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Turboexpanders with Active Magnetic Bearings: History and Looking Ahead

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Abstract

Turboexpanders are important machines in industries where gas expansion to generate refrigeration can be utilized such as ethylene processing and natural gas processing. In many turboexpander applications, oil-free support systems are attractive to avoid process contamination, making turboexpanders with active magnetic bearings valuable. On top of eliminating the risk of oil contaminating the industrial process, active magnetic bearings provide benefits such as increased reliability compared with oil bearings and a smaller footprint. In addition to traditional gas and hydrocarbon processing, new opportunities are under investigation for turboexpanders. To enable active magnetic bearings to thrive supporting turboexpanders in these new opportunities, innovation with the new applications in mind will be necessary for turboexpanders with active magnetic bearings to be a competitive option. In this paper, turboexpander history, a few key case studies, and the authors' experience are used to identify areas that benefit from active magnetic bearings development. The recommendations include ideas for the actuator, the auxiliary bearings, the controller, and industrial specifications and standards. Inspiration is derived from technology in public literature and the applicability to turboexpanders and potential applications are highlighted. Ultimately, with cooperation between industry engineers, academic researchers, and other contributors, active magnetic bearings and turboexpanders can continue working together in novel applications.

Keywords : turboexpanders, industry, active magnetic bearings, innovation, cryogenic

1. Introduction

Turboexpanders with active magnetic bearings (AMBs) rapidly evolved "from novelty to standard practice" (Jumonville, 2004), underscoring their transformative impact. Today they play critical roles in industries such as ethylene production plants, natural gas processing, liquefied natural gas (LNG) pretreatment and liquefaction, and hydrogen liquefaction and purification.

The roots of turboexpanders may be considered part of a "Second Industrial Revolution" in the late 19th century (Landes, 1969) where "science was not just useful; it was essential" (Stokes & Banken, 2015) and progress increasingly relied on theoretical understanding. The 21st century may prove similarly pivotal, with AMBs offering new potential grounded in theoretical insight.

Turboexpanders with AMBs can be advanced and enabled in new markets by gaining insight from history and experience. To that end, this paper covers the following: (1) turboexpander basics, (2) significant milestones in turboexpander history (3) literature review including case studies, and (4) opportunities identified that can broaden the applicability of turboexpanders with AMBs in new industries.

1.2 Turboexpander Basics

A turboexpander is an expansion turbine (the "expander"), radial or axial, connected to a load device. This paper focuses on radial inflow turbines. For detailed coverage of expander types and selection criteria, readers are referred to Bloch and Soares (2001).

A common configuration is the expander-compressor (EC), where the expander is directly coupled to a compressor via a single rigid shaft. When supported by active magnetic bearings, this becomes an expander-compressor with magnetic bearings (ECM). The compressor can reduce upstream or downstream compression requirements and enable a hermetically sealed system without external shaft seals. Figure 1 shows a schematic of an ECM and Figure 2 shows a cross-sectional view with some key details highlighted for reference.

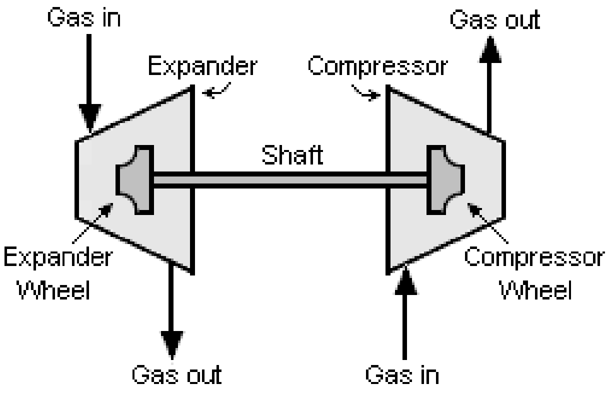

Figure 1- A schematic representation of a turboexpander.

