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MAGNETIC BEARINGS : A KEY TECHNOLOGY FOR ADVANCED ROCKET ENGINES ?

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SUMMARY

For several years, Active Magnetic Bearings (AMB) have demonstrated their capabilities in many fields, from industrial compressors to control wheel suspension for spacecrafts. Despite this broad area, no significant advance has been observed in rocket propulsion turbomachinery, where size, efficiency and cost are crucial design criteria.

To this respect, Société Européenne de Propulsion (SEP) has funded for several years significant efforts to delineate the advantages and drawbacks of AMB applied to rocket propulsion systems. Objectives of this work, relative technological basis and improvements are described in this paper, illustrated by advanced turbopump layouts.

Profiting from the advantages of compact design in cryogenic environment, the designs show considerable improvements in engine life, performances and reliability. However, these conclusions should still be tempered by high recurrent costs, mainly due to the space-rated electronics. Development work focused on this point and evolution of electronics show the possibility to decrease production costs by an order of magnitude.

INTRODUCTION

Every designer in Rotating Turbomachinery has already encountered difficulties in obtaining proper compromise between the machine specifications and the actual bearing capabilities. This is particularly true for Rocket Engine Turbopump (T/P) designs, where size, efficiency and costs are crucial design aspects, resulting in complex turbomachines with very high specific power (about 100 kW/kg for high efficiency engines) and rotational speed (up to 120,000 rpm), with a life limited to a few hours.

Thus the bearings appear to be key components in successful design, as well as imposing major limitations to further improvements in engine performance and life.

The figure 1 illustrates part of this assertion, reporting current and foreseen values for the bearing D.N. product, where D is the shaft diameter (in mm), and N the rotational speed (in rpm). It is clear that significant increase in one of these parameters, as dictated by advanced designs to improve T/P efficiencies and/or dynamic behaviour, exceed the rolling element bearing capabilities and call for innovative solutions.

Among other aspects, it is well-known that the use of on-board cryogenic propellants for cooling these bearings does not offer sufficient viscosity for lubrication, and consequently limits strongly the service life.

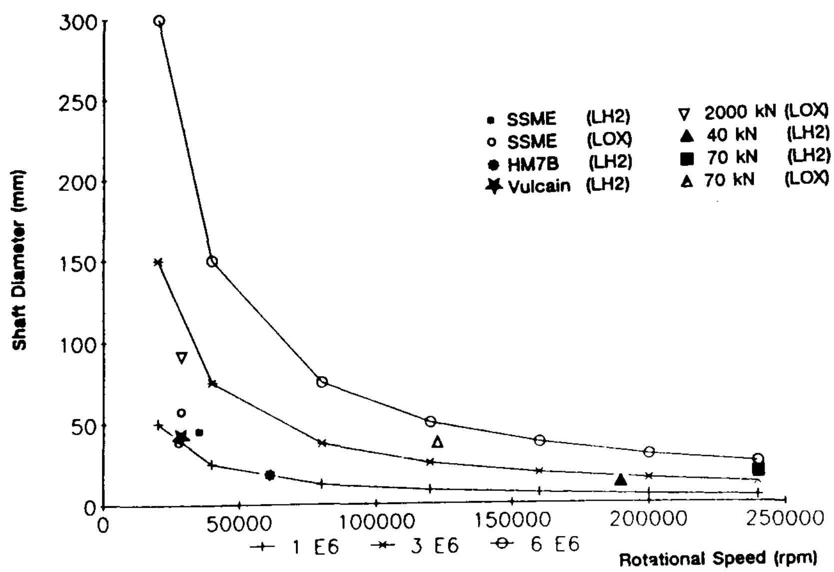


Figure 1 : Bearing D.N. Values for various T/P Designs

Consequently, the bearings, highly stressed by large static and dynamic loads, require careful analysis during the project, contribute predominantly to the failure mode allocations for the T/P, as illustrated figure 2 for a typical liquid hydrogen (LH2) turbopump, and involve expensive development tests and maintenance programs.

Following from this, rocket engine manufacturers have been studying for about two decades the capabilities and drawbacks of alternative bearings without any surface contact, i.e. fluid film bearing and magnetic bearings.

The former technique (fluid bearing) has been studied extensively for its noticeable advantages, with various practical concepts (hydrodynamic, hydrostatic and hybrid bearings) to minimize inherent drawbacks, such as rubbing in transients, complex dynamic behaviour and tight clearances. Actual turbopump tests have been performed (refs. 1, 2, 3) with positive results, but the few applications to space propulsion are biased toward storable propellants and low thrust engines (ref. 4).

Space applications of the second technique (mag bearing) have mainly concerned spacecraft attitude control (ref. 5, 6), with at least one degree of freedom (DOF) actively controlled. Despite numerous applications in industrial compressors and a growing interest in aerospace propulsion (refs. 7, 8), no practical work has been observed, although studies in jet engines are emerging.

In this field, this paper presents the objectives one can expect to meet by implementing such technology in aerospace propulsion together with the required analysis tools and technological basis for successful design, as the results of studies funded by Societe Europeenne de Propulsion (SEP) since 1986, and team work with Rocketdyne, Division of Rockwell International Corporation (RD) (Ref 9).

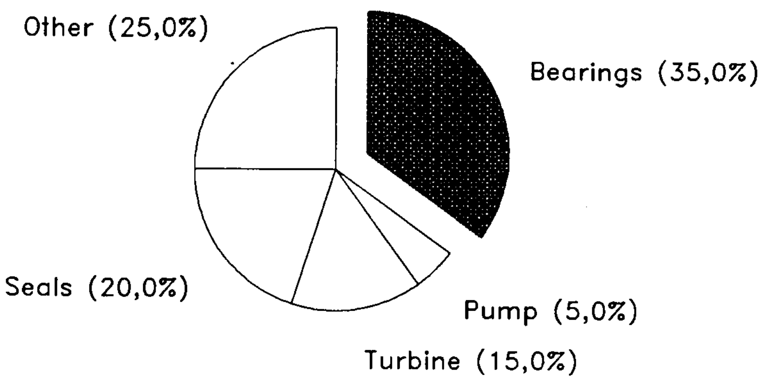


Figure 2 : Failure Mode Allocation for the VULCAIN LH2 Turbopump

T/P DESIGN & FUNCTIONAL FEATURES

Key features and corresponding T/P limitations can be pointed out on the figure 3, showing the strong interaction between the T/P design and the bearings specifications, as well as the inherent iterative process to finalize the T/P architecture.

