Digital Control for Low Cost Industrial AMB Applications

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Abstract:

Active magnetic bearings have many advantages compared to other bearing concepts. However, for many potential industrial applications they have been too complicated and too expensive in the past. Thanks to innovative digital control concepts, active magnetic bearing systems with higher performance, smaller dimensions, lower power consumption, and lower costs are reality today.

This paper discusses various control concepts for active magnetic bearings and presents an innovative solution for low cost.

1. Introduction

In general an active magnetic Bearing (AMB) system (figure 1.1) consists of a mechanical structure (rotor), electromagnetic coils, various sensors and a controller. The overall goal of an AMB controller is to stabilize the plant and to reach optimal technical and economical performance. To achieve these goals, active magnetic bearing systems have to be optimized in an overall mechatronic design approach. This led to new concepts for rotor, magnets, sensors, electronics and control.

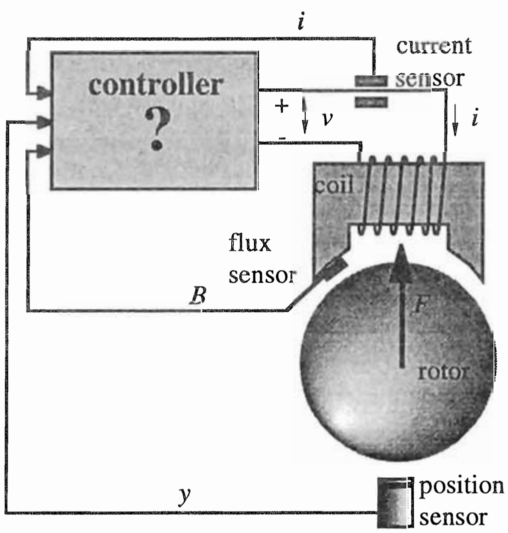

FIGURE 1.1: Schematic of an active magnetic bearing system

Research labs and magnetic bearing companies have developed a large variety of new concepts in the last years, e.g. hybrid bearings using permanent magnets or magnetic bearings integrated into a motor drive. However, most lack of performance or are restricted in some way.

In this paper we focus on fully active bearings with digital control. We assume that the current force characteristic is well represented by the well known quadratic equation and hysteresis, eddy current and saturation effects are negligible. Further more, we assume that the position, current and flux density measurements are the main candidates to be used as input to the controller.

For an optimal technical and economical approach we identified the following key issues:

- Overall AMB concept by means of choosing the appropriate sensor and actuator concept
- Digital controller hardware, allowing to reduce the number of electronic components and giving a high level of flexibility
- Software environment for controller layout and system analysis

2. Control Concepts for AMB

The control concept determines, which input signals (i, B, y) are used for feedback and how the AMB controller is designed. Starting with a general model of an AMB-system (figure 2.1), the basic ideas of current, flux-density, voltage and self-sensing control are derived and discussed in this section.

2.1 Model of AMB Plant

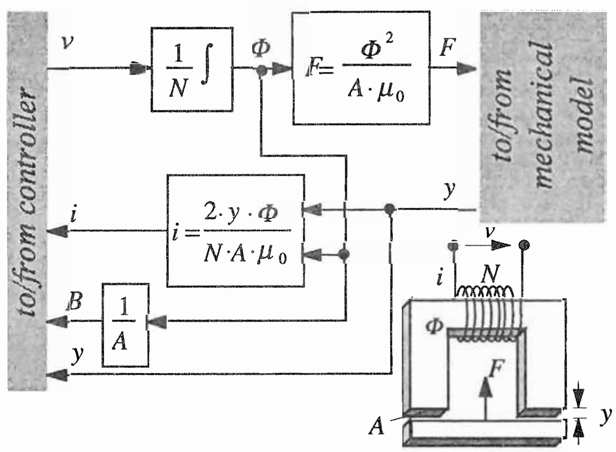

FIGURE 2.1: Simplified model of a single AMB actuator (one coil)

v: applied voltage [V]
i: current [A]
N: number of windings
Φ: magnetic flux [Vs]
B: flux density [Tesla]
y: air gap [m]
A: cross section of pole shoe [m^2]
F: magnetic force of the two pole shoes [N]
μ_0: $1.257 \cdot 10^{-6}$ [Vs/Am]

