WHAT IS THE FUTURE OF MAGNETIC BEARINGS FOR TURBOMACHINERY?

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ABSTRACT

Magnetic bearings offer many technical advantages for turbomachines such as oil-free operation, adjustable bearing parameters and the potential of high operating speeds. Although magnetic bearings have been tried for almost all kind of turbomachines, today this technology is mainly used for special applications and, thus, the real commercial breakthrough is still missing.

This paper describes how two large global players in the compressor drive market envision the future of magnetic bearings for the turbomachinery business. Based on their past experience with magnetic bearings, end-customer feedback and market surveys, the technical and business challenges that need to be solved, in order to satisfy the needs of turbomachinery manufacturers and end-customers, are described.

INTRODUCTION

Turbomachines such as pumps, compressors, gas expanders, steam and gas turbines, fans, turbochargers, motors and generators are used in many different applications. These start with small machines with a fraction of kW of power and end with large power plant turbines with more than a GW of power. Consequently, the turbomachinery market is not only huge but also rather fragmented. Nevertheless, there is an on-going trend towards higher speeds and higher power density. The main drivers are the increased efficiency of centrifugal compressors with rotational speed and a desire for more compact machine designs resulting in reduced size and weight. This trend is supported by on-going improvements in the area of materials, manufacturing technologies, and better calculation tools for mechanical and aerodynamic design. Not only does the technology change and evolve, the turbomachinery business environment is in transition too. Deregulation of the electricity market and the fast growing market of decentralized power generation are just two examples. From a technical point of view, rotordynamic design of high-speed turbomachines is more challenging and bearing technology is a key parameter. At the moment there are different competing designs and technologies such as modified conventional bearings (rolling element bearings, hydrostatic and hydrodynamic bearings), gas bearings (aerostatic and aerodynamic bearings) and magnetic bearings. Up to now, air bearings are only used for small turbomachines and it is rather unlikely that they will be used for larger machines in the near future.

Main criteria for the choice of bearings for an application are technical aspects such as load capacity, space requirements, rotational speed, speed range, vibration behavior, lifetime and reliability. If more than one feasible technical solution exists then cost (product cost, maintenance cost and design and engineering effort) will be the decision maker. It is rather unlikely that a customer will pay more for a better technical solution as long as there is no clear payback. Other aspects such as market perception and acceptance may play a role as well.

The paper will mainly focus on the gas compression market and its requirements.

COMPRESSOR MARKET

The market for compressor drives has experienced a significant growth over the last years. Previsions are revised at more conservative growth levels due to low oil and gas price, but forecasts still foresee a steady growth of a few percent in the next years. This is mainly

due to infrastructure replacement on older pipelines and pipeline expansion in the North American market.
While in the beginning the gas industry met its compression objectives with many small reciprocating compressor units, today gas companies use more cost efficient larger units and eventually gas turbines became the prime mover of choice. While gas fired engine driven compressors are convenient for gas companies, they are becoming increasingly difficult to install. Environmental restrictions have tightened the issue of permits. The Clean Air Act Amendment pushes industry towards technical solutions with high efficiency and low emissions. For the end-customer it is therefore preferable to have no emissions on-site in order to avoid penalties. In addition, noise in urban environment will be more restricted in the future.
The larger gas turbine units seemed a solution because they were the low capital cost prime mover and allowed relatively clean burning. However, gas turbines have not yet achieved the high degree of flexibility and fuel efficiency gas transporters hoped. Flexibility has become an increasingly important issue because of the new “peaking power plants” that are coming on-line. Gas companies are trying to solve the problem of low cost, low maintenance compression that can be quickly ramped up to meet peak demands.
It can be expected that the deregulation of the electricity market will lead to more competition and as a result to lower cost for electric power. Many gas companies have started to build up and/or to acquire power generation business. This will make the companies more independent from the gas price and will allow a proper cost comparison. Thus, the focus will be even more on systems that have low capital costs but nevertheless total operational costs will be of increasing importance.

