Practical Applications of the Active Magnetic Bearings to the Industrial World

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Summary
Active Magnetic Bearings (AMB) are developed, manufactured and marketed by Société de Mécanique Magnétique (S2M) since 1976. This company has made major improvements to the AMB fundamental technology in order to meet industrial requirements. Each component of the AMB system has been improved through a simple, robust, and patented solution. Among others, inductive sensors, flux feedback control, control loops (automatic balancing system), auxiliary bearings,... Many industrial applications in various and severe environmental conditions have been set into operation. They have been into operation for years and have shown their reliability.

Introduction

This paper does not deal much with theory of Active Magnetic Bearings (AMB). Many other papers have previously described the subject; for an introduction to AMB one should refer to them.

We shall focus here mainly on:

- some of the technological improvements brought by S2M to the AMB,

- industrial applications.

The Société de Mécanique Magnétique (S2M) was founded in 1976 by the Société Européenne de Propulsion (SEP) and the SKF group. Its aim was to continue development and to commercialize active magnetic bearings which had been the subject of research programs starting in the 1960s.

S2M is located in the Vernon/Saint-Marcel industrial area in Normandy, France. The S2M plant has been built on 2 hectares (5 acres) and occupies 3,000 m^2 (27,000 sp.ft.). S2M employs 75 persons (January 1st, 1988 figures).

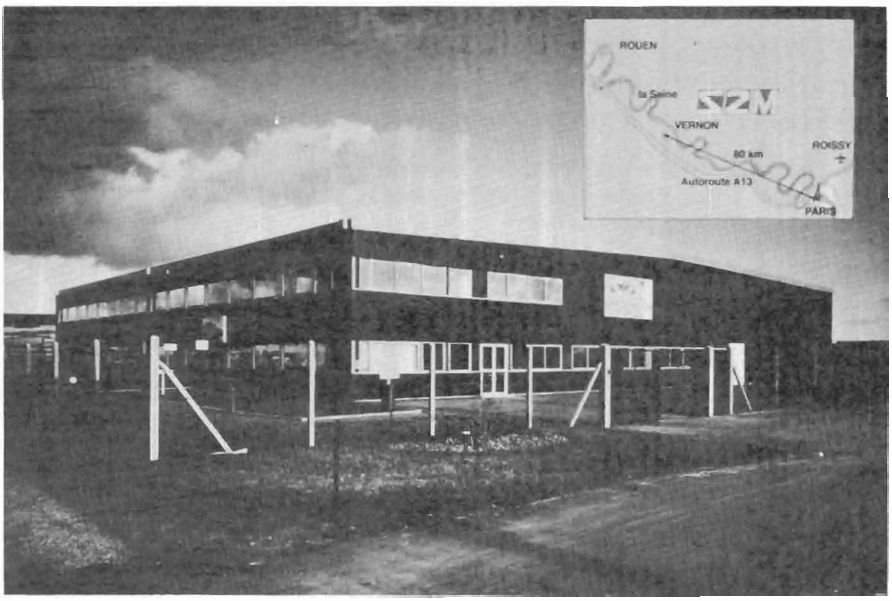

Fig. 1. S2M plant in Vernon/Saint-Marcel

More than 35 patents registered since 1970 (in France, in Europe, in the United States and in Japan) protect SEP and S2M inventions in this field.

For over 15 years the S2M shareholders have invested more than 50 MFF directly in the development of active magnetic bearings, in the form of capital or services. S2M invests approximately 10 % of its turnover in research and development.

S2M is equipped with computerized design and management equipment and has production capabilities both in the electromechanical and electronic fields. S2M also ensures the implementation and after sales service of its active magnetic bearings throughout the world.

S2M's wealth is in its team of men and women, whose work and experience have built an unequalled technological advance in the design and production of active magnetic bearings.

S2M has created two subsidiaries to implement the process in America and in the Pacific and South-East zones:

- MBI (MAGNETIC BEARINGS, INC.) in the United States, with the KOLLMORGEN group,
- JMB (JAPAN MAGNETIC BEARINGS CO., LTD.) in Japan, with the SEIKO group.

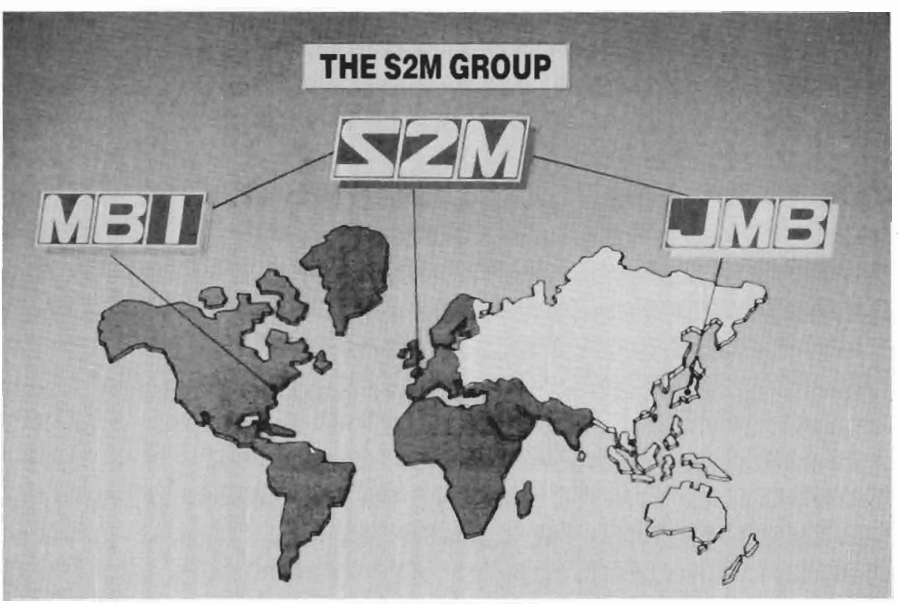

Fig. 2. S2M group in the world

These two subsidiaries make up a worldwide organization based on three poles:

- S2M which is especially orientated towards the European, African and Middle East markets. S2M is, of course, the leader both in research and development and promotion of new applications,
- JMB licensed for the Pacific area and handling the heavy industry market while the sub-licensee SEIKO SEIKI handles the light industry and machine tool markets.

