

SANDIA REPORT

SAND2002-0029

Unlimited Release

Printed January 2002

A Tip Driven Fan Based on SERAPHIM Technology

Barry Marder

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of
Energy under Contract DE-AC04-94AL85000.

Approved for public release; further dissemination unlimited.



Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof, or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof, or any of their contractors.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865)576-8401
Facsimile: (865)576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: <http://www.doe.gov/bridge>

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

Telephone: (800)553-6847
Facsimile: (703)605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: <http://www.ntis.gov/ordering.htm>



SAND2002-0029
Unlimited Release
Printed January 2002

A Tip Driven Fan Based on SERAPHIM Technology

Barry Marder
Target and Z-pinch Theory
Sandia National Laboratories
P. O. Box 5800
Albuquerque, NM 87185-1186

Abstract

SERAPHIM technology appears capable of efficiently driving a tip driven fan. If the motor is powered using an inverter and resonant circuit, the size and weight could be considerably below that of a comparable rotary electric motor.

Contents

I. Introduction	5
II. The baseline design	6
III. Design Issues	9
IV. Inductive behavior	8
V. Scaling and sizing	10
VI. Summary	11
References	11

Figures

1. The basic SERAPHIM	5
2. Normalized force	5
3. A 2 meter diameter tip-driven fan	6
4. Motor circuit	7
5. Simulated performance	8
6. Alternative geometries	9

A Tip Driven Fan Based on SERAPHIM Technology

I. Introduction

A conceptual design of an electric impulse, tip driven fan using SERAPHIM (Segmented Rail Phased Induction Motor) technology [1] is presented. As shown in Figure 1, the basic SERAPHIM consists of two wound pancake coils, one powered and one shorted, in which an alternating current is injected in the former, inducing a current in the latter. The force between the coils is the product of the currents times the gradient of the mutual inductance, M . Since the induced current is proportional M , the force is proportional to $M \frac{dM}{dx}$, plotted in Figure 2 for various axial gaps, g . The thrust stops when the coil centers are slightly over a radius apart. The passive coils typically lie end-to-end along a roadbed and an array of powered coils is on a moving vehicle. For the ducted fan, the passive coils could be along the circumference and the powered coils placed in fixed locations around the rim.

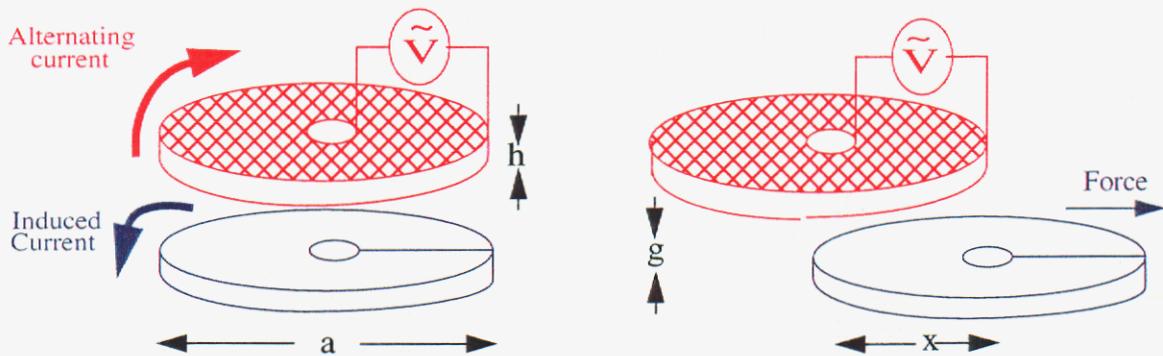


Figure 1. Basic SERAPHIM: a powered (hatched) “pancake” coil and a similar shorted coil. The interaction of the primary and induced currents produces a repulsive force.