This is particularly true by using Active Magnetic Bearings (AMB), where the link between the shaft (i.e. the bearings rotors) and the T/P housing (i.e. the bearings stator) is represented by the transfer functions, themselves function of the bearing specifications (speed, loads). The resulting bearing and associated controller change in turn the shaft assembly, stiffnesses and dampings, which leads to some modifications to the T/P design, thus changing the bearing specifications, until obtention of the final compromise.

Such T/P designs are illustrated in figure 4, reporting LH2 T/P layouts for a 40 kN thrust LOX/LH2 expander cycle rocket engine, and LOX T/P layouts for a 2000 kN thrust gas generator cycle engine. Main features of these designs and associated magnetic bearings are reported in table 1.

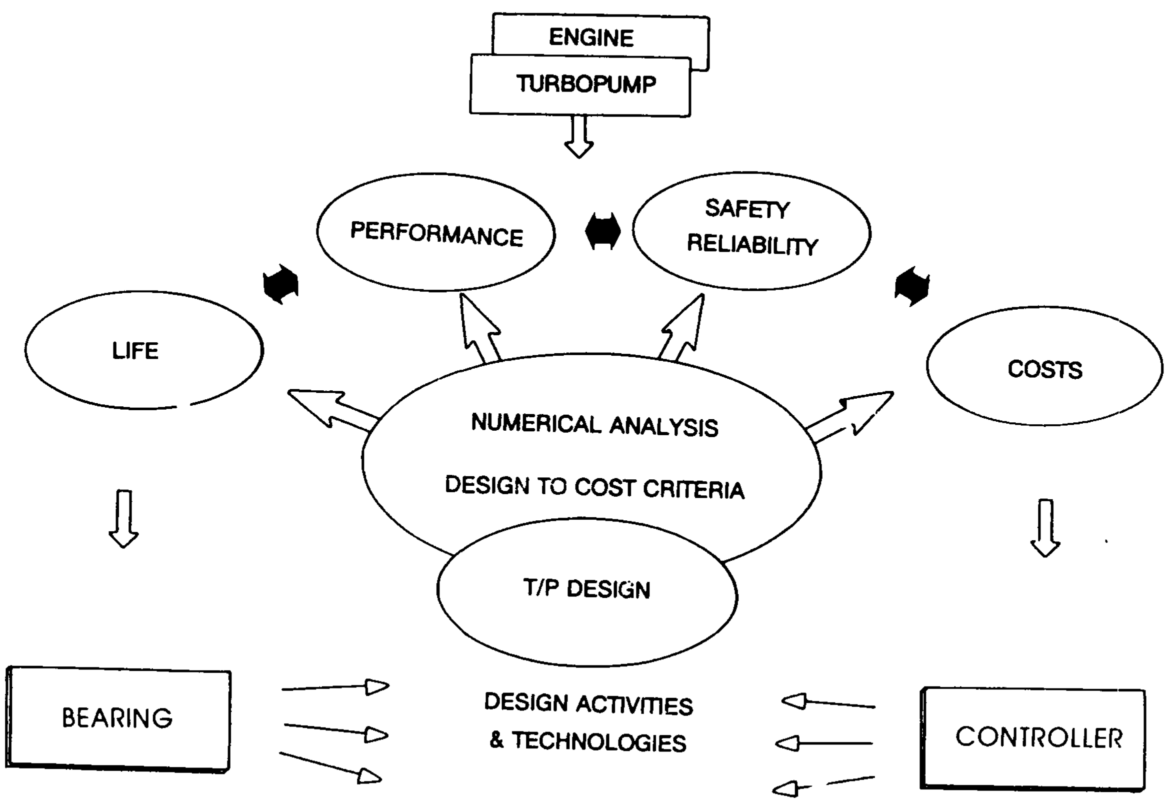
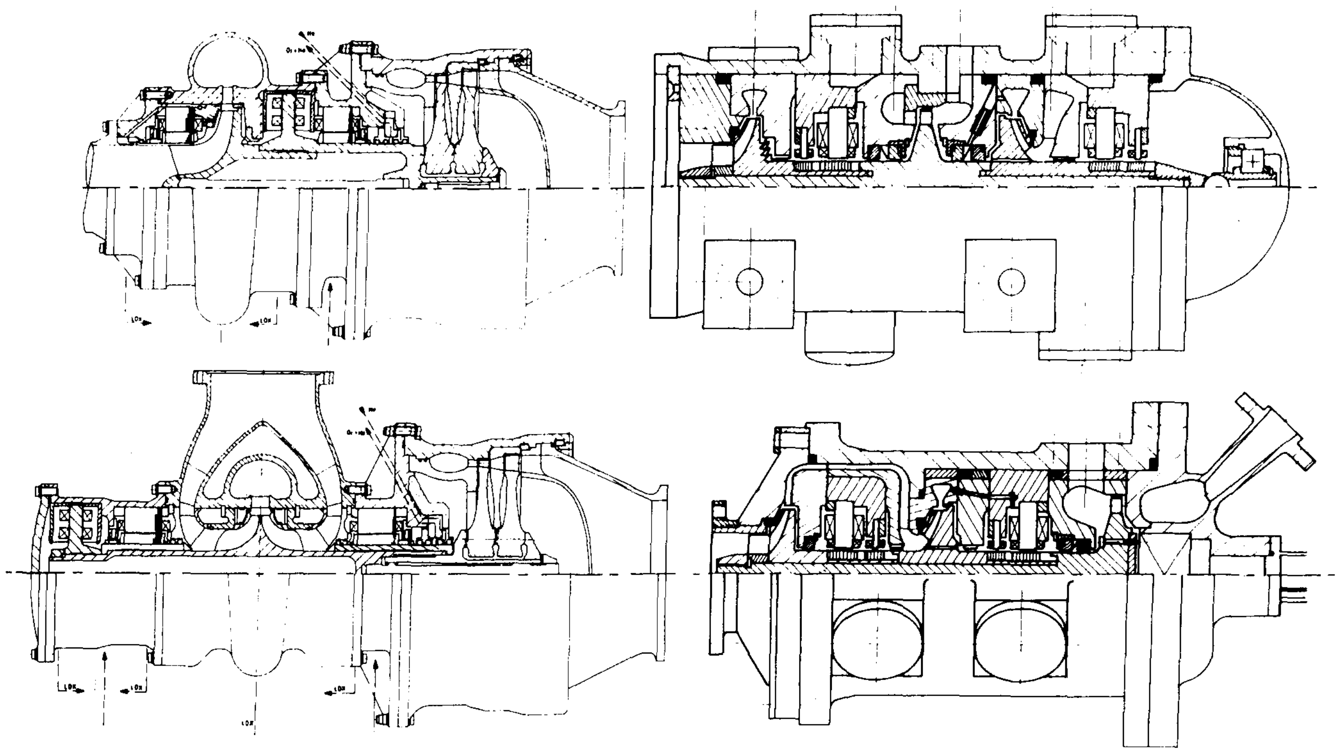


