DEVELOPMENT OF AN INTEGRATED FLUX/POSITION SENSOR

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ABSTRACT

A novel and practical internal flux sensor for a magnetic bearing has been developed. The bearing uses an integral shunt flux path to provide a measurement of the flux density in the bearing stator. The flux density measurement can be used to improve control functions of the magnetic bearing system. Alternatively, the measurement can be combined with the measurement of coil current in the bearing axis to determine the rotor position. The shunt flux path is created in such a way that the bearing specific load capacity is not diminished, and the bearing package envelope is not increased.

INTRODUCTION

Magnetic bearings have several well known advantages over mechanical contact bearings. Among these are a significant reduction in frictional power loss and the elimination of lubrication systems. One significant drawback of traditional magnetic bearing systems, however, is the common use of a separate, non-collocated, position measurement system. This requirement leads to limitations in the stable operating range of flexible systems due to the non-collocation error [Maslen and Lefante, 1992].

One solution to this problem is to develop a self sensing bearing. Several attempts at this have been reported in the literature. Two basic techniques have been explored. The first is the development of a bearing which uses sensing coils wrapped around at least a portion of the magnetic flux path [Keith et al., 1993]. The voltage induced in the coils is then a measure of the change in flux in that portion of the path. By integrating this signal and combining the result with the simultaneous measurement of the coil current, the bearing rotor position can be determined. The second technique involves using the back emf of the drive coils to measure the bearing inductance due to the gap [Okada et al., 1992]. Either the natural switching pulses of the amplifier, or a separate excitation signal is used to generate current changes in the bearing coils. The voltage developed across the coils is then compared to the current changes, and the bearing inductance value can then be calculated. Because the inductance is proportional to the rotor gap, the rotor gap or bearing position can therefore be determined.

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Each of these methods has certain drawbacks. The sense coil method has poor observability at low frequencies [Kucera, 1997]. Under static conditions the sense coil output is zero unless a modulation signal is used to perturb the drive coils. With zero output, it is impossible to determine the absolute position of the rotor. Various techniques have been developed to deal with this difficulty, but all of them add to the complexity of the control system and potentially increase the bearing package dimensions, thus eliminating some of the benefits of a self sensing bearing. Additionally, this method only produces a measure of the position of the rotor relative to its start-up location. In real world applications, the rotor seldom comes to rest in the same place each time the bearings are de-energized. Thus an involved start-up procedure will be required to determine the desired shaft position.

Using the back emf of the drive coils to determine rotor position also presents difficulties. At high frequencies the effective permeability of the magnetic material decreases significantly [Meeker et al., 1995]. Thus the proportion of the inductance due to the rotor gap decreases, reducing the sensitivity of the back emf to rotor gap changes. Additionally, eddy current and hysteresis effects will have some impact on the measured inductance. These effects will decrease the accuracy of the rotor position calculation, and will be more pronounced for small gap systems.

For these reasons it is desirable to develop a self sensing bearing which uses a direct measure of flux density in the bearing to calculate the rotor position. By directly measuring the flux density, and comparing that value to the measured current, the rotor position can be determined over the full bandwidth of the actuator. Previous attempts to do this have encountered difficulties because the measurement was taken at the rotor gap [Zlatnik and Traxler, 1990; Rao and Shilichev, 1997]. In order to insert a flux sensing device (e.g. a Hall probe) in the rotor gap, either a large gap needs to be provided for the probe, or a slot for the probe in the stator face has to be created. If a large gap is used, then either larger coils or more bearing current is required to drive the same amount of flux as a standard bearing system. If a slot is cut into the face of the bearing to house the sensor, then the slot area operates at reduced flux density which decreases the bearing's load capacity. Both of these solutions, therefore, present difficulties by increasing the bearing losses and increasing the bearing physical dimensions. In addition, the large gap option poses a problem in locating a Hall device that is capable of handling the high (> 1T) flux densities normally found within magnetic bearing systems.

INTEGRAL FLUX SENSOR DEVELOPMENT

A new type of self sensing bearing, which addresses all of the above shortcomings, is illustrated in Figure 1. The bearing uses an indirect measurement of flux density, taken with a Hall effect probe, to determine the rotor position. The probe is inserted into a shunt flux path, which is positioned in the backiron of the bearing. This technique requires the solution of two basic problems: 1) determining the flux density in the bearing based on the measured flux density in the shunt path; and 2) using that information in combination with the measured coil currents to determine the rotor position. The solution to each of these problems is discussed below.

