# Magnetic Bearing in INCOR Axial Blood Pump Acts as Multifunctional Sensor

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**Abstract**

The INCOR blood pump is an axial pump with a magnetically suspended impeller. Since June of 2002, it has been successfully used more than 115 times in Europe and in Asia to treat patients with severe left-ventricular heart failure.

The magnetic-suspension bearings of the combined rotor and impeller operate with passive radial and active axial position stabilization. Active stabilization is based on the determination of the rotor's axial motion. In operation, fluid-dynamic forces associated with the active pumping function and the remaining activity of the assisted heart act on the rotor in addition to the magnetic bearing forces. The pressure head across the pump can be deduced directly from the electrical parameters which are sensed in order to operate the magnetic bearings. The blood flow rate through the pump can be determined from the fluid-dynamic characteristics and the pump impeller speed.

The pressure gradient and the flow rate information can be used to adapt the pump speed ideally to the patient's needs. The speed can be varied synchronously to the patient's heartbeat in order to simulate the natural heart's blood flow.

Modulating the control parameter of the magnetic bearing with a higher-frequency signal will cause the rotor to oscillate in an axial direction in relation to the superimposed signal. The amplitude of the oscillations provide information on the viscosity of the blood. This makes it possible to diagnose the patient's liquid balance continually and thus take suitable and timely counteractive measures in critical situations.

The INCOR blood pump's magnetic bearings thus enable the pressure head, the blood flow and the blood viscosity to be determined without the need for additional sensors. This means that it provides information which is essential for optimizing the patient's road to recovery.

## Introduction

The INCOR pump is an axial pump with a magnetically-suspended impeller. The use of magnetic bearings has the advantage that on the one hand, it does not experience mechanical bearing wear and on the other, there is no localized friction-induced generation of heat which might endanger the patient's blood /1/. This pump is used to treat patients with left-ventricular deficiency by supporting circulatory functions and relieving the left ventricle /2/. This means that it may be used as a temporary solution until a donor heart becomes available ("bridge to transplant") or for long-term support ("alternative to transplant"). In some cases, relieving the left-hand ventricle of a part of the load enables it to recover to such an extent that the patient is able to resume life without a supporting device.

This pump obtained CE approval in April 2003. It has been implanted in more than 115 patients in heart-treatment centres throughout Europe and Asia (up to date April 2004). The longest application is 670 days to date and the patient is still being supported by an INCOR system.

The pump weighs just 200 grams, its diameter is 300 mm and its volume 60 cm³. It has been designed to drive a flow of 5 litres against a pressure head of 100 mmHg. The pump's total power consumption comprises the impeller motor power (3.5 W), the bearing suspension power (1 W) and the pump control circuit power consumption (5.5 W). In the currently-used design, both power and control signals are transmitted via a cable passed through the patient's skin. The patient carries the control unit and the batteries in a pouch attached to a belt, allowing him to remain mobile and live in normal surroundings.


Figure 1: INCOR Axial Pump

**The magnetic bearing**

The INCOR axial-flow pump has a radially passive and axially active magnetic bearing. It consists of two stator bearing magnets and two rotor bearing magnets (figure 2). The actuator coils can force the rotor to move in the axial direction, whereby the sensor detects the exact axial position of the rotor.

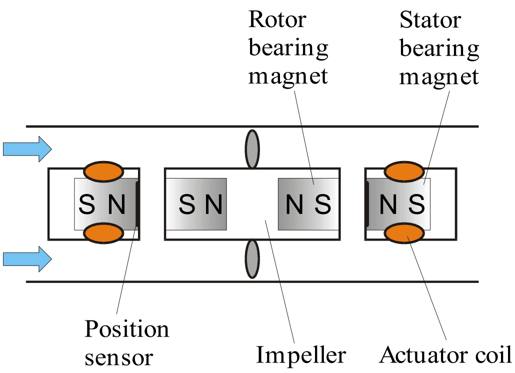


Figure 2: Magnetic bearing principle (longitudinal section)

When the rotor is precisely centred between the stator magnets, the magnetic forces on both sides are equal and opposite, thus cancelling one another and permitting the rotor to "float" in this position. A control unit determines the exact axial position of the rotor and calculates the force which is necessary to keep the rotor suspended. The centred position is given as the set-point for the control unit.

**Measuring the pressure difference across the pump**

During the pumping process, additional forces act on the rotor, which is an integral part of the pump impeller, in the axial direction, caused by active driving of fluid through the pump as well as by the external pressure head across the pump.

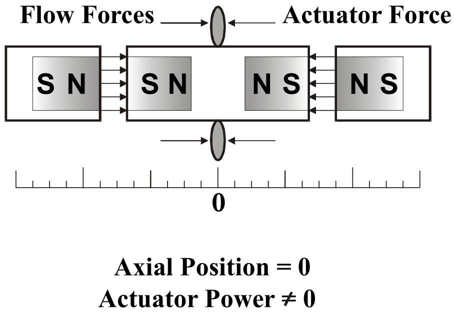


Figure 3: Forces acting on the impeller when the pump is in operation

The actuator must compensate these forces to maintain the rotor's centred position. To achieve this, the actuator will have to perform a certain amount of work.

