the Reynolds number

on C_d is not obvious, the curve of Re as a function of C_d is included here (fig. 3).

Equation (6) combined with equation (5) predicts the windage loss for a smooth cylinder rotating in a smooth bore with turbulent flow in the air gap.

EXPERIMENTAL VERIFICATION OF EQUATIONS (5) AND (6)

To illustrate the accuracy of equations (5) and (6), the windage loss was calculated for a machine whose windage loss was experimentally determined. The curves of figure 4 compare the calculated to the experimental loss. See the appendix for the source of the experimental data of figure 4. The rotor was a smooth cylinder and the stator was from an actual alternator and had slots for the armature windings. The tests were done in air. The maximum difference between the experimental and calculated loss is 7 percent. This represents very good correlation in windage loss testing. The fact that the curves agree so well seems to indicate that the addition of slots in the stator does not significantly change the power loss. A possible explanation of this is that, since the Reynolds number is so high (Re $\approx$ 5000 at 12 000 rpm), a turbulent condition would exist even if there were no slots, and their presence does not significantly increase the amount of turbulence.
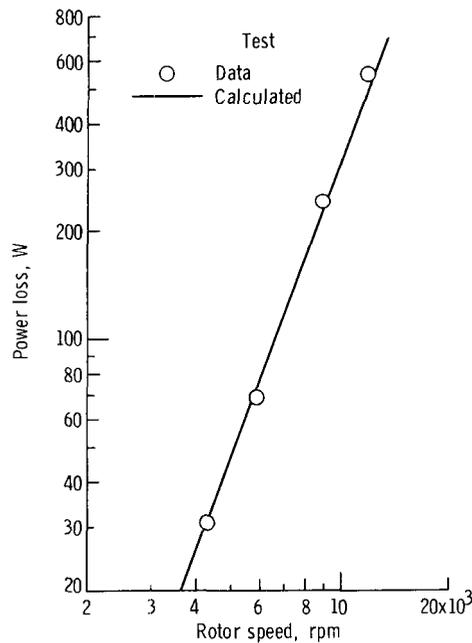
Figure 4. - Power loss for smooth cylindrical rotor rotating in actual stator compared to calculated loss.

EFFECT OF SALIENT POLES

In the previous section an equation was developed that predicted the windage loss of a smooth cylindrical rotor. However, many machines are designed with salient poles so it is desirable to modify the equation to allow it to be used for machines of this type. The problem will be approached here by empirical means since there is no known theoretical approach (see ref. 2).

The power loss of salient-pole generators can be approximated by multiplying the power loss of a cylindrical-rotor machine with the same dimensions by a constant K, that is a function of the rotor radius and the pole depth. The constant should be greater than one since it is expected that the addition of salient poles will result in axial flow which, when added to the smooth cylinder loss, should result in an overall increase of the power loss. Thus, the first assumption listed in the derivation of the power loss for a cylindrical rotor (eq. (5)) no longer applies. However, it will be assumed, and later shown to be correct, that equation (5) times K applies to the salient-pole condition.

If the multiplying constant K is defined as being a function of R and H, the salient-pole radius and the pole depth as shown in figure 5, then it is possible to find a relationship between K, R, and H by using the experimental curve of figure 6. The data used in figure 6 were taken from the appendix for a 16-pole homopolar inductor alternator.

All the data used in this report to derive empirical equations were taken from the appendix and the equations are limited to the type of machine that was tested. A type of machine commonly called a homopolar inductor alternator is considered in the appendix. Fortunately, the homopolar inductor alternator is a popular choice of alternator currently being considered for space use. There is no reason to believe these empirical equations are valid for other types of machines.

The homopolar inductor alternator consists of two stators separated by a toroidal field coil (see fig. 7). Surrounding both stators and the field coil is the yoke. The armature winding passes through both stators and under the field winding.