It is desirable to measure the flux density in the bearing without increasing the rotor gap, and without decreasing the useful bearing pole face area. It is also significantly easier to measure flux levels if they are much lower than those normally encountered in magnetic bearings. The electrical equivalents to both of these problems are routinely solved by using a shunt resistor.

The electrical equivalent of the flux shunt path is shown in Figure 2. This is a very common method of measuring high current levels in electrical equipment, especially when there is no direct access to the load. V1 is a voltage source, such as a generator, that supplies the current to develop power across R2, which is the load. The two resistors, R3 and R4, represent the lead resistances connecting the load to the source. Generally R3 and R4 are small enough to be ignored. For clarity, and for ease in comparison between the electrical system and its magnetic counterpart, these resistors are shown.

Several different techniques could be used to obtain the value of the current (I2) flowing through R2. The first would be to place in series with R2 a meter to measure the current. This technique would be applicable if the expected current level was less than the maximum general purpose current meter (.1 Amp or 100 mA are reasonable numbers). If the current levels are large, however, such as 1000 Amps, this method becomes impractical. A second technique, which is referred to as a current shunt, is depicted in Figure 2. This technique allows M1 to measure high levels of current in R2. In this figure R1 is a resistor of a fixed known value which is much higher than R2 (e.g. R1=R2 x 10000). Using the laws of current flow and the proportionality constant from this example, therefore, 100 mA of current measured by M1 would equate to 1000 A of current in R2.

This same basic concept is used in the creation of the flux shunt. The load in this case is the gap between the rotor and the stator. We wish to know the flux density (magnetic equivalent of current) in the gap, but we do not have easy access to the gap, and the flux density in the gap is too high to be directly measured. We can, however, create a high reluctance path in parallel with the main path and measure the flux in this parallel (shunt) path. Because the reluctance of the main path is not increased by the creation of the shunt path, bearing performance is not effected.

The basic requirement of this approach is that a relationship between flux density in the gap and flux density in the shunt path needs to be determined. If the permeability of the magnetic material were constant, the relationship would consist of a simple proportionality constant. Due to variations in permeability of the magnetic material with flux density, however, non-linearities are introduced into the system. These non-linearities can be reduced to acceptable levels by limiting the operating flux density of the bearing and by carefully shaping both the main and the shunt flux paths. The result is the geometry shown in Figure 1.

Several special features of this geometry are worth noting. First, the shunt path is formed by creating an axial slot through the backiron at the midpoint between pole legs. The minimum size of this slot is determined so that it is large enough to house a commercial Hall probe. If the slot was formed without other modifications to the backiron, the cross sectional area available for the flux would be decreased. This would result in a flux choke point and would degrade bearing performance. It is, therefore, necessary to increase the width of the total flux path by an amount equal to the width of the sensor slot. This is accomplished by creating a "bulge" in the backiron, which extends into the area between the coils. Because this area was previously empty, no increase in bearing outer diameter is required.

By placing the sensor slot in the middle of the backiron, the main flux path is divided into two components: one above (radially outside) the sensor slot and one below (radially inside) the sensor slot. Without further modifications to the geometry, the upper flux path around the sensor slot would be shorter than the lower path. This would result in more flux traversing the upper path, and an uneven flux gradient across the sensor gap. While it is not necessary that this gradient be uniform, for practical reasons it is desirable.

To even the length of the upper and lower paths, notches are formed into the outer diameter of the bearing on either side of the sensor slot. These notches effectively move the natural centerline of the flux path downwards (radially inward) and result in an even flux gradient across the sensor slot.

Extensive FEA optimization has been conducted on this configuration. The result is that the relationship between the gap flux density and the shunt path flux density can be effectively linearized over a wide range of gap flux densities. Further, because magnetic bearing systems usually operate with pairs of opposing quadrants, a differential shunt path flux density measurement can be obtained. This value is formed by determining the difference between sensor output values in opposing quadrants. This method has the advantage that it produces an improvement in the linearity of the relationship between the gap and the sensor differential flux densities. Simultaneously, it minimizes the effects of temperature variations on the Hall effect devices. The resulting plot of shunt path (sensor) flux density versus stator-rotor gap flux density, obtained by FEA, is shown in Figure 3.