To avoid this disadvantage, a new type of control unit uses the actuator power, which must be minimized, as a set-point /3/. Of course, it is also necessary to keep the rotor safely suspended between the stator magnets.

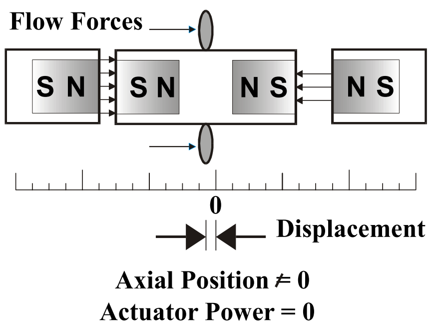


Figure 4: Axial Displacement of the rotor

This results in a displacement of the rotor away from the centred position to a new, off-center position at which the axial forces – that is to say, both the magnetic forces and the forces due to the fluid – cancel each other. This leads to two advantages:

Firstly: the actuator power is minimized and independent of flow and pressure head across the pump. The actuator power of INCOR magnetic bearings is less than 1W.

Secondly: there is a direct correlation between the pressure head across the pump and the rotor displacement. Thereby it does not matter whether the pressure head is caused by an externally-imposed flow or by the active flow driving by the pump.

**Flow measurement**

The pressure head, together with the known rotation speed and the pump's known flow characteristics, provide exact information enabling the flow rate to be calculated.

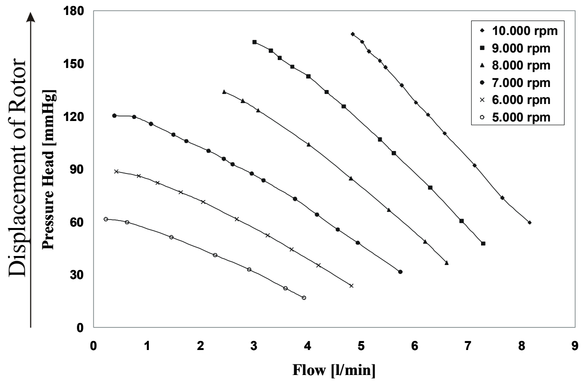


Figure 5: Characteristics of the INCOR axial-flow pump

**Determining the viscosity of the blood**

The pump's magnetically-suspended impeller forms a system of elastic elements and masses, surrounded by blood. In addition to the control current needed to keep the impeller suspended, an alternating current precisely controlled with regard to both amplitude and frequency is passed through the control coils. This causes the impeller to oscillate in an axial direction. The oscillations can be monitored by the position sensors. The amplitude of the oscillations is a function of the bearing characteristics (control loop amplification, axial stiffness and impeller mass) and the characteristics of the blood surrounding the impeller. The impeller's oscillation is subjected to a certain degree of so-called viscous damping, which is a function of the blood viscosity and affects the amplitude /4/.

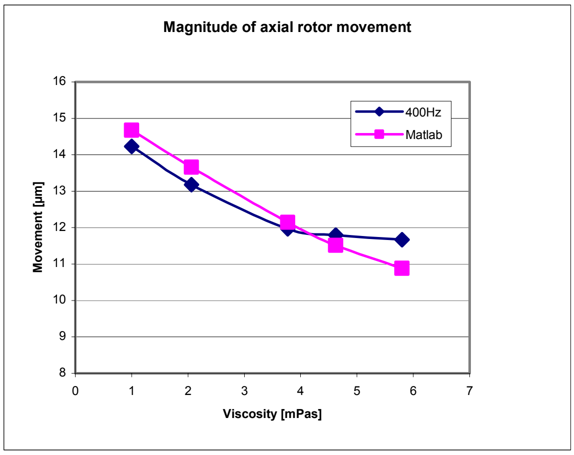


Figure 6: Impeller oscillation amplitude at an effective current of 350 mA flowing through the control coils at 400 Hz, compared with the results of computer simulations (Matlab)

**Summary**

The INCOR pump's magnetic bearings enable measurement of the pressure across the pump and flow through the pump, as well as determination of the blood viscosity, without requiring additional sensors. If the values of these parameters are known, it is possible to monitor the pump functions and adapt these dynamically to the patient's needs, thus contributing effectively to the patient's recovery.

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/3/ Merkel, T. et al.: Magnetic Bearings in the INCOR Axial-Flow Pumps act as Pressure and Flow Sensors, 9th Congress of the ISRBP, Seattle 2001, USA

/4/ Blevins, R. D.: Flow-Induced Vibration, Van Nostrand Reinhold Comp., 2nd edition 1990