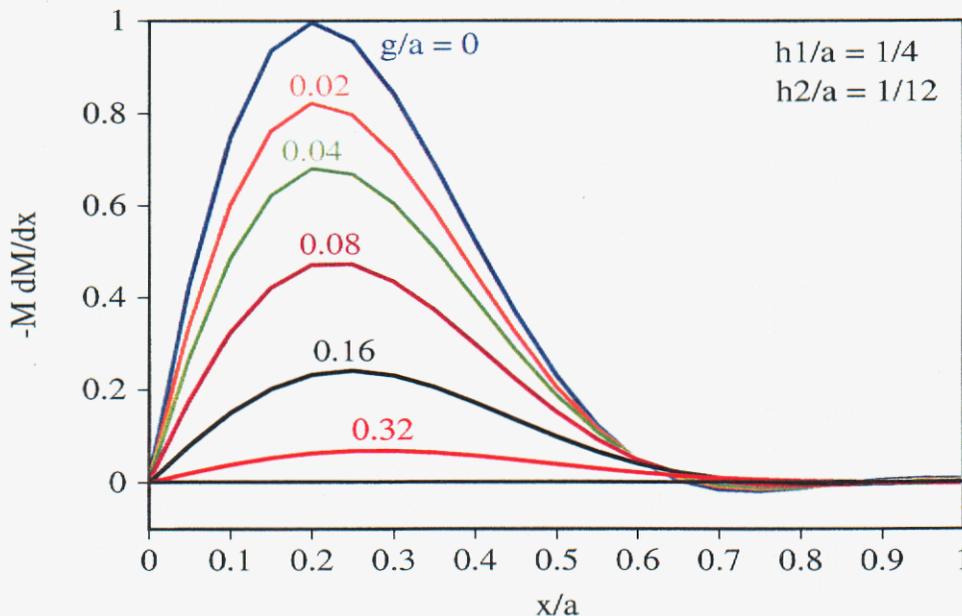


Figure 2. Normalized force, $-M \frac{dM}{dx}$, as a function of position for various gaps. Symbols defined in Figure 1. The coil heights, h_1 & h_2 , are baseline values defined in the next section.

II. The baseline design

Several options, each with their own strengths and weaknesses, will be presented. Only one, a baseline design, will be examined in detail.

The baseline configuration, shown in Figure 3, has an array of shorted coils extending past the rim of a rotating fan, and three motor sets, each with 3 pairs of coils spaced $1/3$ diameter apart. Opposing motor coil pairs are connected in series. Unlike the configuration in Figure 1, two motor coils interact with a fan coil. The baseline has a 2 meter (6 feet) diameter fan rotating with a tip speed of 230 m/s. The three motor sets deliver a nominal 1 kNT (225 lbf) of force at the tip, corresponding to a power input of about 230 kW (300 HP). All coil diameters are 12 cm so there are 56 coils around the rim. The thicknesses of the motor and fan coils are 3 and 1 cm, respectively, and there is a 1 cm gap between them. The conductors in each are assumed to fill 66% of the cross-sectional area, the remainder being taken up by insulator, cooling structure, and support. Their operating temperatures are both assumed to be 100 C. The coils that rotate at the rim of the fan should be as lightweight as possible, so they are aluminum. The stationary motor coils are copper, which is heavier, but a better conductor. The mass of the conductor in a motor and fan coil is 2.6 and 0.26 kg, respectively, so the total conducting motor mass is 18×2.6 , or 47 kg (103 lb) and the total conducting rotating mass is 56×0.26 , or 14.6 kg (32 lb).

The location of the moving fan coils with respect to the motor sets is sensed, and power is switched to that motor coil pair which provides the largest thrust. Switching is done at current nulls to avoid arcing. The frequency must be high enough to permit switching near the optimum time. For the specified coil radius (6 cm) and rim speed (230 m/s), the frequency should be considerably larger than $1/2 \times 230 \text{ m/s} / 0.06 \text{ m} \sim 2 \text{ kHz}$. The factor of one half arises because two current crossings occur in a period. Ideally, a coil is switched on when it is coaxial with a fan coil and remains energized until it moves half its diameter, as depicted in Figure 1.

