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This report describes the second year efforts to develop a Meissner bearing system for miniature cryogenic turboexpanders used in Brayton cycle cryocoolers. During this period, a permanent magnet/Meissner effect bearing was tested, and a system was developed for measuring the stiffness and damping of superconductor/magnet pairs at high frequencies and low amplitudes (1 kHz, <100 μm). Preliminary measurements have shown the feasibility of Meissner effect bearing/damper systems for small turbomachines. A new configuration for the bearing system has been conceptualized, and a patent disclosure prepared. The system provides both accurate positioning of the shaft at room temperature and stable rotation at cryogenic temperatures.

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SUPERCONDUCTING MEISSNER EFFECT BEARINGS FOR CRYOGENIC TURBOMACHINES

Annual Technical Report

Contract No.: F49620-90-C-0007

Javier A. Valenzuela
Jerry L. Martin

CREARE INCORPORATED
HANOVER, NEW HAMPSHIRE

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MAY 1993

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LICENSE RIGHTS LEGEND

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1. INTRODUCTION

This progress report covers the period of performance between 1 January 1991 and 30 March 1993 for our project entitled "Superconducting Meissner Effect Bearings for Cryogenic Turbomachines." This research is sponsored by the Innovative Science and Technology Branch of the Strategic Defense Initiative Organization (SDIO/IST), and managed by the Air Force Office of Scientific Research (AFSOR) under contract F49620-90-C-0007. The Air Force Project Manager is Dr. Harold Weinstock and the Principal Investigator is Dr. Javier Valenzuela. The period of performance for the contract is 1 November 1989 through 31 May 1993.

The program is aimed at the development of a Meissner bearing system for miniature cryogenic turboexpanders used in Brayton cycle cryocoolers.

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2. THE NEED FOR MEISSNER EFFECT BEARINGS

Spaceborne infrared sensors for surveillance and intelligence require cryogenic cooling to achieve high sensitivity and high signal to noise ratio. Conventional open-cycle systems rely on the boil-off of either liquid or solid cryogens. However, such systems become less desirable for extended duration missions, since the cryogen mass at launch becomes impractically large. For these long duration missions, active cryocoolers are under development. These cryocoolers use either Stirling or reverse Brayton cycle refrigerators to cool the focal plane. A key issue in the design of these machines is their efficiency, usually expressed as the number of watts of input power per watt of cooling. Since this ratio of input power to cooling power is large, small parasitic conduction losses at the cold end translate into large increases in input power. To minimize the radiator mass and the power required by the cooler, the efficiency must be maximized.

Creare is currently developing reverse Brayton cryocoolers employing self-acting gas bearings to support the turboexpander. These bearings need to run relatively warm, since their load capacity and damping relies on temperature-dependent gas viscosity. In a practical design, this means the bearings run warm, while the turbine is cantilevered into the cold stream. The temperature difference between the warm end of the shaft and the cold end results in a parasitic heat leak into the gas, decreasing the cooler's efficiency. The relative significance of this effect increases as the cooling capacity decreases; a practical lower limit for cooling power using current technology is in the range of 3 to 5 watts.

If the warm gas bearings could be replaced with bearings running at cryogenic temperatures, then the efficiency of a cryocooler could be greatly increased. In Phase I, we showed analytically that a 40% decrease in input power could be achieved by incorporating Meissner effect bearings. These studies were performed for a 1 watt, 10 K cryocooler, where warm gas bearings for the coldest turboexpander were replaced with Meissner bearings.

Meissner effect bearings have several advantages for turboexpanders:

- they are non-contact bearings, not subject to wear,
- they impose minimal drag on the shaft,
- they do not require an external power supply,
- they do not require a control system.

Meissner effect bearings could also find application in terrestrial applications where the passive nature and low drag of the bearings offset the need for cryogenic coolants.

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3. PHASE II TECHNICAL OBJECTIVES AND APPROACH

The overall objective of Phase II is the development and demonstration of a turbomachine that employs Meissner bearings for radial support of the shaft. In Phase I, we determined that Meissner bearings are feasible for incorporation into turboexpanders. We have also shown that present manufacturing techniques used for ceramic superconductors can be employed in our Meissner bearing design.

