TURBO-MOLECULAR PUMP LEVITATED BY UNBIASED ACTIVE MAGNETIC BEARING

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ABSTRACT

A turbo molecular pump (TMP) is an axial flow compressor used for production of high and ultrahigh vacuum conditions. Ultrahigh vacuum is required for several industrial applications such as semiconductor technology or materials research. Usually the rotor of a TMP is balanced contactless by using magnetic bearings. They are used to achieve reliable high speed operation without any wear and lubrication. Conventional pumps are equipped with actively controled biased magnetic bearings.

This paper gives information and results of an research project which aim was the development of a “low cost” drive system for turbo-molecular pumps. The significant feature of the development is the application of active magnetic bearing without using magnetic bias.

Advantages and disadvantages of magnetic bearing without premagnetization are considered.

As a consequence of the lack of magnetic bias the unbiased magnetic bearing is much more nonlinear than the biased magnetic bearing. Due to nonlinearity a nonlinear fuzzy controller is employed in order to determine the actuating currents. The paper shows that by using active magnetic bearing without magnetic bias a stable position control is feasible.

Advantageously the lack of bias leads to a significant reduction of power losses. Furthermore the simplified power electronics decreases the costs due to the reduction of electronic components.

For determination of axial and radial shaft displacement contactless and low-cost inductive sensors were developed. They operate according to transformer principle. While keeping the construction of TMP as compact as possible a significant effort has to be done in order to obtain an efficient electromagnetic screening effect.

Further on the use of brushless DC motor (500 W, 36.000 r.p.m.) in place of squirrel-cage motor decreases the power loss of the complete system even more. The computer-aided control of a motor occurs sensorless. The lack of compulsory angle resolver and speed sensor leads to a reduction of electronic components and production costs.

INTRODUCTION

The magnetic bearing system described in the present paper has been developed as a low-cost high-speed rotor application used for production of high and ultrahigh vacuum conditions. Due to the reduction of the entire system costs the cartridge case, where the drive unit with the magnetic bearing system is integrated, should belong to an existing production class. This makes a later integration of the cartridge in a production process of TMP feasible.

Conventionally the drive units of the pumps are balanced either by the combination of passive and active magnetic bearings or by five-axis active magnetic bearings. In both cases premagnetization for the active bearing is used. The distinctive feature of the presented device is the five-axis active magnetic bearing without magnetic bias.

The challenge of the project was the development of the control unit, the power electronics, the computer operation systems for magnetic bearings and for the high-speed drive unit by considering the required low costs of the entire system.

CONSTRACTION OF THE CARTRIDGE

Due to the requirements the dimensions of the cartridge case are prescribed. Figure 1 shows the constructional set-up. The total hight amounts to 25 cm. By the installation of the turbo molecular pump the cartridge has to be inserted from the bottom into the pump station. The turbine vane is fixed over a mounting plate at the drive shaft and sticks out over the cartridge.

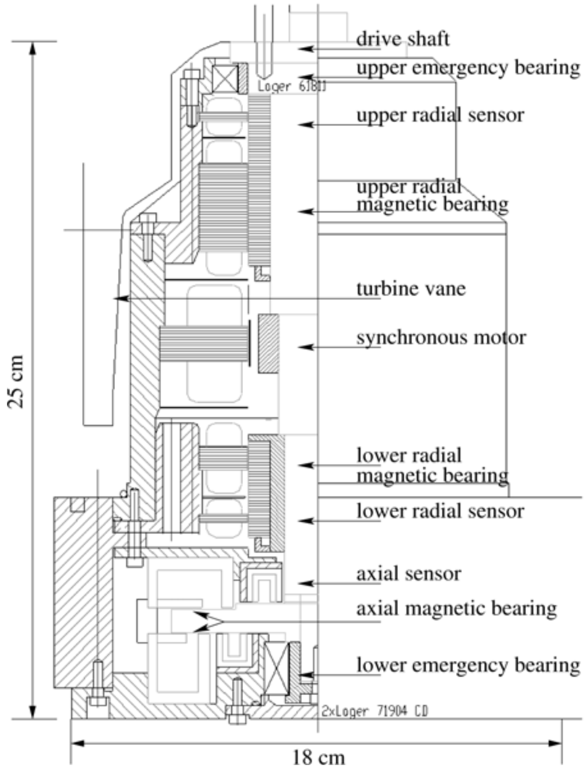

FIGURE 1: Sectional drawing of the TMP

The drive unit located in the middle section of the cartridge is realized as a synchronous motor. The stator windings of the motor are placed in the housing whereas the permanent magnets are fixed on the rotor shaft. Above and below the synchronous motor radial magnetic bearings along with radial displacement sensors are settled. The axial magnetic bearing is set up in the bottom section and is rotational-symmetrically constructed. Due to the compact construction of the pump the two magnet coils of the axial bearing are not identical in construction.