The S2M group, the growth rate of which is about 40% per year, is the only group in the world able to design, manufacture and commercialize active magnetic bearings on an industrial level.

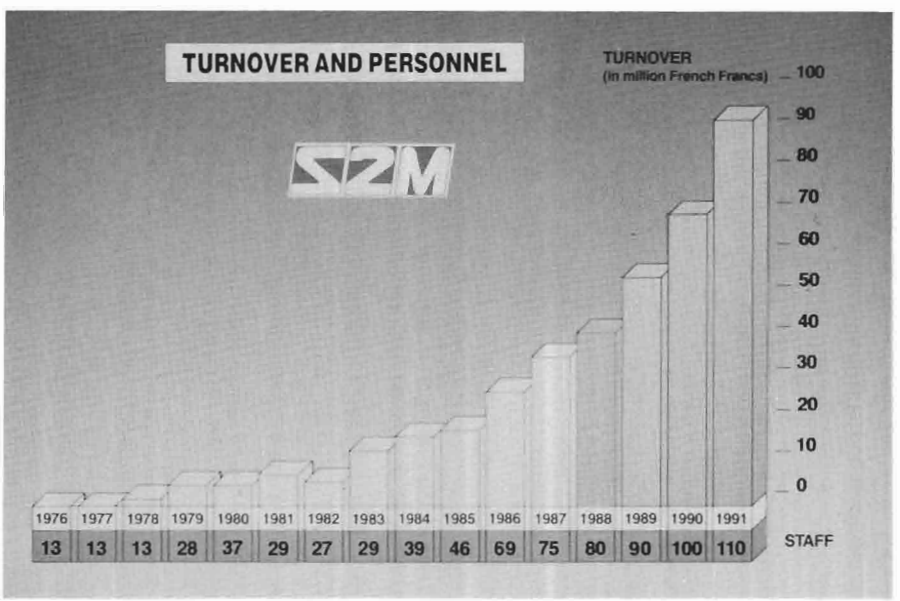

Fig. 3. S2M growth, historic and perspectives

MAJOR IMPROVEMENTS OF AMB'S FUNDAMENTAL TECHNOLOGY BY S2M

The basic AMB technology using electromagnets in attraction controlled by a servo-loop is well-known. However, various major improvements to the AMB fundamental technology are necessary to meet industrial requirements.

Each component of the AMB system has to be improved through a simple and robust solution, to avoid weak points.

Figure 4. shows some of the S2M patented improvements. Thanks to them really operational AMB are manufactured.

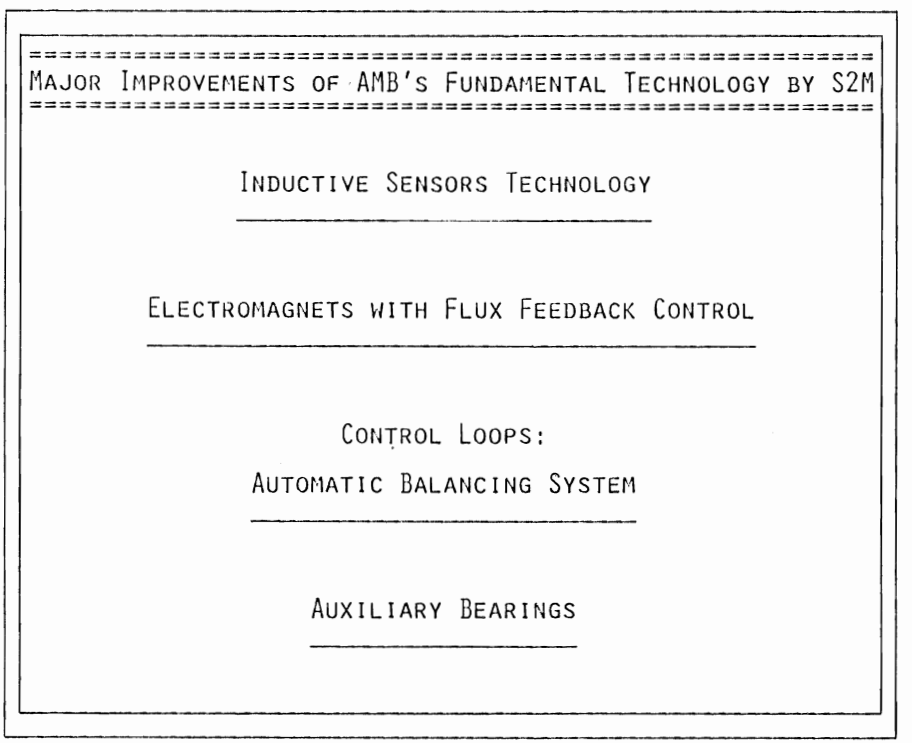

Fig. 4. Major improvements of AMB's fundamental technology

Inductive sensors technology

The technology selected by S2M for the transducer of the servo-loop is the inductive sensors in a Wheatstone bridge. This principle is known as especially accurate (principle of measuring equipment) and simple. It provides a high level signal which does not required to be preamplified before line transmission to the control electronics. It is a noise-free signal, from which rotation harmonics are filtered through a simple, static mechanical device, also patented. Getting rid of any preamplifier on the machine itself increases the reliability of the AMB system. All sensitive parts are under protection in the control room, remote from the machine (up to 50 meters or even more).