The specific technical objectives of the Phase II program are to:

- Fabricate a Meissner bearing test apparatus and generate data from which advanced analytical models can be developed and a final bearing design can be specified.
- Design and fabricate a prototypical turboexpander that incorporates Meissner bearings.

In order to meet these objectives, the following workplan is underway:

Task 1. Fabricate and test Meissner bearing breadboard.
Task 2. Develop advanced analytical models.
Task 3. Design turboexpander.
Task 4. Fabricate turboexpander.
Task 7. Management and reporting.

This report documents the progress for the period 1 January 1991 to 30 March 1993 for Tasks 1, 3, and 7. These were the only tasks active during this period.

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4. SUMMARY OF TECHNICAL PROGRESS BY TASK

4.1. Task 1-Fabricate and Test Meissner Bearing Breadboard

The scope of Task 1 is the design, fabrication, and high speed testing of a Meissner radial bearing.

In earlier work on this task, a 2.5 cm diameter rotor was spun to 1000 rev/s, and the drag on the rotor measured. These measurements indicate that the drag on the rotor is primarily viscous drag, and that the magnetic suspension contributes very little additional drag. A smaller 6.4 mm diameter magnet was successfully spun to 450,00 rpm (7500 rev/s), for a surface speed of 150 m/s. This surface speed far exceeds that required by the turboexpander application (90 m/s).

Following these tests, we proceeded with an experiment designed to give more information on the performance of Meissner effect bearings. This experiment involved the construction of a test facility which allowed the measurement of the bearing stiffness and damping at small gaps and high frequencies. This facility is illustrated in Figure 1.

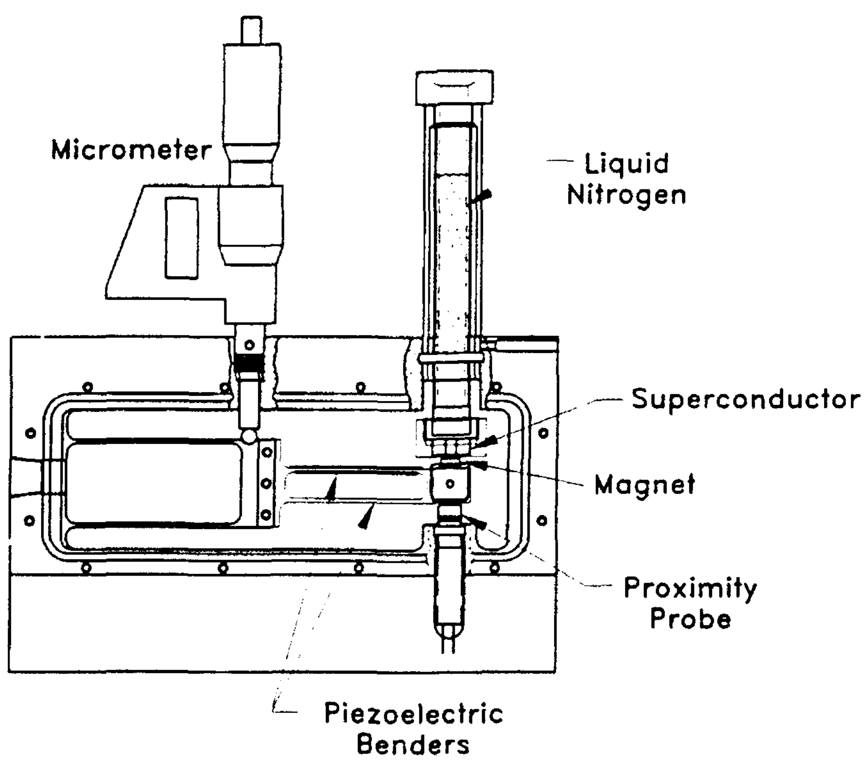

Figure 1. Dynamic stiffness and damping test facility

The facility consists of a vacuum chamber housing a piezoelectric bender with a magnet on its free end. A superconductor sample is attached to a small dewar directly above the magnet. By applying a sinusoidal voltage to the piezoelectric elements, the magnet can be moved closer or further away from the superconductor. A micrometer allows the coarse separation between the magnet and the superconductor to be set. An inductive position sensor measures the magnet position.