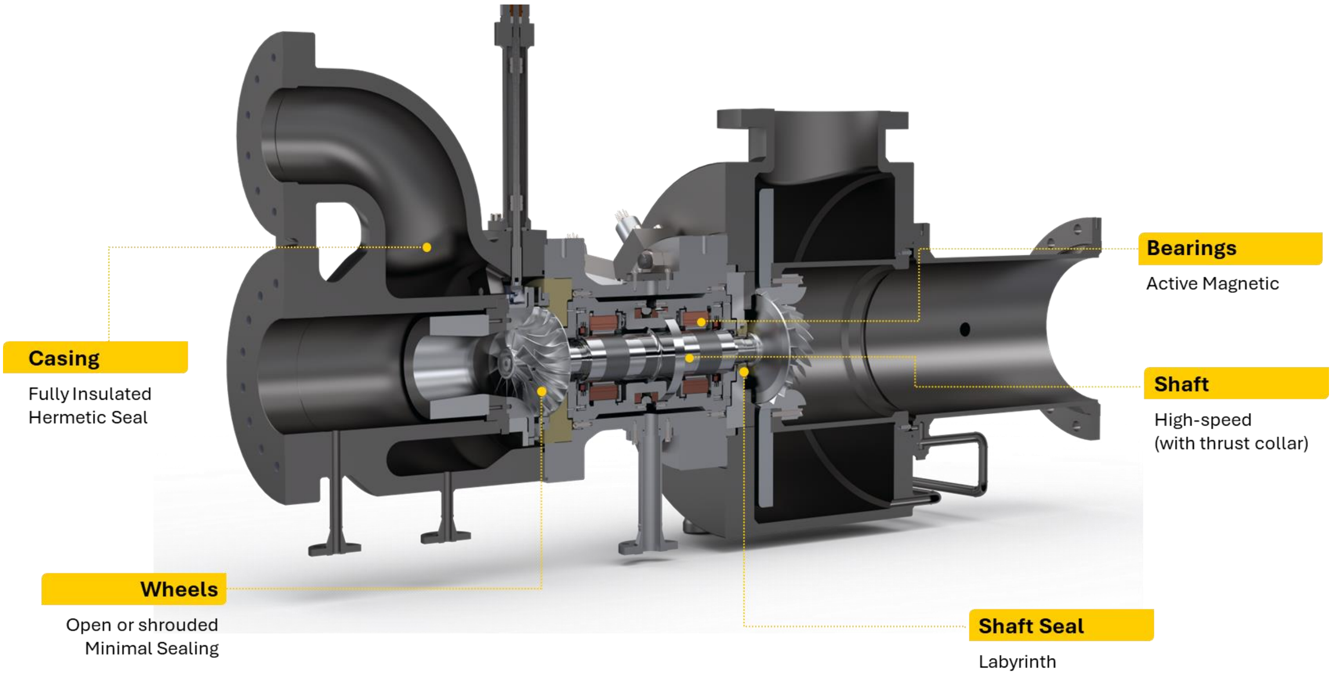

Figure 2 ECM cross-section courtesy of Atlas Copco Mafi-Trench.

Typically, the primary output of turboexpanders is the refrigeration effect of gas expansion through the expander wheel. While the ECs are prevalent, the load can be any system that dissipates or absorbs energy such as oil brake. A notable subset of turboexpanders, expander-generators, is discussed further in Section 3.1.2.

1.3 Turboexpander History

Turboexpanders with radial inflow turbines date back to the 19th century. In 1898, Lord Rayleigh proposed a turbine (rather than reciprocating pistons) for refrigeration using isentropic expansion. (Sixsmith, 1984) In 1936, Zerkowitz of Linde AG patented a turboexpander design that significantly improved gas separation efficiency. (Patent No. 2,165,994, 1936) This innovation built on the legacy of Carl von Linde, who pioneered air liquefaction using the Joule-Thomson effect. (Haring, 2007)

In 1939, Pyotr Kapitsa introduced a design that laid the foundation for modern turboexpanders. (Almqvist, 2002) In

1942, Judson S. Swearingen developed a seal that enabled the K-25 Gaseous Diffusion Plant. (Hewlett, et al., 1962) Though not unique to turboexpanders, the technology helped Swearingen found Rotoflow Corporation, a major pioneer of hydrocarbon turboexpanders.

Rotoflow technology enabled the first turboexpander application beyond air separation, natural gas processing, in the early 1960s. (Avetian & Rodriguez, 2020) Turboexpanders were introduced in ethylene production plants from the 1970s. (Agahi, et al., 2016) Energy recovery, typically via geared generators, becomes a focus in the 1980s in geothermal Organic Rankine Cycle power plants and LNG pressure letdown applications.

