MAGNETIC BEARING TURBOMACHINERY CASE HISTORIES AND APPLICATIONS FOR SPACE RELATED EQUIPMENT

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SUMMARY

The concept of magnetic levitation is not a new one and can be easily traced back to the 1800's. (1) It is only recently, however, that the congruous technologies of electronic control systems, power electronics and magnetic materials have begun to merge to make the magnetic suspension device a viable product.

The following paper provides a brief overview of an active magnetic bearing technology.(2) Case histories of various turbomachinery in North America presently operating on magnetic bearings are reviewed. Finally, projections are made as to the space related machinery that may be benefited by incorporating magnetic bearings into the equipment design.

BACKGROUND

In theory, the principle is quite basic. An electromagnet will attract any piece of ferrous material. By using a stationary electromagnet (stator) and a rotating ferrous material (rotor) a shaft can be suspended in a magnetic field while maintaining accurate position under varying loads. This can be accomplished given a small space (air gap) between the stator and rotor and proper electronic control of the electromagnet. In the following case of the active magnetic bearing, this concept is utilized for both radial and axial configurations. It must be noted that the bearing system described here always operates in an attraction mode and never repulsion.

The radial and axial bearing rotors make use of a ferrous laminated sleeve and solid disc respectively.(3) Applying ferrous rotor elements to the shaft allows the shaft material to be constructed from a non-magnetic metal or composite material. While the radial bearing requires laminations due to the number of flux reversals during rotation, the axial rotor disc can be solid since the magnetic flux level is changing but the polarity is not.

As with any type of electromagnet, a wound field stator is required to produce a force output. Both the radial and axial bearing stators incorporate laminations to minimize stray losses and improve the bearing response time. The radial bearing stator is wound to provide four independently controllable quadrants for maximum rotor stability. The axial bearing, attracting the rotor in only one plane, requires the use of two stators, one on either side of the rotor disc, to provide double acting control.

Inductive position sensors are used to detect the exact radial and axial location of the shaft. Similar to the bearings, these sensors utilize a ferrous rotor and a wound field stator. As the air gap at the sensors changes with shaft disturbances the inductance bridge of the sensor also changes. It is this change in inductance with air gap variation that provides the position feedback signal required for closed loop servo control.

Figure 1 shows an isometric view of both a radial and double acting axial bearing with their associated position sensors.