Figure 2 shows typical results from this facility. The two curves were obtained by driving the piezoelectric benders with a swept sine wave while recording the amplitude of the vibration. The vibration amplitude increases near the natural frequency of the vibrating beam. This natural frequency is determined by the series combination of the beam stiffness and the stiffness of the Meissner effect bearing formed by the magnet and the superconductor. The damping of the system can be determined from the width of the resonance peak. Small values of damping lead to narrow resonance peaks, large values to wider peaks. As Figure 2 shows, lowering the temperature of the superconductor below T_c causes the resonance peak to shift to higher frequencies and to broaden, showing that the Meissner effect bearing is providing both stiffness and damping, even at these small displacements. We are currently using this facility to evaluate the materials planned for use in the turboexpander.

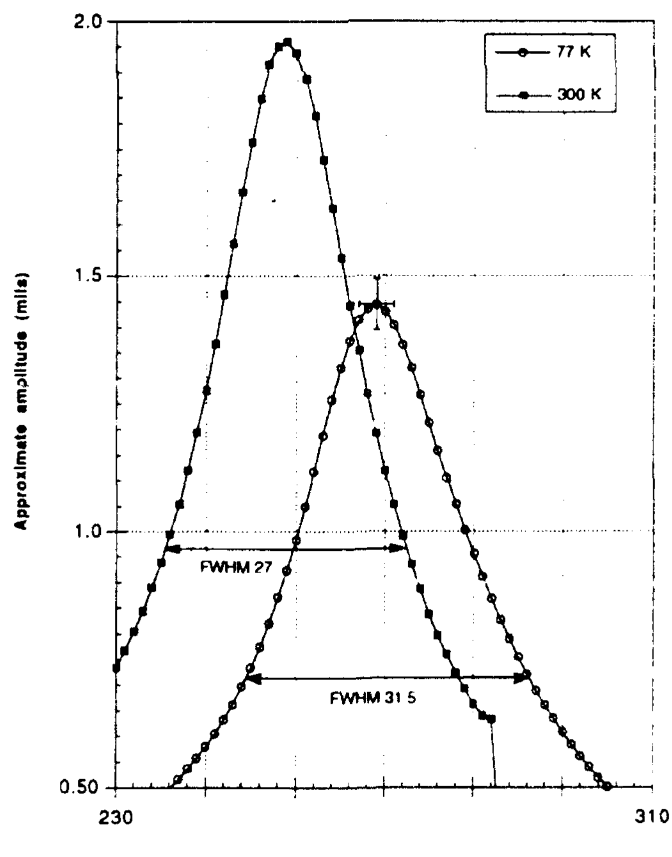

Figure 2. Amplitude vs. frequency for the normal and superconducting states

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4.2. Task 3-Design Turboexpander

The objective of this task is to develop a mechanical design for the miniature turboexpander. The challenge in this task is to design a bearing system that provides sufficient stiffness to allow high speed rotation and also positions the shaft precisely in order to allow small clearances to be maintained.

In earlier work on this task, the bearing system of Figure 3 was developed. This system uses a passive permanent magnet radial bearing and a gas thrust bearing in combination with the Meissner effect bearings. The advantage of this configuration is that the shaft may be stably supported at room temperature, and held in position while the superconductors are cooled below their transition temperature. The magnetic bearing is unstable in the axial direction, so a jet of gas is directed at one end of the shaft in order to position the shaft axially.

