Examination of Technical Gear with the Help of Magnetic Passive Observer Status

Maciej ROSKOSZ¹, Miroslaw WITOS², Mariusz ZIEJA²

¹ Institute of Power Engineering and Turbomachinery, Silesian University of Technology, Gliwice, Poland, Phone: +48 322371039, fax +48 322372680; e-mail: Maciej.Roskosz@polsl.pl
² Air Force Institute of Technology, Warsaw, Poland, Phone: +48 226851353, Fax +48 226851313; e-mail: witosm@itwl.pl, mariusz.zieja@itwl.pl

Abstract
The paper deals with the examination of magnetization of the existing gear to detect unknown history of the effort of teeth and recognize their health/maintenance status. Discussed topics are based on the observation that:
1. Highly loaded gears are usually made of ferromagnetic materials, which are reversible and irreversible magneto-mechanical effects;
2. The microstructure and the current dislocation density strongly affect the magnetic properties of the ferromagnetic material.
The expected typical symptoms of diagnosing damages to gears are material changes in the distribution of magnetization induced during the operation of the transmission in the weak magnetic field of the Earth and the accompanying changes in the distribution of the magnetic field in the close to the test object under examination. The paper presents the theory that underlies the idea of the status observer and exemplary results of diagnosing industrial and aircraft gears. The main differences of studied objects are geometric features gears and position of the test object with respect to the external magnetic field of the Earth. To observe the distribution of the magnetic field applied cheap uni-, di-, and triaxial magnetometers (magnetic passive status observer).

Keywords: toothed gear, over-torque, damage, fatigue, magneto-mechanical effects, magnetovision, non-destructive evaluation (NDE), structural health monitoring (SHM), metal magnetic memory (MMM) method

1. Introduction

Toothed gears are the most essential units of power transmission systems. The major components, i.e. gear (toothed) wheels, shafts, and bearings are subjected to quasi-static and dynamic loads, which proves conducive to various kinds of failures, Figure 1. Safe and efficient operation of a toothed gear requires the diagnosing of atypical operating conditions (e.g. excessive vibration, violation of permissible torque /i.e. over-torque/), but not only; also, any failures to the gear’s material should be recognized as quickly as possible, i.e. at their earliest stages. Various causes of failures may range from the excessive wear-and-tear to a catastrophic breakage. The following statement proves the only right one for few responsible structures [1]:

‘A gear has failed when it can no longer efficiently do the job for which it was designed’

The paper has been intended to present a suggestion for the application of a passive magnetic observer of the state/condition, e.g. the metal magnetic memory (MMM) method [2]. This could be used for:
a) The additional verification of health/maintenance status of gear (toothed) wheels under overhaul generated conditions (after the toothed gear has been disassembled into separate subunits and structural components/parts), as a technique complementary to classical NDT methods (visual inspection (VT), and magnetic particle inspection (MT or MPI), eddy-current testing (ET), or ultrasonic testing (UT)), to detect hidden effects of:
- momentary exceedance of torque limits, with no evident symptoms of any failures to the teeth, Figure 2;
- accumulation of cyclic loads upon teeth, with unknown design, assembling, and operating errors simultaneously affecting the structure.
b) The post-factum analysis carried out in the course of the defected gear examination to identify the cause(s) of the event that had occurred.

c) The monitoring of health/maintenance status of the wheel toothing in the course of the toothed gear operation as a tool complementary to diagnostic methods already in use, such as vibration spectrum analysis, acoustic emission analysis, momentary rotational speed analysis, and oil analysis.

Figure 1. Typical damages to toothed gears: a) scuffing, b) abrasive wear, c) pitting, d) tooth cracking/case-core separation, e) fatigue crack in the root of a gear tooth, f) a broken tooth [1, 3]

Figure 2. Over-torque: a momentary exceedance of the maximum permissible torque of a turbo-prop engines requires expensive verification of gear health/maintenance status in the depot, in spite of the fact there are no other symptoms of a failure (file dust, excessive vibration, external noise)
2. Description of the issue under consideration

Gear failures can occur in various modes and intensities. The fact has to be given consideration at the stage of selecting health/maintenance status monitoring methods and while describing diagnostic symptoms. Hazardous conditions or failures to gears may be classified into five categories [1, 4, 5]:

1. **Scoring (scuffing)**: rapid wear resulting from an oil-film failure due to overheating of the mesh, permitting metal-to-metal contact; this contact produces alternately the welding and the tearing actions, which remove metal rapidly from the tooth surfaces.

