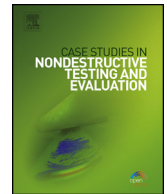


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Simulation and measurement of ferromagnetic impurities in non-magnetic aeroengine turbine disks using fluxgate magnetometers



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ABSTRACT

In this paper, ferromagnetic impurities in paramagnetic aeroengine turbine disks are investigated. Because such inclusions represent a significant threat in aviation, a detailed analysis is required for impured turbine disks. For this purpose, sensitive fluxgate magnetometers are used. After a premagnetisation, this sensor is able to detect small ferromagnetic particles by recording the variation of the magnetic flux density while the disk rotates below the sensor head. This trajectory creates a unique signature. However, the measured signatures are often distorted. A main reason for these distortions is that the particles are not oriented in axial direction (in the direction of the disks axis). Up to now, it was not possible to interpret the measured signatures. Thus, a simulation tool has been developed that provides a catalogue of different magnetic flux density distributions of typical orientations, positions and various distances to the fluxgate magnetometer position. For these simulations, the particles are assumed to be dipoles. As part of impurities are not caused by concentrated particles but by elongated ones, so-called or dipole lines, the model has been expanded for these cases by using numerical integration techniques. Measurements verify the assumption to approximate impurities by dipoles.

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1. Introduction

Aeroengine turbine disks often consist of paramagnetic, that means non-ferromagnetic Nickel based alloys. Sometimes, parasitic small ferromagnetic particles can be included in these disks that may decrease the mechanical stability. For this reason, in case of a suspicion disks are to be analysed with respect to ferromagnetic inclusions. These inclusions generate a magnetic density which can be measured by a flux gate magnetometer using the magnetic remanence method [1]. The detection principle of ferromagnetic impurities in non-magnetic metallic materials is based on their remanence. Before such a measurement can be carried out, the aeroengine turbine disks are premagnetised in axial direction. As ferromagnetic materials show the well-known hysteresis behaviour, those materials can be magnetised by a strong magnetic field which drives the magnetic material into saturation. When removing the magnetic field, the remanence is left. This remaining flux density is used to detect them in non-magnetic materials.

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Fig. 1. Gradiometer second order [2].



Fig. 2. Measurement setup for the analysis of a rotating aeroengine turbine disk with a fluxgate magnetometer [8].

Because the impurities of the turbine disks (if there are any) are very seldom, the magnetic flux densities to be measured are quite low leading to an enhanced measurement effort. On the one hand, the sensors themselves have to be very sensitive. On the other hand, parasitic fields from the environment of the measurement setup have to be suppressed adequately such that they do not influence the signal to be measured significantly.

There are different types of magnetometers available [2]. Examples for conducting magnetometers are induction coils, devices based on the Hall-effect, Magnetoresistance devices, Caesium magnetometers or Fluxgate magnetometers. Superconducting quantum interference devices (SQUIDS) need an external cooling for measuring flux densities in the Picotesla region. However, this is not really appropriate for a lot of applications because it is rather complicate to handle. That is why, for this application, sensitive fluxgate magnetometers of the type Bartington MAG-03IEL 100 were preferred. More information about this sensor can be found in [3] and [4].

2. Measurement setup

When measuring low magnetic fields, the background fields (i.e. variations of the earth magnetic fields or simple 50 Hz alternating currents of electric devices) have to be suppressed such that the resulting signal-to-noise ratio still allows an analysis of device under test. One possibility is the usage of shielded rooms [5]. However, they are impractical due to different reasons (especially due their size and price). Another principal way is the use two or more fluxgate magnetometers to calculate the difference of the measured flux densities. If they are placed adequately and if the magnetic background is sufficiently homogeneous, the difference hides this background such that the field originated from the device under test (DUT) near to the sensors is left. Such a setup is called gradiometer. Often it is advantageous to use three sensors along an axis to obtain a gradiometer of second order to measure the second derivative of the magnetic flux density. Fig. 1 shows such a setup with three sensors. For sake of simplicity, the parts for the mechanical fixation and balancing have been omitted.

Fig. 2 shows the whole measurement setup. The aeroengine turbine disk is placed on a non-magnetic turntable that is mechanically driven by a motor via a transmission belt. This mechanical drive is placed in sufficient distance to the device under test in order to keep its magnetic distortion as low as possible. The gradiometer is fixed on a non-magnetic arm. Its position can be varied regarding the distance to the turbine disk as well as the radial distance to the centre of rotation. During the rotation of the turbine disks (with possible ferromagnetic particles), the gradiometer records the magnetic flux density and provides an electrical voltage that is proportional to it. Thus, depending on the position, size and orientation of the particle, a unique curve is obtained over the rotation angle between 0° and 360° .