The rotor is constructed with salient poles on each end; all north poles are on one
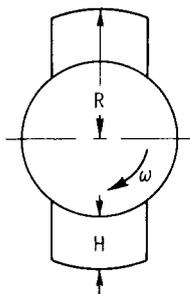
Figure 5. - End view of
salient-pole rotor.
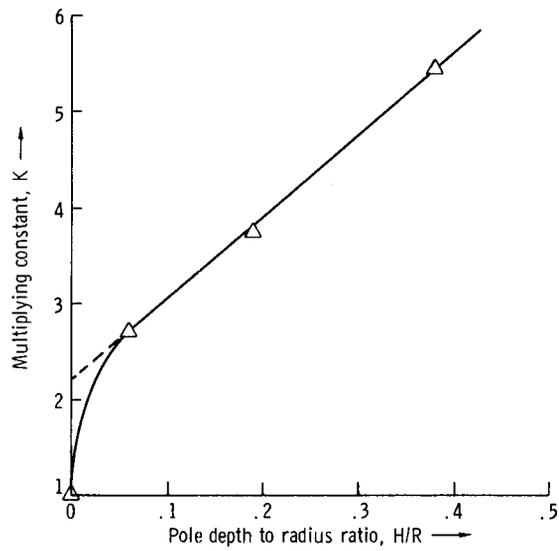
Figure 6. - Salient-pole rotor multiplying factor as function of pole depth to radius ratio.
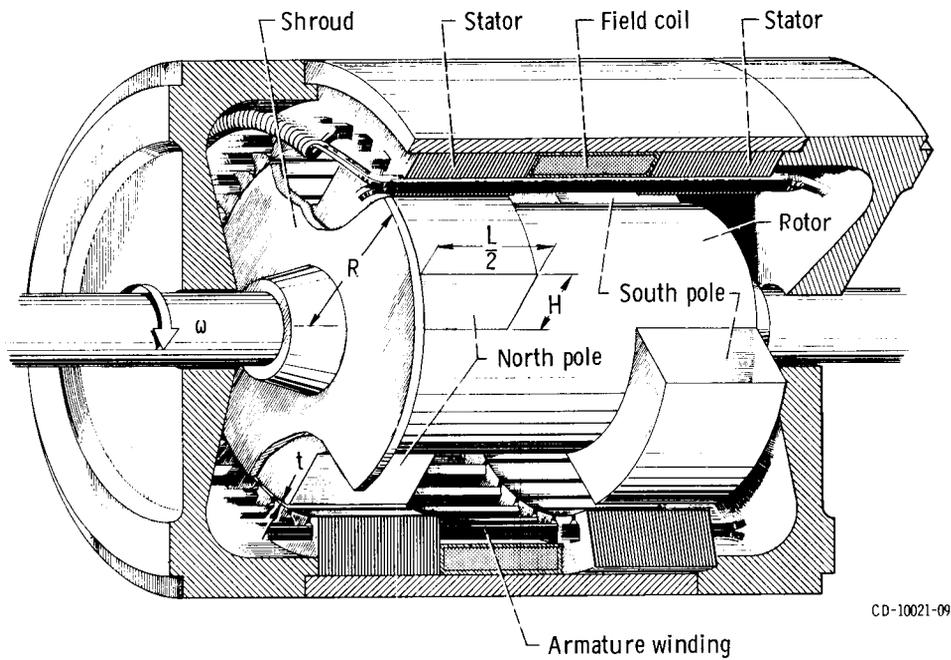
Figure 7. - Test alternator.

9

end and all south poles at the other. As in a conventional salient-pole alternator, the distance between centerlines for a north and south pole is 180 electrical degrees.

For ratios of $H/R > 0.06$, K assumes a linear relationship with H/R. The equation for this linear region of the curve is

$$K = 8.5\left(\frac{H}{R}\right) + 2.2 \qquad (7)$$

The fact that this equation may not be valid for any values of $H/R < 0.06$ is no real restriction, since homopolar inductor alternators are usually designed with H/R values greater than 0.06.

It is possible that K is also a function of the ratio of total pole face area to an equivalent cylindrical-rotor surface ($2\pi RL$). Since no data were obtained relating the pole face area to the windage loss and since the data from the appendix are for a ratio of 1/3, then it is to be expected that K from figure 6 can only be relied upon for area ratios of 1/3.

EFFECT OF AIR GAP LENGTH

As can be seen by figure 3, a large change in Reynolds number results in a small change in the skin friction coefficient C_d. Since the gap dimension is present only in the Reynolds number, a large number, a large change in gap length should produce only a small change in power loss, all else being equal. Theoretically for a cylindrical rotor, when the gap length is changed from 10 mils (0.25 mm) to 25 mils (0.63 mm), which represents a +150 percent change, the power should change by -20 percent (calculated at 12 000 rpm). If it is assumed that this is true even for a salient-pole homopolar inductor alternator (which is the same as saying that K is not a function of air gap length), then figure 8 shows the theoretical effect of a gap length only on power loss of a homopolar inductor alternator of design given in the appendix.