2. **Wear**: a surface phenomenon in which layers of metal are removed, or ‘worn away’, more or less uniformly from the contacting surfaces of the gear teeth.

3. **Pitting**: a surface failure which occurs when the strength/life limit of the material is exceeded, a failure of this nature depends on surface/subsurface contact stress and number of stress cycles.

4. **Plastic flow**: cold working of the tooth surfaces, caused by high contact stresses and the rolling and sliding action of the mesh; it is a surface deformation resulting from the yielding of the surface and subsurface material, and is usually associated with a softer gear material – although it often occurs in heavily loaded case-hardened and through-hardened gears.

5. **Fracture**: a failure caused by breakage of a whole tooth or a substantial portion of a tooth; this can result from overload or, more commonly, by cyclic stressing of the gear tooth beyond the strength limit of the material (LCF and HCF problems).

The appearance of various hazard and failure modes can differ between gears that have through-hardened teeth and those that have surface-hardened teeth. These differences result from different physical characteristics and properties and from the residual stress characteristics associated with the surface hardened gearing.

The operating conditions of a gear and the toothed wheels health/maintenance status can both be monitored with indirect methods, with no account taken of probable effects of manufacture defects (e.g. of the microstructure of tooth material), assembling defects (e.g. mesh clearances, actual teeth contact surface), and maintenance ones (e.g. quality of lubrication) on actual endurance limit of particular teethed wheels.

Under overhaul conditions, the teethed wheels are subject to verification with typical NDT methods. The testing work is aimed at detection of untypical instances of tooth surface fatigue (e.g. scoring, scuffing, pitting), of cracks and breakages. Beyond the range of typical NDT methods, there is the work hardening (in other words, the strain hardening, or cold working) process accompanied by changes in residual stresses and increase in both dislocation density and material brittleness, i.e. the process that increases the risk of fatigue cracking in teeth throughout the time between overhauls (TBO).

The most common failure mode that may occur in a toothed gear usually results from a failure to the bearing and/or due to poor quality of the assembly (e.g. misalignment, assembly- attributable clearances, quality of surface treatment). Once the excessive tooth effort has been detected, it becomes a starting point for the increase in the toothed gear’s reliability and safety of operating the object to be diagnosed; reduction in the operating/maintenance costs remains of significance, too.

2.1. **Peculiarities of teeth operating conditions**

Teeth of two operating (meshing) toothed wheels pass through three stages of contact [6]:

1. Coming into mesh, initial contact occurs in the dedendum (lower) portion of one tooth (on the driving wheel) and in the addendum (upper) portion of the mating tooth (on the
driven wheel). At this point of torque transfer, tooth loading is relatively light, since most of it is carried by the teeth in full mesh and a portion by the teeth going out of mesh. Contact between the two teeth moves in a sliding action as they proceed through mesh. The sliding velocity decreases to zero when the points of contact reach the intersection of their common pitch lines.

2. At full mesh, the two teeth meet at their common or “operating” pitch line, there is only a rolling motion, no sliding. However, this stage produces the greatest tooth loading (bending).

3. Coming out of mesh, the two mating teeth also move in a sliding action, basically opposite of the initial contact stage.

Performance stresses (both normal and shearing ones) arise in tooth material. They are correlated with torque, rotational speed and design features of a toothed wheel. At the design stage they are estimated as:

a) The AGMA bending stress

$$\sigma_t = Tq \cdot \frac{2P_d}{DFY_j} \cdot \frac{K_aK_bK_mK_s}{K_v}$$

where: Tq – the torque; P_d - the diametral pitch; D - the pitch diameter; F - the face width, Y_j - the Lewis form factor corrected for several geometry factors, including stress concentration effects; K_a - the application factor that accounts for pulsation and shock in the driver and load; K_b - the rim thickness factor which penalizes for the rim flexibility of non-solid gears; K_m - the load distribution factor that is a function of face width; K_s - the size factor which penalizes very large or wide teeth; K_v - the dynamic factor, essentially a tailored Barth velocity factor that takes account of the quality of a gear in question [6];

b) The Hertzian contact pressure (subsurface and surface stresses)

$$p = \sqrt{\frac{E^*W}{\pi F} \left(\frac{1}{R_{eg}} + \frac{1}{R_{ep}}\right)}$$

where E* is the effective modulus of elasticity; W is the normal tooth force; F is the tooth face width; R_{eg}, R_{ep} are equivalent radii of cylinders, equal to pitch radius / sin \(\phi\) for each gear [6].

