Implementation of Active Magnetic Bearings on Advanced Rocket Engine Turbopumps

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Summary

Preliminary studies are conducted at SEP to clarify the advantages and drawbacks of using S2M ACTIVE MAGNETIC BEARINGS (AMB) to suspend rotors of rocket engine turbopumps.
After having pointed out their specific interest for rocket propulsion, technological keys for development will be presented. These latter are found among the following subjects: AMB materials properties (mechanical and chemical), miniaturization of the electronic controller, rotordynamic prediction, fluid and electrical interfaces.

1. Introduction

The constant care of every engineer in propulsion field is to increase the machine efficiency and to minimize the weight and overall dimension of the engine and of the feeder turbopumps.

This care most often results in a search for higher rotor speed, beyond the limitations of the components currently used, especially for the bearings. This basic rule is worsened by the requirements adherent to modern engines : increased life, high safety, extended reusability, low development and recurrent costs. Thus is layed the necessity to use alternates found among the fluid bearings (hybrid/hydrostatic/ hydrodynamic) or active magnetic bearings (AMB).

The first option is explored since twenty years, particularly in the United States where advanced turbopumps have been tested with hybrid/hydrostatic bearings [1] [2].

However, the use of such bearings has drawbacks due to their complexity and recycled flow rates.

Therefore, beside trade-off studies on fluid bearings, detailed investigations are conducted at SEP since 1986 to determine specific interest of AMB in space propulsion. These works are based on conceptual and technological studies, both being tightly connected. Some of them are linked to cooperation works with american companies.

This paper is intended for a brief description of the works trends and the main results obtained during this preliminary phase.

2. General studies

2.1 Realm of interest

Most of the features of the AMB are attractive for rocket engine components as turbopump bearings. The high level of reliability obtained in previous space applications [3] [4], the potential high life, an increased rotational speed, the shaft dynamic control, are among their most interesting characteristics [5].

But they have also some counterparts, as they need power supply, on-board control cabinet, dedicated transfer function and safe compatibility with the propellants used.

Company funding were then committed to conduct applicability studies precising the requested efforts to implement AMB on rocket engine turbopumps. These investigations start from the system specifications to obtain the AMB parameters in terms of mass, power consumption, cost, life, reliability, load capacity (fig. 1)

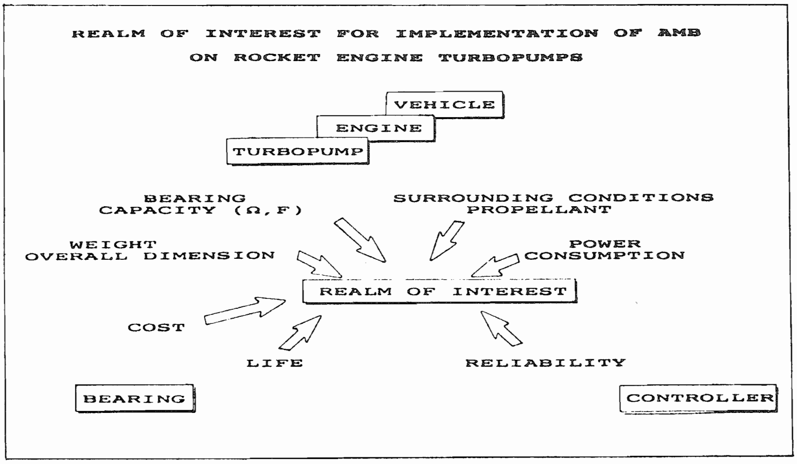

Fig. 1 AMB's applicability on rocket engine turbopomps

Those specifications are related to each particular engine, but generally speaking, we have scanned an engine thrust from 30 kN to 3000 kN, life requirement up to 500 cycles/20 hours with no fail occuring before 2 years, and cryogenic/storable propellants.

The main results show that :

(a) weight and power dissipations increase largely with the AMB load capacity, i.e. the engine thrust (fig 2,3)

(b) cryogenic propellant allow smaller sizes (increasing the current density by a factor of 6 compared to ambient conditions)

(c) higher rotor speeds can be obtained with an increase of about 50 % compared to cryogenic ball bearings. Expected improvements in mechanical strength of the rotor sheets should increase this value.

(d) AMB expected life seems consistent with the system requirements. On-going works on fatigue behaviour will complete this topic.

(e) axial thrust capacity appears too low regarding the loads encountered in start/shutdown transients. Improved designs for axial AMB has to be compared to mechanical/hydraulic devices currently used on turbopumps.