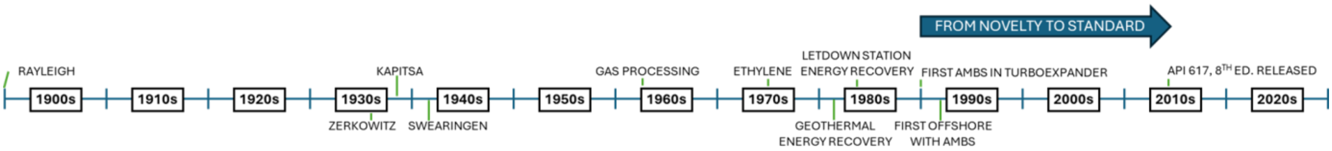

Figure 3- A High-Level Timeline View Leading Up to and including Turboexpanders w/ AMBs

1.4 Active Magnetic Bearings in Turboexpanders

The first turboexpander supported by active magnetic bearings (AMBs) was developed by Cryostar in 1988. Offshore applications followed in 1993, with S2M supplying the bearings for these and many subsequent installations. AMB control systems transition from analog to digital in the 1990s (Ueyama, 2003) and ECMs with digital control were being commissioned by the early 2000s. (Bloch & Soares, 2001)

In 2014, the API Standard 617 (Eighth Edition) introduced an annex specifically addressing AMB requirements including ECMs. This marked a significant step in industry acceptance of ECMs. The ninth edition, released in 2022, expanded on these requirements. API 617 and the AMB annex reference and build on ISO 14839 which has sections published as early as 2002.

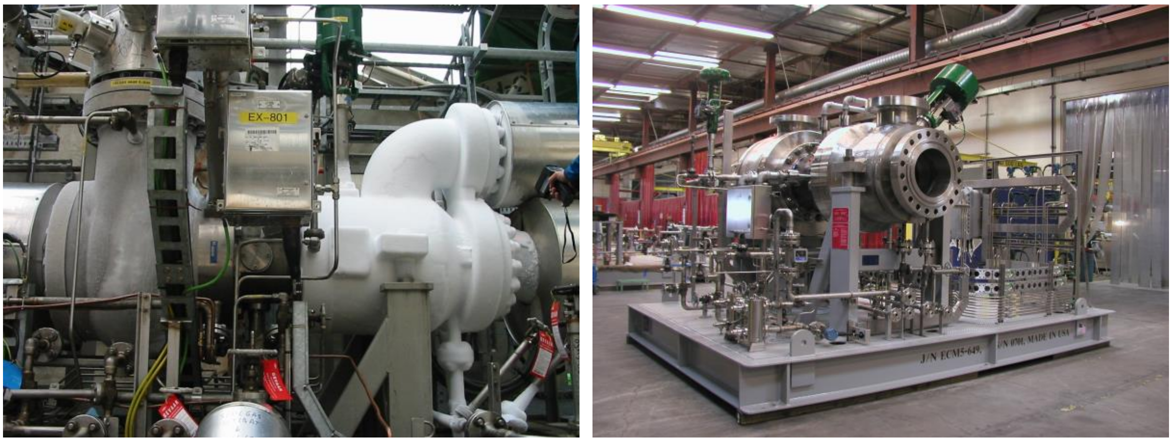

Figure 4 - An ECM installed on-site (left) in an ethylene production plant and an ECM shown on a skid (right). Images courtesy of Atlas Copco Mafi-Trench

1.5 Scope

This paper focuses on ECMs, though topics discussed may be broadly applicable. Reviewed literature will focus on systems with AMBs, but studies with other bearing systems may be considered if they highlight relevant challenges for AMBs. Key performance characteristics include reliability, availability, cost, and efficiency. Because modern ECMs have high reliability and availability, potential improvements may focus on cost and efficiency. The authors' experience designing and building turboexpanders will also help identify more subtle aspects such as impacts to assembly.

2. Literature Review: Market Opportunities & Case Studies

Interest in ECMs continues to grow, as shown by shipment trends in Figure 5. While this growth is promising, expanding turboexpander applications beyond traditional markets remains a key industry goal. Standard applications often drive incremental improvements, but broader adoption will require innovation. As turboexpanders gain traction, AMBs stand to benefit as well.

This section outlines the foundation for future development. It begins with general market trends and challenges, followed by case studies that highlight specific technical hurdles. These insights, combined with the authors' experience, inform the opportunity areas explored in Section 3.