In practice, the maximum surface stress is proportional to this maximum pressure. AGMA further refines the stress by adding modifying factors similar to those for bending stresses. Beyond the zone where the teeth mesh there are only residual stresses \(\sigma_t\) introduced at the manufacturing stage. They experience modifications as affected by the operational history of the wheel and due to changes in microstructure resulting from the proceeding material degradation.

3. Toothed wheel diagnosing – a general idea

Toothed wheels in large industrial gears are most often made of ferromagnetic steels or metastable stainless steels, where paramagnetic austenite \(\gamma\) is transformed by deformation into ferromagnetic martensite \(\alpha\) (\(\gamma \rightarrow \alpha\)). Toothed wheels in aircraft gears are made of ferromagnetic steels, metastable stainless steels or paramagnetic titanium alloys. Magnetic properties of toothed-wheel material, i.e. magnetic permeability \(\mu\), coercivity \(H_c\), remanence \(B_r\), and magneto-mechanical properties (linear and volumetric magnetostrictions, \(\lambda\) and \(\omega\), respectively) are very sensitive to a change in [7-15]:
✓ microstructure (in phase components, dimensions of a grain in a predominant phase, the number and arrangement of inclusions),
✓ density of dislocations and other lattice defects (initial state, the effect of unknown operational history, level of material structure destruction),
✓ applied and residual stresses,
✓ external magnetic field $H$,
✓ temperature $T$,
which is clearly shown by the following relationships, (3) and (4):

$$ B = \mu_0 (H + M) \cong B_0 (H_0) + \Delta B_{structure} + \Delta B_{defects} + \Delta B_{stress} + \Delta B_{H-H_0} + \Delta B_{T-T_0} \quad (3) $$

where $H_0$ and $T_0$ are reference values of external magnetic field intensity and temperature of the material, $\mu_0$ is the vacuum permeability.

$$ M = M_i + M_r = M_0 + \Delta M $$

$$ H_c \propto \left\{ \sqrt{\rho_d \cdot d^{-1}} \right\} \rightarrow \left\{ L_i^{-1}, \sigma_r \right\} $$

$$ B_r, \mu_{r_{\text{max}}} \propto \left\{ \rho_d^{-1}, d \right\} $$

$$ \mu_i \propto \left\{ L_i^2, \sigma_r^{-1} \right\} \quad (4) $$

with $M$ – material magnetisation; $M_i$ – induction magnetisation; $M_r$ – residual magnetisation; $M_0$ – initial magnetization of the object; $\Delta M$ – performance-attributable changes in material magnetization; $H_c$ - coercive force; $B_r$ – remanence; $\mu_{r_{\text{max}}}$ – maximum magnetic permeability; $\mu_i$ – initial magnetic permeability; $\sigma_r$ – the magnitude of unidirectional internal stress which represents the irregularly fluctuating magneto-elastic energy distribution, $L_i$ – periodic distance between residual stress centres [15].

The above-mentioned observations have been suggested for use while diagnosing condition of toothed wheels by means of a magnetic passive state observer, e.g. with the MMM method.

### 3.1. The Metal Magnetic Memory Method

The MMM method, described in the ISO-24497:2007 [16] and the MMM Training Handbook [17], has been based on three key phenomena:

a) **reversible and irreversible magneto-mechanical effects** (a generalized Villari effect, the first loading cycle effect) [7-11].

In the material that shows non-zero magnetostriction and hysteresis of magnetic properties (remanence $B_r \neq 0$, coercive force $H_c \neq 0$, losses in internal energy $W > 0$) or transformation $\gamma \rightarrow \dot{\gamma}$, the following effects occur:

- change of the magnetization due to mechanical or thermal stresses;
- ‘memorization’ of information on conditions of maximum material effort and accumulation of cyclic (mechanical and/or thermal) loads, information that can be read out after the material unloading by means of changing the magnetic field scattering/distribution in the vicinity of the object under examination.

In the Earth’s magnetic field, the magneto-mechanical effects prove strongest for cold plastic deformations (strains) [7] – what occurs in the material is the increase in the crystallographic and magnetic anisotropies, and in dislocation density (the number of locked magnetic domains).