Electric drives offer the necessary flexibility and have lower capital cost than gas fired drivers. With electricity available at competitive cost, total cost of operation is favorable as well. The next logical step is the use of electric high-speed drives that eliminate the need for a gearbox. Power converters are already available for the power range needed at competitive cost and further progress can be expected during the next years. In combination with the use of magnetic bearings such drives allow the elimination of the entire lube oil system resulting in a dry rotor string. The elimination of the gearbox and of the drive lube oil system results in increased efficiency and increased availability. This leads to reduced operation and maintenance cost. Furthermore, such electric high-speed drives can easily be adjusted to specific requirements, allow a wide operating range and thus the pipeline operation can be optimized. High efficiency, oil-free operation and no emissions make electric high-speed drives the most environmental friendly compressor drive.
As a result, it can be expected that the market share of electric high-speed drives will increase over the next years. The use of electric high-speed motors does offer the possibility to really exploit the advantages offered by magnetic bearings. The economic evaluation will be more favorable for magnetic bearings when not only the compressor but the drive as well can be realized oil-free.
In general, the customer expectations for a compressor drive are mainly based on the process requirements. Thus, first of all the customer buys the necessary compression (pressure ratio, head, etc.) and the main aspect for a compressor manufacturer is to fulfill these customer requirements. The next important point is to guarantee operation without interruptions and for varying conditions. Thus, customers rank availability and flexibility rather high. The next criteria are high efficiency, low maintenance and operating cost, and environmental aspects.
Whereas the compressor delivers what the customer and his application needs, the driver is only necessary to do the job. It is mainly seen as a part of the compressor drive with the expectation that the necessary performance can be delivered. The main criteria for the drive evaluation is therefore cost. After capital cost, efficiency and availability are ranked next because these points influence the operating cost of the system. Another criteria that is often mentioned from the compressor manufacturer is delivery time of the drive. Technical aspects such as the choice of the bearing type and the insulation class are at the end of the customer ranking.

MAGNETIC BEARINGS FOR TURBOMACHINES

Magnetic bearings have been applied successfully in centrifugal compressors for many years. However, the acceptance of magnetic bearings in many compression applications has not been widespread among the user community. Many problems in the beginning arose from a lack of experience at all parties (magnetic bearing supplier, compressor manufacturer and end-customer) and installations that have not been adequate for the heavy industry environment. These problems have been solved and, in combination with the progress in power electronics and digital control, the reliability has increased and achieved a satisfactory level [2]. These installations have demonstrated the technical feasibility and that the technical advantages of magnetic bearings can lead to economical advantages for some applications. Although the perception of magnetic bearings in general is positive in the turbomachinery business, there is still skepticism against this relatively

new technology. This is not only due to a rather conservative business environment with large capital investment and high cost for down-time but due to inherent problems of the technology and the business approach as well.
Yet, there are many potential benefits associated with magnetic bearings as well. Some of these are reduced energy consumption, lower parasitic losses, adjustable bearing parameters, excellent damping properties, contact-free and oil-free operation and that they therefore require no maintenance. The question is why this technology is not used for more applications and in larger quantities.

DESIGN OF TURBOMACHINES WITH MAGNETIC BEARINGS

From an equipment manufacturer's perspective, there are certain considerations associated with magnetic bearings that must be taken into account during the early design phase of a turbomachine. Some of these are now explained in more detail.

Load carrying capability

The most critical factor from an equipment design perspective is to have a good understanding of what loads each component of a machine is subjected to during operation. While most oil lubricated bearings can be run indefinitely at loads exceeding 200 psi (1.4 MPa), magnetic bearings typically have a maximum load capability of about 70 psi (0.5 MPa). Therefore, the equipment manufacturer must have a good grasp of all loads that the bearing can be expected to encounter. Steady state and dynamic loads arise from the rotor weight, unbalance forces, and aerodynamic excitations. Additional forces can arise from piping thermal growth, and variation in shaft alignment.
Magnetic bearings are less forgiving for deviations between simulation and reality than conventional bearings. When overloaded oil lubricated bearings usually will continue to function although they may overheat and lifetime may be drastically reduced. Magnetic bearings will saturate when overloaded and thus there is a maximum load they can take. If this maximum is exceeded then the magnetic bearing is no longer able to hold the rotor and the rotor will touch the auxiliary bearings. Such deviations may occur due to uncertainties in many parameters during the design and due to overload at off-design operating conditions.
There is a significant difference between compressors and motors. Motors are usually heavier but there are no fluid forces acting on the rotor and therefore there are less uncertainties in predicting the necessary load capacity. Furthermore, motors usually encounter small axial forces and therefore almost all motors do not need a thrust bearing. For compressors rather high axial loads may occur and the design of balance piston and thrust bearing is important. The possibility of significantly reducing thrust bearing losses may be an advantage of magnetic bearings.