This information can be used to improve the linearity of the bearing force output, to extend the operating flux density range of the bearing, and/or to compensate for the actuator's negative positional stiffness. If the objective of the sensor is to determine the rotor position, however, additional work is required. To accomplish position measurement, the sensor flux density information needs to be combined with the bearing coil current information. Again, because the bearing is typically configured with a bias and a control current, it is more efficient to use the differential flux density and the control current to determine position. A FEA generated plot of differential sensor flux density versus relative rotor displacement is shown if Figure 4. This plot was generated for one value of control current.

In practice, control current and rotor position will be constantly varying to some degree. For this reason it is necessary to develop a general formula for rotor displacement based on the inputs of differential sensor flux density and control current. It is, therefore, necessary to know how the sensor gap flux density vs. differential current relationship varies with positional changes. This information is shown, for a typical case, in Figure 5. This figure shows equivalent curves for various positions of the rotor. The positions have been normalized to the full design deflection of the rotor element. These curves are projections of the three dimensional surface that represents the value of differential sensor gap flux densities for all possible combinations of bias current and rotor displacement. Note that any combination of bias current and differential sensor gap flux density correspond to a unique value of rotor displacement. This fulfills a basic requirement for any position sensor, in that a unique position can be determined for any combination flux density and current.

In order to actually determine the position of the rotor based on the flux density and current measurements, the surface equation represented schematically in Figure 5 must be solved for $X(B,I)$, where B is the measured differential flux density and I is the measured current ratio. One simplistic approach to solving this problem, as a demonstration, is to curve fit orthogonal polynomials to the surface. The results of this procedure, applied with third and fourth order polynomials is shown in Figure 6. While the resulting equation for X is somewhat unwieldy in this example, the procedure is clear, and the calculations are well within the capability of digital control technology. This approximation method gives results for X within 5% of the actual values, which is sufficient for most applications. Improved methods of calculating X may be used where desirable.

CONCLUSION

A new bearing geometry has been developed, which includes provisions for an integral flux sensing element. The application of this new geometry and sensor system will significantly improve magnetic bearing performance and information content. The shunt flux sensing element is positioned in a formally "unused" section of the stator backiron. This configuration has the benefits of protecting the sensor, and causing no degradation in the performance of the bearing, while not increasing the bearing footprint.

The output from the sensor can be used to provide flux feedback to the bearing control system. Flux feedback has been shown to provide multiple benefits, from improving the stability of the system to extending the load capacity of the bearing. Alternatively, the flux sensor output can be combined with measurements of coil currents to determine the rotor position, thus creating a new type of self sensing bearing. A method of accomplishing this has been illustrated, and the results of extensive finite element analysis (and testing) have been reported. The developments presented in this paper are patent pending.

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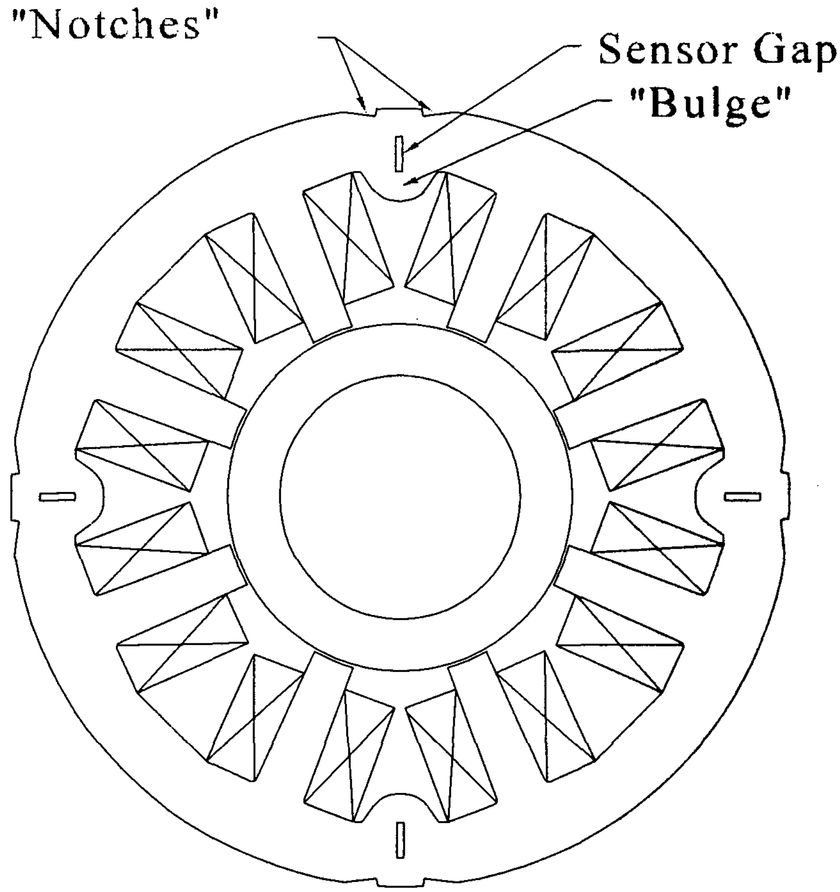
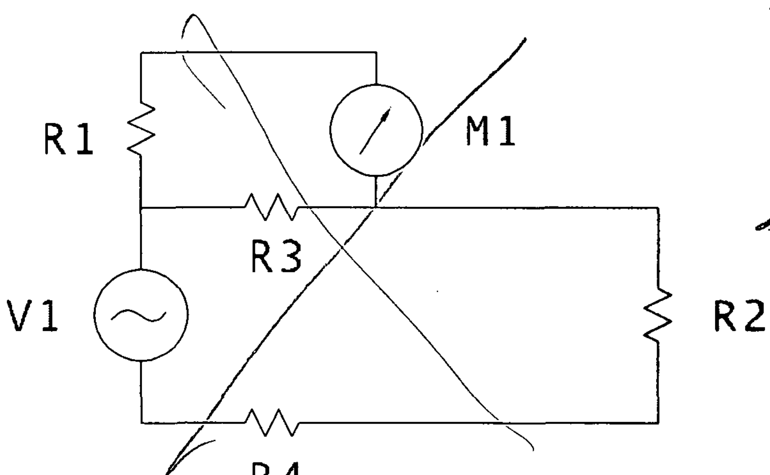