The stress-induced magnetization process at a given point of the material, $P(x,y,z)$ can be written down in the form of the following equation (5) (with account taken of both the
demagnetization tensor \( N = [N_x(P), N_y(P), N_z(P)] \) and spectral properties of magnetic induction components from equation (3):

\[
\mathbf{B}_P = \mu_0 \left( \mathbf{H}_0 + \mathbf{M}(x, y, z, N, \mu_r, H_c, B_r, \lambda, \omega, \Delta H, \Delta \sigma, \Delta T, t) \right) \cong \mathbf{B}_{DC} + \mathbf{B}_{AC}
\]

\( \mathbf{B}_{DC} \neq 0 \) represents an aperiodic component of the magnetic field produced by the centrosphere and mantle of the Earth, which makes approx. 96-99% of the magnetic field of the Earth \( \mathbf{B}_E \) [18]. The module of vector \( \mathbf{B}_E \) and its components \( (B_x, B_y, B_z) \) within a local system of coordinates for the object under examination and the magnetometer depend on:

- Geographic coordinates of the object’s under examination location (geographic latitude and longitude, and altitude above sea level),
- Location of the magnetometer.

The component \( \mathbf{B}_{DC} \) (initial polarization) proves conducive to the increasing stress-induced magnetization of the ferromagnetic material as affected by the variable component \( \mathbf{B}_{AC} \), even for the symmetric cycle [7-9]. The effect of the stress-induced magnetization gets more intense for the asymmetric cycle of mechanical or thermal loads affecting the teeth in the gear.

b) Magnetovision – taking records of the magnetic field distribution in the vicinity of the object under examination (loaded or unloaded) with a vector magnetometer or the matrix of vector magnetometers, with no artificial magnetization of the object under examination. In the MMM method, the measurements of \( \mathbf{B}_m \) carried out in the air are recalculated to get the magnetic field intensity \( \mathbf{H}_m \), according to the relationship (6)

\[
\mathbf{B}_m \cong \mu_0 \mathbf{H}_m
\]

If the distance \( h \) between the magnetometer and the surface of the object under examination is known, and the principles underlying reliable measurements of the magnetic field – maintained (e.g. proper selection of the magnetometer, measuring range, sensitivity, and measurement resolution.; also, with the Nyquist criterion satisfied for the digitized signal), the recorded measurements \( \mathbf{B}_m(x_1, y_1, z_1) = f(\mathbf{B}_p, h) \) include:

- Aperiodic component \( \mathbf{A} \) correlated with: average magnetic properties of the material under examination, with account taken of the effect of the demagnetization tensor \( N \) (geometry of the object under examination and its attitude towards the Earth’s magnetic field) and the aperture of the magnetometer;
- Periodic component \( \mathbf{P} \) correlated with magnetic anomalies resulting from: local changes in shape of the object under examination (e.g. gear tooth form/profile), defects and structure heterogeneity, also, stress heterogeneity and variable history of the material’s effort;
- Measuring noise and interference component \( \mathbf{I} \) correlated with features/properties of the measuring line and environmental conditions at the site where the MMM investigations are carried out.

Equation (7) describes a model of the measuring signal \( \mathbf{S} \) used with the MMM method:

\[
\mathbf{S} = \mathbf{A} + \mathbf{P} + \mathbf{I}
\]

c) Theory of the magnetostatics – analyses of recorded measurements as based on the magnetic monopole and dipole theory, with account taken of the signal theory. The recorded signal \( \mathbf{S} \) is subjected to numerical decomposition into components \( \mathbf{A}, \mathbf{P} \) and \( \mathbf{I} \). At the stage of detecting the ‘defect’ the expected spectral characteristics of magnetic
anomalies (width, gradient amplitude) are taken into consideration. To localize the source of a magnetic anomaly, one should also take account of the criterion of the magnetic field’s deflection line at the boundary line between two centers of different magnetic permeability (i.e. between air and examined material).