(f) recurrent costs remain relatively high today, due to a low number of parts intended to be produced. This point turns AMB application towards high life, reusable advanced turbomachineries.

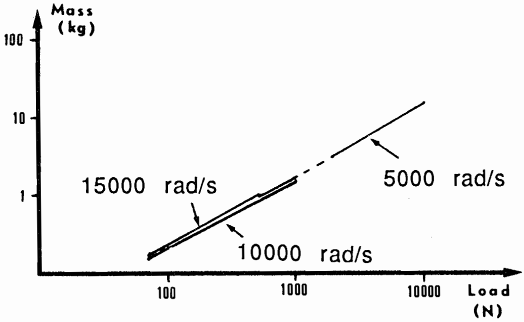

Fig. 2 AMB's mass vs radial load

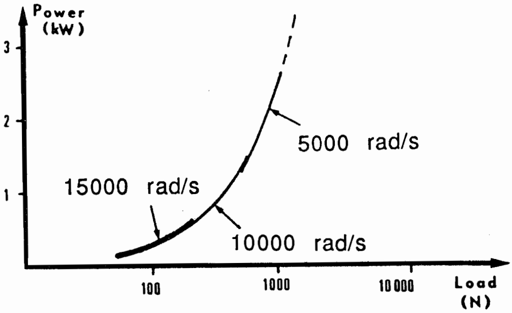

Fig. 3 AMB's power dissipation vs radial load

2.2 Turbopump Designs

These designs were undertaken to complete the applicability study, to point out the technological assessments and to illustrate the possible concepts.

Two exemples are proposed here, one imaging a high thrust engine, liquid oxygene turbopump (HTOTP Fig 4 (a) (b)), the other picturing a low thrust engine, hydrogen turbopump (LTHTP Fig 5 (a) (b)). Their main features are reported Table 6 and the AMB characteristics are found Table 7.

The location of the forward bearing on HTOTP Fig. 4(a), placed on the inducer shroud, shortens the axial length and enables better dynamic control. All bearings are cooled with a small propellant flow rate through them.

The main technological keys are detailed in the following chapter.

Table 6 . Advanced Turbopumps Features

CHARACTERISTICS	HTOTP	LTHTP
Pressure rise (MPa)	28	24
Shaft Power (kw)	17,000	670
Rotor Speed (rpm)	30,000	190,000
Overall length (m)	1.0	0.25
TP weight (kg)	260	4.8