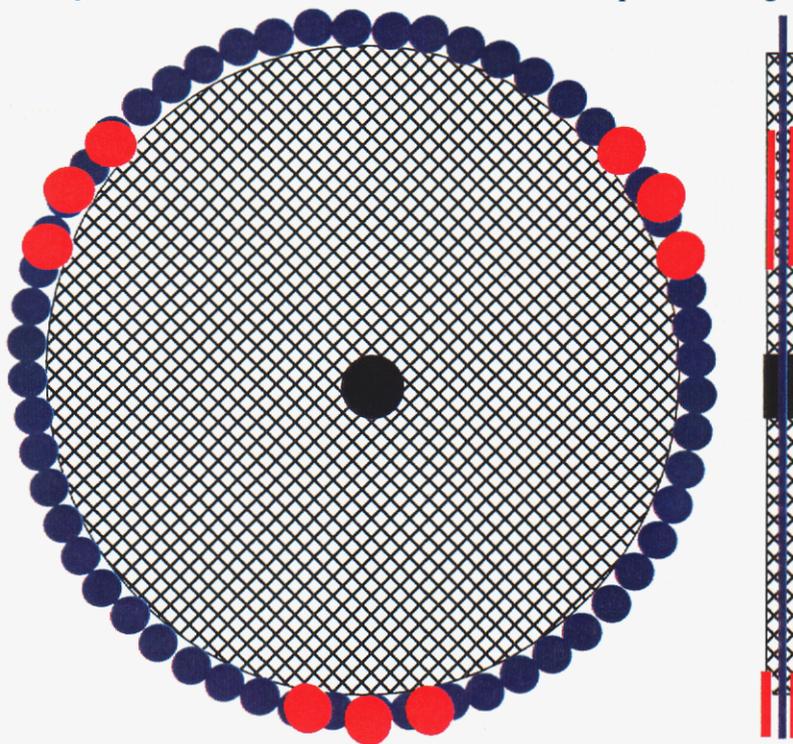


Figure 3. Front and side views of a 2 meter diameter fan with three motor sets, each with 3 coil pairs (red) $1/3$ diameter apart, and 56 adjacent passive coils (blue). All coils are 12 cm in diameter.

The motor coils have a very large inductance, so that at peak current, the stored energy is high. As the current diminishes, most of this energy returns to the source. Only a small fraction is used to produce the desired force, and the unwanted parasitic heat. One way to power such a motor is with a resonant LC circuit in parallel with the voltage source, as shown in figure 4. The electrical energy sloshes back and forth between the capacitor and the inductive coils. Ideally, the source merely adds what is consumed. Thus, while the circulating power may be large, the input can be only slightly above the average, reducing the power demands on the source. The input voltage is determined by the desired thrust. This, together with the resonance condition, requires that when the capacitor voltage, V_c , is rising, the input voltage is 210 V; when it is falling, the input is -210 V. The motor coils have 21 turns and the fan coils have 100 turns. Their resistances, R_m and R_f , are 4 and 57 $m\Omega$ and their inductances, L_m and L_f , are 35 and 100 μH , respectively. The resistances, R_a and R_b , are both taken to be 1 $m\Omega$, the inductance, L_a , is 10 mH and the capacitance, C , is 73 μf .