Figure 2.1 shows a simplified model of an AMB actuator not considering eddy current losses, stray fields, resistance of the coil, permeability and saturation of the iron. The actuator gets a voltage v from the controller a feeds the possible sensor signals (i, B, y) back to the controller. The magnetic force generated in the coil can be expressed as a function of the voltage v, the flux density B or the current i.

$$F = \frac{1}{N^2 A \mu_0}\left(\int v \cdot dt\right)^2 \tag{2.1}$$

$$F = \frac{A}{\mu_0} B^2 \tag{2.2}$$

$$F = \frac{N^2 A \mu_0}{4} \cdot \left(\frac{i}{y}\right)^2 \tag{2.3}$$

To produce bi-directional forces, the coils are usually designed in an axially opposed arrangement (fig. 2.2). For this arrangement equation 2.1 through 2.3 can then be found as followed.

$$F(v) = F_+(v_+) - F_-(v_-)$$

$$F = \frac{4}{N^2 A \mu_0} \Phi_0 \int v \cdot dt$$

$$\text{with } v_+ = v_0 + v \ ; \ v_- = v_0 - v \tag{2.4}$$

$$v_0(t) \text{ so that}$$

$$\Phi_0 = \int v_0 \cdot dt = \text{bias flux} = \text{constant}$$

$$F(B) = F_+(B_+) - F_-(B_-)$$

$$F = \frac{2 \cdot A \cdot B_0}{\mu_0} B \tag{2.5}$$

$$\text{with } B_+ = B_0 + B \ ; \ B_- = B_0 - B$$

$$B_0 = \text{ bias flux density } = \text{ constant}$$

$$F(i,y) = F_+(i_+, y_+) - F_-(i_-, y_-)$$

$$F = N^2 A \mu_0 \cdot \frac{i_0^2 y_0 y + i_0 y_0^2 i + i_0 i y^2 + y_0 y \cdot i^2}{\left(y_0^2 - y^2\right)^2}$$

$$\text{with } i_+ = i_0 + i \ ; \ i_- = i_0 - i$$

$$\text{and } y_+ = y_0 - y \ ; \ y_- = y_0 + y \tag{2.6}$$

$$i_0 = \text{ bias current } = \text{ constant} \ ; \ y_0 = \text{ nominal air gap}$$

for $y << y_0$ and $i << i_0$ (linearisation)

$$F_{lin} = N^2 A \mu_0 \cdot \frac{i_0^2 y_0 y + i_0 y_0^2 i}{y_0^4} = N^2 A \mu_0 \cdot \left(\frac{i_0^2}{y_0^3} y + \frac{i_0}{y_0^2} i\right)$$

For the two coil arrangement the bearing force is linear with respect to the control voltage (2.4) and the flux density (2.5) if appropriate bias flux is used. In respect to the current in the coil (2.6) we find a non-linear equation and a coupling with the actual air gap. For small control current and small displacement from the nominal air gap y_0 the well known linearized force-current relation (F_{lin}) can be derived.

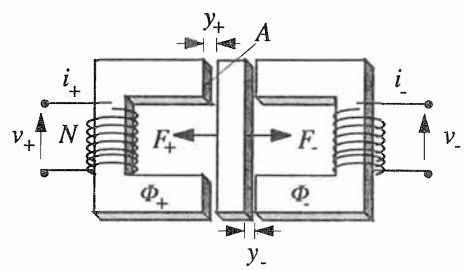

FIGURE 2.2: Axially opposed coil arrangement for bi-directional forces

If we assume the rotor to be a simple mass, the dynamics can be described by the second order differential equation.

$$m\ddot{x} = F \tag{2.7}$$

Equation (2.7) together with (2.4) to (2.6) from the simplified mathematical model of the AMB plant.