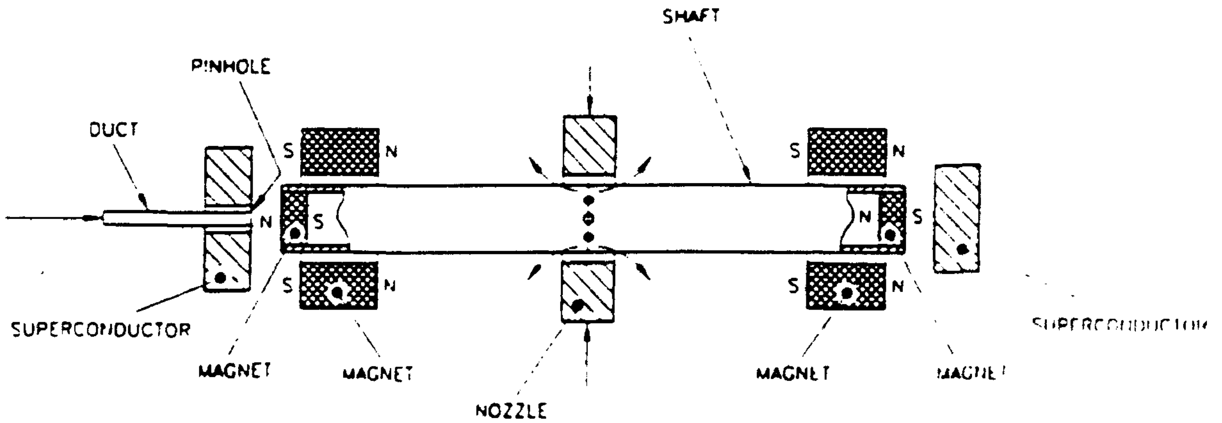

Figure 3. Meissner bearing system

We fabricated a small bearing test rig which incorporates this bearing system. The shaft was stably levitated at room temperature and rotated at up to 1000 rpm. Higher speed rotation was not possible since the magnetic field of the magnet was not sufficiently uniform in the azmuithal direction. This nonuniformity leads to unbalance forces on the shaft which exceed the bearing load capacity at high speed. Initial tests of the bearings at 80 K indicate that the bearing runout is reduced as the superconductors pass below their critical temperature. These tests verified the basic principle of the bearing system. While this system is capable of supporting and centering the shaft over a range of temperatures, it does not have sufficient stiffness for high speed cryogenic turbines, which require very small tip clearances (on the order of 5 μm) for high efficiency. Since the bearings are not very stiff, any residual unbalance in the shaft leads to large amplitude vibrations at the critical speeds.

In order to work around the problems with the non-uniform magnetic field and low stiffness, we have conceived a new bearing configuration which will provide stable suspension at both cryogenic and ambient temperatures. This bearing is shown in Figure 4. The bearing uses tilt-pad gas bearings to support the shaft at room temperatures. Tilt-pad gas bearings are well

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developed and are used in small turboexpanders produced by Creare. While they have demonstrated excellent performance near room temperature, supporting shafts at up to 600,000 rpm, their performance degrades at low temperatures. Our investigation into the stability of these bearings at low temperatures indicates that the stability degrades due to a combination of the reduction in stiffness and damping at low temperatures. Meissner effect bearings can provide the additional stiffness and damping required to stabilize the shaft at low temperatures. The attached patent disclosure elaborates on the effect of low temperatures on gas bearings.

The combination of Meissner effect and self-acting gas bearings could provide a solution to the dilemma which has plagued many researchers in the superconducting bearing field—the same applications which lend themselves to Meissner effect bearings (small, high speed systems), usually require a level of accuracy in positioning the shaft which cannot be achieved using the Meissner bearings alone. By combining the excellent room temperature performance and shaft positioning accuracy of gas bearings with the low temperature stiffness and damping available from the superconductors, a bearing may be constructed which provides both accurate positioning and robust operation at low temperatures. We plan to test this configuration in the coming months.