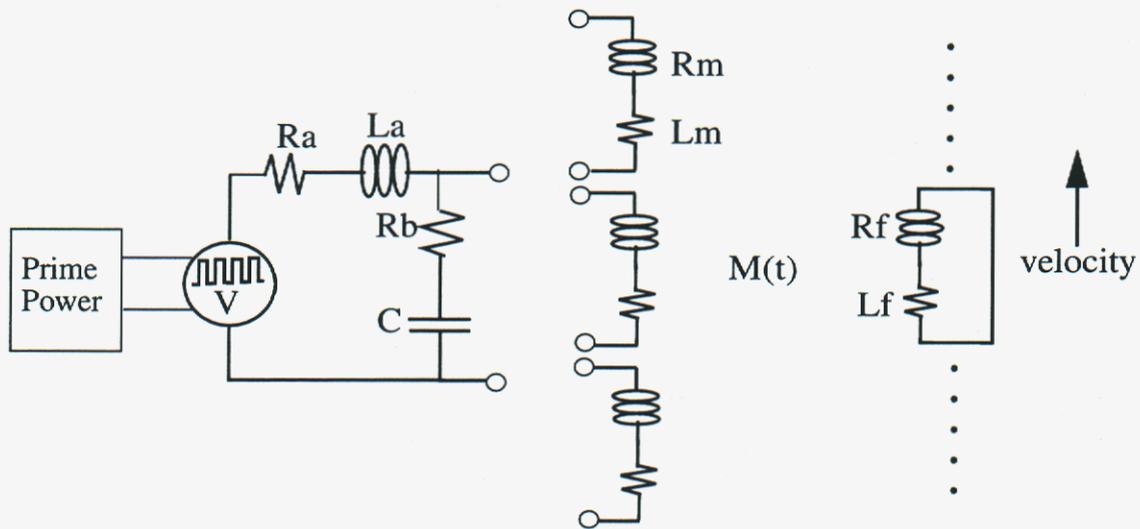


Figure 4. Motor circuit. A square wave voltage source drives a parallel resonant circuit. R_m and L_m are the resistance and inductance for the powered motor coil pairs. R_f and L_f are the values for the shorted fan coils. M is the time-varying mutual inductance between them. Power is switched (switches not shown) among the three motor coil pairs. There are many fan coils.

Modeling is done with the Sandia code SERMOTOR, which solves the coupled circuit equations. The steady state results for a single motor set are plotted as a function of time in Figure 5. Figure 5a gives the source and capacitor voltage. The 210 volt square pulse produces about 1.8 kV peak on the capacitor. Figure 5b plots the current through the coil, the capacitor, and the source. Figure 5c shows which of the 3 motor coil pairs is being powered. Figure 5d plots the instant and average force on the fan coils. The three motor sets produce about 1 kNt average force. Figure 5e predicts that, without cooling, a motor coil's temperature will rise 2.5 degrees centigrade per second. The fan coil rise is below one degree per second. Figure 5f shows how the input power is distributed. The circulating inductive power, which is not shown, peaks as high as 3 MW. Were it not for the resonant circuit, this would have to be provided by the power source. With the circuit, the peak input power is only 150 kW, a factor of 20 less. The efficiency, defined as the average kinetic power divided by the average input power (71 kW / 99 kW), is about 72%.