Based on equation (2.4) to (2.7) one can find different control concept for system stabilization. The most relevant control concepts are discussed in the following.

2.2 Current Controlled AMB with Position Feedback

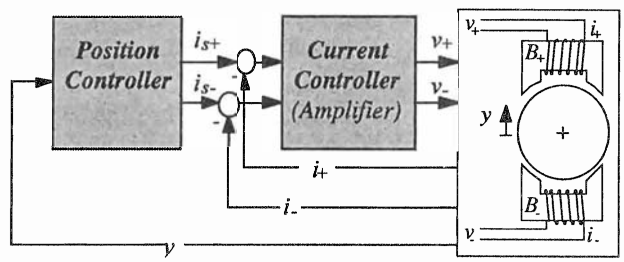

FIGURE 2.3: Control schema of a current controlled AMB

The most common control concept for active magnetic bearings is current control. In this concept the current in each coil is measured and controlled by a separated path. Usually the current control loop is tuned much faster than the outer position control loop. Around the nominal position the command current i_x can be regarded as the actual current in the coil which is proportional to the magnetic force.

Advantages:

+ easy physical understanding; with PD-controller the system is equivalent to a spring damper system
+ power amplifier with current control is decoupled from position controller

Disadvantages:

- position and current sensor required
- high bandwidth for current controller required -> high switching frequency of power stage
- nonlinear behavior for high loading and large position offset
- complex and expensive

2.3 Flux Controlled AMB with Position Feedback

To avoid problems with saturation or non-linearity of the magnetic actuator, flux density controlled amplifier can be used. The flux density control loop is much faster than the position control loop. To limit the maximal current in the coils usually also a current measurement is required. However, the current measurement has not to be very accurate and very dynamic.

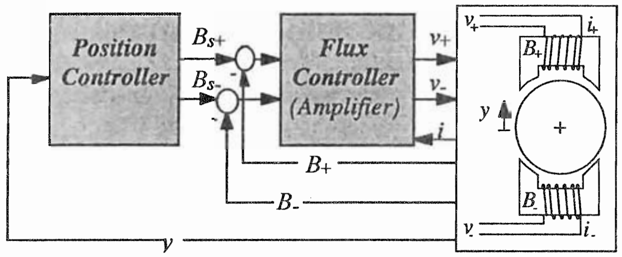

FIGURE 2.4: Control schema of a flux controlled AMB

Advantages:

+ easy physical understanding; with PD-controller the system is equivalent to a spring damper system
+ precise and linear force control, compensation of stray field, eddy current and hysteresis inherent
+ power amplifier and position controller are decoupled

Disadvantages:

- position and flux density and rough current measurement required
- high bandwidth for current controller required
  -> high switching frequency of power stage
- very complex and expensive
- reliability of flux sensor, cabling critical

2.4 Integrated Position Measurement based on Current or Flux density Controlled AMB

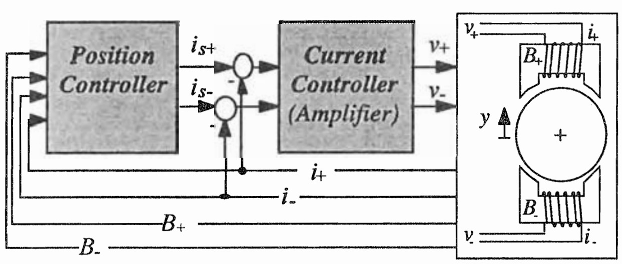

FIGURE 2.5: Control schema of a current controlled AMB with integrated position measurement

By rearranging equation (2.5) and (2.6) it can be shown that the position signal can be obtained from the current and flux density measurement.

$$y = \frac{2y_0^2}{N\mu_0 i_0} B - \frac{y_0}{i_0} i \qquad (2.8)$$

Therefore we do not need a separate sensor coil with this concept. However, saturation effects and non-linearity may cause problems and the amplifier noise directly interferes with the position signal.