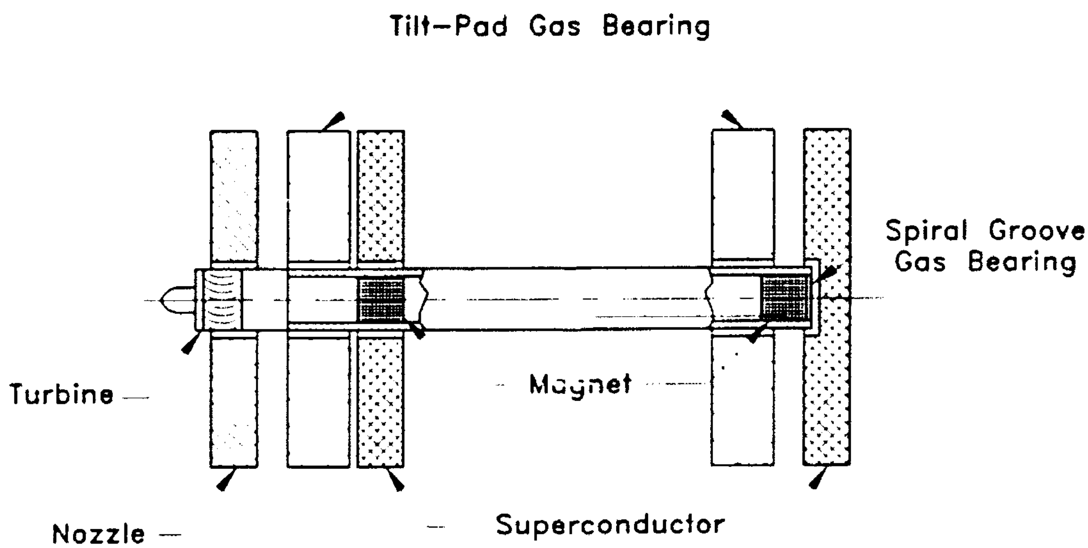

Figure 4. Hybrid gas/Meissner effect bearing

4.3. Task 7-Management and Reporting

This task covers general project planning, monitoring and reporting activities. There was a change in the Principal Investigator for this project during the reporting period. The original Principal Investigator was Victor Iannello. The Principal Investigator as of 1 July 1992 is Dr. Javier A. Valenzuela.

A patent disclosure describing the hybrid tilt-pad Meissner bearing has been prepared under this task.

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5. FUTURE WORK

The following tasks are planned for the remainder of the project.

5.1. Test Permanent Magnet/Superconducting Bearing

In this task, we will test the second generation permanent magnet/superconducting bearing. This bearing has been fabricated and tested initially at room temperature, but has not yet been tested cold. We will test this bearing with state-of-the-art melt-textured YBCO which was not available at the time of fabrication. The radial runout of the shaft in its bearings will be monitored both during room-temperature operation on the permanent magnet suspension alone, and during low-temperature operation on the permanent magnet and superconducting bearings. We will measure the damping coefficients of the permanent magnet and combined permanent magnet/superconductor bearing.

5.2. Design a Gas/Superconducting Test Facility

In this task, we will design a test facility to implement the bearing concept of the attached patent disclosure. This facility will incorporate a hybrid self-acting gas bearing with a superconducting Meissner effect bearing/damper. We believe this configuration is more likely to achieve the shaft positioning accuracy required by turboexpander applications. The design task will incorporate experimental measurements of Meissner effect stiffness and damping at small displacements. These measurements will be taken in our recently developed dynamic stiffness measuring device.

5.3. Fabricate Gas/Superconducting Bearings

In this task, we will fabricate the hybrid gas/superconductor bearing. Superconductor discs will be purchased and machined to size. We plan to use melt-textured YBCO material with properties tailored to our application (most notably high damping). The test facility will incorporate an air turbine drive capable of spinning the shaft to speeds in excess of 4 kHz. Fabrication of the housing, shaft, and turbine will all be done in Creare's precision shops. The superconducting disks will be fabricated by outside suppliers.

In order to conserve funds and focus on the superconducting aspects of the hybrid bearing, we will use an existing 6.35 mm tilt-pad gas bearing as part of the hybrid bearing. These bearings were developed as part of a NASA compressor project. These bearings have operated in room temperature air and neon at speeds in excess of 7 kHz. We will build a 6.35 mm shaft with both gas bearing journals and permanent magnets. The shaft will utilize an air turbine drive. This drive may be either a impulse turbine or a crude radial-inflow turbine, depending on the configuration chosen for the superconductors.