THE MAGNETIC BEARING

The drive unit of the turbo molecular pump is levitated by active controled magnetic bearings in radial and axial directions. Compared with conventional constructions which use passive magnetic bearings in radial directions, several advantages are obtained:

- arbitrary fitting position
- variable stiffness
- variable damping behaviour
- active disturbance-variable (feed-forward control)

The disadvantage of the 5-axis active control magnetic bearings system are the heavy costs. By using active magnetic bearings without magnetic bias an increase in costs can be minimized or even eliminated. In this case the radial or axial attraction force of each magnetic bearing is directly generated from the actuating current of a separate electromagnet. The control network is realized as a nonlinear active fuzzy-controller.

DISPLACEMENT SENSOR

For proper control of the magnetic bearing system of TMP the information of the exact position of the rotor shaft is essential. The contactless sensors for radial and axial rotor displacement-measurement act according to the transformer principle. Figure 2 shows the schematic construction of the axial displacement sensor. It is made up of two primary and two secondary coils. As a result of disturbance minimization one primary and one secondary coil are mounted side by side on a synthetic reel. Each reel is embedded into an iron core and placed oppositely in respect of the axial disk which is mounted at the drive shaft.

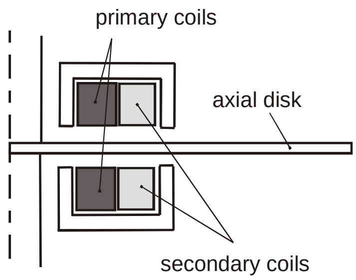

FIGURE 2: Schematic construction of displacement sensor

Both primary coils are realized with equal winding direction and are series-connected. The two secondary coils are also series-connected but with reverse winding direction. If the primary coil is stressed by the sine wave voltage, the induced voltage in a secondary coil is build up as difference of the induced voltages of each sencondary coil sections. Due to the excentricity of the axial disk the secondary voltage can mark positive or negative values or is equal to zero if middle position is reached. Within the evaluation unit which is realised by chip NE5521 from *Philips Semiconductor* the primary and the secondary signal are compared. The resulting signal is demodulated, filtered and amplified so that the output voltage is straight proportional to the rotor position.

The assembly of the radial displacement sensors occurs in an analogous manner. Figures 3 and 4 demonstrate the setup of the radial displacement sensor and the sensor-electronics. By reason of the reduction of eddy-current losses laminated cores are used. Two cogs build one pole of the sensor.

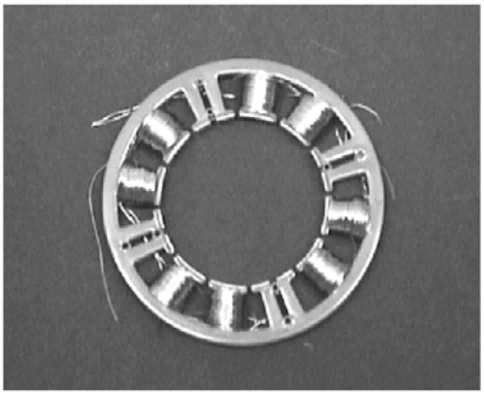

FIGURE 3: Radial sensor

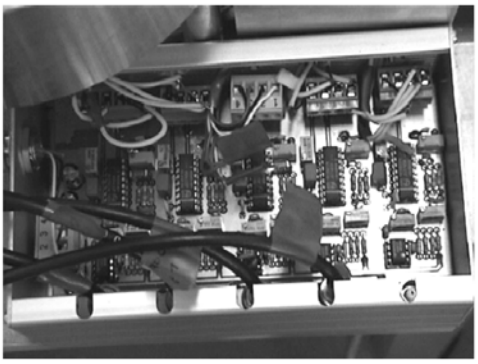

FIGURE 4: Sensor electronics

Great importance has to be attached to electromagnetic compatibility in respect of the compact construction. Only by the use of additional shielding plates and high quality shielding measure- and supply-conductors, the sensor signal gets proper for the displacement measurement.

CONTROL NETWORK

If an excentricity of the rotor shaft occurs, the gap sensor quantifies this and assigns the displacement value to the controller. Due to the controller characteristic the actuating current is generated and the magnetic field is built up. The generated attraction force on the shaft is equal to the square of the actuating current. Thus the behaviour of the magnetic bearing is nonlinear and demands for an active nonlinear controller. The developed controller operates according to the fuzzy theory. Measurement and actuating values are specified by three linguistic values. Controller action depends on the excentricity and the current velocity of the shaft. The transmission behaviour of the controller is shown in figure 5. The control circuit is realized with an outer gap-/velocity- and an inner current control loop.