Advantages:

+ easy physical understanding; with PD-controller the system is equivalent to a spring damper system
+ no separated coils for position measurement required
+ power amplifier and position controller are decoupled

Disadvantages:

- precise flux density and current measurement required
- nonlinear position signal for high loading and large position offset
- complex, not very robust

2.5 Voltage Controlled AMB with Position Feedback

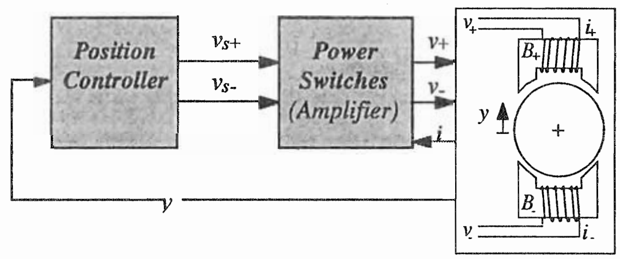

FIGURE 2.6: Control schema of a voltage controlled AMB

Equation (2.4) shows probably the simplest way to generate and control the bearing force. Avoiding the current or flux feedback loop in the power amplifier reduces the complexity of the system. However, it can be difficult to generate the bias flux Φ_0 in the general case.

Advantages:

+ only position measurement necessary
+ simple control schema
+ no separate control loop for the amplifier
+ using a micro-controller with integrated PWM-unit the amplifier consists of the power switches only
+ nearly no phase lag between voltage request (v_{s+}, v_{s-}) and actual voltage (v_+, v_-) across the coils.
+ Compact and robust design possible

Disadvantages:

- current limitation required to avoid overload. For low power, switches with integrated current limitation are available. With the concept described in the following chapter the current limitation is inherent.
- bias flux generation difficult
- physical understanding not so intrinsic
- at minimum a PD^2 controller is required for stabilization. This is only a main disadvantage when using analog control

2.6 Self-Sensing AMB, Voltage Control with Current Feedback

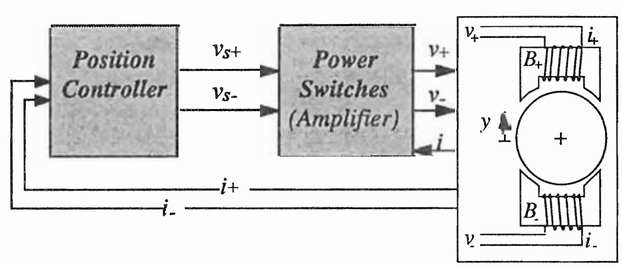

FIGURE 2.7: Control schema of a self-sensing AMB

Unequal to all the other concepts the self-sensing system does not require a position signal for stabilization. It has been demonstrated that stabilization is possible using the current feedback only [1], [2], [3]. However, since the position signal is not explicitly fed back, the controller finds its equilibrium for zero current. In reality this means that loading results in an position offset against the direction of the external force. The actual rotor position in the air-gap is not known and also not observable.

Advantages:

- \+ Simple control schema
- \+ no separate control loop for the amplifier
- \+ using a micro-controller with integrated PWM-unit the amplifier consists of the power switches only
- \+ nearly no phase lag between voltage request (v_{s+}, v_s) and actual voltage (v_+, v) across the coils.
- \+ Compact and robust design possible
- \+ no separated sensor coils for position measurement required

Disadvantages:

- hysteresis effects, eddy current losses, stray-fields and non-linearities reduce the performance of the system or make it even impossible.
- physical understanding not so intrinsic
- at minimum second order controller is required for stabilization.
- high quality current signals required