The most impressive application in the S2M sensors know-how is the ultra-precision spindle for optical lenses machining. The spindle drives the lense (lathe principle) at 2,000 rpm, with a power of 1 kW. On this spindle an accuracy of 0.05 micron on the machined part is achieved. This value is not dependent of the material.

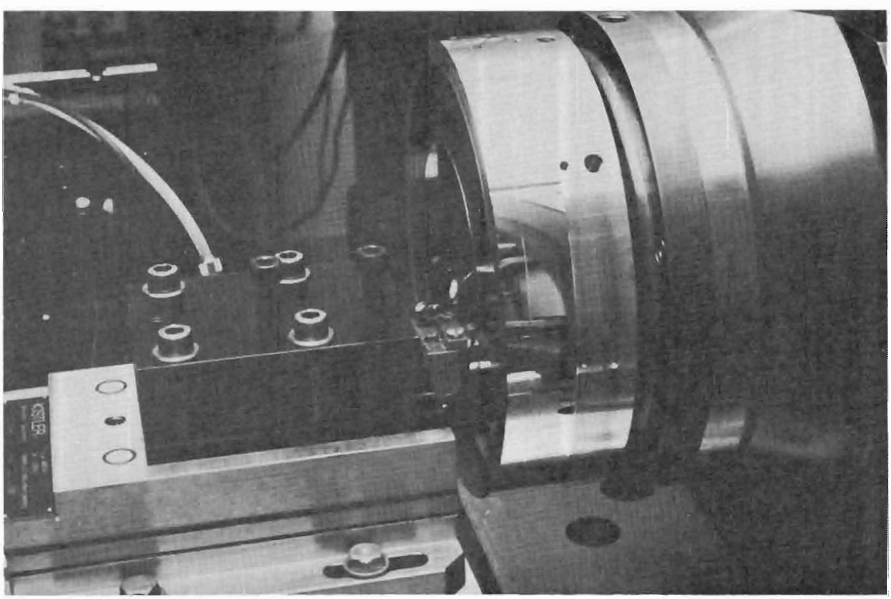

Fig. 5. Example of ultra-precision achieved with S2M inductive sensors technology: spindle for optical lenses machining. Machining accuracy: 0.05 micrometer.

The electromagnets with flux feedback control

The well-known drawback of the electromagnets is the non-linearity of the electromagnetic force in a variable airgap. The S2M solution (patented) is the flux feedback control by means of a simple flux measurement coil. This technology avoids any fragile sensor on the machine.

Most of S2M applications are equipped with this device. The figure hereafter shows one example. This is a turbo expander unit used for air liquefaction. On the turbine wheel side the gas is expanded and cooled to -190°C, the shaft transmits the power (300 kW, 38,000 rpm) to the compressor wheel on the other side. The thrust reaches 7,500 N, i.e. 25 times the rotor weight. This high load factor would not be possible without the flux control.

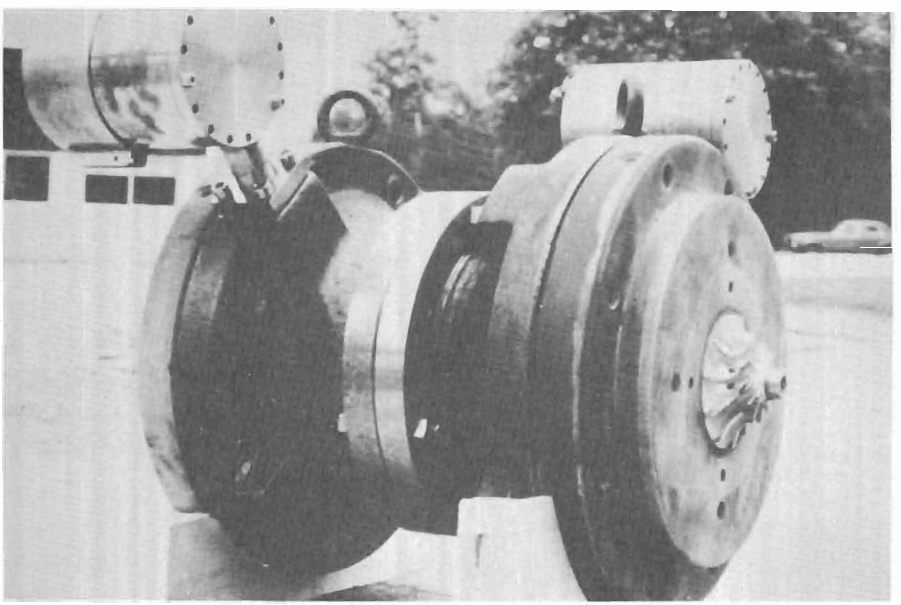

Fig. 6. Example of high load factor: turbo expander with a 7,500 N thrust load on a 30 kg rotor weight.

Control loops: Automatic Balancing System

The classic PID (Proportional, Integral, Derivative) network has been improved by various filters and cross-coupling devices.

One of the S2M patents is the Automatic Balancing System (ABS). Target of this system is the elimination of stator vibrations at variable speeds, even in case of high and variable unbalance by a rotation of the rotor on its inertial axis. The ABS system uses rotating coordinates driven by the rotation speed. The "frequency filter" of the bearing is thus directly indexed on the rotation speed.