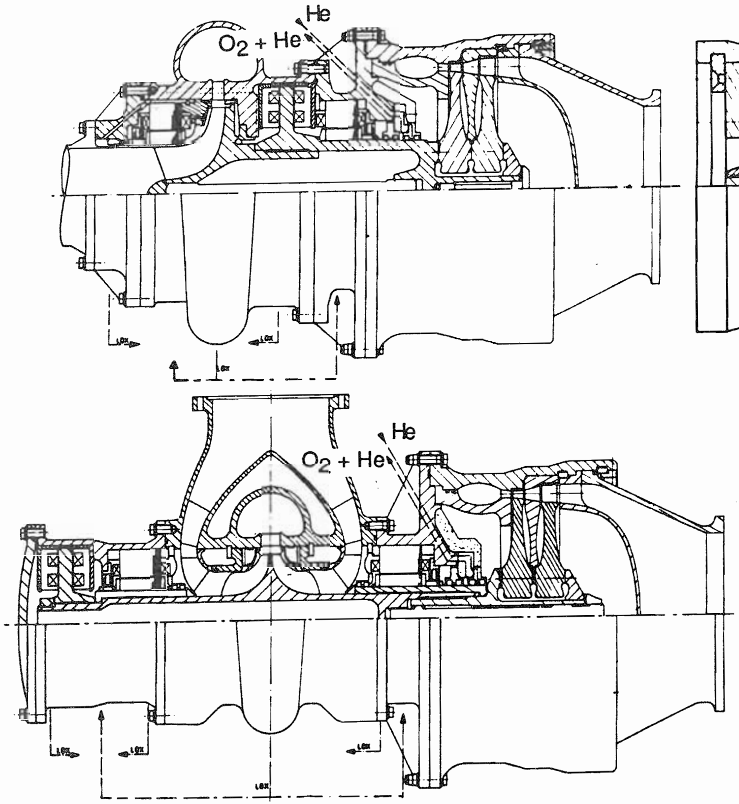

Fig. 4 (a) (b) HTOTP Concepts

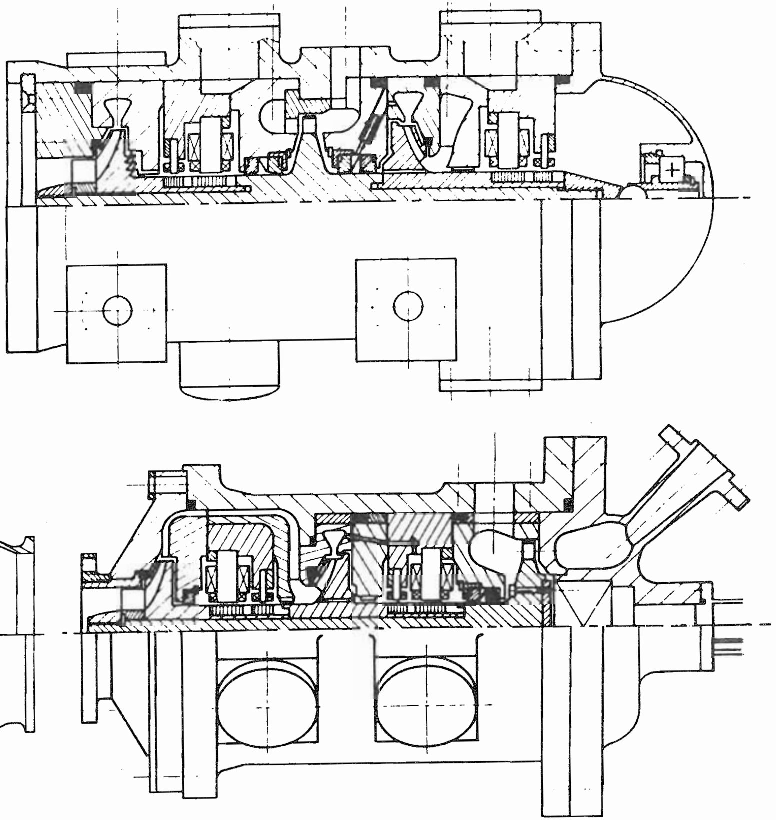

Fig. 5 (a) (b) LTHTP Concepts

Table 7 . Radial AMB's Characteristics

CHARACTERISTICS	HTOTP	LTHTP
Airgap (mm)	0.4	0.2
Materials (rotor) (stator)	Fe-Si3 Fe-Co50	Fe-Si3 Fe-Co50
Stator O.D. (m)	0.21	0.06
Load (N)	4,600	65
Weight (kg)	30	0.6
Power consumption (W)	5,000	500

3. Technological works

3.1 Size reduction of the control cabinet

This is obviously a major point, allowing or not the use of AMB on flight systems. The challenge is to miniaturize the circuitry and the power amplifiers while keeping the high level of reliability obtained with industrial cabinets.

The expected size reduction is about 5 to 7 times, implying the use of digital processing, deep hybridation and optimisation of the control box design. Those are trends of our works.

This effort will also give us ability to use complicated transfer functions and real-time health diagnostic capability.

3.2 Rotordynamic

As far as turbopump design are concerned, an accurate mean of predicting the rotor responses is needed. Significant effort has been done at SEP to obtain such an efficient tool taking into account :

- any transfer function
- non-isotropic behaviour of the bearing
- all the hydraulic connections between stator and rotor parts: pump and turbine stages, seals, AMB airgaps
- any location for the bearings and the displacement probes.

This computer code, developped with assistance of the University of Liege (LTAS), is a finite element program with formulation allowing non-linearities. This control system can be adequately expressed in the standard quadratic form : $M\ddot{x} + C\dot{x} + Kx = F(t)$, by mean of extra degrees of freedom [6].

An operating code is currently used for quasi-steady calculations, with shafts controlled plane by plane or axis by axis. Improvements are on-going yet to allow for non-linearity of the control loop and start/shutdown transients.

The shaft behaviour is analyzed with :

(a) Campbell diagrams (Critical speeds and damping coefficients, fig 8 (a) (b))

(b) the mode shapes showing appropriate deflections at the bearing/detector locations (fig 9)

(c) the synchronous response (unbalance response) allowing to check gaps vs displacements.