2.7 Overview on the Different Concepts

Concept -> Criteria	2.2 Curr. Contr.	2.3 Flux Contr.	2.4 Int. Sens.	2.5 Volt. Contr.	2.6 Self-Sens.
No. of sensors per channel	3	3/4^x	4	1/2^{xx}	2
Robustness to copper resistance	++	++	+	-	- -
Robustness to noise	-	+	-	+	- -
Validity of linearisation	-	++	0	0	-
Robustness to 2nd order effects*	-	++	- -	+	- -
Robustness of controller	+	+	-	+	-
Simplicity Low Cost	0	- -	- -	++	++

TABLE 2.1: Comparison of the different concepts

x usually current feedback is required for over-current detection

xx usually feedback of the sum of the current of the two coils is required for bias flux generation and over-current detection

* second order effects are namely related to eddy current, stay-fields, hysteresis or time lag

++: very high rating; +: high rating; 0: average; -: low rating

- -: very low rating

The comparison of the different concepts shows flux controlled AMB with position feedback as a clear leader for high performance systems. However, its clear disadvantage is its complexity and high costs. Concerning cost, a voltage controlled AMB with position feedback or self-sensing AMB are clearly ahead. Out of these two candidates voltage control with position feedback has clear advantages concerning performance. Thus voltage control with position feedback should be the concept of choose if looking for low cost and still good performance.

In the next chapter we therefore focus on this concept. We will also present an optimal solution of the electromechanical design and the bias current generation.

3. Low Cost AMB system Based on Voltage Control

In recent applications, active magnetic bearings usually consist of ten magnet poles (two for each degree of freedom), a sophisticated sensor system with at least five sensors, a fast *Digital Signal Processor* (DSP) for digital control, ten current/flux amplifiers with current/flux measurement, and an internal feedback loop. The current/flux controlled power amplifier is the most expensive part of the electronics, mainly because of the required internal feedback loop and the supervision system.

We consistently analyzed all the functions required of the individual parts of an AMB system and incorporated the individual parts in an optimized new concept.

3.1 AMB System Design

If significant cost reduction must be achieved, the electronics can no longer be treated as three isolated parts and the number of sensors and actuators are reduced to a minimum. The whole system has to be optimized in an overall mechatronical approach to find a superior solution with a minimum of electronics and electromechanical components. This process led to the Highly Integrated Magnetic Bearing Systems [4]. Its main features are:

- Voltage controlled power amplifier without internal feedback or current measurement
- Minimum number of bearing magnets -> 6 poles for 5 degrees of freedom
- Sensor circuit for future integration in an ASIC's chip -> 5 displacement and 1 pulse sensor
- Use of a single chip controller with integrated A/D converter, digital I/Os, serial ports and a pulse width unit for direct control of the power switches
- Motor controlled by the AMB controller
- Emergency power supply realized through energy recovered by the inverter
- Powerful serial link based on MATLAB for on-line development, calibration and diagnostics [5]

Figure 3.1 shows the block diagram of the whole system. The prototype electronics needs about 400 cm^2 of board space in conventional through-hole technology.

3.2 Voltage Control

In our approach we use voltage control instead of current control, the natural consequence of the discussion in previous chapter. This means that the position controller outputs the desired *voltage* for the bearing magnets instead of the *current* allowing to save current feedback for all channels of the power amplifier. By using a current source and only six magnets (figure 3.2) also the current measurement for supervision can be omitted. Thus, it is easy to realize the voltage control with the digital PWM signals of the single chip computer, and the resulting switching power amplifier is very simple, only consisting of one power switch for each magnet. The PWM signals can easily be generated by the microprocessor using the appropriate software. This leads to minimum and low cost bearing electronics (figure 3.1).