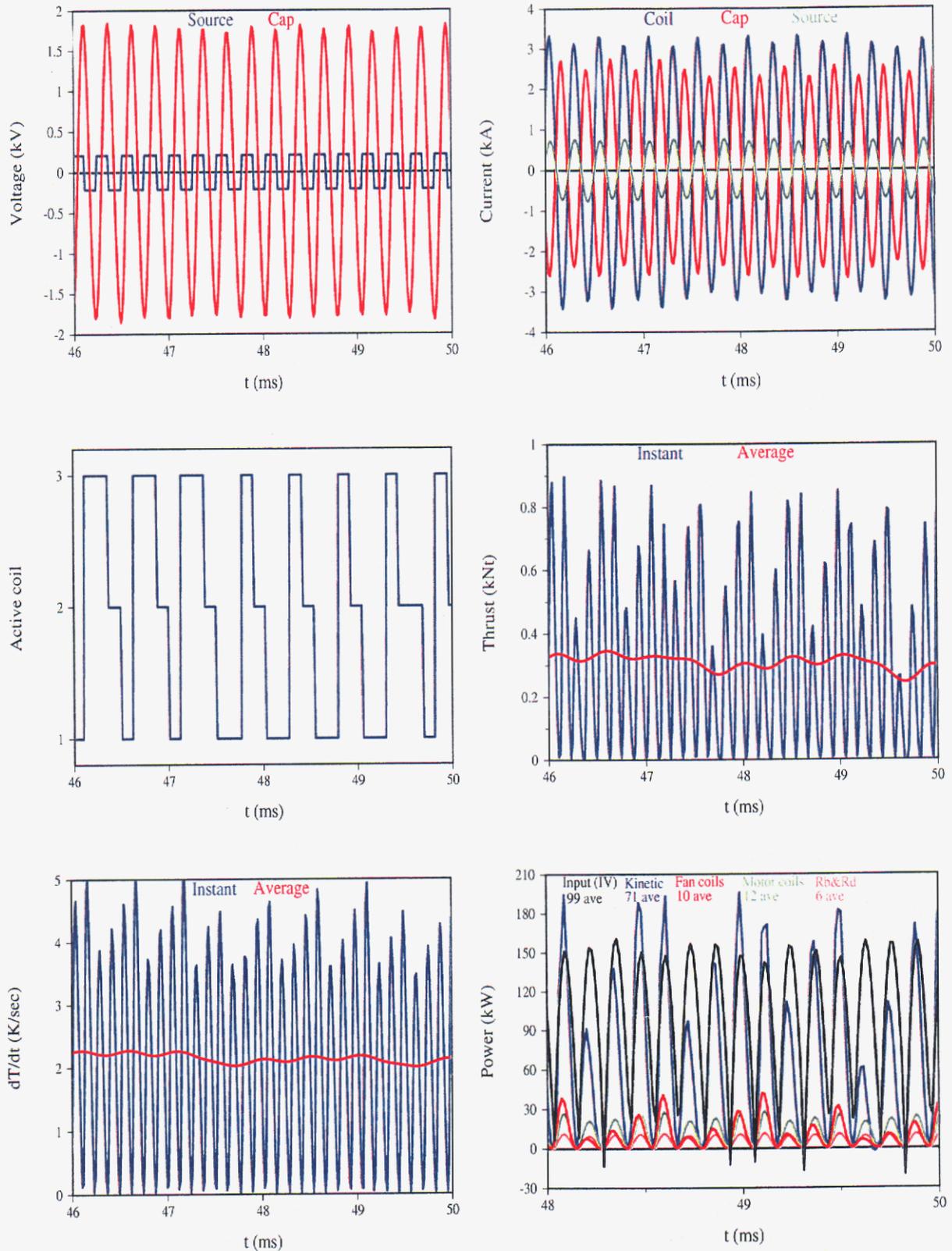


Figure 5. a) Source and capacitor voltage; b) coil, capacitor, and source current; c) active motor coil; d) instant and average thrust; e) instant and average temperature rise; f) power budget with averages.

III. Design issues

Approximately 2 kW of heat must be removed from each of the 18 motor coils and 100 Watts from each of the 56 fan coils. The motor probably requires liquid cooling, but perhaps the rapidly moving fan coils can be air cooled. The 1 cm gap between the motor and fan coils is the electrical separation. Much of the actual space will be taken with cooling and structural support. If this proves to be insufficient, the gap can be increased, but at the cost of reduced performance.

As Figure 5a shows, the frequency of operation is about 4 kHz. The skin depth of copper ($\eta = 10^{-8}$ ohm-m) at this frequency, is 0.8 mm. The cross sectional area of the copper in a motor coil (taking into account the fill factor) is $6 \text{ cm} \times 3 \text{ cm} \times 0.66 = 12 \text{ cm}^2$ and there are only 21 turns, meaning that the wire diameter is about 8.3 mm, much bigger than a skin depth. Using wire strands with diameter larger than the skin depth increases the AC resistivity. To avoid this, Litz cable, consisting of many small braided wires in parallel, can be used. While this solves the electrical problem, it makes heat removal more difficult. Increasing the number of turns would also reduce the wire diameter, but would increase the inductance. As we shall see, the lower inductance is instrumental in keeping the capacitor mass down.