Figure 3 : T/P Design Methodology



2000 kN ENGINE 40 kN ENGINE

Figure 4. Advanced T/P Designs with AMB

TABLE 1 : MAIN FEATURES OF ADVANCED ROCKET ENGINE T/P AND ASSOCIATED MAGNETIC BEARINGS (AMB)

ENGINE THRUST - T/P	40 kN/LH2	60 kN/LH2	2000 kN/LOX
T/P CHARACTERISTICS			
. Pressure rise (MPa)	24	11	28
. Shaft Power (kW)	670	610	17,000
. Rotor Speed (rpm)	190,000	60,000	30,000
. Overall Length (m)	0.25	0.35	1,0
. Weight (kg)	4.8	28	260
AMB CHARACTERISTICS			
. Load (N) (max)	65	475	4,600
. Stator O.D. (mm)	60	75	210
. Shaft O.D. (mm)	12	25	91
. Airgap (mm)	0.2	0.2	0.4
. Materials (rotor)	Fe-Si or Fe-Co	Fe-Si or Fe-Co	Fe-Si
. Materials (stator)	Fe-Co	Fe-Co	Fe-Co
. Weight (kg)	0.6	-	30(w/axial)
. Power consumption (W)	500	400	5,000

The use of AMB in these Advanced T/P designs results in high rotational speed for optimal pump efficiencies and reduced T/P size and weight. Thrust modulation and dynamic control is also facilitated by high damping over a large operating speed range, including the first two or three critical speeds. Unbalance requirements can be also relaxed to some extent to simplify assembly procedures and minimize production costs. Finally, the AMB Control System means the existence of Health and Control Monitoring (HCM) integrated in the T/P at the earliest steps of the design, making the development easier, safer and less expensive.

The results have been substantiated by comparison with alternative T/P designs fitted with fluid film bearings and/or rolling element bearings. This has shown important simplification of the fuel (LH2) T/P originally designed with ball bearings (e.g. 2 stages pump instead of 4 stages with ball bearings, and inboard bearing with overhanging turbine disc) but minor or no significant advantage for the oxidiser (LOX) T/P. For this latter, the viscous losses at the bearings increase drastically, as illustrated in figure 4. The high fluid density (about 16 times more for the LOX than for the LH2) leads also to moderate pump tip speeds, thus reducing interest in high peripheral speed at the AMB airgap, compared to LH2 cases.

Thanks to the cryogenic environment (between 40 and 100 K) in both cases, the bearing stator size can be reduced by more than 2, compared to ambient temperature applications, thus improving bearing integration.

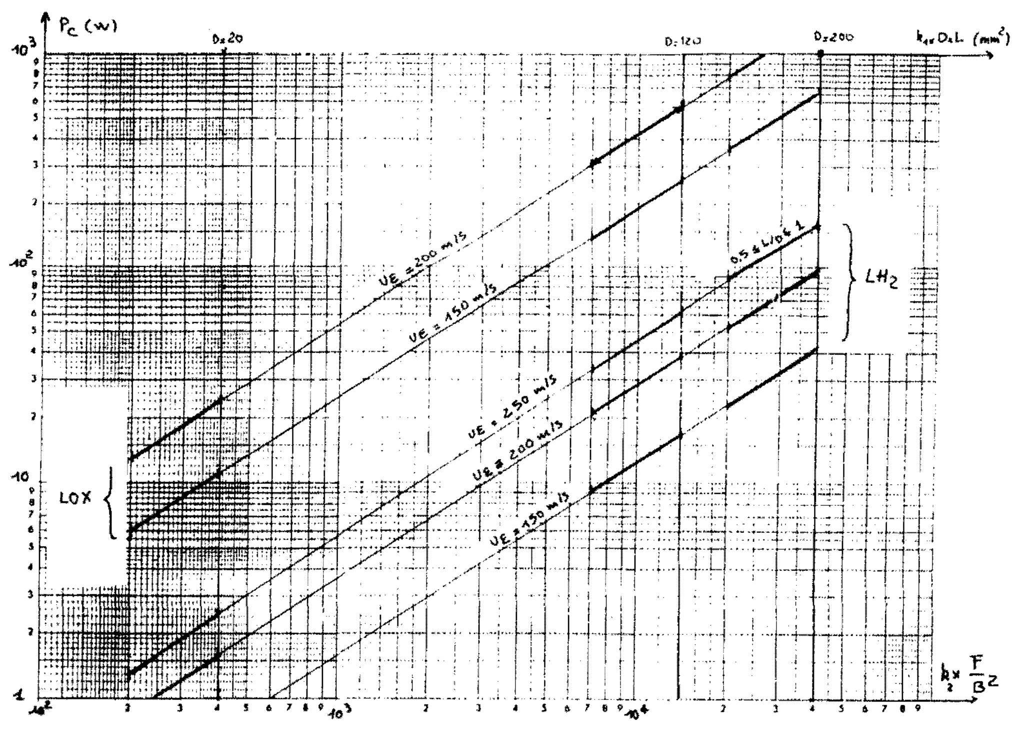


Figure 4 : Normalizes viscous losses as a function of speed at the airgap, fluid and bearing size

Trade-off between the AMB features and the clearances required along the shaft (with provision for misalignment and unbalance responses) generally results in a 0.2 mm (200 μm) airgap for engine thrust up to about 100 kN. This is 5 to 10 times more than the clearance required for fluid film bearings, thus facilitating inactive long-term storage in space and misalignment tolerance.

On the other hand, the small LH2 flowrate required to chill down the bearing and maintain cryogenic temperatures improves the pump efficiency and reduces shaft power losses, leading to LH2 saving. Numerical values as reported(table 2)illustrate this point. For cumulated duty cycles in space, long-term storage and/or long duration propelled missions, this allows considerable LH2 tank size and mass reduction. For a gas generator (GG) cycle engine, in this thrust range, this will save between 30 and 50 kg of LH2 per hour. For expander cycle engine, this allows slight increase of the chamber pressure, increasing the engine specific impulse.