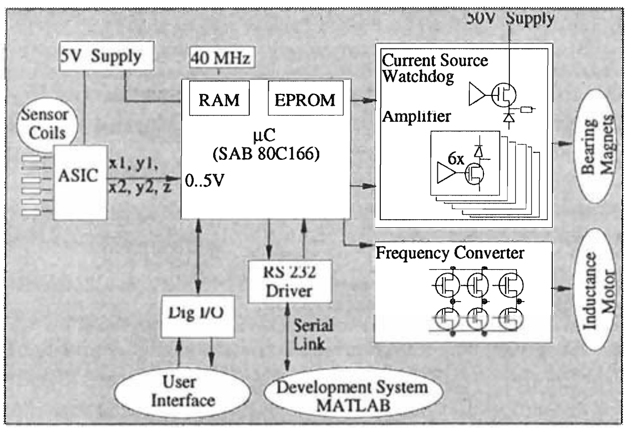

FIGURE 3.1: Block diagram of the voltage controlled AMB system for low cost application

3.3 Configuration of the Bearing Magnets

An AMB system usually has ten bearing magnets, two for each of the five degrees of freedom, to provide positive and negative forces in all directions. The number of active magnets can be reduced by substituting some of them by passive bearings (permanent magnets or reluctance principle). However, stiffness and damping values of passive bearings are very low and are not acceptable in many applications.

In our configuration according to figure 4.2, the number of magnets is reduced to six, and no passive axes are needed. [6],[7].

To control this configuration, a coordinate transformation is used. The output signals of the five controller channels (v_{xl}, v_{yl}, v_{x_2}, v_{y_2}, v_z) are transformed to the six signals (v_{a_1}, v_{b_1}, v_{c_1}, v_{a_2}, v_{b_2}, v_{c_2}) for the PWMs which drive the switches of the amplifier. Active control is achieved in all five axes. Thus, the power amplifier needs only six channels instead of ten.

3.4 Bias flux generation

A bias current i_0 is necessary for high dynamic forces. It improves the linearity of transfer characteristics of the magnets and can be adjusted by an offset voltage v_0 on the outputs of the transformation. The resulting bias current i_0 is v_0/R_{cu} while R_{cu} is the copper resistance of the magnets. Since the copper resistance is dependent on temperature, it is preferable to measure the sum of the bearing currents and to control it with a feedback loop. This control loop may be very slow because it only has to compensate for temperature drift.

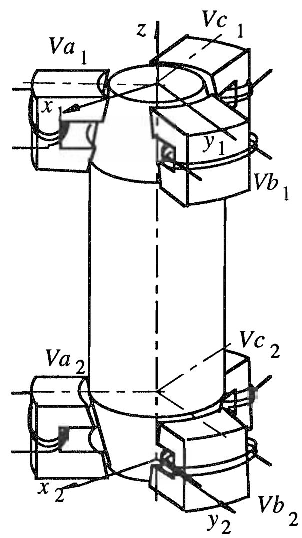

FIGURE 3.2: Minimum AMB system with six pole arrangement

A current limitation must be provided to make the whole system save and reliable. In normal operation, when the rotor is suspended in the center of the magnets, the stationary bearing currents reach a moderate level according to rotor mass. Excessive currents only occur during transient operating conditions, e.g. load changes or touch–down of the rotor. In case of unexpected operating conditions the bearing currents could reach extremely high values according to the actual controller output signal. However, the bias control is still active and the bearing currents are limited by that controller. In a worst case situation, five of six coils are at zero current and the remaining coil reaches six times the bias current. But this situation is not critical because the microprocessor can detect it and switch off the amplifier after a short lapse of time. If the bias current control can is realized as a current source also the maximum current is limited. Therefore, no current measurement is needed in the amplifier.

4. Application Examples

4.1 The Textile Spindle Example

The concept described in previous chapter was first installed on a textile spindle for thread manufacturing [4]. The electronics, mounted on a two circuit boards is directly attached to the spindle (figure 4.1). Integration of the electronic onto on circuit board using SMD (surface mounted device) technology is under development.