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5.4. Test Bearings

The hybrid bearing will be tested for its performance at both room temperature and at cryogenic temperatures. The test facility will include capacitance probes to sense the radial and axial motions of the shaft. By monitoring the output of these probes, we will be able to determine the amplitude of the shaft vibrations as we traverse the bearing critical speeds. By applying an impulse to the turbine housing, we will be able to drive the shaft into oscillations. The damping coefficient of the bearing can then be determined by measuring the rate of decay of these oscillations. The shaft will be accelerated until the damping coefficient becomes too small for stable operation, or until subsynchronous vibrations appear, indicating the onset of unstable half-speed whirl.

Once the operation of the bearing is characterized at room temperature, we will proceed to characterize its performance at cryogenic temperatures. Initially, we will test the bearing without the superconductors in place. Based on earlier work at Creare, we expect that the maximum stable operating speed will decrease as the temperature decreases. We will quantify this effect by operating the bearings at a number of temperatures between 80 and 300 K. Following these tests, we will replace the superconductors and operate the bearings below the critical temperature. In this condition, the additional stiffness and damping provided by the superconductors is expected to allow higher-speed operation.

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6. SUMMARY AND CONCLUSIONS

This technical report documents the progress made between 1 January 1991 to 30 March 1993, for the program entitled "Superconducting Meissner Effect Bearings for Cryogenic Turbomachines." The main accomplishments during this period were:

- Testing of a permanent magnet/Meissner effect bearing.
- Development of a system for measuring the stiffness and damping of superconductor/magnet pairs at high frequencies and low amplitudes (1 kHz, <100 μm).
- Conceptualization of a novel bearing system that provides support at room temperature and accurate positioning of the shaft over a range in temperatures.

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PATENT DISCLOSURE PD-142

Title: Hybrid Gas/Meissner Effect Bearing
Inventors: Javier A. Valenzuela, Jerry L. Martin
Date of Conception: March 1993
Date of Disclosure: 12 May 1993

Background

Recently it has been shown that passive magnetic bearings utilizing the Meissner effect are feasible. Moon[1] and Agarwala [2] describe rotating assemblies employing superconducting bearings. At Creare, a bearing system was developed that was used to rotate a magnetic rotor to a rotational speed of 450,000 rpm, with a peripheral velocity of 150 m/s. A fundamental limitation of these bearings is the lack of a means to support the shaft while the bearing is cooled below its transition temperature. Iannello and others at Creare demonstrated a bearing system utilizing permanent magnets for radial support and a hydrostatic gas bearing for axial support at room temperature. This system could levitate the shaft while the superconductor was cooled below its transition temperature. However, the permanent magnet radial bearing does not have sufficient stiffness for some applications where extremely precise positioning of the shaft is required. An example of such a system would be a miniature turboexpander, where tip clearances might be limited to on the order of five microns in order to control leakage and achieve high efficiency.

We have improved our superconducting bearing to increase the stiffness, and allow precise positioning of the shaft over the entire temperature range from room temperature to cryogenic temperatures.

The Hybrid Gas/Meissner Effect Bearing

The improved bearing system is essentially a combination of a hydrodynamic gas bearing and a Meissner effect bearing. Hydrodynamic gas bearings are used on a number of small high-speed devices including gyroscopes and small turboexpanders. These bearings rely on the viscous pumping of gas between moving surfaces to produce the pressure needed to support the shaft. Creare uses tilt-pad gas bearings on small turbomachines of up to 25 mm in diameter. On our smallest turboexpanders (3 mm diameter), these bearings operate at shaft speeds of up to 600,000 rpm.