The centrifugal acceleration, v^2/r , at 1 meter radius moving at 230 m/s, is $5.3 \times 10^4 \text{ m/s}^2$, or 5400 gravities. Thus, a rim coil weighing 0.26 kg feels an outward force of 14 kNt (3160 lb), considerably more than the thrust it gets from a motor coil.

It might be necessary to reduce the surrounding magnetic field by using ferromagnetic shields. These would be slotted to suppress eddy currents. Preliminary investigations indicate that shielding could actually enhance motor performance by increasing the coil inductance. Any benefit must, of course, be weighed against the added mass.

The baseline geometry, Figure 6a, was chosen to maximize motor performance with minimum rotating mass. In this configuration the two motor coils in series repel the fan coil and attract each other, creating a variable torque as the fan coils move between them. Because of the symmetry, there is no net sideways force on a fan coil. Other configurations are possible. There could be just one row of motor coils and pairs of fan coils as in Figure 6b. This has comparable efficiency, but it doubles the rotating coil mass and reduces access to the motor. It also produces a net outward force on the fan coils. The fan coils could also be placed transversely and a single motor coil could power it from outside the rim as in Figure 6c. This is somewhat less efficient. It produces a net inward radial force on the fan coils and might require a larger gap to accommodate the radial motion.

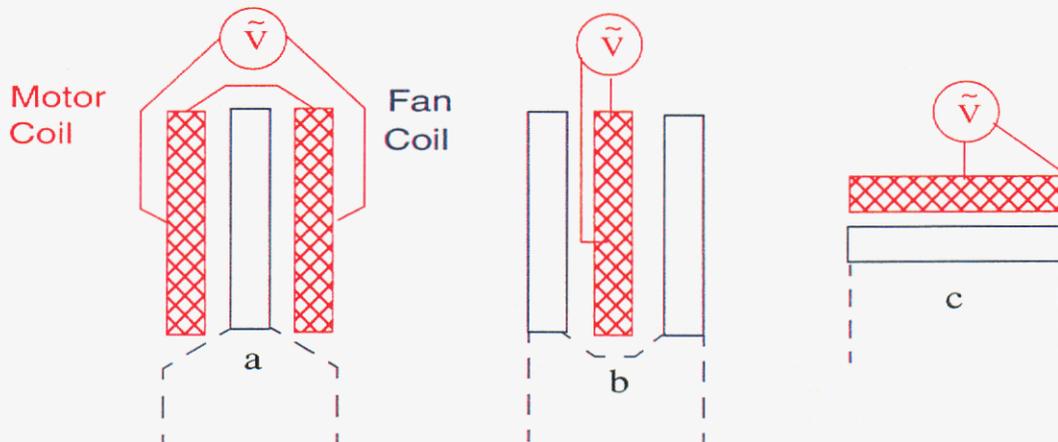


Figure 6. Possible tip mounted fan drive geometries. a) Baseline with two powered coils on either side of the passive coils; b) one powered between the passive coils; c) single sided, with one powered coil outside the passive coils. Fan indicated by dashed lines.

The baseline has three motor sets each with one power supply, but more of either could also be used. The roles in Figure 3 could be reversed, having motor coils completely surrounding a few sets of fan coils, reducing the rotating mass, but increasing the electrical complexity. Or, both the rim and motor could be densely packed with coil sets have different periodicity so they are not all in phase. With this geometry, up to half the motor coils could be active at any time, increasing the duty cycle from 1/3 to 1/2. Clearly, for the same total force, using more coils, either in the motor or on the rim, reduces the stress and heating load on individual coils.

IV. Scaling and sizing

All currents scale directly with the applied voltage. Power, force, and heating scale as the applied voltage squared. Most of the results in Figure 5 depend on the coil size and tip speed, not the fan diameter. Halving the fan diameter, while keeping the same coil size and tip speed, doubles the centrifugal force and fan coil heating rate (as there would be fewer of them), but does not otherwise alter the performance. Reducing the coil size along with the fan diameter is another story. As Figure 2 indicates, the performance of the motor depends on the ratio of the gap to the coil diameter, g/a . For 1 cm gap and 12 cm diameter coil, this ratio is 0.083, which places it fairly low on the normalized force axis. To achieve comparable performance with half sized coils requires not only a proportional reduction in the already small gap, but a doubling of the frequency. On the other hand, using larger coils can improve both the electrical and thermal performance, but at the cost of increasing the rotating mass.