Figure 1



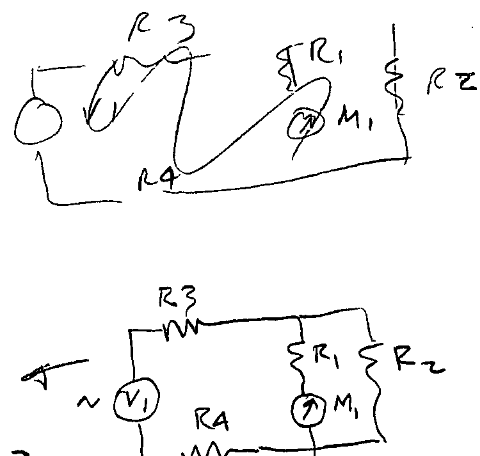


Figure 2

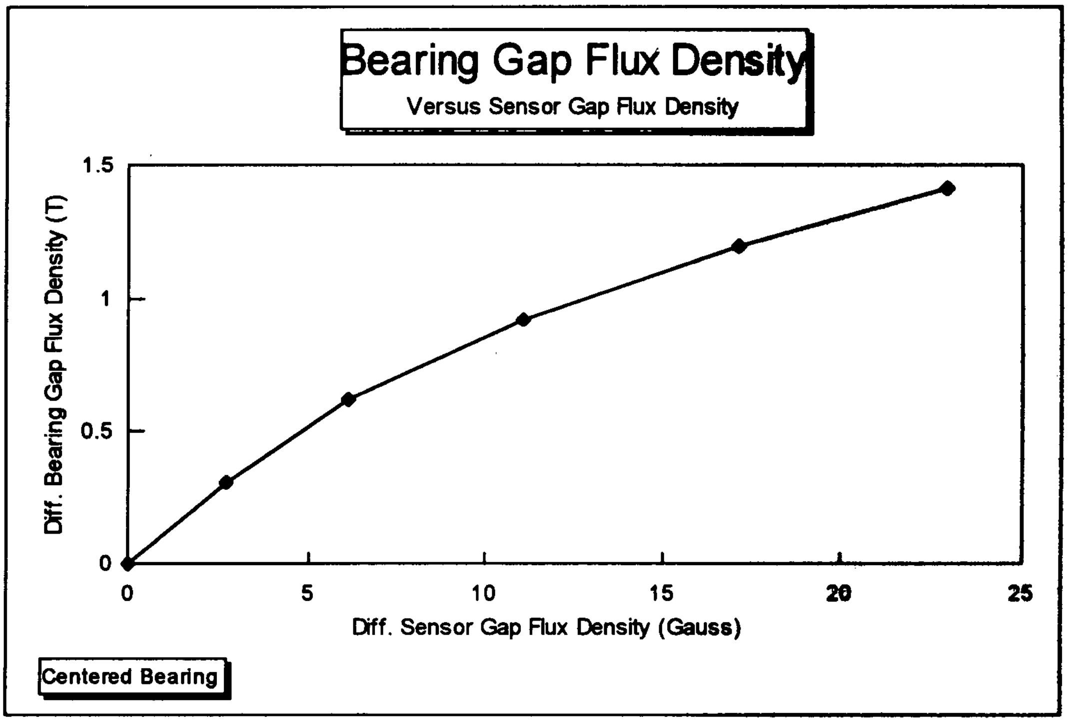


Figure 3

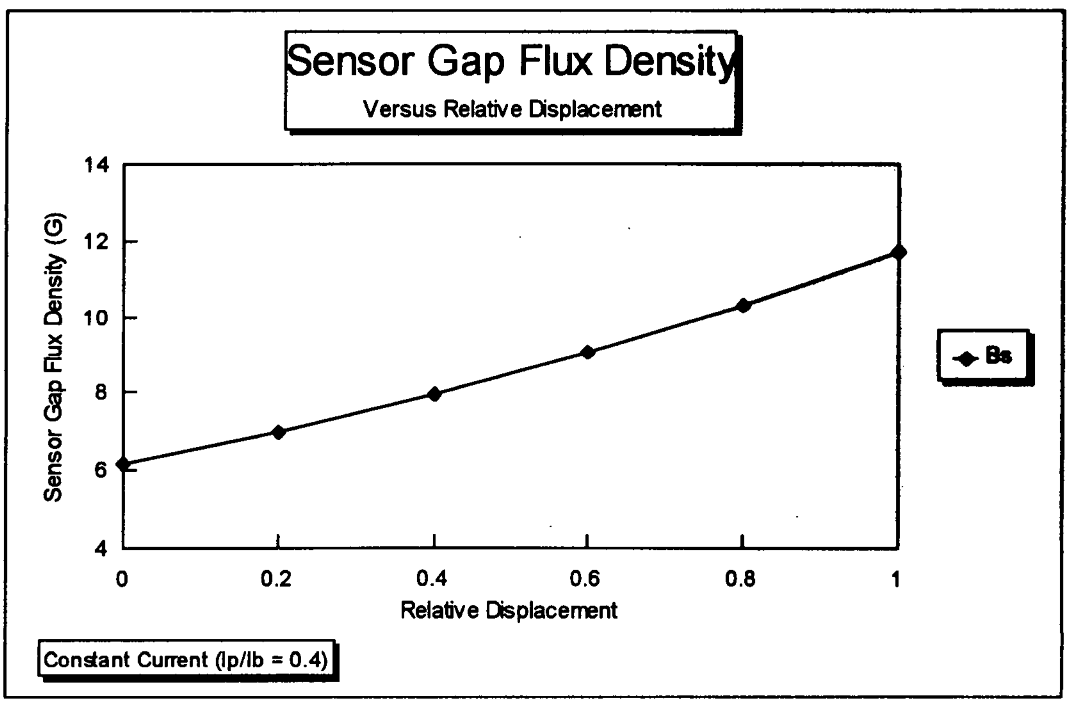


Figure 4

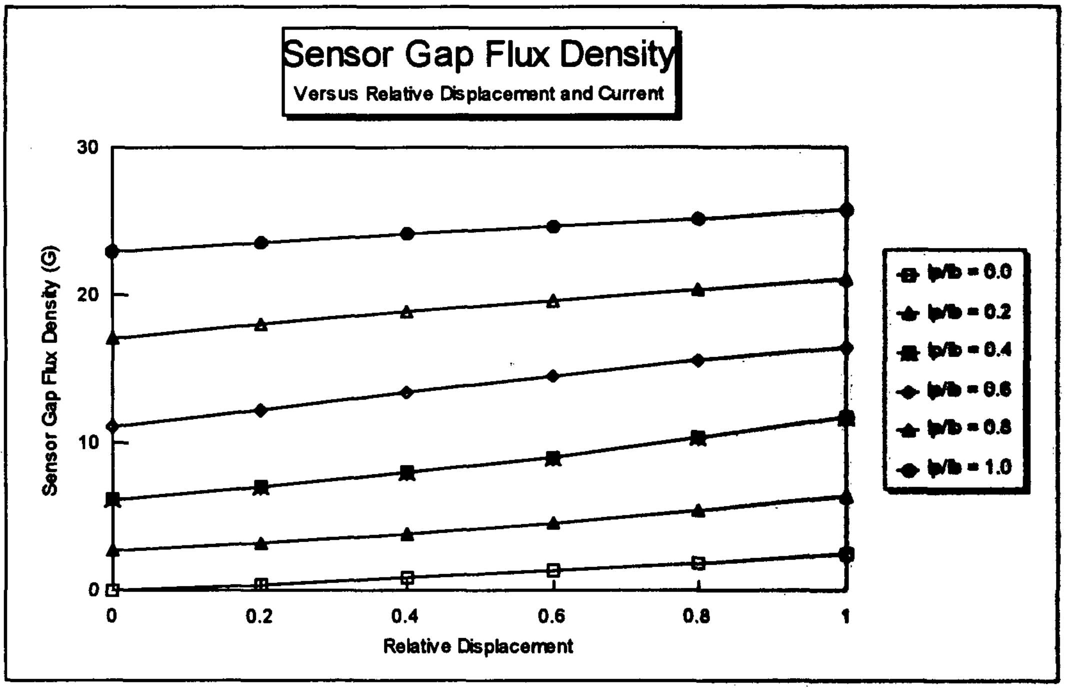

Sensor Gap Flux Density
Versus Relative Displacement and Current
30
20
10
0
0
0.2
0.4
0.6
0.8
1
Sensor Gap Flux Density (G)
Relative Displacement
Ip/Ib = 0.0
Ip/Ib = 0.2
Ip/Ib = 0.4
Ip/Ib = 0.6
Ip/Ib = 0.8
Ip/Ib = 1.0

Figure 5

Figure 6

The surface represented in Figure 9 can be approximated by the equation:

$$B(x,i) = a(i) + b(i)\cdot x + c(i)\cdot x^2 + d(i)\cdot x^3$$

A curve fit of this example surface results in the following coefficients

$$a(i) := 14.2158\cdot i - 12.2095\cdot i^2 + 48.7454\cdot i^3 - 27.7645\cdot i^4$$