The ABS system has been used many times, it is integrated in the majority of the S2M applications, especially the turbo-machines.

For example, this turbogenerator equipped with a 8,000 kg rotor rotating at 3,000 rpm in a very dusty environment of hot blast furnace exhaust gas (energy recovery expander). The process dust by sticking on or abrasing the expansion wheel changes permanently the unbalance. Thanks to the ABS, the rotor rotates around its inertial axis and no vibration is transmitted to the stator. The unbalance allowed is 250 g.m.

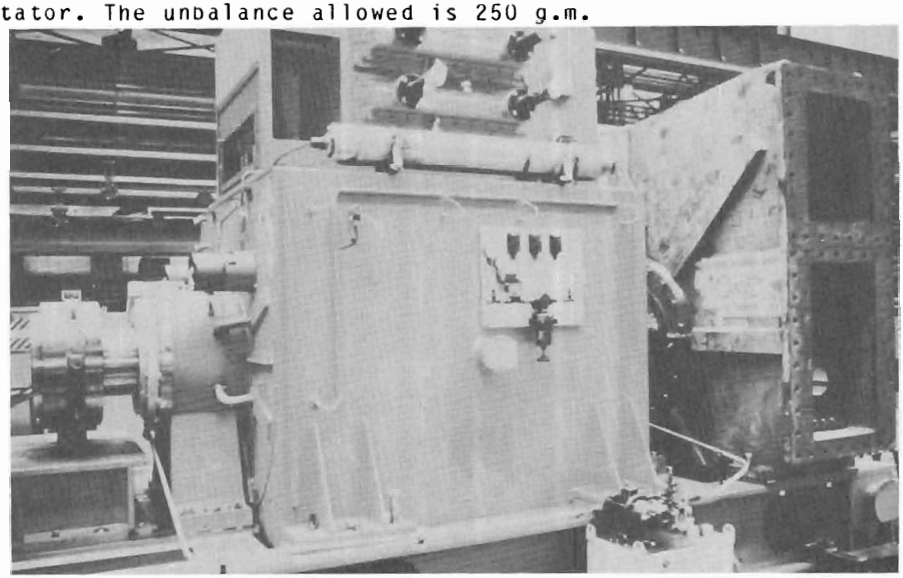

Fig. 7. Example of high unbalance: turbogenerator with 250 g.m. acceptable unbalance.

Auxiliary bearings technology

S2M has now a great practical experience of auxiliary bearings improvements. These systems provide good damping for a "smooth landing" of the rotor in case of ailure in the control system, even in case of a flexible rotor rotating over its first free-free bending mode.

The figure shows a centrifugal compressor with flexible rotor (300 kg, 13,500 rpm) on which evidence of good landing behaviour has been made.

The shaft can cross its first free-free critical speed on the auxiliary bearings.

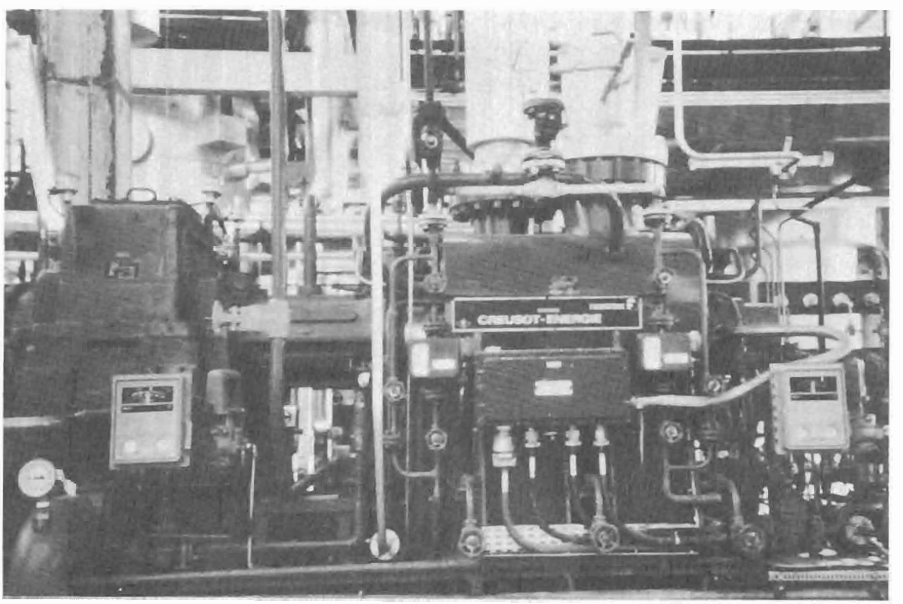

Fig. 8. Example of landing capability on auxiliary bearings: centrifugal compressor.

INDUSTRIAL APPLICATIONS

Many industrial applications in various and severe environmental conditions have been set into operation. They have been in operation for years and have shown their reliability.

Vacuum:	**Ultra-high vaccum pump**
	Neutron chopper
Extreme temperatures:	**Cryogenic turbo expander**
	Liquid helium cryogenic compressor
	Hot helium blower
Machining:	**Very high speed milling**
	Creep feed grinding
Turbomachines:	**Steam turbine**
	Centrifugal compressor
	Synopsis of turbomachines.

Ultra-high vacuum pump:

This design makes use of an internal stator. The external rotor (7 kg) rotates at 30,000 rpm. The turbomolecular pump enables to achieve a very high level of vacuum (10^{-11} Torr). It is well suited for vibration-sensitive applications such as electron microscopy and mass spectrometry. It is also absolutely oil-free.