Gas bearings rely on gas viscosity to develop load capacity and damping. Therefore, their performance degrades at low temperatures because of the reduction in gas viscosity. Tests at Creare have shown that the maximum speed for stable bearing operation decreases with temperature. For these reasons, the bearings on our turbomachines typically run relatively warm, while the expander is cantilevered into the cold stream. This configuration leads to parasitic heat

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leaks into the cold stream from the warm end of the machine. If the bearings could operate at lower temperatures, this heat leak would be reduced and the efficiency range of the operation of turbo-Brayton cryocoolers would increase substantially, specially in the 1-2 W load range required by many sensor cooling applications.

Some researchers have attributed the reduction in maximum stable speed for gas bearings at low temperature to the reduction in bearing stiffness brought on by decreased viscosity. As we show below, this may not be strictly true. For the operating points of Creare's tilt-pad gas bearings, the bearing stiffness is fairly insensitive to the gas viscosity since the bearings are operating in a range where compressibility is important.

Performance of Gas Bearings at Low Temperature

The load capacity of gas bearings depends strongly on the effects of compressibility in the gap. At low speeds and moderate atmospheric pressures, the pressure rises in the gap are small compared to the atmospheric pressure, and the bearing may be analyzed using incompressible assumptions. As speed increases or the bearing operating pressure decreases (on a high-altitude aircraft, for example), the effects of compressibility become important.

The effect of compressibility is typically expressed as a function of the compressibility parameter, Λ.

$$\Lambda = \frac{6\mu\,\omega R^2}{p_a C^2}$$

where

- μ is the dynamic viscosity,
- ω is the rotational speed in rad/s,
- R is the shaft ~~diameter,~~ radius
- p_a is the atmospheric pressure,
- C is the shaft-pad radial gap.

For values of Λ less than 1, the bearing performance may be adequately predicted by incompressible theory. In this range, the load capacity depends strongly on the value of Λ. Since the viscosity of gases decreases with temperature, the load capacity decreases with temperature for $\Lambda<1$.

As Λ increases from 1, the slope of the load-capacity vs. Λ curve decreases. For the typical design point for our turboexpander bearings, doubling Λ from 6 to 12 gives only a 20% increase in load capacity. Beyond $\Lambda=10$ or so, the load capacity may be considered independent of Λ. This means that the load capacity becomes independent of shaft speed. The only effects of temperature are the variation in viscosity and the possible differential expansion of the shaft and the bearing. For titanium shafts in a Be-Cu bearing, the gap at 100 K is approximately half of that at room

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temperature. This decrease in gap tends to compensate for the decrease in viscosity, with the net effect being to keep Λ large and the load capacity high. As shown in Table 1, Λ is greater than 6 at temperatures as low as 80 K for a typical expander design.

Table 1

neon viscosity	μ	1.18E-05 kg/(m-s)
speed	N	7000 rps
angular frequency	ω	43982 rad/s
shaft diameter	d	4.76E-03 m
shaft radius	r	2.38E-03 m
ambient pressure	p	1.01E+05 Pa
radial clearance	C	5.08E-06 m
temperature	T	80 K
compressibility parameter	Λ	6.76

Since the above analysis shows that the bearing stiffness varies only a small amount over this temperature range, we ascribe the decreased stability to decreased damping. As a class, gas bearings exhibit little damping, with perhaps the only significant sources of damping being squeeze-film damping in the gap and any structural damping in the bearings. The first of these damping sources is dependent on the gas viscosity, and therefore will decrease with decreasing temperature. If additional damping could be generated at low temperatures, we expect that the region of stable operation could be extended.

High temperature superconductors can provide the additional damping needed to stabilize the bearing. Takahata [3] has shown that a high temperature superconducting bearings could provide up to 5 N-s/m of damping. Our calculations indicate that the tilt-pad bearings require a minimum of 3-4 N-s/m of damping for stable operation. It appears, therefore, that by combining the gas bearing with a Meissner effect bearing/damper, that the gas bearing could be stabilized at cryogenic temperatures.