$$b(i) := 2.46105 - 7.36684\cdot i + 49.9859\cdot i^2 - 60.5381\cdot i^3 + 18.5224\cdot i^4$$

$$c(i) := -.486065 - 7.13401\cdot i + 88.0890\cdot i^2 - 180.308\cdot i^3 + 99.3232\cdot i^4$$

$$d(i) := .92304 - 17.4822117\cdot i^2 + 26.1171217\cdot i^3 + 1.8207053\cdot i - 10.496617\cdot i^4$$

Solving the equation of B(x,i) for x yields three roots. Two of the roots contain imaginary turns and are not realistic solutions. The remaining is displayed below. The rather lengthy repeated term T(B,i) has been extracted to simplify the presentation of the result.

$$T(B,i) := \sqrt{4\cdot b(i)^3\cdot d(i) - b(i)^2\cdot c(i)^2 + 18\cdot b(i)\cdot c(i)\cdot d(i)\cdot B - 18\cdot b(i)\cdot c(i)\cdot d(i)\cdot a(i) + 27\cdot d(i)^2\cdot B^2 - 54\cdot d(i)^2\cdot B\cdot a(i) - 4\cdot B\cdot c(i)^3 + 27\cdot d(i)^2\cdot a(i)^2 + 4\cdot}$$

$$x(B,i) := \left[\frac{1}{6}\cdot\frac{b(i)}{d(i)^2}\cdot c(i) + \frac{1}{2}\cdot\frac{(B - a(i))}{d(i)} - \frac{1}{27}\cdot\frac{c(i)^3}{d(i)^3} + \frac{1}{18}\cdot T(B,i)\cdot\frac{\sqrt{3}}{d(i)^2}\right]^{\left(\frac{1}{3}\right)} - \frac{1}{3}\cdot\frac{c(i)}{d(i)} - \frac{\left(\frac{1}{3}\cdot\frac{b(i)}{d(i)} - \frac{1}{9}\cdot\frac{c(i)^2}{d(i)^2}\right)}{\left[\frac{1}{6}\cdot\frac{b(i)}{d(i)^2}\cdot c(i) + \frac{1}{2}\cdot\frac{(B - a(i))}{d(i)} - \frac{1}{27}\cdot\frac{c(i)^3}{d(i)^3} + \frac{1}{18}\cdot T(B,i)\cdot\frac{\sqrt{3}}{d(i)^2}\right]^{(}}$$

This approximation agrees, to within 5%, with the original surface. Higher order polynomil fits, or other curve types, could yield higher accur