AC capacitors are characterized by VAR's, the peak energy times the angular frequency, $1/2 \omega C V_{\text{peak}}^2$. With $C = 73 \mu\text{f}$, $V_{\text{peak}} = 1.8 \text{ kV}$, and $\omega = 2\pi \times 4000 \text{ Hz}$, a total of 2970 kVAR is required. GE Industrial Systems (Ft. Edward, NY) produces a commercially available AC capacitor, designated 19L0299WH, with the following catalogue specifications: 3000 kVAR, 1250 Volts RMS, 2400 Amps RMS, at 4 kHz. It's width, length, and height are 5.12, 13.5, and 9 inches respectively and it weighs 38 lb. One of these capacitors satisfies the electrical demands for a single motor set.

Marvin Bone of the Bone Frontier Company (Brighton, CO; 800-379-BONE) estimated that an inverter, indicated by the square wave voltage source in Figure 4, capable of delivering 300 kW at 650 volts might be about 40 x 40 x 20 inches and weigh some 250 lb. One unit could power the three motors in series. These devices are intended for use in induction heating where they sit on a factory floor, where size and weight may not be critical. Were these issues to become important, it is possible that smaller, lighter units could be developed.

The analysis done here does not include the prime power source, which will obviously add to the size and weight. The size and weight estimates of the other components are summarized below.

<u>Component</u>	<u>Number</u>	<u>Size (cu. ft)</u>	<u>Weight (lb)</u>
Motor coils	18	0.22	103
Fan coils	56	0.22	32
AC Capacitors	3	1	115
Inverter	1	19	250
Total		20.44	500

Switching can be done with thyristors, such as the Silicon Power (Exton, PA) model c718, rated at 5 kV and 750 Amps. These are the size of a hockey puck and, compared with the capacitors and inverters, do not contribute significantly to either the size or weight, at least for the baseline design.

For comparison a 300 HP electric motor rotating at approximately 2200 RPM, as in our baseline, would weigh at least 3000 lb and have an efficiency in the mid 90% (a good reference can be found at www.electricmotorwarehouse.com). This, too, excludes the prime power.

There is, obviously, considerable flexibility in both the basic design and the circuit parameters. For example, the motor coil wire size can be reduced by using more turns, increasing their inductance. This requires less capacitance to produce the 4 kHz resonance, which, in turn, needs increased voltage to deliver the required energy. The search for AC capacitors and power supplies that would satisfy these demands, however, yielded only ones that were larger and heavier, often requiring multiple capacitors in series.

V. Summary

A first cut at determining the feasibility of a tip driven ducted fan powered by SERAPHIM technology has been attempted. There is considerable design flexibility in the motor configuration. The goal here was to minimize the total size and weight. Details of the thermal and stress management were not considered, but assuming these can be successfully achieved, an efficient design appears feasible. The total size and weight could be considerably below that of a comparable rotary electric motor.

References

[1] Barry Marder, "The Physics of SERAPHIM", Sandia National Laboratories report SAND2001-2951, October 2001.

Distribution

1 MS 0836 Ron Dykhuizen, 9116
1 MS 1186 Tom Mehlhorn, 1674
1 MS 1182 Ron Kaye, 15335
5 MS 1182 Bob Turman, 15335
1 MS 9661 Peter Van Blarigan, 8214
1 MS 9018 Central Technical Files, 8945-1
2 MS 0899 Technical Library, 9616
1 MS 0612 Review and Approval Desk for DOE/OSTI, 9612
1 MS 0161 Patent and Licensing Office, 11500

3 Mark Moore
NASA Langley Research Center
Hampton, VA 23681-2199

3 Barry Marder
8215 Waterview Blvd.
Bradenton, FL 34202