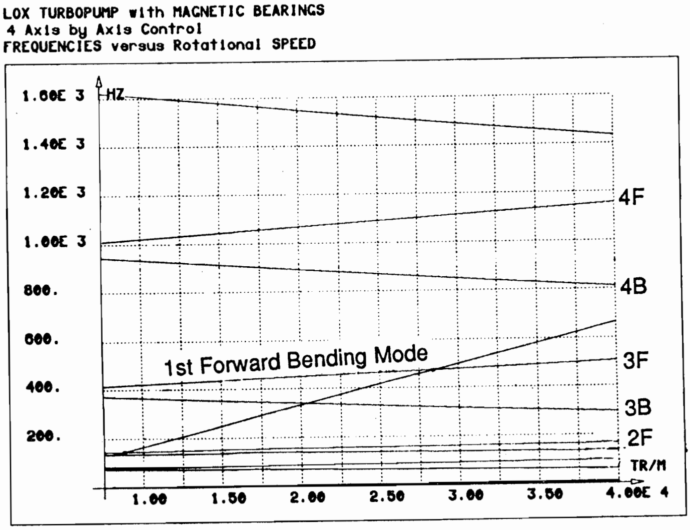

Fig. 8(a) HTOTP Critical speeds

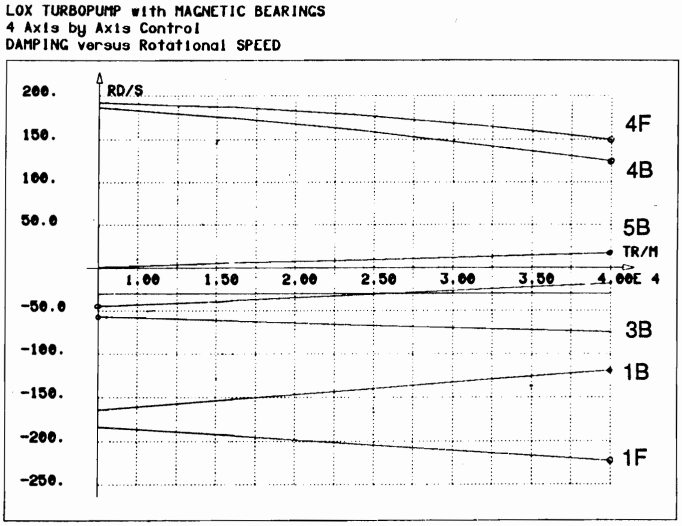

Fig. 8 (b) HTOTP Damping coefficients

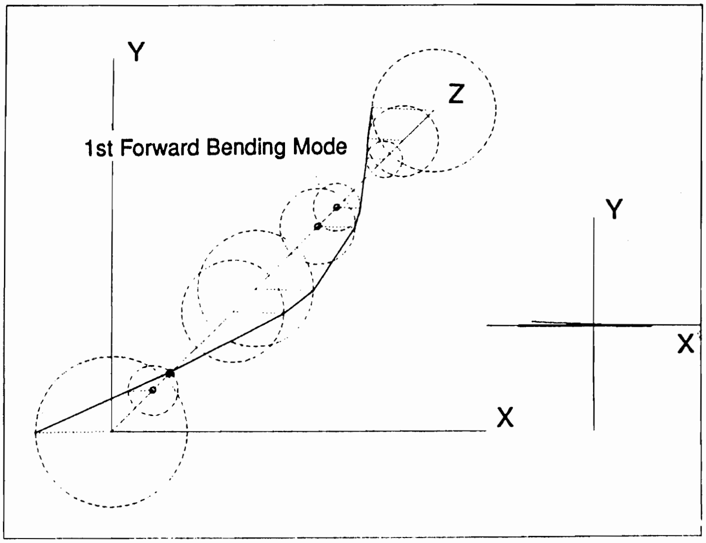

Fig. 9 HTOTP 3rd Mode shape

Those given exemples illustrate potential problems encountered on these machines : broad frequency range control and tight relationship between the turbopump design and the stability of the machine.

3.3 Material compatibility

Following extensive literature review and flight profiles required in future, priority propellants has been retained, i.e. liquid oxygen (LOX) and liquid hydrogen (LH2). Preliminary tests then have been performed to check :

(a) cryogenic behaviour of the Fe-Si3 sheets employed
(b) compatibility with GOX and LOX
(c) hydrogen brittleness for the Fe-Si3 alloy

Those tests were conducted with the assistance of the National Test Laboratory (LNE) and Air Liquide company.

(a) Tensile tests carried out with notched and unnotched Fe-Si3 samples confirm the usual results [7], with rupture stress higher than 500 MPa and no yield for cryogenic temperature ($\theta<77K$). These alloys has a light sensitivity to the notch. High-cycle fatigue tests done also at cryogenic temperatures show rupture stresses higher than 350 MPa for a number of cycles equal or higher than 10^7.