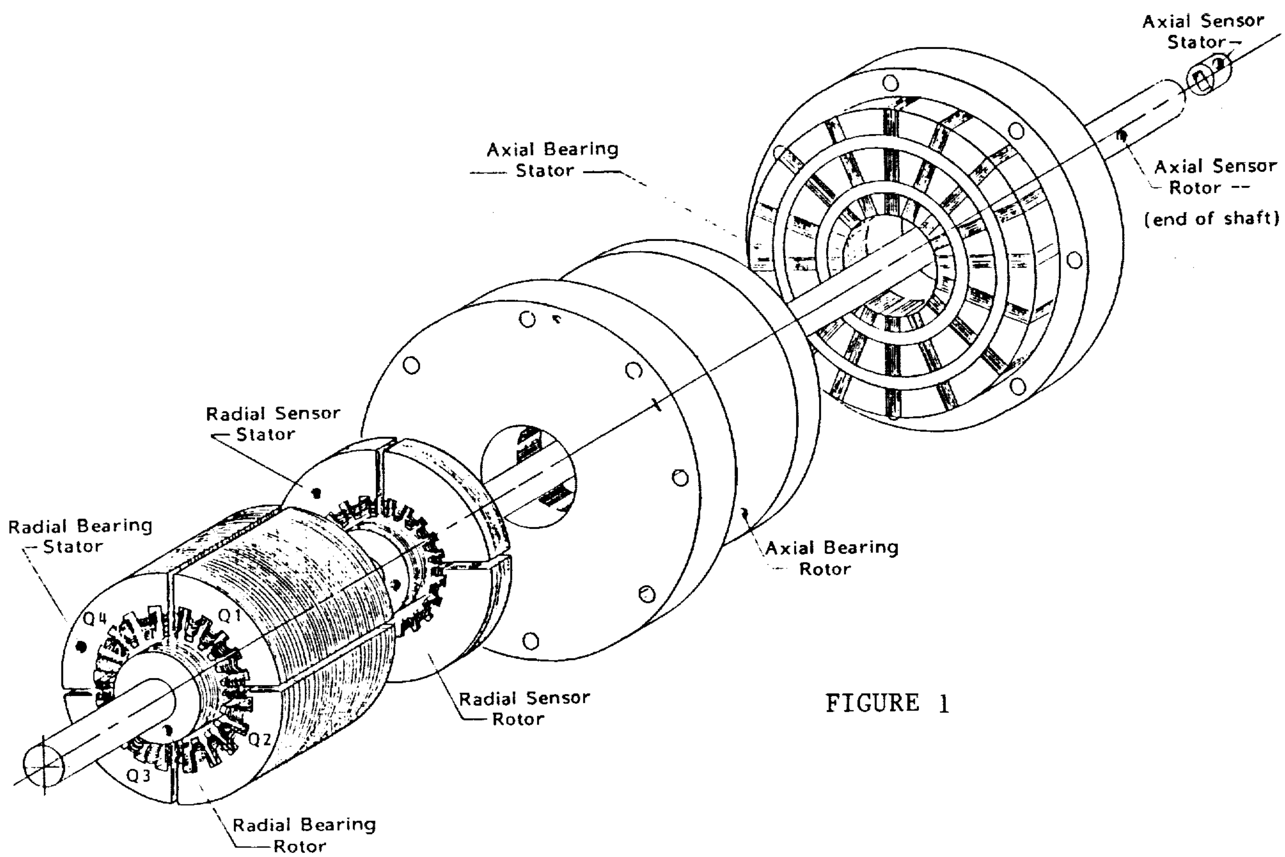

FIGURE 1

Control electronics are required to process the position signal and power the appropriate bearing coils. The exact shaft location is detected by the position sensors, and a DC voltage is generated which is relating to rotor displacement. This DC voltage (where the shaft is) is compared to the position reference signal (where the shaft should be). Any difference between these two signals generates an error signal which is used to maintain control of the rotor. This signal is then amplified, filtered, and conditioned prior to commanding the specified power amplifier(s). Current is increased or decreased in the appropriate bearing coil(s) to maintain the rotor at equilibrium. Figure 2 shows a basic block diagram of the closed loop servo control.

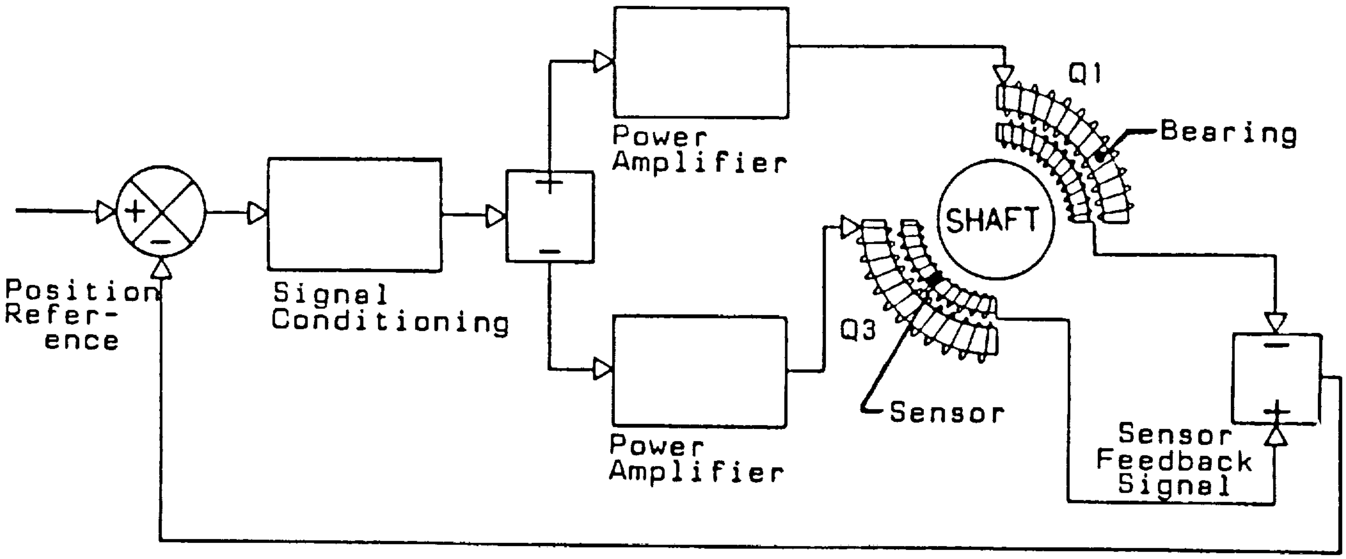

Figure 2

RADIAL BEARING CONFIGURATION

CASE HISTORIES

At the time of this writing, there are presently nine industrial machines in North America operating on this type of magnetic bearing system. Table 1 provides a listing of these units including basic machinery data.