TECHNOLOGICAL BASIS

In parallel with design studies, technological effort was aimed at validating the bearing design and improving the current state-of-the-art.
This effort has been oriented along two axis : the bearing materials and the controller size reduction.

Bearing materials

Earlier work has been reported in 1988 (ref. 8), and the results are here completed. They are mainly driven by cryogenic aspects, compatibility with liquid and gaseous oxygen and hydrogen, and improvements of mechanical and magnetic characteristics.

Silicon-iron rotor laminations have been the traditional choice for industrial bearings. This cheaper material offers good mechanical properties in cryogenic conditions : a yield stress higher than 500 MPa, high fatigue limit (better than 120 MPa at 10^7 cycles), together with reasonable flux density (up to 1.5 Tesla).
Moreover, a GH2 brittleness experimental study, performed with disc burst tests as depicted, figure 5, have shown classical behaviour, with disappearance of GH2 brittleness in cryogenic conditions (fig. 6).
Standard tests to check compatibility with LOX or GOX (bomb test, adiabatic compressions) confirm suitability for use in T/P environment.

Accordingly, most of the T/P designs briefly presented here have used iron/silicon alloys for the rotor laminations and conventional iron/colbalt alloys for the stator laminations.
Nevertheless, to further improve future designs, new iron-cobalt alloys have been carefully studied. This kind of alloy traditionally exhibits very high flux density (up to 2.2 Tesla) together with poor mechanical properties (low yield stress, limited to 200 MPa and excessive brittleness). However, metallurgical progress has renewed interest in such alloys, exhibiting

TABLE 2 : COMPARISON BETWEEN MAGNETIC AND HYDROSTATIC BEARINGS FOR A 40 kN THRUST ENGINE LH2 T/P

	MAGNETIC	HYDROSTATIC
Flow rate (g/s)	5	30
Decrease in pump efficiency	1 %	5 %
Viscous losses (W) at the bearing	450	800 (shaft centered, $\epsilon = 0$) 2500 ($\epsilon = 0,5$)
Load capacity (N)	65	800 (at $\epsilon = 0,5$)
LH2 saving	+ 30 kg/hour	

GH2 EMBRITTLEMENT ON FeSi SAMPLES

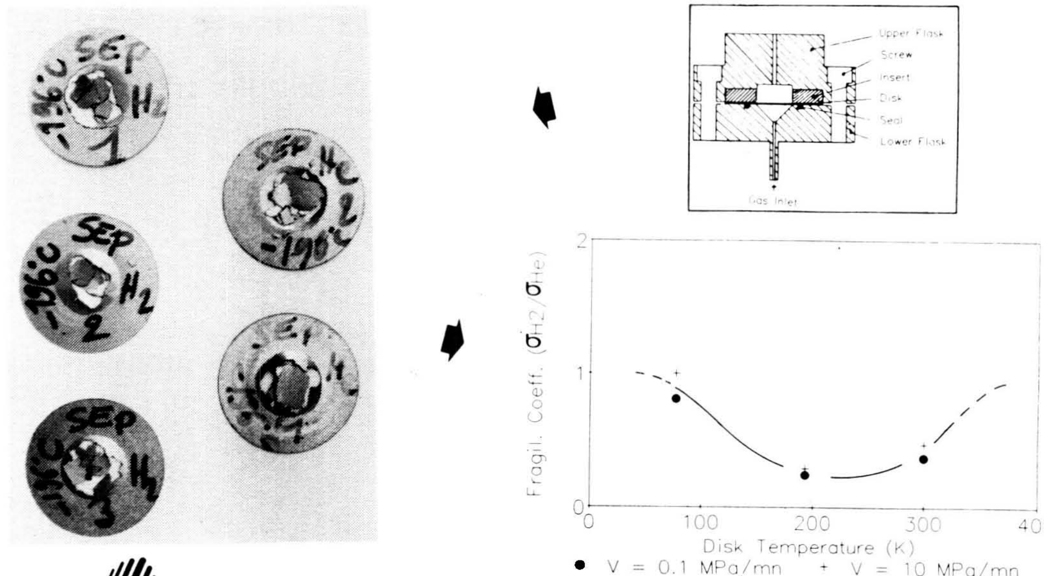


Figure 5 : Disc burst test for GH2 brittleness study

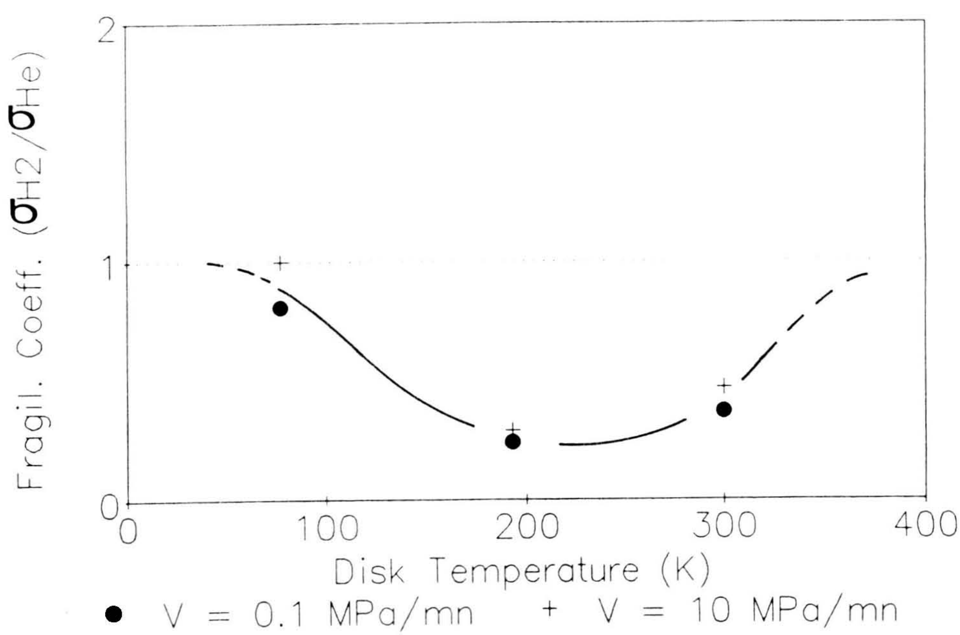


Figure 6 : Results of GH2 brittleness studies on Fe-Si laminations

more than 900 MPa for the yield stress in cryogenic conditions, together with high flux density (up to 2 Tesla). Hysteresis losses are higher than iron/silicon alloys at low frequencies and/or low magnetic field, but similar for higher values.