Physical size (dimensions)

Because of the relatively low load carrying capability, magnetic bearings usually have physical dimensions that are significantly larger than a conventional oil lubricated bearing. The impact upon the design of a compressor is usually manifested by an increased rotor length and more space being required to accommodate the bearing housings. Figure 1 illustrates the amount of space required for the magnetic bearings for a small sized multi-stage compressor rotor.

FIGURE 1: Multi-stage compressor rotor with magnetic bearings

Heat generation

Even though the magnetic bearing parasitic losses are significantly lower than a conventional oil lubricated bearing, heat is still generated by the eddy current and windage losses, that must be dissipated by external cooling. This represents a small utility that must be provided to the bearings in the form of slightly pressurized air or inert gas. For motors the cooling of the magnetic bearings can be integrated into the cooling concept.
Validated accurate magnetic bearing loss models that allow design checks and better predictions are crucial for the design of turbomachines with magnetic bearings. On this topic additional research seems to be necessary.

Rotordynamics

Today, compressors run successfully with hydrodynamic bearings at high rotational speeds. Most compressors operate below the first lateral critical speed. Multi-stage compressors, however, often operate above the first lateral critical speed.
Motors to drive such compressors tend to be larger and heavier. For high-power high-speed motors, operation above the first lateral critical speed is rather likely. It

will be difficult to design motors for the future demands of compressors with hydrodynamic bearings because the operating speed range would be limited. Although a single design might be feasible, a range of motors will be difficult to realize. Magnetic bearings offer a very good possibility for equipment manufacturers to overcome such design restrictions. Due to the programmable rotordynamic behavior and due to the excellent damping properties it is much easier to achieve the desired speed range and to fulfill international standards such as API 617. The challenge is to design a range of motors with magnetic bearings avoiding high engineering effort and high cost.

Off-design operation and process upset conditions

Loss of electric power resulting in de-levitation of the rotor is perhaps the most severe condition encountered by a magnetic bearing. The rotor must also be designed to have acceptable dynamic behavior when coast down is required on the auxiliary bearings. The auxiliary bearings are typical rolling element or stationary sleeve bearings. This is very important for multi-stage compressor rotors that typically operate above the first lateral critical speed. High-speed motors usually are heavier and most often operate above the first lateral critical speed too. Therefore, for a high-speed motor design the auxiliary bearings are crucial as well. For turbomachinery manufacturers it is absolutely necessary to be able to simulate and predict the rotordynamic behavior during a de-levitation in order to check clearances, rotordynamic stability and mechanical integrity.

Today, there is still not enough confidence in the design of the auxiliary bearing and in the simulation of a de-levitation event. Testing is required to prove the functionality of the auxiliary bearings. Such testing is time consuming and expensive. It is therefore necessary to develop simulation tools for equipment manufacturers that allow the prediction of the de-levitation behavior. In addition, design rules and guidelines would be very useful.

Furthermore, bearing manufacturers should be more involved in the design of auxiliary bearings. These companies do have the necessary experience, know-how and calculation tools to design a bearing for the special conditions that occur during rotor de-levitation. From an equipment manufacturer's point of view it would be desirable to have auxiliary bearings as a stand-alone product that is developed and marketed by bearing manufacturers. From this point of view it is promising that large bearing companies such as SFK, Federal Mogul and Koyo are, at least financially, involved in the magnetic bearing business.

System design and system responsibility

Let's face it, a magnetic bearing is still a bearing. Of course, the design process and the control system make it different to a conventional bearing. Nevertheless, for an equipment manufacturer the main functionality of a magnetic bearing is to suspend the rotor. Today, turbomachinery manufacturers understand the bearings they use for their applications. Bearings are not a core competence and thus they are purchased from bearing suppliers. The bearing design is highly standardized and if custom designed bearings are needed this work is done by the bearing manufacturer. Nonetheless, equipment manufacturers have design rules, experience, and rotordynamic simulation programs that are capable to calculate their turbomachines.

Due to the different load capacity and the different space requirements the design of applications with magnetic bearings usually needs a new design. It will be very hard to convince equipment manufacturers to use magnetic bearings if they somehow have to give up full system responsibility. As long as the equipment manufacturers do not have the necessary know-how and design and simulation tools in-house, magnetic bearings will fall out of many prototype and product developments. It must be possible for equipment manufacturers to do conceptual pre-studies and design evaluations in-house. It is just too painful and too expensive to start a magnetic bearing development in parallel.