(b) 16 organic materials amoung insulations, coatings, various protections were tested by normalized check-out in GOX. Following these first choices, 4 materials have been retained and used to make small components similar to magnetic bearings (fig 10).
They were tested successfully during adiabatic compression tests, opening the way to a full compatibility with liquid oxygen.

(c) The foreseen implementation on hydrogen turbopump compel to measure GH2 brittleness, especially for the highly stressed rotor sheets. This so-called "external brittleness" study was conducted with disk ruptures in GHe and GH2 [8].
The results show classical curves with a peak around 200K and its disappearance at cryogenic temperatures.

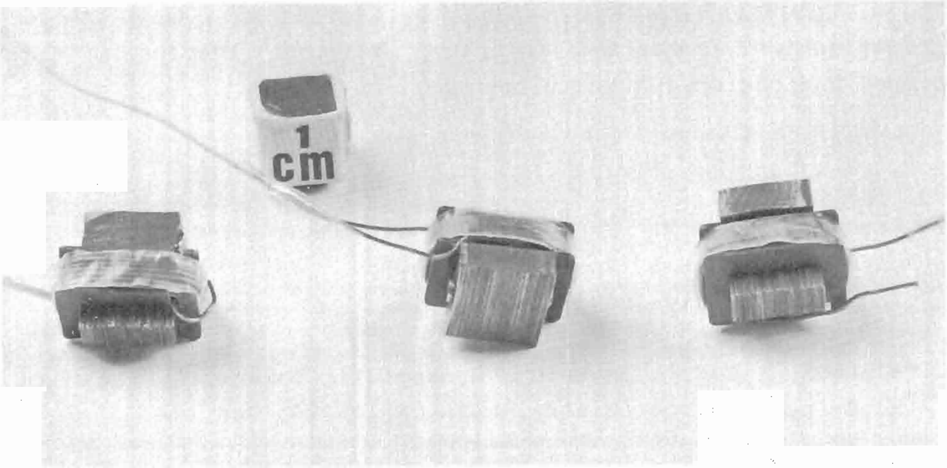

Fig. 10 Subscaled Components for LOX compatibility tests

4. Conclusion

A preliminary program was started by SEP in 1986 to verify a possible implementation of AMB on advanced turbopumps.

These studies has confirmed their potential interests :

(a) high reliability, with an expected MTBF higher than 40 000 h. This will allow high life in orbit and high cycles reusability.

(b) possible use into cryogenic propellants (LOX and LH2), related to attractive turbopump design.

(c) active control of the rotor dynamic, with effective engine thrust throttling, realtime diagnostic and easier development.

These advantages should balance for numerous applications the two major drawbacks of these bearings : a mass penalty and a relatively high recurrent cost.
These both disadvantages come mainly from the control cabinet, whose required spatialisation is possible for mean term.

According to these results, the design of a high speed test device was initiated beginning of 1988. Extensive tests planned for 1990 should confirm and precise this balance.

Those global results will be compared to similar investigations conducted on fluid bearings leading SEP to proper choices on future turbopumps

References

1. REDDECLIFF, J.M. ; VOHR, J.H. : Hydrostatic bearings for cryogenic Rocket Engine Turbopumps. Jal of Lubrication Technology, July 1969, pp 557-575

2. NIELSON, C.E. : Hybrid Hydrostatic/ball Bearings in High-Speed Turbomachinery, NASA-CR-168124, Jan 1983

3. GAUTHIER, M. ; ROUYER, C. : Semi Active Magnetic Bearings for Space Applications. ESA 2ème Symposium Europeen sur les Mecanismes Spatiaux - RFA Oct. 1985.

4. STUDER, P.A. : "Magnetic Bearings for Instruments in the Space Environment" NASA-NT-78-15492.

5. HABERMANN, H. ; BRUNET, M. : The Active Magnetic Bearing enables Optimum Damping of flexible rotor, Trans. ASME, 84-GT-117.

6. BRUNE, C. : Rotordynamics and Active Magnetic Bearings. Paper presented at 8th annual ROMAC Industrial Research Conference, June 20/24, 1988.

7. Rutherford and Saclay Laboratories Results , private communications.

8. BARTHELEMY, H. ; BRYSELBOUT, J. : BARBE, C. : Testing methods to select steels for GH2 storage and transport vessels. World Hydrogen Energy Conf. Pasadena, June 1982.