This alloy can then reduce by 30 % to 50 % the bearing length, or increase in the same proportions the load capacity, providing the AMB with a higher load factor (up to 190 N/cm^2).
Regarding coil wire materials and insulations, tests performed with copper and copper-beryllium alloys, as well as fluorine polymers, has allowed final material selection, wire diameters decrease with thin insulation (less than 50 μm) and production optimisation.

Controller

A significant step toward a flightweight controller (including power amplifiers and control PC boards) has been made by producing a space-rated power amplifier, whose electrical characteristics meet Upper Stage Engine LH2 Turbopump requirements.

This program has been focused on the power amplifier size reduction, due to the fact that they represent about 80 % of the controller size and weight, and almost 100 % of the power consumption of the board. Accordingly, joint effort between S2M, subsidiary of SEP and SEP personnel involved in space mechanism electronics has been funded to design, fabricate and test space-rated Pulse Width Modulation (PWM) power amplifiers. Trade-off studies have shown a significant gain in slightly decreasing the output voltage (from 120V to 100V) and increasing the current (from 6A to 7A) in order to meet component rating for space qualification. On the other side, design of PC board including two power amplifiers on the same card has been preferred for size reduction, thermal control and EMI requirements.
This concept is illustrated figure 7, with controller characterics reported table 3.

Those power amplifiers can be driven by analogic or digital control PC boards, the latter solution being preferred for easier T/P development and integration of health and control monitoring (including Expert System). The former solution offers cheaper development and production costs, as well as full availability of space qualified components.

This prototype has highlighted the high recurrent costs resulting for the electronics, mainly due to the space-rated components and necessary quality management, with an order of magnitude of 100 k $/kg.
This result is similar to existing electronics onboard rocket engines (e.g. the SSME flight controller), but progress in this field indicates that decrease by a factor of 10, consistent with reliability and life specifications, could be achieved (e.g. keeping the existing MTBF of 10.000 hours for life requirements limited to launch and transfer missions, and increasing up to 40.000 hours for long duration propelled mission).

TABLE 3 : 700 W AMB controller characteristics

	Industrial 120 V / 6A	Space-rated 100 V / 7A	
Volume (l)	78	15 (+)	10 (*)
Mass (kg)	35	9 (+)	6 (*)
Power cons. (W)	-	30	-

+ current
* project

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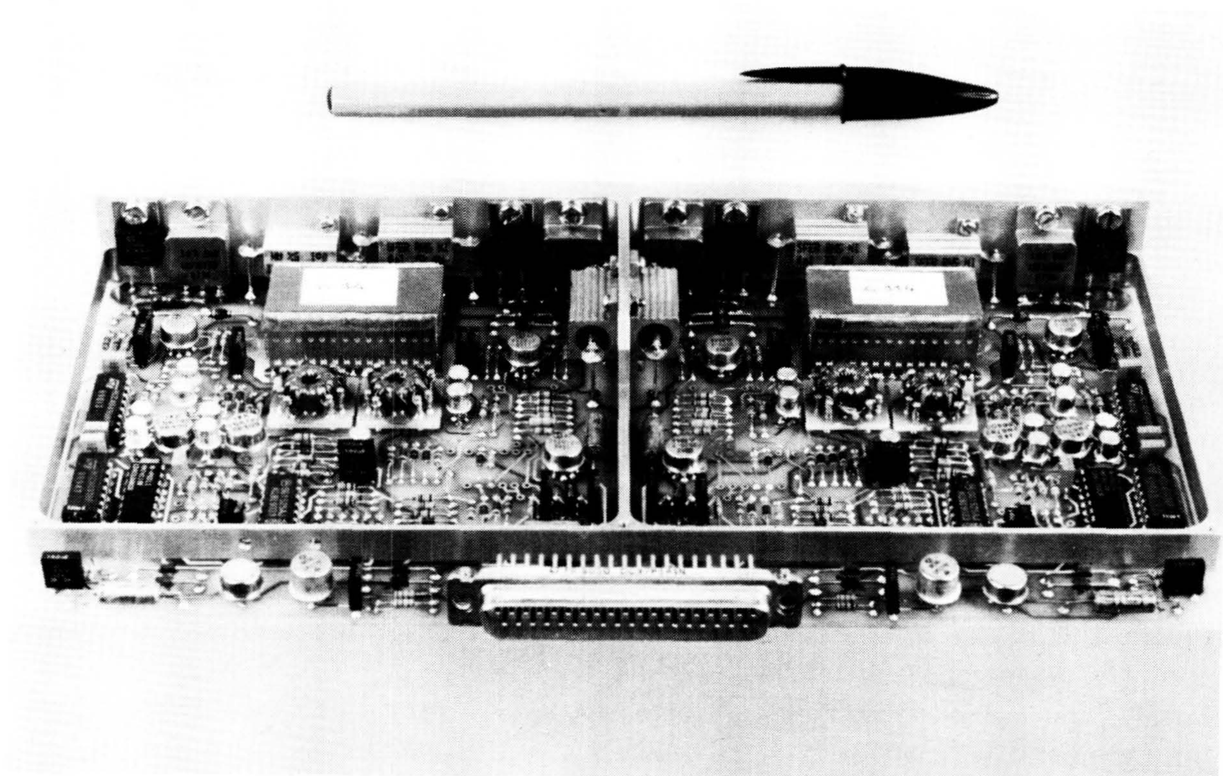

Figure 7. PC Board Prototype for Space-rated Power Amplifiers

A TYPICAL EXAMPLE

To further illustrate the magnetic bearing abilities, detailed design and studies of a demonstrative turbopump has been performed.

This machine (in battleship configuration) is illustrated, figure 8, showing a concept similar to LH2 T/P for Upper Stage Engine with two radial AMB. A retractable ball bearing is used to absorb axial loads during the transients.

Detailed rotordynamic analyses have been done during the design stage, both to optimise the design as explained previously, and to check consistency of the bearing specifications and machine behaviour.

During the iterative design process, modifications have been applied to bearing dimensions, as well as to the bearing impedances (modulus and phase), as reported, fig. 9. Explanations of the method and analysis tool can be fund in ref. 10.