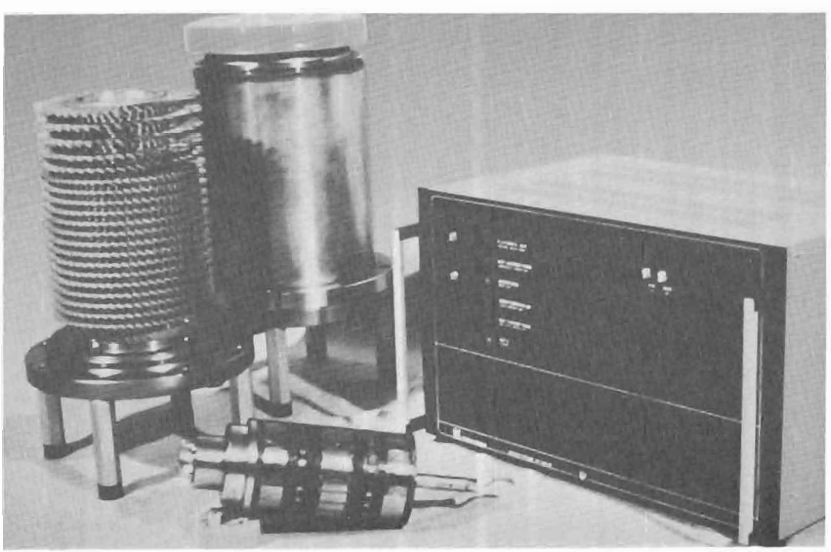

Fig. 9. Ultra-high vacuum pump

Neutron chopper:

The principle of this laboratory equipment which works in vacuum is to chop a neutron flux by a rotating shutter.

The synchronisation of the shaft speed with the neutron source is essential. Therefore, a constant speed of 30,000 rpm is required ($\Delta\omega/\omega = 10\text{-}6$).

Thanks to the very low and constant electromagnetic friction torque of the AMB the speed control can be achieved.

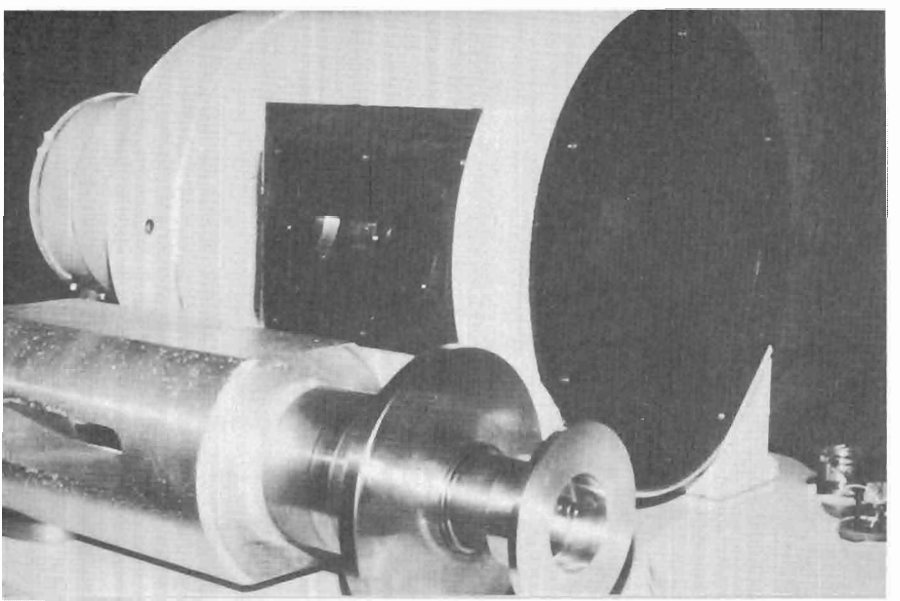

Fig. 10. Neutron chopper

Cryogenic turbo expander:

This application has been shown before as an example of high load factor. We focus now on its industrial operation. As said before, it is used in air liquefaction plants. The temperature difference on this short shaft (900 mm) is very high: -190°C on the expander side, +110°C on the compressor side. The complicated lubrication system has been eliminated. The machine is now fully oil-free and can be started at any time without heating up. Therefore, it can follow very easily the production demands in liquid gases.

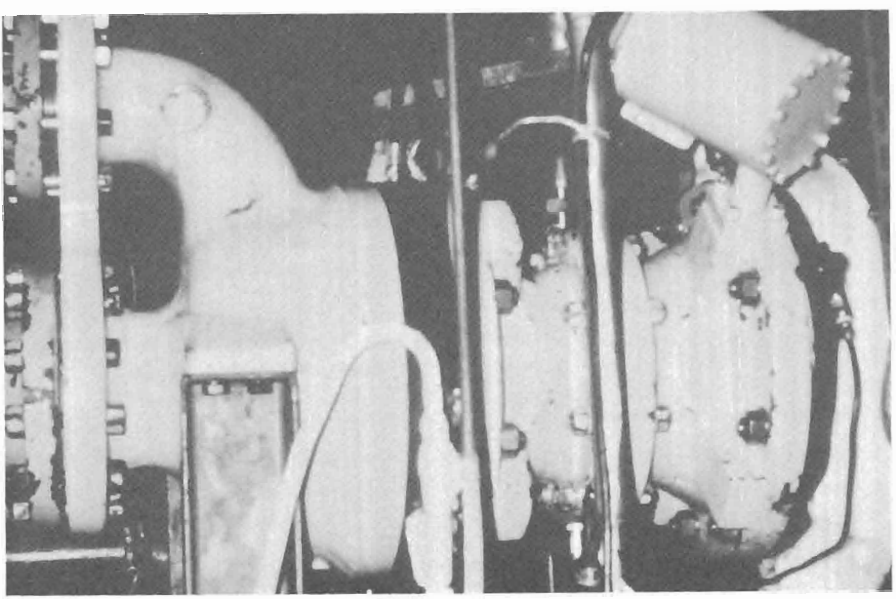

Fig. 11. Cryogenic turbo expander

Liquid helium cryogenic compressor:

Liquid helium (supercritical phase) at a temperature of 4 K requires a special compressor design. This compressor has a vertical shaft (6 kg) rotating at 36,000 rpm, on AMB. The heat transfer from the motor and AMB to the liquid helium is less than 1 W. This is of major importance. The efficiency of the whole refrigerating loop is much improved (1 W heat input means 1 kW energy consumption to cool it down).

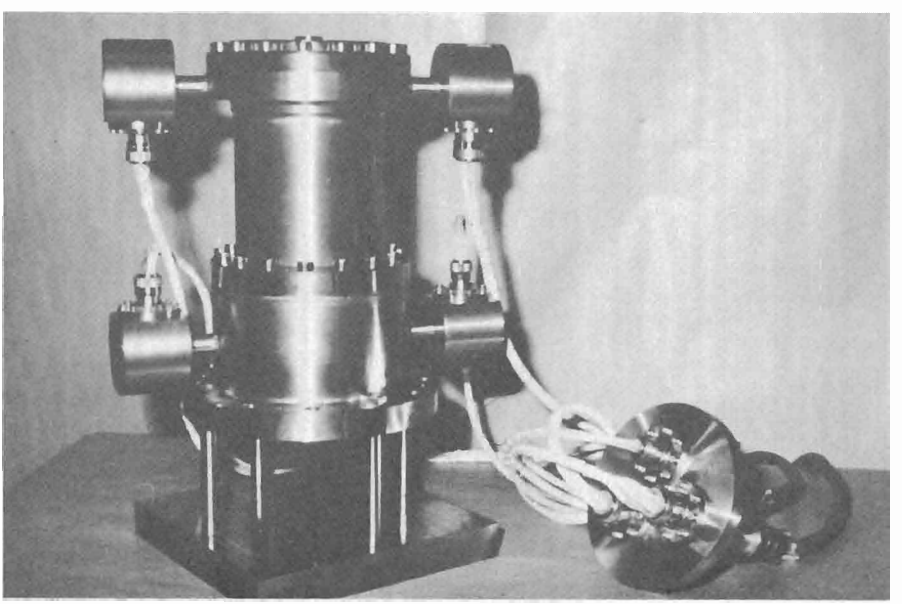

Fig. 12. Liquid helium cryogenic compressor

Hot helium blower:

The hot helium blower is developed within the scope of the very high temperature nuclear reactor program. In these reactors the core is cooled by helium which goes to heat exchanger and brought back to the reactor by blowers.

The AMB of the blower presented here have been insulated with a special ceramic coating. They withstand a temperature of 450°C. Other AMB advantages for this application are the non-pollution of the helium by lubricant and the high reliability.

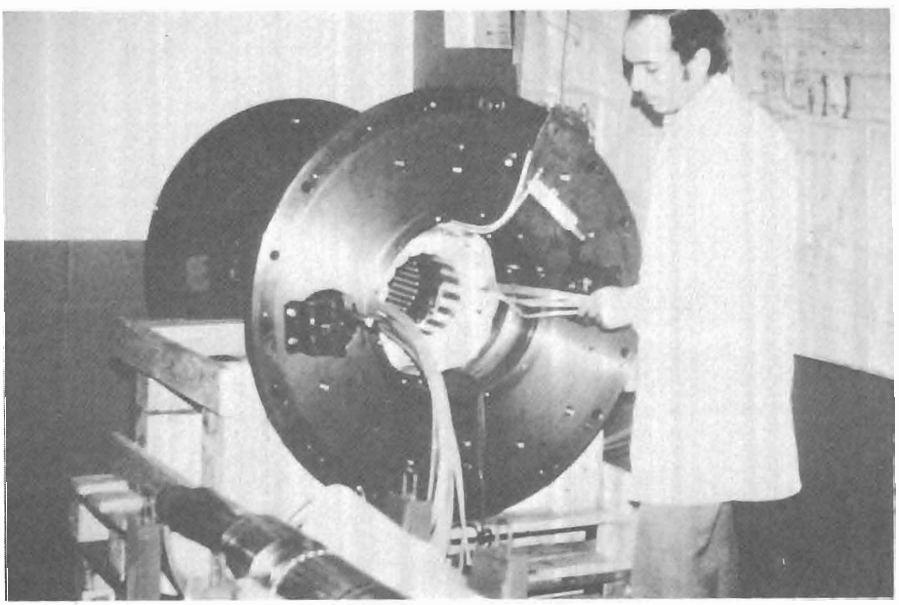

Fig. 13. Hot helium blower

Very high speed milling:

The very high speed milling is especially interesting in the aircraft industry where finished parts (such as frame, wings, integral structures,...) come out from solid parts with more than 90% chip removal.

The S2M electrospindles on AMB provide both very high speed and high power (from 30,000 rpm/ 35 kW up to 60,000 rpm/22 kW).

The milling machine shown here is equipped with a 45,000 rpm/ 30 kW electrospindle.