Measurements in [2] showed that the noise level of the gradiometer second order could be reduced to a level that is comparable to SQUID-systems based on high temperature superconductors. Thus, small magnetised iron particles of $60 \mu\text{g}$ can be detected in 10 mm distance. For 1 m distance, the detection level is about few milligrams of iron.

3. Simulation

The aim of this case study was to develop a catalogue of different signatures depending on the position, size and orientation of the ferromagnetic particle. Theoretically, these results could have been obtained by real measurements. But to reduce this effort, these measurements were replaced by simulations and verified for some typical cases. The basic assumption of the following simulations was to model the magnetic flux density of ferromagnetic particles by infinitesimally small magnetic dipoles as illustrated in Fig. 3. Moreover, the gradiometer is modelled as a sensor that measures the magnetic field on a concentrated point.

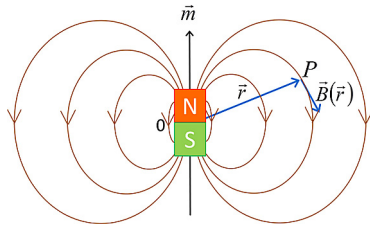


Fig. 3. Magnetic field of an infinitesimally small magnetic dipole.

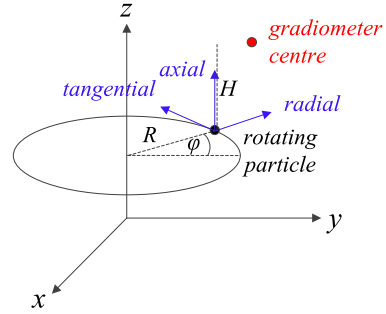


Fig. 4. Measurement geometry.

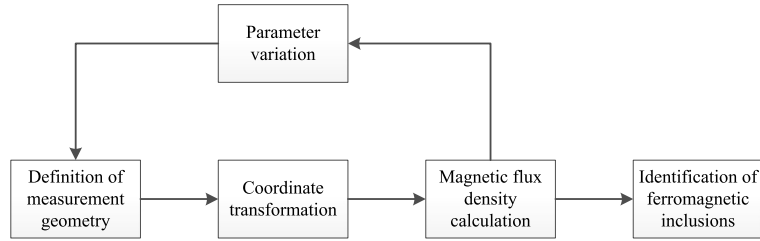


Fig. 5. Calculation scheme.

The magnetic flux density vector \vec{B} of such a dipole is given by

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi \cdot |\vec{r}|^3} \cdot \left(\frac{3 \cdot \vec{m}^T \cdot \vec{r}}{|\vec{r}|^2} \cdot \vec{r} - \vec{m} \right) \tag{1}$$

where μ_0 is the permeability constant, \vec{r} denotes the position vector of the point P where the field has to be calculated, and \vec{m} is the vector of the magnetic dipole moment [6].

Fig. 4 shows the measurement geometry. The magnetic dipole (particle) is marked by a black dot that rotates with the angle φ on a circular trajectory in the distance R around a circulation centre on the z axis. The height difference to the centre of the gradiometer is denoted by H . Equation (1) is adapted to this geometry to calculate the flux density signatures. The dipole can be oriented in tangential, radial or axial direction or compositions of these directions.

The calculation flow is illustrated in Fig. 5. In a first step, the geometry of the setup is defined including the height difference of the gradiometer to the particle, distance of the particle to the rotation centre and the orientation of the particle which is identical to the direction of the magnetic dipole moment. Moreover, the number of measurement points and angle resolution is defined. In order to apply the setup to (1), a coordinate transformation from cylindrical to Cartesian coordinates is performed by using standard mathematical manipulations. After that, (1) can be applied directly yielding the z -component of the magnetic flux density in dependence of the rotation angle φ . By varying the geometry, one obtains a catalogue of different typical curves that can be used in a next step to identify the ferromagnetic impurity.

Fig. 6 shows exemplarily a simulation result of one magnetic dipole oriented in axial direction. The radii of the dipole trajectory as well as the distance of the gradiometer to the rotation axis are chosen equally. As can be expected, the peak of the flux density appears at that rotation angle when the gradiometer is situated exactly above the dipole. Due to the axial orientation of the dipole moment, the magnetic field does not change its sign. Moreover, when the radii become larger, the magnetic field rises and declines faster with respect to the rotation angle as the distances between the dipole and the gradiometer becomes larger, too.