3.2. Comments about the MMM method

Some substantial mistakes can be found in the ISO-24497:2007 [16] and the MMM Training Handbook [17], just to mention few of them:

a) a converse sign of the vertical component of the Earth’s magnetic field has been assumed for current calibration of the measuring probe; this is the reason for discrepancies between the observed symptoms of stress-induced magnetization and the literature-delivered data;

b) the following items have been disregarded in algorithms for quantitative analyses of the MMM data:
   - magnetic and magneto-mechanical properties of the material, which change in the Heat Affected Zone (HAZ) due to changes in both the microstructure and the residual stresses;
   - shape of the object under examination (demagnetization tensor);
   - distance between the magnetometer and the examined surface; values of disturbances in the external magnetic field by the ferromagnetic object under examination and gradients of particular components of the magnetic field decrease exponentially as the distance increases.

The Authors have corrected the above-mentioned mistakes, which, in turn, has resulted in extension of functional capabilities of the MMM method; corrections have been based on:

a) verified results of the examination of magnetic and magneto-mechanical features of some selected grades of steel, theory of dislocations [19, 20], and the Ashby’s maps;

b) verified numerical model of the terrestrial magnetism IGRF-11 and WMM [18];

c) the state-of-the-art metrological capabilities to measure the magnetic field; inexpensive, mass-produced uniaxial, diaxial, and triaxial magnetometers represent the Hall, magnetoresistive (AMR, GMR, TMR) and magnetoimpedance (MI, GMI) technologies, Figure 3. Application of electronic magnetometers eliminates weak points of the S.M. Saxby methodology (XIX century) with an ordinary compass used to detect magnetic anomalies typical of defects to material structures;

d) the modelling of the expected magnetic field distribution in the vicinity of components under examination, sometimes of complex and complicated shapes, e.g. toothed wheels (computations made with COMSOL MultiPhysics software applied) and verification of computed results using the magnetometer matrices.

4. Examples of findings

Capabilities of the magnetic passive state observer have been presented by means of several selected examples gained in the course of passive experiments.

4.1. Verification of the toothed wheel’s magnetization level after being dismounted from the gear

More than 10 wheels were analyzed in two series of measurements. The first sequence was to establish a reference level for the already operating wheels. The second series of measurements was conducted after one-year operation with no knowledge of the load history.
The results were averaged for the whole wheel to identify the trends of magnetic field variations. The analyzed parameters were the normal $H_n$ and tangential $H_S$ components of the magnetic field as well as their gradients along the teeth. The results are shown in Figure 4.

![Figure 3](image1.png)

Figure 3. The FXOS8700CQ Xtrinsic 6-axis sensor combines industry-leading 3-D accelerometer sensor with 14-bit resolution and 3-D magnetometer sensor with 16-bit resolution into a small 3x3x1.2 mm package [21].

![Figure 4](image2.png)

Figure 4. Gear (toothed) wheel 1: a) average values of components in the magnetic field; b) average changes of components in the magnetic field [22]

### 4.2. Post-factum analysis

The MMM examination was carried out using toothed wheels dismounted from an aircraft’s reversible worm gear with some teeth broken out in the output kinematic pair. Findings of the examination showed considerable difference between levels of magnetization of teeth in the kinematic pair and in the toothed wheel $z_1$ at gear’s input. Major changes in values referred to the normal component and magnetization vector amplitude, Figure 5, i.e. to a parameter disregarded in the ISO-24497; to have this parameter found, one has to record three components of the vector.
4.3. Monitoring of structural health of the gear

A passive state observer has also been applied to detect difference in magnetization of toothed wheels in the course of toothed gear’s operation. The TMR and MI wide-band analogue magnetometers were used in the measuring system [23]. The measurements gained confirmed capability of monitoring levels of magnetization in particular teeth. Contrary to variable reluctance sensors, e.g. a passive eddy-current sensors preferred for non-contact monitoring of quick-change gear trains and rotating compressor and turbine blades [24], the proposed solution does not produce magnetization of tooth material.

3. Conclusions

Application of magneto-mechanical effects and a passive magnetic state observer to diagnose health/maintenance status of toothed wheels seems realizable.

Values of the magnetic self-field in a toothed wheel are related to:
- initial magnetic and magneto-mechanical properties of the material,
- the number of load cycles (working time),
- load level (quality of the use, influence of hidden resonances of the structure),
- load distribution along the gear teeth (design features, quality of the assembly and greasing),
- geometric parameters of the gear.

Further laboratory tests are necessary to verify quantitative and qualitative relationship between magnetization and health/maintenance status of the teeth.

Acknowledgements

The study has been prepared under research projects financially supported by the National Centre for Research and Development (Poland).
References

3. R. Errichello, ‘Wind Turbine Gearbox Failures’, GEARTECH.