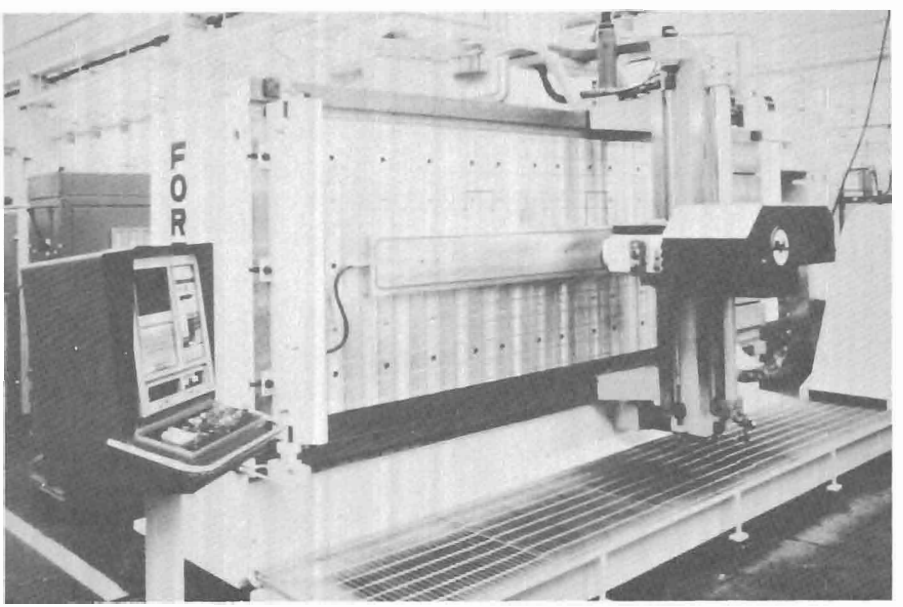

Fig. 14. Very high speed milling

Creep feed grinding:

The grinding machine presented here has been designed with a S2M electrospindle B15/1000 (60,000 rpm/22 kW).

Thanks to Cubical Bore Nitrid (CBN) tools, this grinding process may be now performed at very high speed (up to 300 m/s). A high productivity is reached together with high precision.

The machining is done in one pass and a width accuracy of 1 micron can be reached by the electronic displacement of the electrospindle rotor in the air gap.

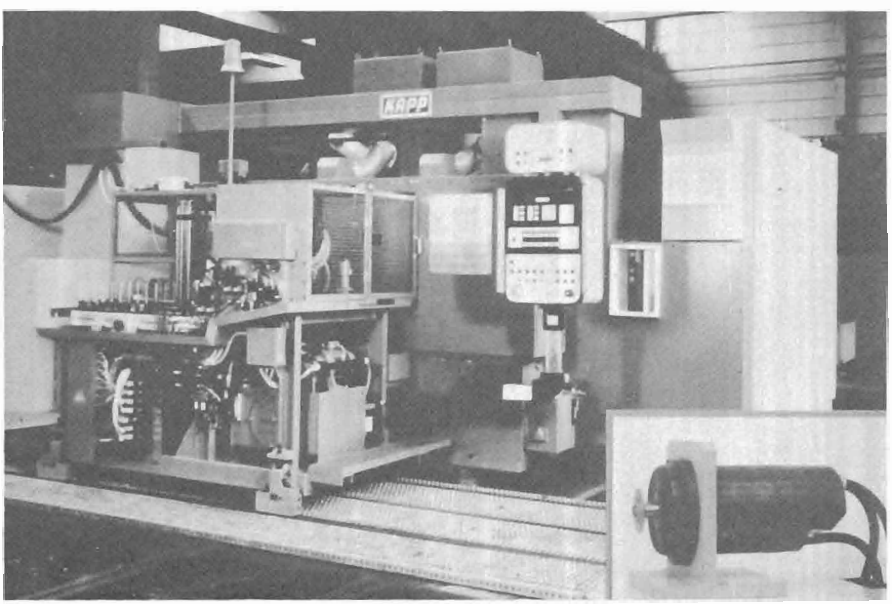

Fig. 15. Creep feed grinding machine

Steam turbine:

The first steam turbine on AMB has been started by S2M and JMB in Japan (Mitsubishi Heavy Industries).

It is a new machine of 3 MW at 15,000 rpm, which has been designed in order to integrate all the new technological developments available today, and, among others, AMB. Thanks to them, the mechanical design has been simplified by the elimination of the lubrication system. Other major advantages are the fact that no vibrations are transmitted to the stator, and the fact that the user has at his disposal a continuous monitoring of the rotor dynamic without additional equipment.

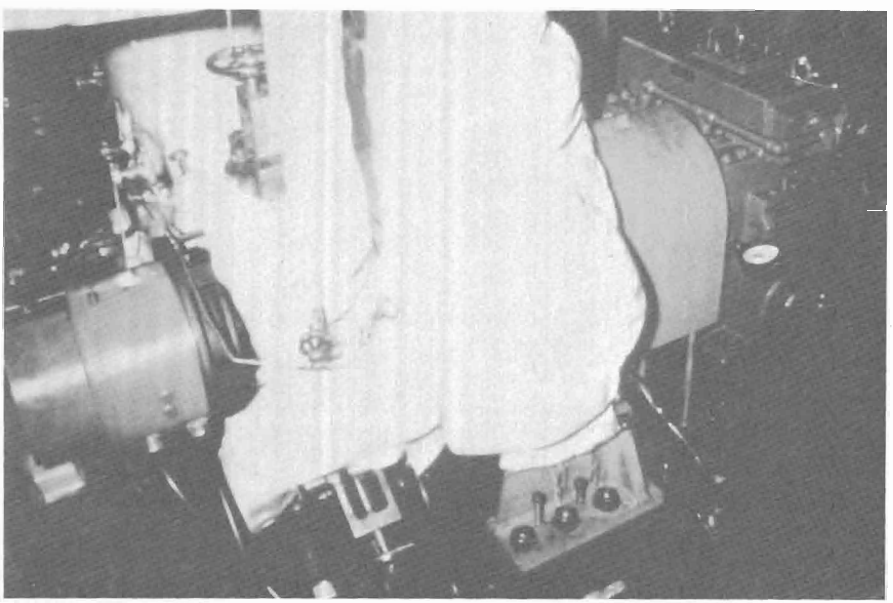

Fig. 16. Steam turbine

Centrifugal compressor:

The picture presented here shows the same compressor before and after its retrofit with AMB and dry seals. The difference is obvious. All the accessories have disappeared.