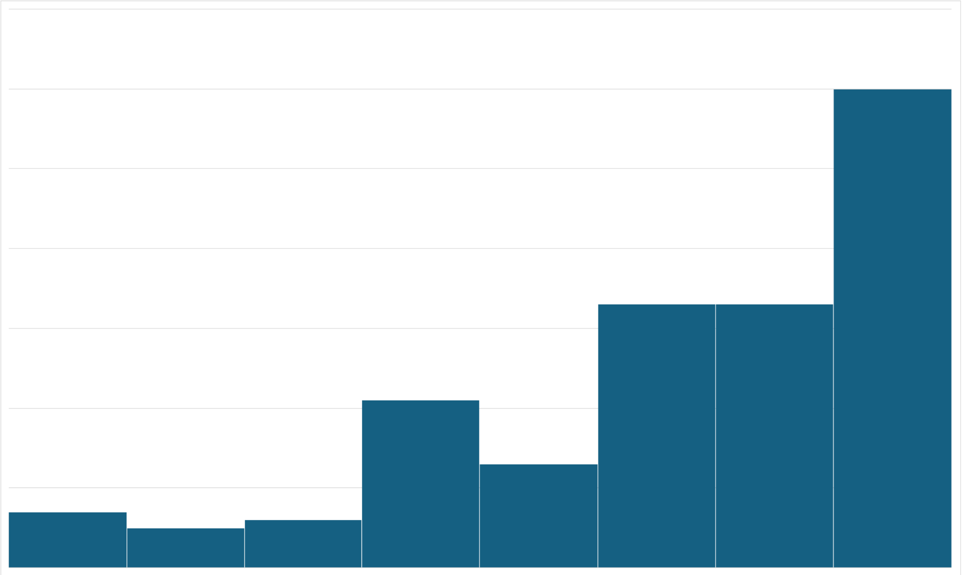

Figure 5 – Trend in ECMs shipped by a single OEM, 1992-2025. Data courtesy of Atlas Copco Mafi-Trench.

2.1. General Challenges for Turboexpanders with AMBs

Gelin and Lucas (2023) outlined focus areas for AMB systems, many of which apply directly to turboexpanders:

- Limited stiffness and damping at low frequencies
- Sub-synchronous instability for both forward and backwards modes
- AMB thrust load requirements
- Process gas compatibility and qualification
- Auxiliary bearings especially protocols on replacement
- Tuning and making sure AMBs are not "black boxes"
- Acceptance Criteria during Factory Acceptance Testing
- Spares strategy and obsolescence
- Cost

Cost is a critical factor. As machine size and power decrease, cost becomes proportionally more significant . (Danieli, et al., 2020) For AMBs to be competitive in emerging turboexpander applications, further cost reductions are essential.

Jumonville and Yates make recommendations for systems with AMBs for mitigating age-related problems. (2003) In a similar time-dependent sense, unbalance degradation can occur due to erosion on the wheels. (Davidson, et al.)

Kulhanek et al. present a case study that indicates a challenge common to all turboexpanders: operation at high power can be highly sensitive to process variation. Cross-coupling greater than typical design equations in labyrinth seals were suspected to be one source of sensitivity. Analytical study with rotordynamic models supported the hypothesis and additional evidence was obtained from improvement after swirl brakes were introduced.

2.2. Sensor Failures from Contamination at Shah Deniz (Ershaghi, et al., 2012)

Shah Deniz, one of the world's largest turboexpander gas processing facilities, experienced its first sensor failure just months after commissioning. Losses are estimated at $0.5 million per day, highlighting the importance of turboexpander reliability.

A root cause analysis revealed that under certain conditions, seal gas differential pressure was lost, allowing contaminants to enter the AMB system causing sensor failure and loss of bearing control. Attempts to modify the sealing system did not fully eliminate the issue. Ultimately, S2M developed a more robust bearing design (known as S2M Upstream Technology) that enabled more reliable operation.

The case study highlights two key lessons: First, all upset conditions should be checked during initial simulations and system design. Second, protecting AMBs from contamination is essential by improving AMB robustness and ensuring proper sealing.


Figure 6 – Left: A platform at the Shah Deniz field (The Shah Deniz Field, 2025); Right – Picture of sensor contamination

2.3. Sub-synchronous Vibrations at N’Kossa field (Shokraneh, et al., 2016)

The N’Kossa facility began operation in 1996 with two ECMs that accumulated over 250 thousand hours of runtime. In 2010, the equipment was redesigned for higher gas volumes. The opportunity was taken to upgrade the AMB control cabinet. The original AMBs were deemed suitable and retained. After successful Factory Acceptance Tests, the redesigned ECMs were commissioned in 2013. However, subsynchronous vibration of around 100 Hz was detected at 15,000 rpm.