In Fig. 7, the dipole is assumed to be on a fixed position 124 mm away from the rotation centre. As it can be expected, when the distance from the gradiometer to the dipole increases, the amplitude of the flux density decreases. Obviously, the amplitude also depends on the size of the particle. To get an estimation of the depth of the particle inside the turbine disk, the magnetic field can be measured at different sensor heights. This approach is described in [7]. The axial position of impurities can be identified by varying the distance of the gradiometer to the rotation axis in order to determine that position where the maximum amplitude occurs. Alternatively, a sensor array could be used which however yields to a higher hardware effort. The depth of the impurity inside the disk can be calculated by a kind of calibration curve. After measuring the amplitudes or the peak-to-peak values of the signatures in two different gradiometer heights, the depth information can be derived directly from ratio of the peak-to-peak values. The achievable accuracy is about 1 to 2 mm.

Based on the dipole model, elongated impurities can be computed in the same way. These impurities can be modelled by multiple dipoles whose moments are all oriented in the same direction. Each dipole contributes in the same manner to the total field. The model provides the best fit to the measured data when an infinite number of dipoles is considered. For

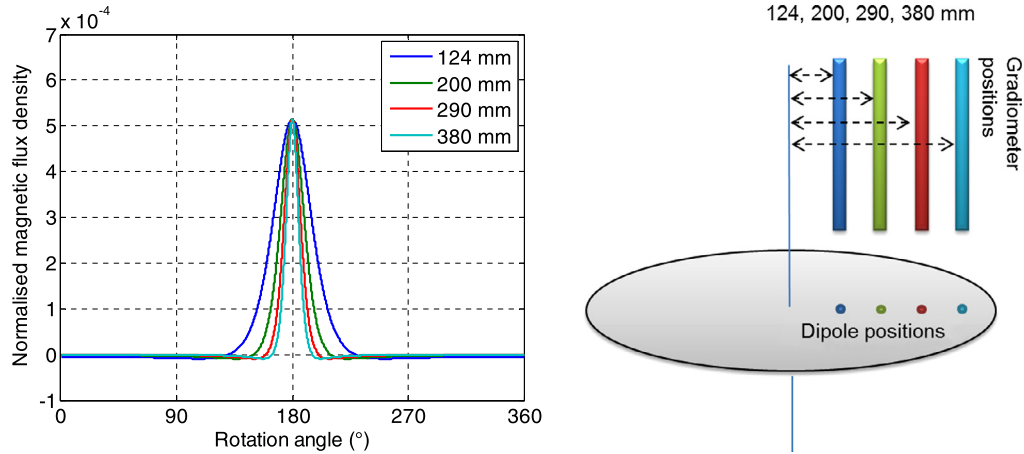


Fig. 6. Magnetic flux densities for variable distances (124 mm, 200 mm, 290 mm, 380 mm) of the dipole to the rotation axis, axial direction, gradiometer height 53 mm.

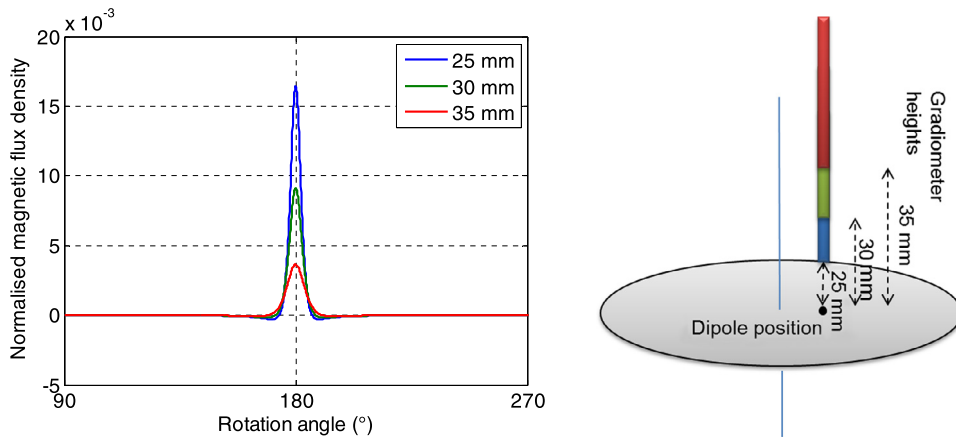


Fig. 7. Magnetic flux densities for different gradiometer heights (25 mm, 30 mm, 35 mm).