It is a compressor of pipeline rotating at 11,500 rpm (4,100 kW).

The AMB brings the following advantages to the user of a centrifugal compressor:

- reduced losses,
- availibility (immediate starting of the machine, without lubrication system heating time),
- elimination of mechanical maintenance,
- elimination of vibrations,
- no pollution of the process gas by the lubricant...

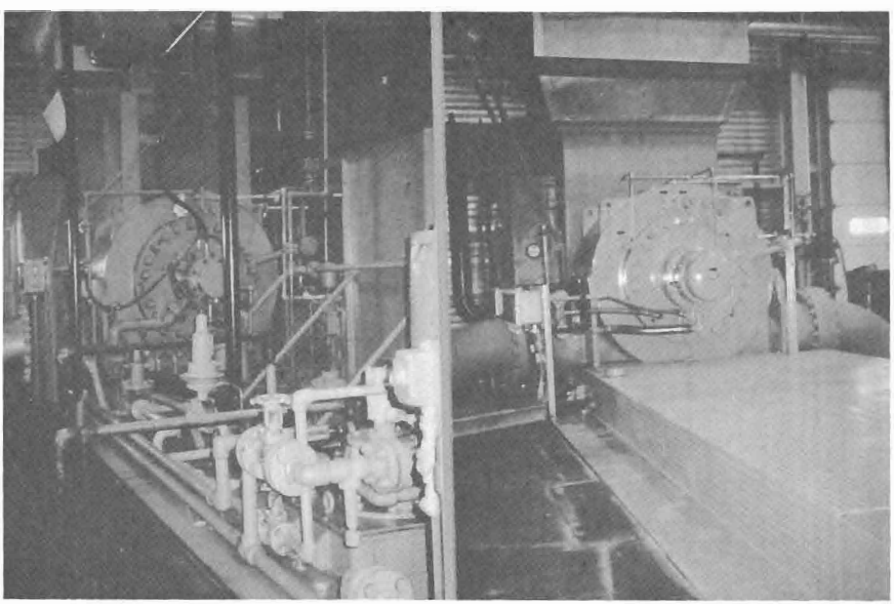

Fig. 17. Centrifugal compressor

Synopsis of turbomachines:

More than 30 turbomachines are now running on AMB.

TURBOMACHINERY EQUIPPED WITH ACTIDYNE® ACTIVE MAGNETIC BEARINGS

MACHINE TYPE	QUAN-TITY	START UP DATES	POWER RANGE kW	NOMINAL SPEED RANGE	APPLICATION
TEST COMPRESSORS	5	1980 - 1987	20 kW to 4,000 kW	10,000 rpm/ 16,000 rpm	- TEST STANDS
INDUSTRIAL COMPRESSORS	15	1985 - 1988	3,100 kW to 26,100 kW	5,000 rpm/ 14,500 rpm	- PIPELINES - REFINERIES
HERMETIC COMPRESSOR	1	1981	300 kW	18,000 rpm	- TEST STAND
MOTORIZED BLOWERS	4	1980 - 1987	5 to 200 kW	3,600 rpm/ 12,000 rpm	- TEST STANDS - HELIUM LOOP
GAS TURBINE	1	1988	12,000 kW	5,250 rpm	- COMPRESSOR DRIVE
STEAM TURBINE	1	1987	3,000 kW	15,000 rpm	- COMPRESSOR DRIVE
TURBO-GENERATOR	1	1986	5,000 kW	3,000 rpm	- ENERGY RECOVERY (BLAST FURNACE GAS)
TURBO EXPANDERS	3	1985 - 1988	300 kW to 900 kW	30,000 rpm/ 38,000 rpm	- AIR LIQUEFACTION

Fig. 18. Synopsis of turbomachines

Conclusion:

Thanks to its 20 years of experience and development, S2M has transformed the concept of AMB into an industrial reality, as easily demonstrated by its achievements to date.

PRESENT STATUS OF ACTIDYNE® ACTIVE MAGNETIC BEARINGS	
ROTATION SPEED	0 to 800,000 rpm
ROTOR DIAMETER	14 mm to 1.25 m (0.6 in to 50 in)
LOAD PER BEARING	up to 100,000 N* (22,000 lbs)
AMBIENT TEMPERATURE	-253°C to +450°C (-420°F to +840°F)
ENVIRONMENT	air, vacuum, helium, nitrogen, hydrocarbons
QUANTITY OF SUSPENSIONS MANUFACTURED	> 400 related to more than 30 different applications

*The present technology allows 300,000 N (66,000 lbs) per bearing.

The companies of the S2M group, thanks to their wealth of huma resources and their constant effort in research, development, and industrialization have provided the industry with highly performing economical and efficient AMB.

As our clients conclude:

"We choose Active Magnetic Bearings
For their high performance
And S2M for its experience."