Figure 7 - N'Kossa field facility from Shokraneh et al. (2016)

Further rework was required to address the vibration and the ECMs have been running continuously at full speed since May 2014 (at least up to the publication of Shokraneh, et al.). Liquid presence was identified as a major source of the subsynchronous vibration, highlighting the importance of impeller design and seal design to minimize the issue. Liquid ingress was further controlled with a system to adjust the expansion across the nozzles. Downtime would further be minimized if AMBs have sufficient capacity to handle forces from subsynchronous vibration as determined by a thorough rotordynamic evaluation.

2.4. Subsynchronous Vibrations in a Natural Gas Processing Facility (Avetian, et al., 2019)

In this case study, a turboexpander system failed to reach design speed due to high subsynchronous vibrations, triggering shutdowns around 15,000 rpm. Drawing from prior experience at N’Kossa, the OEM suspected liquid accumulation in the wheel and seals. However, mitigation efforts targeting liquid ingress did not solve the issue.

After months of troubleshooting, it was agreed that a rotordynamic analysis became necessary. The system had originally been designed under API 617 (7th edition), which did not require a stability analysis due to the first bending mode being well above the maximum continuous operating speed. Avetian et al. observed the following:

1. AMB systems may be more susceptible to unstable rigid body modes from aerodynamic cross-coupling
2. Limited options for retrofitting AMBs compared with oil bearings where clearance changes, adding squeeze film dampers, changing oil properties, and other changes are feasible
3. Fundamental limits including flux density limits, thermal limits, and current limits

Ultimately, the AMB capability could not be improved to solve the problem, and an "invasive re-design" was required. The redesign was considered successful even though the machine did not achieve the original design speed.

2.5. Experience with Nitrogen Turboexpanders (Benton Jr. & Eisworth, 2018)

Benton and Eisworth shared insights from successful deployments of turboexpanders for LNG production using nitrogen as the working fluid. Although AMBs offered advantages such as reduced weight, smaller footprint, and fewer components, oil bearings were ultimately selected for contractual offerings. The primary concern was the transient thrust loads expected during startup and shutdown. Field validation confirmed these predictions and revealed additional unanticipated loadings that exceeded design expectations—further justifying the use of oil bearings.

Beyond technical considerations, the publication emphasized the importance of clear communication throughout the project lifecycle. Standards like API 617 help align expectations between OEMs and customers, but the case highlights the need for even more effective collaboration, especially when it comes to AMBs which are newer and require more specialized resources than oil-lubricated bearings

2.6. Emerging and Potential Markets

Organic Rankine Cycle (ORC) applications have seen significant growth in the last twenty years. (Tartiere & Astolfi, 2017) While the concept is mature, turboexpander adoption is limited by cost, especially for lower power systems. (Alshammari, et al., 2018) Alshammari, et al. also note that turboexpanders are more limited in handling multiphase flows.

Interest in supercritical CO_2 (sCO2) has surged in the last 15 years. (Tamilarasan, et al., 2024) Systems using sCO2 cycles are typically power dense systems that can achieve high power outputs with very small machines. Various sCO2 cycles use turboexpanders. AMBs are a promising fit, but challenges remain. (Kim, et al., 2021) Compared to air, sCO2 is denser and introduces greater destabilizing forces. Machines using sCO2 cycles are also sensitive to any leakage (Bidkar, et al., 2017), so any improvements in the AMB design that may help reduce seal clearances are significant.

Hydrogen "has the potential to be one of the largest global commodities in the decades to come." (Mann, et al., 2022) In addition to the expected applications such as hydrogen liquefaction where turboexpanders can provide the cooling required, related infrastructure may also benefit from turboexpanders. For example, the National Renewable Energy Lab (NREL) of the US Department of Energy investigated using turboexpanders for precooling hydrogen at hydrogen filling stations for vehicles. (Post, et al., 2023) The precooling "represents a significant part of the station capital and operating costs", therefore reducing overall turboexpander costs may make this type of application more feasible with turboexpanders.

Bioenergy with Carbon Capture and Storage, or BECCS, is a recent technology that promises decarbonization of the power sector and industrial sector. (Bartocci, et al., 2022) In addition to efficiency being a high priority, it was noted that another concern could be solid entrainment in the turboexpanders from the BECCS process design. Handling solid particles is atypical for turboexpanders and would need to be investigated.

Ocean thermal energy conversion (OTEC) uses turboexpanders to convert energy from the temperature differential between the ocean surface and deeper water. (Nithesh, et al., 2015) Similar to hydrocarbon floating platform applications, OTEC could benefit from turboexpanders with AMBs to improve the economics of developing an OTEC power plant.