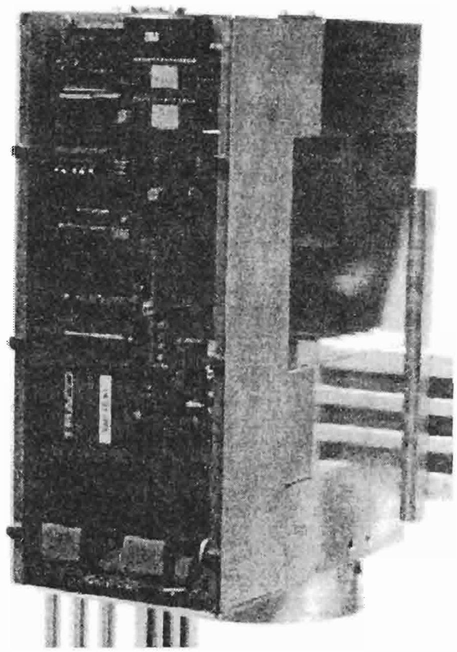

FIGURE 4.1 Textile spindle example sizing around 120 x 160 x 400 mm

The textile spindle features

- 5 axis active control
- homopolar bearing design with 6 coils and massive rotor
- 80.000 rpm, 200 Watt
- running in vacuum
- Integrated electronics for AMB and motor drive is directly installed on the spindle housing

4.2 Turbo Compressor Prototype

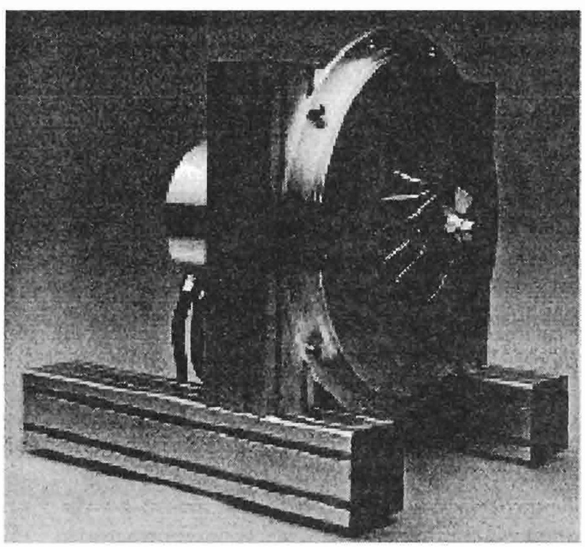

FIGURE 4.2 Turbo compressor prototype with a motor/bearing housing diameter of 160 mm

Based on the experience gained with the textile spindle a prototype of a radial compressor was developed (figure 4.2 and 4.3). To reach an axial load of 500 N one entire pole of each of the 6 homopolar magnets is acting in axial direction. This allows also a very compact design with high rotor stiffness. The rotor is designed to reach 50.000 rpm at a power of 20 kW. Levitation and preliminary run up tests have been conducted.

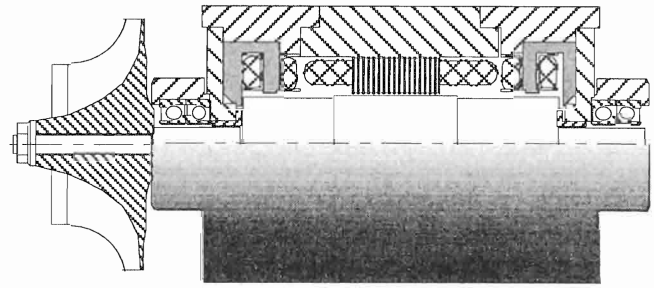

FIGURE 4.3 Drawing of the turbo compressor prototype with homopolar magnetic bearings

5. Conclusion and Outlook

Various control concepts for AMB's with digital control have been discussed. The most promising candidate was identified and its realization has been described in detail. Two prototypes based on this concept have been presented. They show the potential which lays in the low cost concept.

In a next step the electronics will be further integrated using SMD technology. The low cost concept will be implemented to other applications, thus widening the field for active magnetic bearings.

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