The automatic control is realized by using a DSP TMS320F2406. The performance of the processor is not sufficient to work off the fuzzy control for all axis in real time. Therefore the transmission behaviour of the control unit is calculated previously and the discrete results are stored tabularly. The implemented algorithm accesses the stored results according to the measured displacement and velocity values. For each control step the velocity is determined as a displacement derivative with respect to time. A velocity sensor doesn't exist.

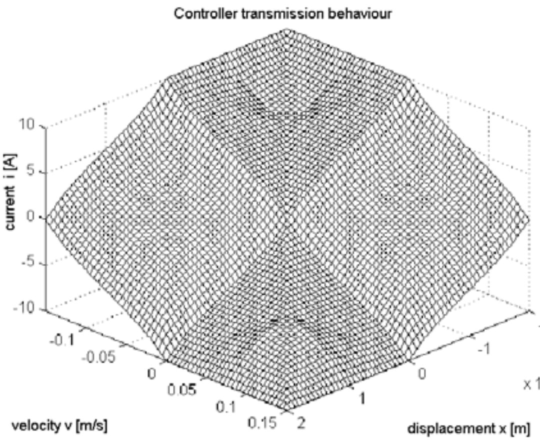

FIGURE 5: Controller transmission behaviour

Each value in the performance graph comprehends positive and negative quantities. Considering one axis of the magnetic bearing, the sign reversal of the gap- and velocity values indicates a direction reversal of the shaft displacement from the midposition (*x=0*, *v=0*). The sign reversal of the actuating current represents positive or negative force influence on the rotor. An inversion of the current within the electromagnetic actuator doesn't occur.

ELECTROMAGNETIC ACTUATOR

Figure 6 clarifies the basic principle of a radial magnetic bearing and an appendant electromagnetic actuator. With relation to one action axis of the magnetic bearing, two electromagnetic coils are placed contrarily. Each electromagnetic coil consists of two coil sections connected in series. They are comprising two neighbouring cogs. If one of the electromagnetic coils is activated, a magnetic field is generated and runs through the mentioned two cogs, the yoke and the drive axle.

FIGURE 6: Magnetic field and upturned force action in a single radial magnetic bearing

The demonstration shows the magnetic field and upturned force action as a result of actuating current in the upper electromagnet. The contrarily placed electromagnet is responsible for the opposite force action and thereby dead.

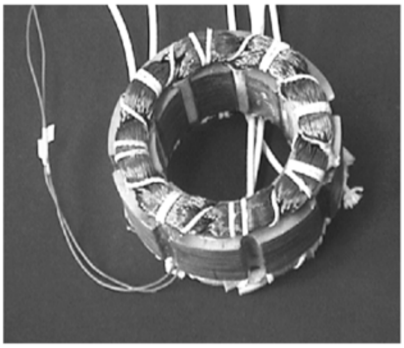

FIGURE 7: Upper radial magnetic bearing

FIGURE 8: Lower radial magnetic bearing

Figures 7 and 8 illustrate both the upper and lower radial magnetic bearing actuators. The upper laminated core is more powerful in purpose of higher force production.

POWER ELECTRONICS

Because of renunciation of using magnetic bias the circuit unit for the supply of the bias current is not necessary. Only one coil is to pulse with current. The reversion of polarity is not needed. This leads to the circuit of the double coil system for one axis shown in the figure 9.

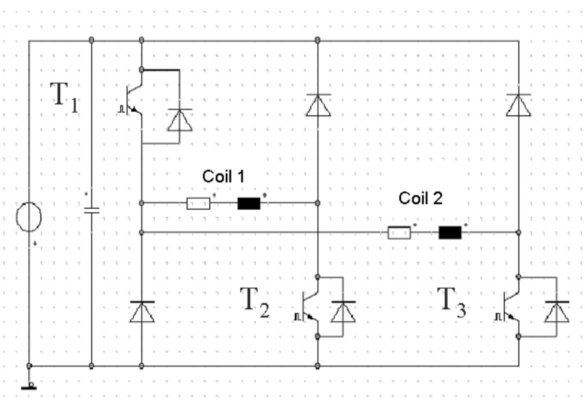

FIGURE 9: Schematic of a power device for one axis

The power electronics required for a single motion axis needs only three power transistors and three free-wheel diodes. Coil 1 and coil 2 represent two contrarily placed electromagnetic coils of the single magnetic bearing axis. Depending on desire of force direction either coil 1 with the transistor combination T1-T2 or coil 2 together with transistors T1-T3 are supplied with the actuating current. The quantity of current is related to pulse-width modulation of the transistor control pulse.