As long as magnetic bearing companies try to sell a system a key question is, what is the motivation for a compressor or motor manufacturer to use magnetic bearings? First of all, it is not attractive to buy in a "black box" that is a crucial part of the application. On the other hand the equipment manufacturer has to guarantee performance, reliability, etc. to the end-customer. Furthermore, for many equipment manufacturers packaging and service is an important part of their business. It is not surprising that many requests for installations with magnetic bearings were motivated more by the end-customer than by the equipment manufacturer.

The only way to make magnetic bearings more attractive to equipment manufacturers is to make them a standard, easy to use product with clear interfaces.

Standardization and standards

Standardization will be the key for wider use and for cost reduction. This will allow easier design and interchangeability for equipment manufacturers. In addition, systems from different suppliers could be used, and the dependency on a single supplier would be reduced. Without standardization changing the supplier results in a significant design and engineering effort and thus in cost. Furthermore, it is more difficult to combine

systems from different suppliers. Although there is no real technical reason not to do this, customer acceptance might be low. The better the components are standardized and the better the interfaces are defined, fewer problems can be expected and therefore the higher the acceptance for such a solution.
A lack of international standards leads to the problem that design criteria and acceptance criteria are missing and need to be discussed between equipment manufacturers and end-customers. This is time consuming and involves risks on both sides due to unclear specifications and misunderstanding.
The situation is similar to where hydrodynamic bearings were about 30 years ago. Focussing on core competencies and standardization helped to significantly reduce cost, to make them a commodity and, finally, to increase their market share and customer acceptance. If magnetic bearings want to do the step from an enabling technology to an industrial product then the business approach needs to change. Today, magnetic bearing suppliers do everything from bearing design and manufacturing, system design and commissioning. Defined standards and interfaces would allow sub-suppliers to deliver sub-systems. Ultimately, standardization and increased competition would result in lower product cost.
If magnetic bearing suppliers are not willing to define such standards, then equipment manufacturers need to work on this. It should be a common interest of magnetic bearing users to progress into that direction.

Cost

Although cost of magnetic bearings has decreased over the years, they are still very expensive and their use can only be justified for some special applications. Cost consists of product cost, design and engineering effort, and commissioning. Standardization is the most likely way to reduce cost to a level where magnetic bearings become attractive for more applications. Today, hardware cost of magnetic bearings may be 10 to 15 times higher than hydrodynamic bearings and result in 30 to 50 percent of the total cost of an electric motor. Here, manpower (design, engineering, commissioning) is not included. It is obvious that for many applications such an investment is hard to justify, even when savings for a gearbox and oil supply systems are taken into account.

OPERATION, SERVICE AND MAINTENANCE

In-house expertise for troubleshooting

Most users of centrifugal compressors look to the manufacturers of those machines to provide expertise for problem resolution. The on-line diagnostic capability of today's modern control systems allows the compressor manufacturer's design engineers and field service engineers to work closely with the magnetic bearing manufacturer's engineers and the user's engineers to quickly correct any problem conditions.
It is often mentioned that magnetic bearings would increase the intelligence of the system and allow better condition monitoring. This is true, of course, but for the equipment manufacturer and the end-customer there is only a benefit if the data can be fed in and analyzed in existing monitoring and diagnostics systems. A joint approach between magnetic bearing suppliers, suppliers of monitoring and control systems, and equipment manufacturers should lead to solutions that are helpful for the end-customer.

Reliability

In many compressor applications reliability and availability are very important. It is often stated that magnetic bearing systems are very reliable but published data are missing. Especially for large turbomachines magnetic bearings should be designed and tested for reliability. Redundant systems, however, are not necessarily a good solution, if cost is increased too much. Drive manufacturers spend a lot of effort in product reliability [9] and it is clear that magnetic bearings must not decrease reliability of the overall system.
Auxiliary bearings are another point that needs to be addressed with reliability. Disassembly and assembly of a turbomachine may result in significant cost. Therefore, replacement of auxiliary bearings will only be done if necessary. This requires auxiliary bearings that will function even after many years and tests to check their functionality.

Service and maintenance

Today, service and maintenance is done either by the equipment manufacturers or by the end-customer. Engineers at compressor sites are often not familiar with magnetic bearing equipment and thus troubleshooting on-site may become more difficult.
It is very unlikely that large turbomachinery manufacturers are willing to put themselves in a situation where they fully depend on small magnetic bearing companies. It is doubtful that these could do the necessary service and maintenance full-time on a worldwide basis. From that point of view it would be desirable for equipment manufacturers to do commissioning, service and maintenance with their own crew. In addition, service contracts are a vital part of the business of many turbomachinery companies.