10
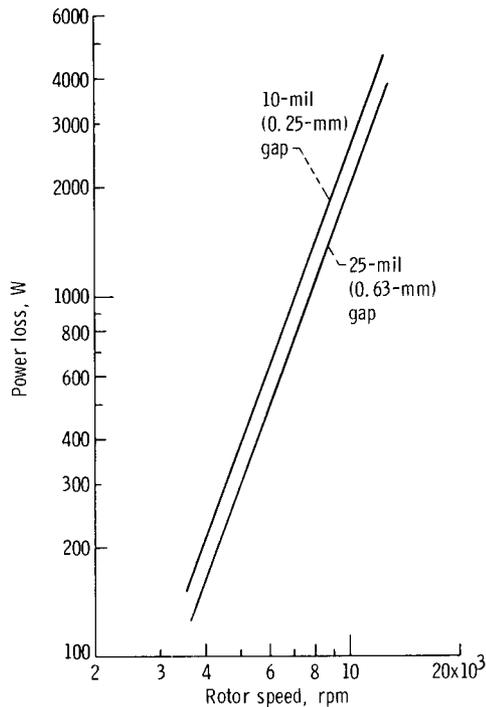
Figure 8. - Theoretical effect of gap length only on windage power loss.

EFFECT OF SHROUDS ON THE ROTOR

A shroud is a circular disk that is attached to a salient-pole rotor as shown in figure 9.

When shrouds are used in a salient-pole machine, the amount of axial flow of gases is greatly decreased. The same result can, of course, be achieved by attaching a stationary shroud to the stator. If the basic power loss equation, equation (5) is multiplied by K, the factor for salient poles, the predicted losses are too high when shrouds are used. However, if the basic power loss equation, equation (5), is used alone to predict the losses of a shrouded salient-pole rotor, the prediction will be low, since shrouding a rotor is never as effective in reducing windage loss as is making the rotor cylindrical.

The data points of figure 10 (from the appendix) show the measured windage loss of a shrouded eight-pole salient-pole homopolar inductor alternator rotor. Curve A shows the calculated losses (from eq. (5)) of a smooth rotating cylinder of the same outside dimensions as the rotor. Curve B is curve A multiplied by a scaling factor, 3/2, which was chosen to result in a curve having substantial coincidence with the experimental points. Therefore, the windage loss of a salient-pole rotor of the type tested is 3/2 times the equivalent cylindrical-rotor power loss. Curve C shows the
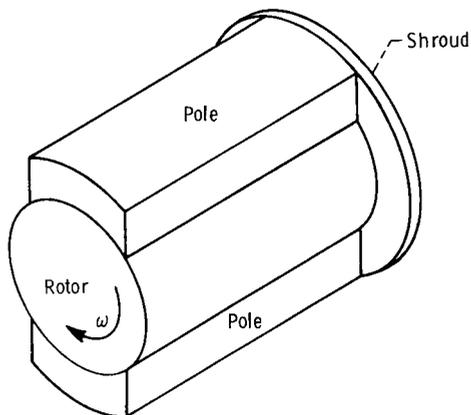
Figure 9. - Salient-pole rotor with one shroud.
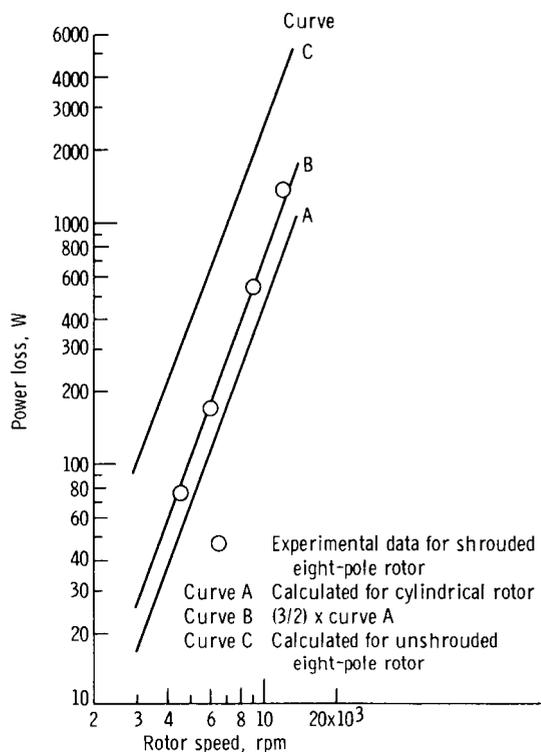
Figure 10. - Effect of shrouds on eight-pole rotor.

calculated loss of the previously mentioned rotor without shrouds. The factor of 3/2 will be used in the following section to predict the loss of an actual machine. It will be seen that highly accurate results are obtained. However, the effect of shrouding may vary with pole depth, pole face area, the gap the shroud and the stator and probably other variables.