EXPERIMENTS

The behaviour of the magnetic bearing system is shown in figures 11-13. They document the step function respons of the radial disturbance force at the upper side of TMP-rotor. For this test the drive shaft doesn't rotate. The disturbance force is caused by an extern electromagnet and act as shown in the illustration 10 in the single upper axis which direction is marked as a X-negative.

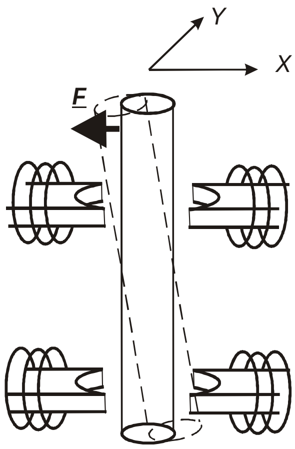

FIGURE 10: Radial electromagnets placed in X-direction

The quantity of this force is mount to 15 N. As shown in the figure 11 the upper radial sensor measures the shaft displacement which follows the attraction force. This marks a control deviation whose value is tolerable. In this case the rotor levitates.

The figures 12 and 13 illustrate the magnetic bearing current answers in the upper and lower magnetic bearings mounted in X-direction. The upper electromagnet placed in positive X-direction and the lower electromagnet at the negative X-direction build current signals which result in a reacting force. The remaining X-axis-electromagnets are inactive.

Due to the required rotor levitation the actuating currents can be unequal zero even if attraction force doesn't exist. The magnetic bearings placed in upper X-positive- and lower X-negative direction demonstrate this.

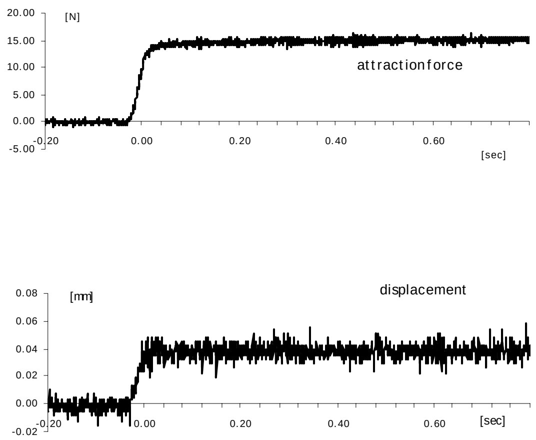

FIGURE 11: Attraction force and displacement

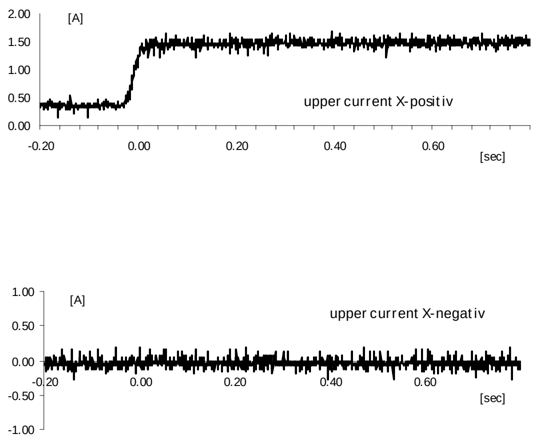

FIGURE 12: Upper magnetic bearing currents at X-axis

The figure 13 shows the force respons at the lower radial magnetic bearing pointed in X-direction. As a consequence of the cross-talk force the actuating current in X-negative direction is increased, while X-positive-electromagnet is dead.

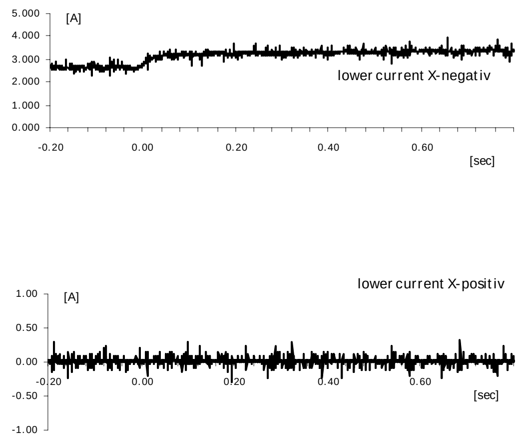

FIGURE 13: Lower magnetic bearing currents at X-axis

CONCLUSIONS

The experiments confirmed that magnetic bearings without magnetic bias make a stable position control feasible.

As a result of the development a simplified realization of the electromagnetic actuators along with the power electronics is achieved. This causes a reduction of power losses and economic benefits. The use of low-price displacement sensors and the lack of the velocity sensor lower the entire costs of the magnetic bearing system even more.