Figure 1 shows the hybrid gas/Meissner effect bearing. The tilt-pad gas bearings are the same as those used in other small high-speed systems. The shaft, however, contains a small magnet mounted inside the shaft near each of the gas bearings. High temperature superconductors are located at the same axial locations as the magnets. As the shaft is displaced from the center of the bearing, the magnetic field at the surface of the superconductor varies. The resulting changes in the current distribution inside the superconductor dissipate energy, so the superconductors act to damp oscillations. In addition, the superconductor/magnet combination will supply some stiffness to the hybrid bearing.

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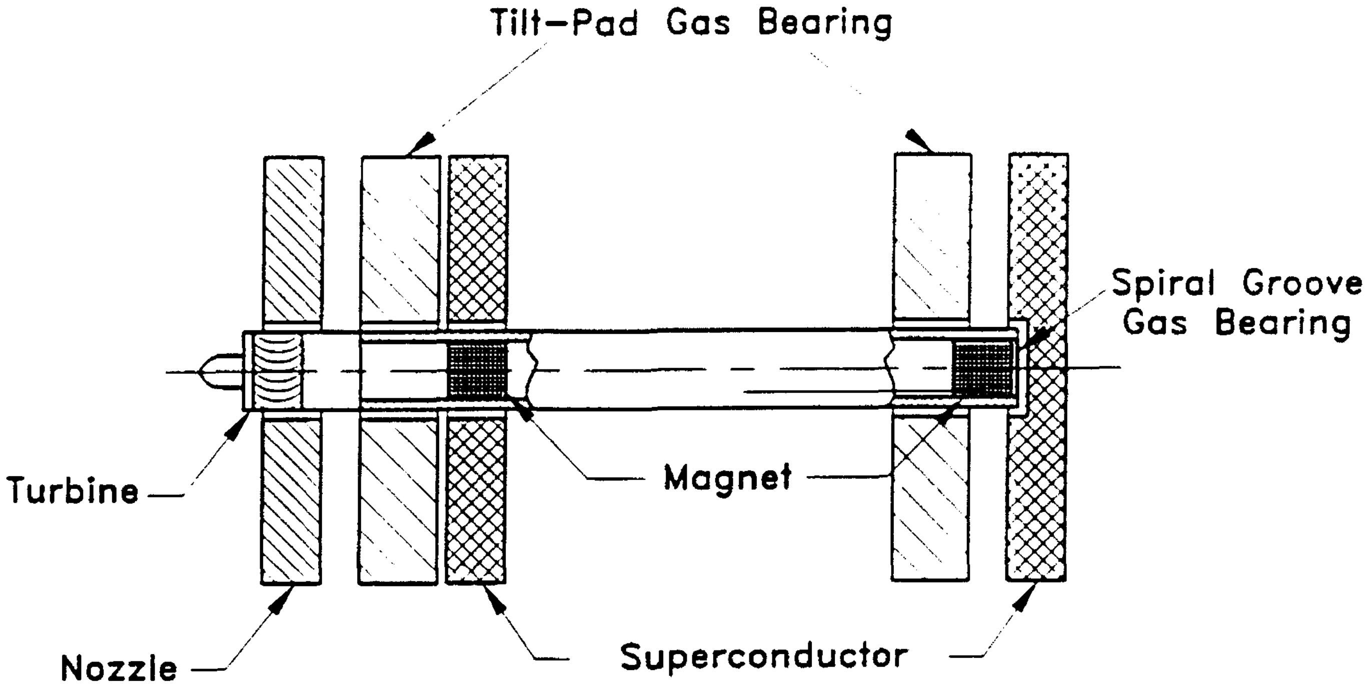

Figure 1. Hybrid gas/magnetic bearing

References

[1] Moon, F.C. et al., "Superconducting Rotating Assembly", U.S. Patent No, 4,886,778, Dec. 12, 1989.

[2] Agarwala, A.K. " Electric Machinery Employing a Superconducting Element", International Patent Application Number PCT/US89/04165, Sep. 26, 1989.

[3] Takahata, R., et al., "Characterization of Superconducting Magnetic Bearings", NASA CP-3152, Part 1, pp. 289-296, Aug. 1991.

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