Calculations and Experimental Results of Test Alternator

The accuracy of the developed equations was checked by comparing the calculated results with the loss of a real alternator. The test alternator was a three-phase, 400-hertz 120/208-volt alternator with an output rating of 15 kilovolt-amperes and 12 kilowatts. Physically, it was the shrouded four-pole homopolar inductor machine shown in figure 7 (p. 9). Its physical dimensions were as follows:

Radius, R, in. (cm). 2.60 (6.60)
Cylinder length, L, in. (cm) 3.91 (9.94)
Air gap length, t, in. (cm) 0.040 (0.102)
Pole depth, H, in. (cm). 0.85 (2.16)

The rotor speed was 12 000 rpm ($\omega = 1258$ rad/sec).

Tests were performed to determine the power loss for two gases at pressures ranging from 5 to 40 psia (3.44×10^4 to 2.75×10^5 N/m^2). The two gases used were argon and Freon-12. The power loss was determined by measuring the torque to the input shaft of the unexcited alternator (after first subtracting the bearing loss) with a torque transducer and multiplying by the angular velocity. The test made with argon was at a machine cavity temperature of 100° C. Argon at that temperature has a viscosity of 2.69×10^{-4} gram per second per centimeter (ref. 5). The test using Freon-12 was done with a cavity temperature of 66° C corresponding to a viscosity of 1.36×10^{-4} gram per second per centimeter (about one-half of the argon viscosity). From equation (5) it can be seen that the only remaining quantity needed to calculate the power loss is the density. Since no gas density data were available for the temperatures and pressures used in the tests, the perfect gas law was used. This law is expressed as follows:

$$PV = nR_0T \tag{8}$$

Note that $n = m/M$ and $\rho \simeq m/V$; then equation (8) becomes

$$\rho = \frac{PM}{R_0T} \tag{9}$$

where $M = 40$ for argon and $M = 121$ for Freon-12 and $R_0 = 82$ cubic centimeter per atmosphere per mole per K. It is now possible to calculate the value of the windage loss of an equivalent cylindrical rotor by using equations (5) and (6) and the definition of the Reynolds number. Since the poles of the test alternator are shrouded, the calculated value of W, the loss of an equivalent cylindrical rotor, should be multiplied by 3/2. The curves of figures 11 and 12 show the experimental loss of the machine for two gases compared to the calculated loss, (3/2)W, as a function of cavity pressure. Both curves show agreement within ± 10 percent between the test points and the calculated windage loss from standard atmospheric pressure, or below, to 40 psia (2.75×10^5 N/m^2).
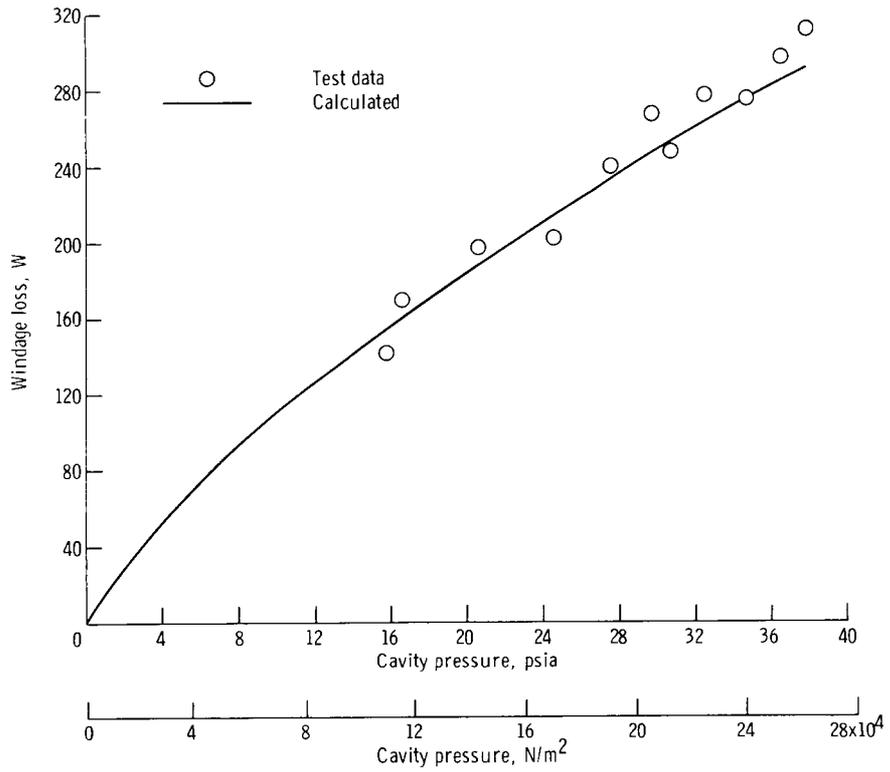
Figure 11. – Test alternator windage loss in argon at 12 000 rpm compared to analytical results.
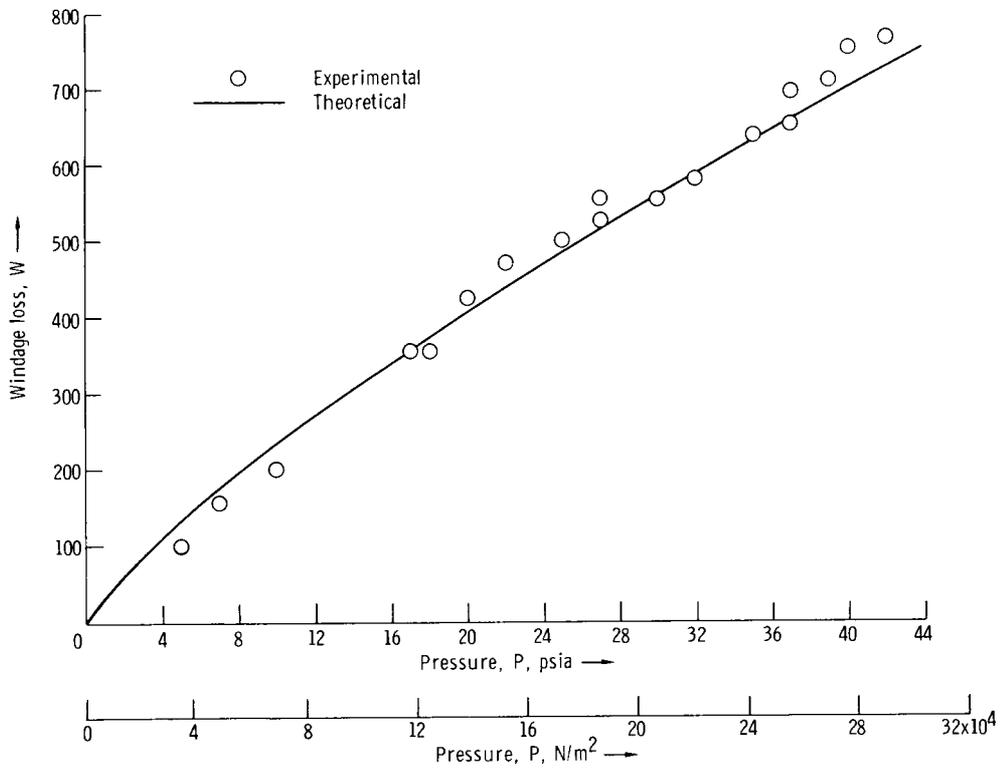
Figure 12. – Windage loss in test alternator with Freon-12 gas in cavity.

SUMMARY OF RESULTS

A method of predicting the windage loss of rotating electrical machines operating in various gases under different pressures and temperatures was developed. The results of this study are as follows:

1. The windage loss of a smooth cylinder rotating within a concentric cylinder was determined. The equation which describes the windage loss W is

$$W = \pi C_d \rho R^4 \omega^3 L \tag{5}$$

where C_d is skin friction coefficient and for turbulent flow is evaluated as

$$\frac{1}{\sqrt{C_d}} = 2.04 + 1.768 \ln (\text{Re} \sqrt{C_d})$$

where ρ is density, R is radius, ω is angular velocity, L is cylinder length, and Re is Reynolds number. The equations are theoretical except that the constant 2.04 is empirical. Calculated windage losses are within 10 percent of experimental data.