Summary

Due to a changing business environment it can be expected that more electric drives will be used in the future for gas compression. As a result, the motivation to use magnetic bearings will increase as well because oil-free rotor strings are now possible.

The main disadvantages of magnetic bearings are technical and business related. The main technical drawbacks are the need for auxiliary bearings in the case the magnetic bearings fail and lower load capacity compared with other bearings. Existing compressor and gas expander installations show that these points can be overcome with a proper design. Due to the fact that magnetic bearings need to be designed to a specific application the design process is usually complex, time consuming and expensive. Today, most turbomachinery manufacturers and end-customers have neither enough experience nor the necessary know-how to do design evaluations. Thus, there do not exist clear product specifications, company standards or design and engineering procedures. Furthermore, there is a clear lack of standardization of magnetic bearings as well as a lack of international standards. This leads to a typical prototype approach and results in high hardware and engineering cost. As a result, it is difficult to do design changes or to change the supplier, and service, operation and maintenance are often problematic.

At the moment, magnetic bearings are not overly attractive for turbomachinery manufacturers. Standardization, international standards and a different business approach would make magnetic bearings a more cost efficient, easy to use product.

OUTLOOK ON OTHER MARKETS AND APPLICATIONS

Very high-power turbomachines

For “traditional” power generation it is not foreseeable that the technology is moving into a direction where magnetic bearings would lead to business opportunities. It cannot be expected that power generation will go to higher speeds. As long as fixed speed operation at grid frequency is used the advantages of adjustable bearing properties are limited. In addition, the rotors tend to be very heavy and may weigh more than 100 tons. Here, the much better load capacity of hydrodynamic bearings and the need for auxiliary bearings are clear disadvantages of magnetic bearings.

Small turbomachines

In the smaller power range the applications as well as their requirements are widespread. The trend to higher power density is combined with a trend towards system integration and packaging. This reduces the complexity of the system and helps to reduce cost. Interesting examples for highly integrated systems operating at high speed are high-speed compressors and micro-turbines for decentralized power generation. It is noteworthy that machines that are already commercially available either use air bearings (compliant foil bearings) or rolling element bearings similar to aircraft gas turbines. For smaller machines, magnetic bearings need to compete with air bearings; both allow oil-free operation. The load capacity given in literature for compliant foil bearings is similar to magnetic bearings. Today, air bearings need high development effort as well. Magnetic bearings could be of interest for small turbomachines if they have attractive cost and are easy to use. Therefore, the technical and business related problems are similar to larger turbomachines.

CONCLUSIONS

Whether magnetic bearings have a bright future in the turbomachinery market or remain a product for niche applications will very much depend on a change from a prototype approach towards a standard product. Thus, magnetic bearings need to become an easy to design and easy to use commodity in order to achieve better market acceptance.

REFERENCES

[1] Ahrens, M.; Frei-Spreiter, B.; Wieser, R.: Cost efficient electric high-speed drives with magnetic bearings for the COG market, International Symposium on Magnetic Bearings, Zurich, 2000

[2] Alves, P.S.; Alavi, B.M.: Magnetic Bearing Improvement Program at Nova, Presented at the International Gas Turbine and Aeroengine Congress & Exhibition, Birmingham, June 1996

[3] Electric Power Research Institute (EPRI): Market Analysis for Natural Gas Compression Technologies, TR-107547, 1996

[4] Gilon, D.C.; Boutriau, L.: Experience with High Speed Induction Motors for Direct Driving of Compressors, Proceedings of the 27th Turbomachinery Symposium, Houston, pp. 1 - 6, 1998

[5] Kleiner, F.; de Wit, B.; Ponick, B.: Ecology and Economy Decide for 50'000 HP Electric Turbocompressor Driver, IEEE Paper No. PCIC-99-05, 1999

[6] Oliver, J.A.; Poteet, D.C.; Kempers, G.: Electrification of natural gas pipelines, the opportunity and the available technology, American Power Conference, Chicago, 1995

[7] Rama, J.; Giesecke, A.: High-Speed Electric Drives: Technology and Opportunity, IEEE Industry Applications Magazine, Vol. 3 No. 5, pp. 48 - 55, Sep/Oct 1997

[8] Swanson, E.; Heshmat, H.: Capabilities of large foil bearings, ASME Turbo Expo, Munich, 2000

[9] Wikstroem, P.; Terens, L.; Kobi, H.: Reliability, Availability and Maintainability (RAM) of High Power Variable Speed Drive Systems, IEEE Paper No. PCIC-98-16, pp. 139 - 148, 1998