TABLE 1

MACHINE	TYPE	SERVICE	DUTY	COMM	ROTOR WEIGHT LB	THRUST LOAD LB	SPEED RPM	JOURNAL DIAMETER	RATING HP	OPERATING HOURS (*)
CDP-230	CENT COMP	PIPELINE	SEASONAL	1985	3200	12000	5250	10.6"	14650	6800
CDP-416	CENT COMP	PIPELINE	SEASONAL	1986	280	3370	14500	3.7"	4150	6700
1B26	CENT COMP	PIPELINE	CONTINUOUS	1986	780	4050	11000	6.5"	5540	4800
1B26	CENT COMP	PIPELINE	CONTINUOUS	1987	780	4050	11000	6.5"	5540	300
CBF-842	CENT COMP	REFINERY	CONTINUOUS	1987	1420	4590	10250	6.0"	4500	750
8DD-300	CENT COMP	LAB	INTERMIT	1980	850	3150	13000	7.5"	5360	750
B15/1000	SPIN TESTER	PROD/TEST	INTERMIT	1985	17	17	60000	2.5"	20	375
7CK148	TEST RIG	LAB	INTERMIT	1980	675	2700	12000	5.9"	1800	610
	TEST RIG	LAB	INTERMIT	1985	350	300	10000	7.5"	40	50
HSNC-CN1	NEUTRON CHOPPER	LAB	INTERMIT	1984	33	33	48000	2.4	4	250

*AMB CABINET OPERATING HOURS AS OF DECEMBER 15, 1987

To date all of the above mentioned equipment have operated with a very high level of performance. The limited failures incurred have been attributed to human error (i.e.. wire rubbing on shaft after final machine assembly) or electrical component failure and not to design or technology flaws.

Reasons for utilizing magnetic bearings in rotating machinery vary with each particular application, although many common threads are evident. Heavy equipment users, typically employing oil lubricated tilting pad bearings, see many advantages, including efficiency and safety in eliminating the oil lubrication system.[4] Such a system utilizes external lube oil pumps, piping, reservoirs and filters which are also costly elements to install and maintain. In many cases, more heavy equipment down time is attributable to failures in machinery subsystems than actual machinery failure itself. Other users of magnetic bearings site higher speeds, harsh environment operation and optimized rotor dynamic characteristics[5] as reasons for using magnetic bearings.

While researching the operating histories of the previously mentioned machinery it became apparent that discussing each unit in depth would become monotonous. Following the commissioning of each machine multiple starts and stops have occurred and operating hours have accrued with very little attention brought by the fact that it is a "magnetic bearing" machine. In every case, there have been few or no equipment shutdowns attributable to the magnetic bearings. Those that have been were previously mentioned. Therefore, it was decided to expand from Table 1 only the one machine with the most operational hours.

The machine researched is an Ingersoll-Rand pipeline compressor model number CDP-230. The unit is part of the NOVA natural gas pipeline system in Alberta, Canada and was put into service at the Hussar compressor station in 1970. This train is ISO rated at 14,650 Hp and consists of a General Electric LM-1500 gas generator exhausting into an Ingersoll-Rand GT-51 power turbine dry coupled to the compressor. The normal operating speed range is from 3000 to 5250 rpm.

As originally supplied, this compressor incorporated oil film seals and bearings. In 1982 the conventional oil seal system was replaced by a mechanical dry gas seal.[6] Three years later conversion of this unit to the world's first oil free compressor of its type in production service was completed with the retrofit of the oil film bearings to active magnetic bearings.[7]

Following the installation of the magnetic bearings extensive dynamic testing took place. Two bearing resonant frequencies were identified at 28 and 42 Hz with first three shaft modes occurring at 89, 142 and 190 Hz. It can be seen that the first bending mode at 89 Hz (5,340 rpm) is very near the maximum operating speed of 5,250. However, the bearing control system maintained shaft movements no less than 0.8 mils peak-to-peak with no noticeable excess current draw during operation. Bearing parameters were monitored under various load conditions and data collected as per Table 2.