The nominal point has been placed slightly before the seventh mode (2nd shaft bending mode) at a speed of 200,000 rpm. Associated critical speed map and damping coefficient evolutions are reported figures 10 and 11. Reliability improvement is illustrated by the figure 12, where the bearing failure mode allocation becomes negligible compared to other potential failure sources (not improved here).

Different control modes have been simulated (axis by axis or plane by plane) as well as special features, such as notch filters or Automatic Balancing Control (ABC). Effect of such a feature is illustrated figure 13, showing drastic decrease in bearing synchronous load.

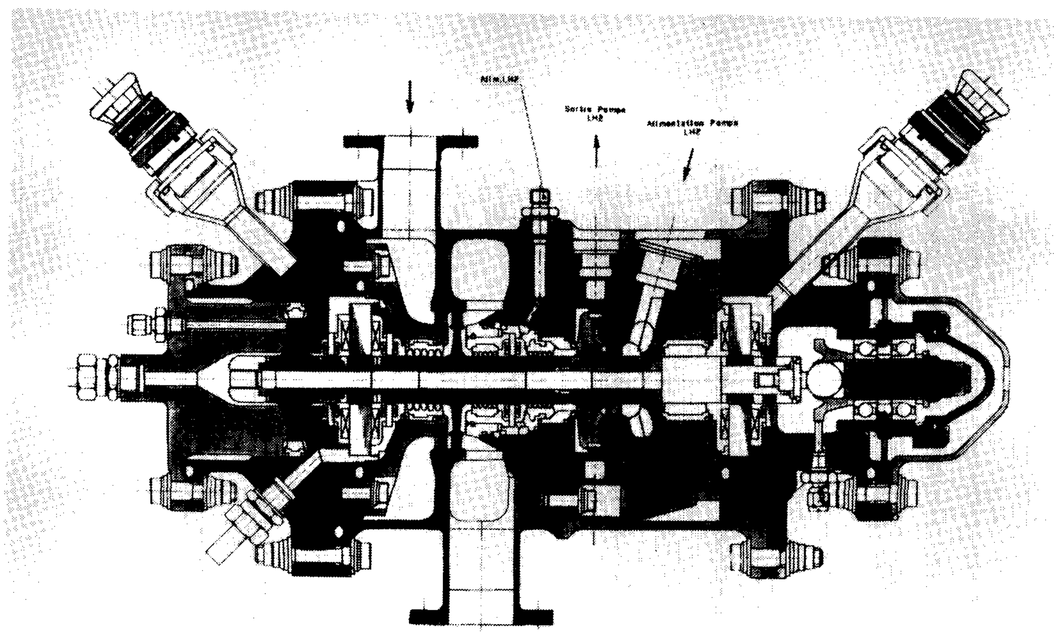

Figure 8. Turbomachine Design for AMB Qualification

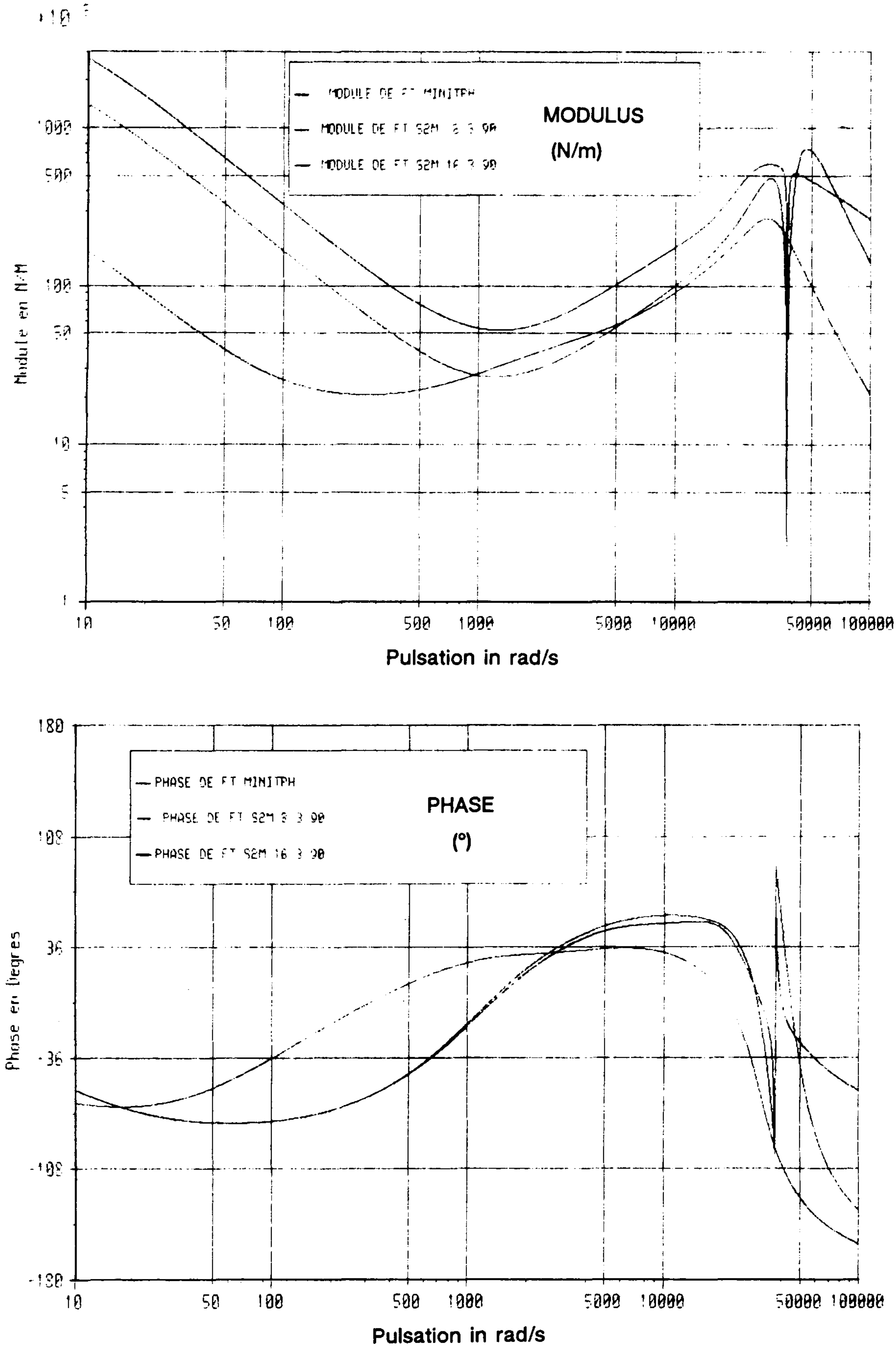

Figure 9. AMB Transfer Function

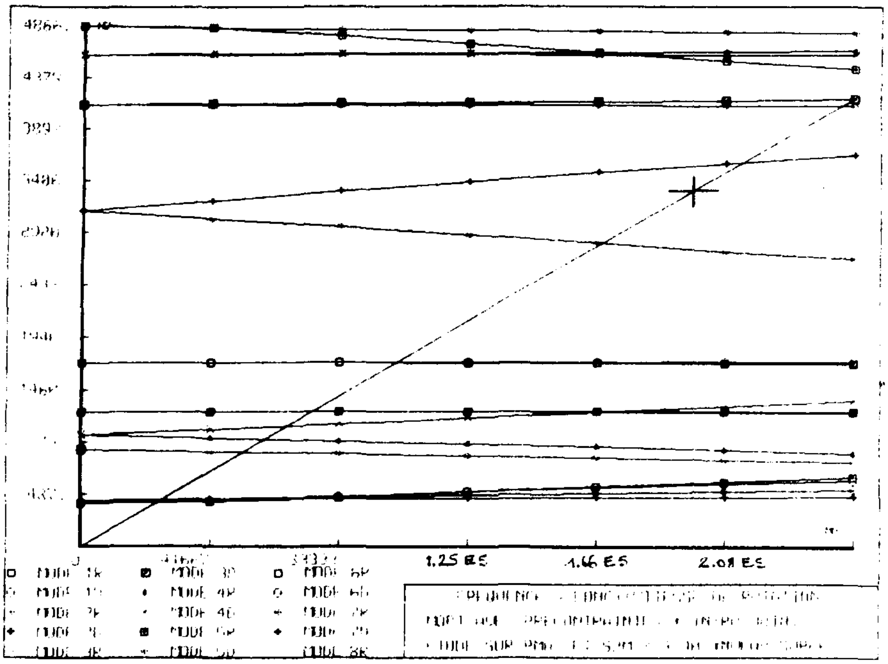

Figure 10. Critical Speed Map

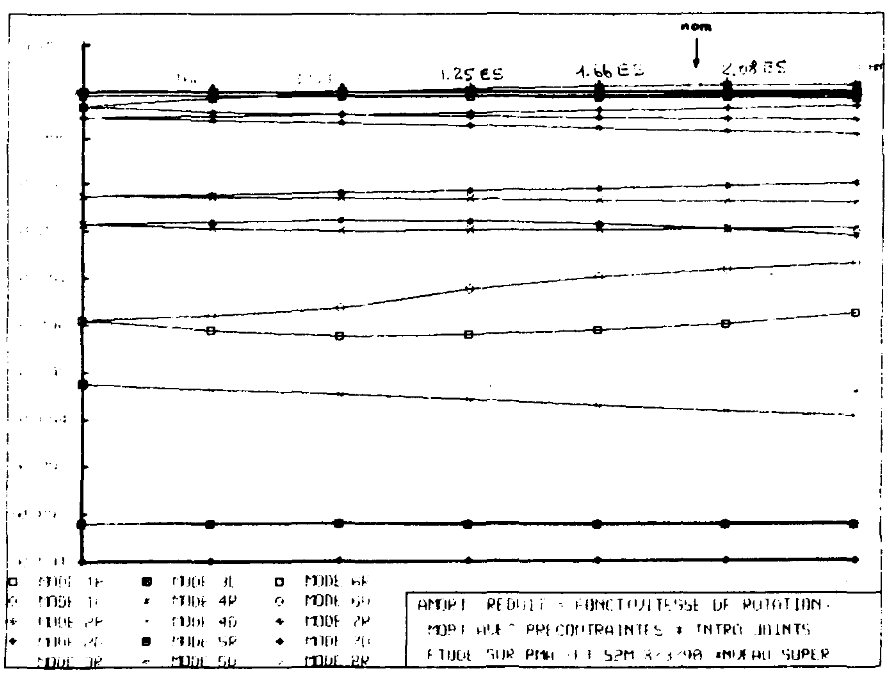

Figure 11. Damping Coefficients vs Rotational Speed

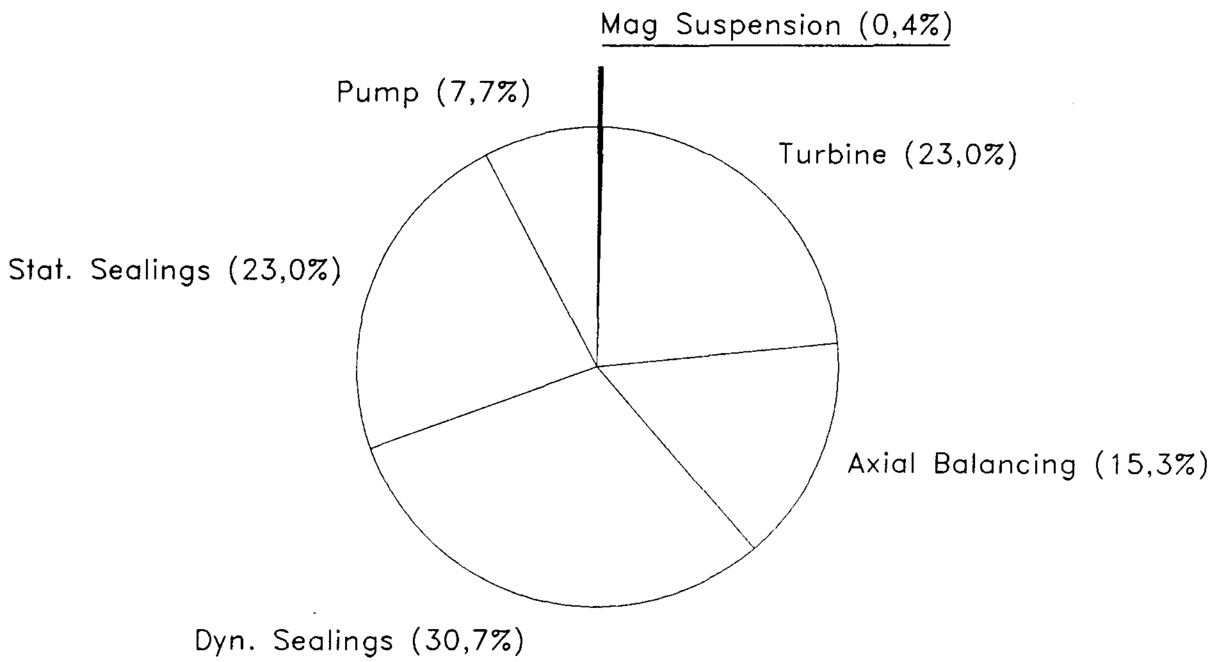

Figure 12. Typical Failure Mode Allocations with AMB (for a duty cycle of 600 s)