An application closer to home, turboexpanders have been proposed for use in a residential heat pump to improve overall system efficiency. (Barta, et al., 2020) It is common to use thermostatic expansion valves or electronic expansion valves in the heat pump vapor-compression cycle to control the expansion process. Turboexpanders provide an alternative to harness the energy available in the expansion process. To best support residential applications, minimizing cost and simplicity would be top priorities.

Last, but not least, an intriguing application of turboexpanders in hypersonic propulsion is proposed by Gao et al. (2023) It would be a challenging application using high energy density hydrocarbons. Turboexpanders with AMBs must have the highest level of robustness to be competitively suitable for this type of application.

3. Opportunities

Based on literature and the authors' experience, key factors for expanding use of turboexpanders with AMB are:

1. Minimizing cost
2. Maximizing robustness
3. Maximizing efficiency
4. Maximizing load capacity

Possible paths of investigation are grouped into the following categories: System/Actuator Architecture, Manufacturing Techniques and Technologies, Instrumentation and Controls, Auxiliary Bearings, and Specifications/Requirements. Improvements can be made to the actuator, to the magnetic bearing controller (MBC), or both. The topics covered in this section are not intended to prescribe solutions but rather encourage ideation and inspire novel developments with the collective ingenuity of involved parties.

3.1. System/Actuator Architecture

3.1.1. Reducing Amplifier Requirements

There are two ways that amplifier requirements may be reduced. First, the total amplifier count may be reduced. Second, the requirements for the amplifier such as continuous current needed may be reduced. In both cases, the MBC cost may be reduced.

A common method of reducing amplifier count is by using a homopolar configuration for the radial AMBs rather than a heteropolar configuration. However, this typically requires permanent magnets. Generally, permanent magnets may struggle in the harsh environments AMBs for turboexpanders are subject to. Furthermore, other practical impacts such as sourcing permanent magnets or assembly considerations for a system with permanent magnets may prove problematic. Still, provided other challenges can be sufficiently mitigated, having more robust permanent magnets that can survive in required environments would allow more homopolar AMB systems to be utilized.

An alternative method of reducing amplifier count without permanent magnets is a three-pole radial AMB. (Meeker & Maslen, 2006) It may be possible to have as few as two amplifiers for the radial AMB, but a design with three amplifiers may have additional benefits by tapping into available three-phase drive hardware.

For reducing amplifier currents, there may be opportunities in making materials with higher saturation flux densities more economical. In addition to reducing requirements on the MBC (and thus cost), there may be practical benefits such as having smaller wires that are easier to route and manage as well as easier to scale down to smaller systems. Further actuator design optimizations may also reduce requirements on the MBC.

3.1.2. Generator as a Load Device

The compressor end of an ECM can be replaced with a generator. The basic concept is not novel and turboexpanders connected to generators with gearboxes have been used since the 1980s. With more recent developments in power electronics, it is possible to directly couple an expander to a generator without any gearing. This makes expander-generator machines with magnetic bearings (EGM) economically viable for systems smaller than 100 kW. (Hawkins, et al., 2004) Developments in power electronics and consequently converting from high frequency AC to line frequency became more cost effective in the late 1990s/early 2000s. (Agahi & Schroder, 1996)

Continued advancement in power electronics will see EGMs become increasingly practical. To maintain cost effectiveness (such as due to geopolitical reasons with rare earth mineral production concentrated in China), it may be necessary to develop generators that don't rely on permanent magnets. (Trench & Sykes, 2020) (Podmiljsak, et al., 2024) Furthermore, permanent magnets can face challenges in harsh environments such as hydrogen environments and difficulties during assembly which may offset other benefits to some degree.

3.2. Manufacturing Techniques and Technologies

3.2.1 Additive Manufacturing

Additive manufacturing of soft magnetic materials is a recent technological advancement. While offering geometric flexibility, it is not possible to directly print laminated parts such as stators and rotors. However, other techniques for reducing eddy currents have been developed. The authors could not find literature directly addressing AMBs with additive technologies, but related efforts show promise for AMBs. (Klein, et al., 2024) The ability to generate more complex geometry while also retaining favorable eddy current properties could yield benefits such as increasing power density by making use of the dead space between coil and laminations or having built-in wire-routing features that can make actuators more compact.