2. The equation for the salient-pole correction factor K (K = 8.5(H/R) + 2.2 where H is pole depth), the factor that the calculated cylindrical rotor loss is multiplied by to find the loss of the homopolar inductor alternator 16-pole machine, was shown to be reliable for the homopolar inductor alternator machines tested but it should be noted that all machines tested had a pole face area ratio of 1/3. Caution should be used when applying the correction factor K to the loss of a homopolar inductor alternator when the area ratio is different from 1/3 or the number of poles is different from 16.

3. It was shown theoretically, for a cylindrical rotor, that a large increase in air gap length produces a relatively small decrease in windage power. This is true for a homopolar inductor alternator if it is assumed that K is not a function of the air gap.

4. The effect of shrouds for the homopolar inductor alternator tested is shown. The windage loss calculated by the cylindrical-rotor equation (eq. (5)) could be corrected to include the effect of shrouds by multiplying by 3/2. The factor, 3/2, was obtained empirically.

5. The equations developed in this report were checked against actual test data taken on a four-pole homopolar inductor alternator having shrouds. Tests were made in two gases having different densities, viscosities, and temperatures. The correlation between calculated and experimental data was very good. Since only one configuration of shroud was used, an estimate of the accuracy for other configurations is impossible.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, July 26, 1968,
           701-01-00-06-22.

APPENDIX - WINDAGE LOSS DATA

The data used in figures 4, 6, and 10 (pp. 7, 9, and 12) are from an unpublished report written by O. G. Smith entitled Windage Power Losses in Aerospace Generator in 1961 for Westinghouse Electric Corporation. This data is reproduced as table I and Figure 13 with permission of Westinghouse.

The following is the experimental method used to obtain the data:

A generator stator of 7 inches (17.78 cm) inside diameter was used throughout the experiment. Special rotors were machined from aluminum to allow for ease of modifica-

TABLE I. - WINDAGE LOSS DATA[a]

[Radius, 3.94 in. (10.0 cm); Density, 0.074 lb/ft^3 (1.185×10^{-3} g/cm^3); viscosity, 1.21×10^{-5} lb/(ft)(sec) or 1.84×10^{-4} g/(cm)(sec); kinematic viscosity, 1.635×10^{-4} ft^2/sec (0.152 cm^2/sec).]

Rotor	Cylindrical	16-Pole	Eight-Pole
Cylinder length, L. in. (cm)	4.50 (11.42)	4.50 (11.42)	5.25 (13.32)
Air gap length, t, in. (cm)	0.025 (0.063)	0.025 (0.063)	0.010 (0.025)
Pole depth, H, in. (cm)	0	0, 0.25, 0.75, 1.5 (0, 0.64, 1.91, 3.81)	1.50 (3.81)
Data curve	Figure 13 (curve A)	Figure 6	Figure 13 (curve B)

[a]From unpublished report by O. G. Smith of Westinghouse Electric Corp.

Curve A Cylindrical rotor
Curve B Eight-pole rotor
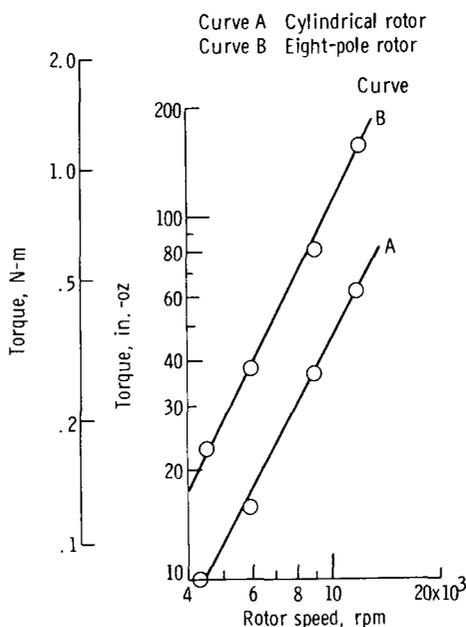
Figure 13. - Torque as function of rotor speed.

16

tion for further tests.

The resultant model was driven at speeds up to 12 000 rpm by a four-pole induction motor excited by a variable frequency source outside the altitude chamber. The chamber was necessary to evaluate the effect of changes in fluid density. Torques were indicated through a torque head and a calibrated transducer.

Bearing friction was eliminated by plotting curves of torque against air density for constant speed and extrapolating the torque to zero density. This value was then subtracted from all the torque values, leaving windage torque only. Bearing torque was reduced from normal levels by removing the grease and grease seals and lubricating the bearing with a drop of light oil.

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