this reason, a dipole moment \vec{m}' per unit length has to be introduced. In this case, the summation can be replaced by a finite line integral, whose integration boundaries are given by the length l of the dipole line.

$$\vec{B}(\vec{r}) = \int_{s=0}^l \frac{\mu_0}{4\pi \cdot |\vec{r}|^3} \cdot \left(\frac{3 \cdot \vec{m}'(s)^T \cdot \vec{r}}{|\vec{r}|^2} \cdot \vec{r} - \vec{m}'(s) \right) ds \quad (2)$$

The integration can be computed by different numerical integration methods (trapezoidal rule or Simpson rule) in MATLAB. An example is given in Fig. 8. Dipole lines in tangential direction with different lengths have been simulated. Obviously, when the sensor is exactly above the dipole line, no z component of the magnetic flux density can be measured as the magnetic field lines are in parallel to the x - y -plane. During the rotation, the sign of the flux density changes as the magnetic field lines (from north to south pole) in dependency of the gradiometer position have a component in positive or negative z direction. The lengths of the dipoles have a direct influence on the resulting flux density curve. As expected, when the dipole becomes longer, the magnitude of the dipole moment spreads over a larger length that reduces the magnitude of flux density. Moreover, due to the non-symmetrical arrangement of the dipoles in the simulation, the zero-crossing of the flux density varies as the position of the boundary between north- and south pole depends on the dipole length. For the length $l = 0$, the result is identical to the flux density of a concentrated dipole in tangential direction.

4. Comparison of simulation and measurement

In order to verify the chosen model, some typical measurements with separate ferromagnetic particles with 10 mg mass have been carried out. The distances of the particle to the rotation axis and to the gradiometer were 70 mm and 68 mm, respectively. The rotation velocity was about 20 rounds per minute.

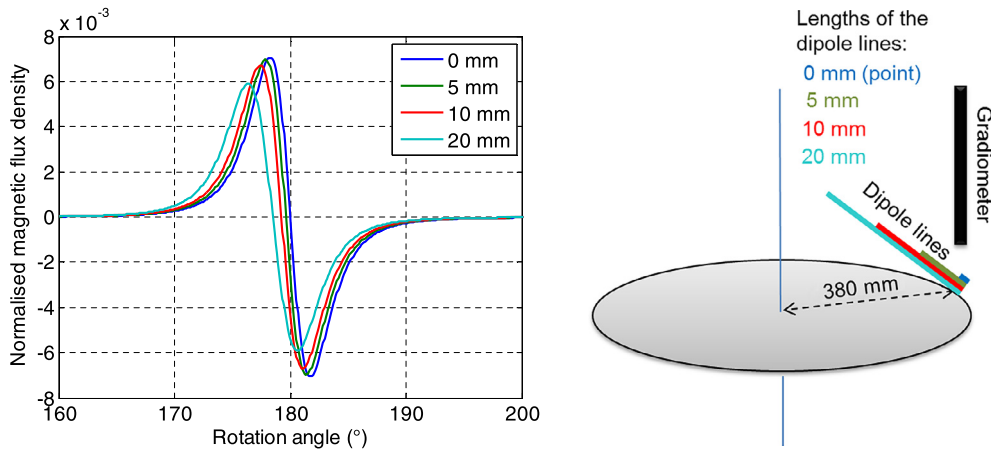


Fig. 8. Magnetic flux densities of dipole lines with different lengths (0 mm, 5 mm, 10 mm, 20 mm) in tangential direction 380 mm away from the rotation centre. The fluxgate gradiometer has the same distance.

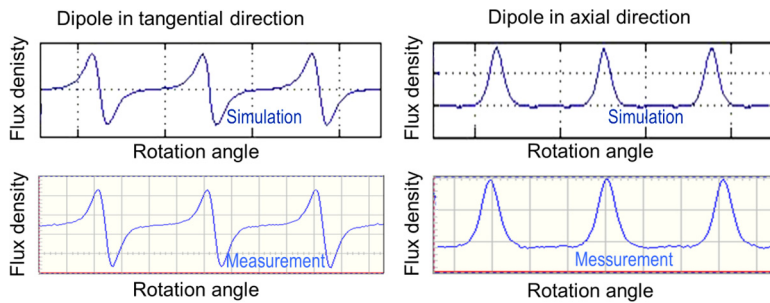


Fig. 9. Simulated and measured magnetic flux densities of dipoles in tangential (left) and axial direction (right) over three rotation cycles.