3.2.2 Soft Magnetic Composites (SMCs)

Like additive manufacturing, SMCs are seeing interest recently. (Pennander, 2014) AMBs using SMCs may offer interesting benefits in eddy current reduction. There is a trade-off between electrical resistivity and hysteresis losses, but it may be worthwhile as an enabler for some new possibilities. SMCs for AMBs have been investigated. (Hofer, et al., 2016) (Mason, et al., 1998) For turboexpander applications, compatibility with process gases need to be evaluated before it can be feasible.

3.3 Instrumentation and Controls

3.3.1 Self-sensing Bearings

Self-sensing AMBs are not a new idea. Numerous publications can be found on the topic. Maslen provides an overview on the topic. (Maslen, 2006) The impact for turboexpanders can be significant. Perhaps the biggest hurdle might be qualifying self-sensing bearings for industrial use. Specifically, specifications such as API 617 have requirements for sensors worded such that separate sensors may be required. If self-sensing can be evaluated against the specifications and either determined to be acceptable or the specification can be modified, self-sensing AMBs would result in more compact, less costly systems. On top of an axially smaller rotor due to elimination of dedicated sensor targets, there are cost and complexity savings on the physical hardware due to likely needing fewer wires and passthrus. The MBC may also be less expensive. Even if the industry consensus is that dedicated sensor planes are ideal (if not required), being able to use the actuators as “free” sensors may be worthwhile for robustness or for novel control strategies with additional data.

3.3.2 Flexible Rotor Control for Operating Near/Above First Bending Mode

The most common strategy for ECM design is to have a thick shaft with the lowest length over diameter ratio as possible that increases the first bending mode above separation margin requirements. The separation margin requirements can make designing for operating closer to or above the first bending mode challenging, but the benefits may be worthwhile. For example, if the shaft can have a larger length over diameter ratio, an application could potentially use a lighter, less costly shaft. Alternatively, another benefit could be that for a given rotor class, larger expander and/or compressor wheels may be used successfully. Specifications such as API 617 in principle allow for this kind of design and operation so long as criteria based on peak-to-peak vibration amplitudes and amplification factors are met.

3.3.3 Skid Mounted MBC

Typically, the MBC for ECMs are located in a control room away from hazards at the machine installation site. A skid-mounted controller avoids a number of cost drivers needed to locate the MBC farther away including cabling, infrastructure such as larger buildings and fixtures, and signal conditioning. The MBC and its housing increases in cost, but the tradeoff may still be worthwhile considering the schedule improvement and simplified on-site installation. (Jayawant, et al., 2018) In addition to the potential cost reductions, AMB control robustness may be improved by avoiding the effects of long cables on the controller.

3.4 Auxiliary Bearings

3.4.1 Reducing Clearances/Leakage

In an ECM, as with many machines with AMBs, the smallest clearances are designed to be at the auxiliary bearings. This limits seal clearances to be larger than the auxiliary bearing clearance. As machine sizes get smaller, such as for sCO2 machines, the seal clearances become increasingly significant.

There may be several different types of strategies to address this. One path would be to develop strategies to minimize the clearance. For example, it may be possible that designs such as the “Zero Clearance Auxiliary Bearing” (Chen, et al., 1997) or “Auto-Eliminating Clearance Auxiliary Bearings” (Chengtao & Longxiang, 2012) reduce required clearances. In both designs, a rotor drop triggers some moving mechanisms in the auxiliary bearing system that then engages and re-centers the rotor. In principle, the re-centering feature may assist in minimizing transient vibrations in a drop or overload condition, which may then allow seal clearances to be smaller without damage when the aux. bearings need to be used.

The other path forward might be investigating seal technologies that may reduce leakage. The typical labyrinth seals in ECMs could possibly be replaced with a helical groove seal, for example. (Watson & Wood, 2017) There may be other seal types or perhaps seal arrangements that would also reduce leakage.

In either path cost and reliability must be considered. With the auxiliary bearings that re-center in a drop, the additional moving components may prove to be points of failure. A rigorous testing regimen may assuage any concerns. Still, more parts may mean more cost. In applications where reducing leakage is critical, the trade-off may be worthwhile. A detailed cost study will be beneficial. When considering different seals or arrangements, the same considerations must be evaluated. Present configurations have many thousands of hours of experience, so new configurations must be vetted thoroughly.