TABLE 2 — TEST VALUES - CURRENT, BEARING LOADS AND POWER CONSUMPTION

BEARING LOCATION		STATIC TESTING (0 RPM) CASING PRESSURIZED	NORMAL OPERATION 3600 RPM $\Delta P = 112$ PSI	CHOKE CONDITION 4500 RPM $\Delta P = 12$ PSI	SURGE CONDITION 4100 RPM $\Delta P = 152$ PSI	IN-SERVICE 12-15-87 4280 RPM	
OUTBOARD RADIAL BEARING	UPPER (2) QUADRANTS (AVERAGE)	17.6	18.3	17.7	18.0	17.2	CURRENT (AMPS)
		1370	1460	1370	1439	1339	LOAD (LBS)
	LOWER (2) QUADRANTS (AVERAGE)	5.0	5.0	5.0	5.0	5.0	CURRENT (AMPS)
		112	112	112	112	112	LOAD (LBS)
INBOARD RADIAL BEARING	UPPER (2) QUADRANTS (AVERAGE)	21.0	20.2	20.1	21.0	19.3	CURRENT (AMPS)
		1933	1798	1776	1933	1705	LOAD (LBS)
	LOWER (2) QUADRANTS (AVERAGE)	5.0	5.0	5.0	5.0	5.0	CURRENT (AMPS)
		112	112	112	112	112	LOAD (LBS)
THRUST BEARING	OUTBOARD	11.8	5.0	41.5	5.0	19.2	CURRENT (AMPS)
		679	112	8610	112	1790	LOAD (LBS)
	INBOARD	5.0	15.8	5.0	18.8	5.0	CURRENT (AMPS)
		112	1259	112	1753	112	LOAD (LBS)
TOTAL BEARING POWER CONSUMPTION (Hp)		4.7	5.1	5.4	5.1	4.8	

Subsequent evaluations of the operating history of this machine provided additional economic and performance data.[8] While most of this data includes improvement from the installation of both the gas seal and the magnetic bearings, it is representative of the benefits associated with a lubrication free machine.

By total elimination of the oil system, parasitic and oil shear horsepower losses improved the units output power by approximately 2%. The magnetic bearing system on the compressor uses about 5 Hp of energy. This compares to 302 Hp lost in the conventional bearing and seal oil system.

Maintenance savings were also calculated and determined to be a rather substantial figure. With the total absence of contacting stationary and rotating components no wear related maintenance was seen. Also maintenance to the lubrication and seal oil subsystems was eliminated. Overall machinery maintenance, call outs, and downtime have been reduced by 85%. With the total average scheduled maintenance cost for the compressor and associated equipment of $41,250 and $22,500 typically related to call outs and unscheduled maintenance, an annual maintenance savings of $54,187 was calculated.

Based on these maintenance savings and the additional savings associated with oil consumption and oil and pipeline contamination a payback period of 4.4 years is anticipated for this retrofit. Installation of magnetic bearings and dry gas seals in a new compressor where the initial bearing and seal costs are partially offset by not purchasing a bearing and seal oil system can improve the payback period to less than one year.

Lubrication free equipment capable of harsh environment operation is definitely seen as the future for many types of rotating machinery. At the time of this writing, the author's company is actively involved in the installation or commissioning of magnetic bearings in fourteen machines encompassing five different areas of application.

SPACE RELATED EQUIPMENT

If it can be stated that commercial applications are just now beginning to grow, it is safe to say that space related applications are still in their infancy. Most of the investigations and applications to date have been related to gyroscopes and momentum wheels.(9)(10) While these are indeed good applications of magnetic bearings which have proven to be successful to the space program, the real benefits can be gained by utilizing magnetic bearings in machinery with more of a production output.

With the potential seen today in zero-gravity space experiments and the possibility of specific production products being made in space, equipment requiring no lubrication and minimal maintenance is very attractive. Some equipment has already been developed with this particular application in mind. A turbomolecular vacuum pump having a magnetic bearing supported rotor has been developed for experimentation requiring a constant vacuum.(11) Where total vibratory isolation of a test table is required a magnetic suspension device to provide damping and stabilization could be incorporated.(12)

Further benefits can be gained by utilizing magnetic bearings in the power plant and life support systems of such projects as the upcoming space lab. Some of the advantages of high horsepower commercial equipment have already been discussed. By adopting magnetic bearings in the original design of equipment such as environmental control units for cabin pressurization and air circulation, these units output per weight ratio can be substantially increased. Smaller and lighter equipment, electric motor driven and operating at very high speeds (50,000 to 80,000 RPM) can now provide the same output as larger previous equipment typically less efficient and requiring some type of external lubrication system.

Work in the field of magnetic bearings has not gone unnoticed by NASA and indeed in many ways has been enhanced by them. Over the years, NASA has generated multiple patent activity relating to various magnetic bearing configurations.(13)(14) Additionally, some actual equipment, including a Stirling cycle cryogenic cooler operating on magnetic bearing, has been designed by NASA.(15)

CONCLUSION

The operational history of machinery utilizing magnetic bearings has uncovered many benefits provided to ground based equipment. With the advances continually being made in the areas of electronic components and control systems, magnetic alloys and superconducting materials, the field of magnetic levitation will continue to grow as fast as its associated technologies will allow. Investigation and applications work should be continued to fully understand and exploit the total potential of magnetic suspension devices for the United States space program.

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