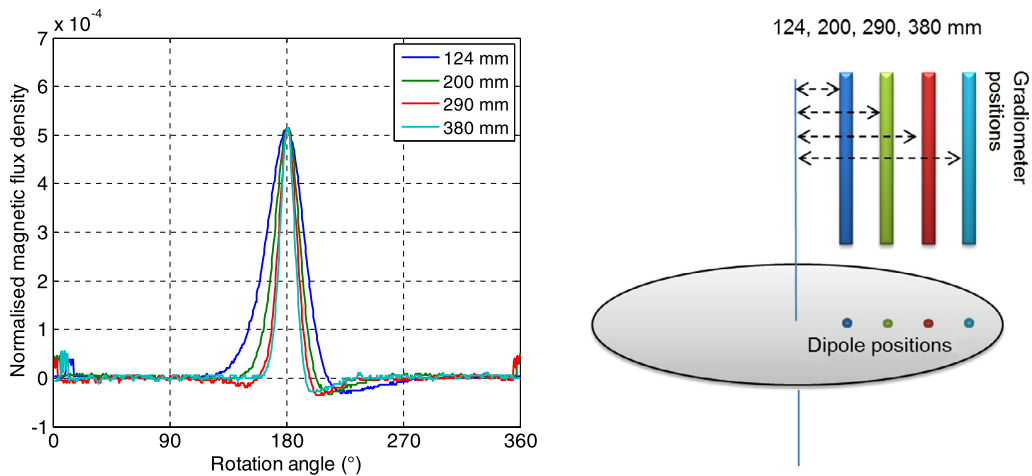


Fig. 10. Measured magnetic flux densities for variable distances (124 mm, 200 mm, 290 mm, 380 mm) of the particle to the rotation axis, axial direction, gradiometer height 53 mm.

These results are compared with the simulations that have been adapted to the chosen geometry. In Fig. 9, two of these measurements are shown exemplarily [9].

Apart from a multiplicative factor that depends on the magnitude of the dipole moment of the ferromagnetic particle, the different measured curve progressions in tangential and axial direction match very well with the simulated ones. These results show that the initial assumption to model ferromagnetic impurities as magnetic dipoles is sufficiently accurate.

A further measurement of the same situation described in Fig. 6 is depicted in Fig. 10. In order to compare simulated and measured results, DC offsets of the raw data have been removed and the amplitudes of the signatures have been adjusted individually to those of the simulation. This was necessary as the electronics of the sensor backend contains a low pass

Table 1

Comparison of simulated and measured full widths at half maximum for various distances of the dipole to the rotation axis.

Distances of the dipole to the rotation axis	Simulated FWHF	Measured FWHF
124 mm	34.5°	33.8°
200 mm	22.0°	22.5°
290 mm	15.3°	16.2°
380 mm	11.7°	12.6°

filter that reduces the amplitudes with increasing distance of the particle to the rotation axis. The reason for this is simple to explain: All measurements have been carried out with a rotational speed of 6 rounds per minute. However, the angular velocity of the particle increases linearly with increasing distance to the rotation center leading to a slight attenuation of the signatures. The little peaks at the beginning and end of the rotation cycle are distortions caused by the trigger signal that is necessary for the data recording.

The curves of Figs. 6 and 10 match very well. As discussed in the previous section, the signatures obviously become narrower with increasing distance of the particle to the rotation center. In order to quantify the differences between simulations and measurements, the full widths at half maximum (FWHF) for the different distances of the particle to the rotation axis are compared in Table 1. The maximum deviation is less than one degree.

5. Conclusion

In this case study, ferromagnetic inclusions on aeroengine turbine disks have been investigated. Three high sensitive and low-noise fluxgate magnetometers have been interconnected to a gradiometer second order to remove any magnetic background fields. This sensor is located above the turbine disk that rotates on a turn table. Depending on the orientation, size, position and elongation of the impurities, various signatures are obtained during the rotation. In order to solve the inverse problem – to gain information of the impurities based on the measured flux densities – the simulation results of different measurement configurations are stored in a catalogue. For these simulations, the impurities are modelled as simple magnetic dipoles or dipole lines. Real measurements show the very good agreement between the model and the reality.

In future, intelligent pattern recognition algorithms can be implemented to select that curve out of the catalogue that fits best to the measured data.

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