3.4.2 Alternative Auxiliary Bearings

It may be more optimal to replace the auxiliary bearings with other technologies altogether. For example, studies pairing AMBs with foil bearings have been in literature since about the year 2000. Some good references include an early theoretical overview by Heshmat et al. (1998) and a subsequent test rig study by Swanson et al. (Swanson, et al., 2000) The pairing has even been investigated for use in jet engines. (USA Patent No. 12,326,172, 2025)

In short, AMBs are used in parallel with foil bearings (or similar bearings). In theory, the two technologies complement each other well where AMBs can offer zero speed performance and a significant boost to capacity and damping while foil bearings can help support static and dynamic loads at higher speeds. If it is considered carefully, this is less of an “auxiliary” bearing and more “partner” bearing.

Perhaps the most interesting thing for turboexpanders would be some reduction in requirements on the AMB. For example, if the “partner” bearing is supporting some load at speed, the AMBs do not need to have as much force capacity. Another facet would be an AMB and “partner” bearing working in the axial direction together, potentially addressing some of the load capacity issues noticed in the literature. The behavior of delevitations and emergency shutdowns fundamentally change with the “partner” bearing concept. In fact, depending on the dynamics of the system, it may be possible to run on the non-AMB bearings for some time at a derated state without ever having to stop rotation (i.e. in the case of a power outage). Seal clearances could be more aggressive and help reduce seal leakage and improve cycle efficiencies, which as noted in the literature review can be important in some applications.

3.5 Specifications/Requirements

Having specifications such as API 617 is beneficial to the industry so suppliers and customers can have common ground for communicating and understanding AMBs. This is compared with other bearing technologies such as oil-film bearings where the experience and understanding is more widely distributed than for AMBs. However, there can still be improvements made to overarching guidelines to improve customer experience and have more willingness to use AMBs in machines. The following comments are made primarily with API 617 as the benchmark because it is most familiar to the authors.

3.5.1 Load Capacity Specifications

Because AMBs don't have the ability to handle overloading, understanding AMB capacity is critical. API 617, Annex D does specify that force calculations must fall within "vendor-specified allowable dynamic force capacity envelop vs frequency." This leaves quite a few factors that may differ between two suppliers of AMBs. For example, different AMB suppliers may have different rules of thumb for what is considered "peak capacity." For example, different gap flux targets may be used as part of the analysis. Depending on supplier experience, they may also have different air gap lengths for a particular machine which also affects the AMB design. Perhaps the design variation can be considered competitive edge for each supplier. But even allowing that variation, additional ambiguity may be introduced depending on how the values are calculated. For example, analytical formulas can yield drastically different results than 3D finite element analysis.

Without a more "apples-to-apples" comparison, AMB suppliers may have systematically biased computations for load capacity. If this leads to a system operating suboptimally, the resulting experience could dissuade the customer from using AMBs in the future. This uncertainty is not unique to AMBs, as evidenced by an API survey performed by Kocur et al. (2007) including a review of dynamic properties of tilting pad journal bearings. In short, despite prescribing many aspects of a machine identically between bearing suppliers, outputs returned by the bearing suppliers varied sometimes by orders of magnitude. One potential solution might be to prescribe a common process to verify the rated load capacity vs. frequency of an AMB system so that suppliers can use that as the standard to calibrate whatever method they use for computations and customers, if needed, can audit the capability as well.

3.5.2 Common Interface for AMBs

API already specifies some interface details for AMBs in API 617's Annex D. For example, ECMs are required to have "all the magnetic bearing stationary components… inside the casing can be removed and replaced with the cartridge as a single unit." Taking it a step further, it is possible to specify more details about the interface such as possibly bolt circle diameters per size class, cartridge diameters, or other interface details. This would push the AMBs towards something like how rolling element bearings have a standard for defining a bearing design that is the same across suppliers. There are trade-offs for homogenizing AMB design across suppliers. Perhaps the biggest benefit, if such a system could be created, is that AMB design can be democratized, leading to lower barrier of entry for AMB suppliers and greater confidence from customers knowing that an AMB they invest in won't cripple their machine if they can't get a replacement for some reason. However, AMBs have many more details to consider than rolling element bearings.

4. Conclusions

Turboexpanders with AMBs are introduced with a brief history. ECMs are the primary focus of this investigation. A literature review revealed that cost, reducing or managing subsynchronous instability, and load capacity are significant factors to address for ECMs to penetrate new markets. Some areas of investigation are discussed that could lower the barrier to entry into new markets.

Ultimately, this paper aims to give engineers and researchers perspective on turboexpanders and their use of AMBs. The information is intended to inspire new innovations that can enable ECMs and similar machines to thrive.

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