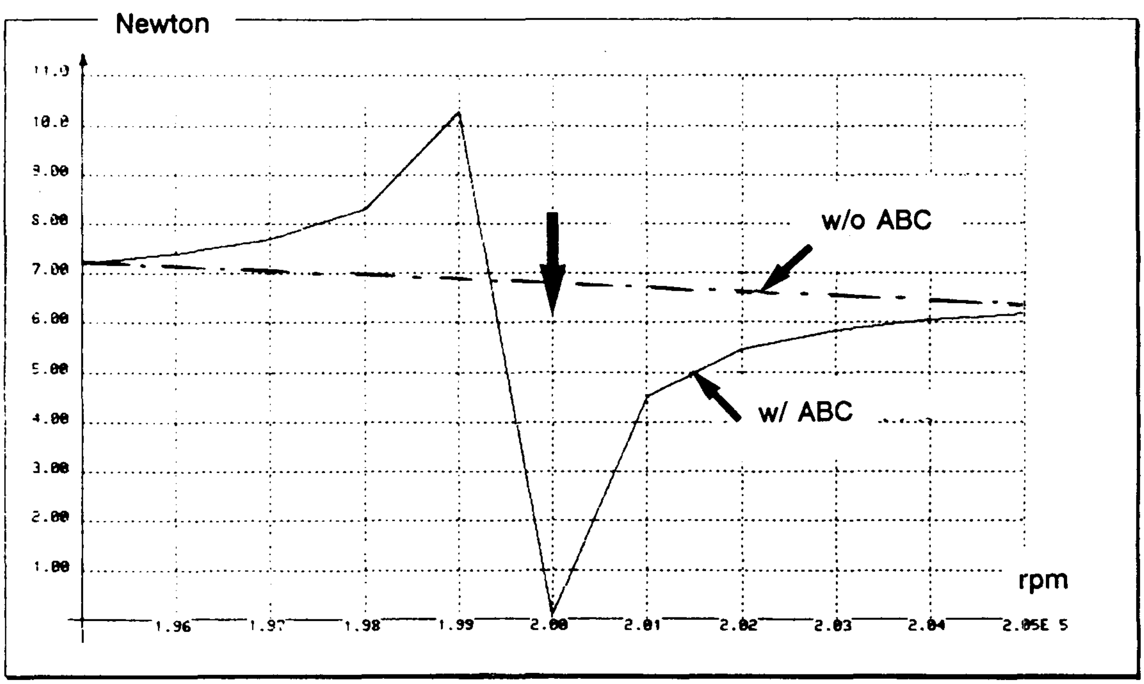

Figure 13. Effect of Automatic Balancing Control on the Bearing Dynamic Load

CONCLUSIONS

Advanced Turbopump (T/P) Designs implementing Active Magnetic Bearings (AMB) have been presented in this paper, together with associated technological basis and rotordynamic analysis. Objectives of such integration have been emphasized, as well as the availability of the required hardware and sophisticated numerical tools.

As a result, it is clear that AMB Technology offers important improvements in turbomachine performances, life and reliability. This is particularly true for Liquid Hydrogen T/P, where the low fluid density does not limit the AMB capabilities.

Integrated Health Monitoring and throttleability are offered, as well as long-term and/or repetitive space storage or propulsion.

The production cost, estimated according to fabrication of space-rated power amplifiers, appears high today. Nevertheless, this feature can be favourably balanced in space or flight applications, especially with the expected evolutions in electronic components and avionics.

<u>References</u> :

[1] J.M. Reddecliff, J.H. Vohr, *Hydrostatic Bearing for Cryogenic Rocket Engine Turbopumps*, Pratt & Whitney A., Journal of Lubrication Technology, Juky 1969, pp. 557-575

[2] C.E. Nielson, *Hybrid Hydrostatic/Ball Bearings in High-Speed Turbomachinery*, Rocketdyne Division, NASA-CR-168124, January 1983

[3] P.S. Buckmann, N.R. Shimp, and F. Viteri, M. Proctor, *Design and Test of an Oxygen Turbopump For a Dual Expander Cycle Rocket Engine*, Aerojet TechSystems & NASA Lewis R.C., AIAA Paper 89-2305, July 1989

[4] R.L. McMillion, T.J. Treinen, S.L. Stohler, *Component Evaluations for the XLR-132 Advanced Storable Spacecraft Engine*, Rocketdyne Division, AIAA Paper 85-1228, July 1985

[5] A. Nakajima, *Research and Development of Magnetic Bearing Flywheels for Attitude Control of Spacecraft*, Japanese National Aerospace Laboratory, Proceedings of the 1st International Symposium on Magnetic Bearings, Zürich, June 1988, pp.3-12

[6] J.P. Roland, *Magnetic Bearing Wheels for Very High Pointing Accuracy Satellite Missions*, Aérospatiale, Proceedings of the Int. Symposium on Magnetic Suspension Technology, NASA Langley R.C., August 1991

[7] J.P. Girault, *Implementation of Active Magnetic Bearings in Advanced Rocket Engine Turbopumps*, Société Européenne de Propulsion, Proceedings of the 1st International Symposium on Magnetic Bearings, Zürich, June 1988, pp.199-210

[8] D. Hibner and L. Rosado, *Feasibility of Magnetic Bearings for Advanced Gas Turbine Engines*, Pratt & Whitney and Wright laboratory, Proceedings of the Int. Symposium on Magnetic Suspension Technology, NASA Langley R.C., August 1991

[9] J.P. Girault and K.W. Lang, *Long Life and Reliability : Expectations for Advanced Turbomachinery in Space*, Société Européenne de Propulsion and Rocketdyne Division, AIAA Paper 91-2416, 27th Joint Propulsion Conference, Sacramento, June 1991

[10] C. Brune, *Rotordynamics and Active Magnetic Bearings*, Société Européenne de Propulsion, 8th annual ROMAC Industrial Research Conference, June 1988