New Options for a Cost-Saving Wear Monitoring in Fluid Power Systems

Roman Cecil Krähling

ARGO-HYTOS GmbH, Industriestr. 9, 76703 Kraichtal Menzingen,
E-Mail: r.kraehling@argo-hytos.com

Dr.-Ing. Thomas Meindorf

ARGO-HYTOS GmbH, Industriestr. 9, 76703 Kraichtal Menzingen,
E-Mail: t.meindorf@argo-hytos.com

Abstract

In recent years oil condition sensors have been proven as a reliable way to reduce the total cost of ownership. A major application hereby is the cleanliness or wear monitoring. During the operation of hydraulics and gearboxes contamination and wear will cause high costs for the machine owner. The damage by particle contamination results in unexpected downtime, long lead time of spare parts and loss of production.

Contamination and wear in gearboxes and hydraulic systems are nowadays monitored with optically operated automatic particle counters and monitors. Alternatively, inductively operating metal particle counter are used to detect metallic particles. However, in certain applications these types of meters are impractical due to the high costs and technical limitations, such as inadequate measurement accuracy or sensitivity to air bubbles.

An old fashioned and cost-effective way to detect ferromagnetic wear particles are magnetic plugs, which are still widely used in many applications. Although the sensors are relatively cheap in the production, a costly service is needed to manually inspect and clean the sensor during operation, such as the high-wear situation at the run in of a machine.

As part of the contribution a novel sensor concept based on a magnetic debris sensor is presented, which overcomes the shortcomings of known magnetic plugs. The sensor uses a permanent magnet to attract ferromagnetic particles on the sensor surface and accumulate them. The measurement of the accumulated amount of particles is done inductively, which makes a visual inspection unnecessary. Through the sensitivity of the measurement principle even small amounts of wear particles can be measured. The accumulation of wear can be further assessed as sum over time and not as separately occurring events. To enable a repetitive measurement the sensor cleans

itself automatically, using an electromagnet, which produces an opposing field to compensate the permanent magnet.

By evaluating the time between two cleaning cycles of the sensor the contamination of the system or the wear of a component can be detected. Long cycle times between indicate small ferromagnetic wear, short times indicate increased wear. The sensor principle is initially designed for wear monitoring of tribological systems with ferromagnetic materials, e.g. roller bearings. However, it is also possible to detect the wear of non-ferromagnetic materials, through secondary induced abrasion.

KEYWORDS: wear, particle counting, condition monitoring, magnetic plug, debris detector

1. Motivation

Reasons for machine breakdown do have many facets. Besides mechanical fatigue and overload a main issue is the lubrication. Water ingression, lack of lubricant, oil deterioration or the use of an improper lubricant are reasons for machine breakdowns. For bearings numbers are given, that up to 60% of all breakdowns are caused by these influences. Another crucial factor is particle contamination. Particles might result from extrinsic factors, such as particles passing through the breathers and sealings, or intrinsic factors. Intrinsic factors means wear that is caused by mechanical load or secondary wearout. Two typical wear characteristics over the machine lifetime are illustrated in **figure 1** /1/, /2/.

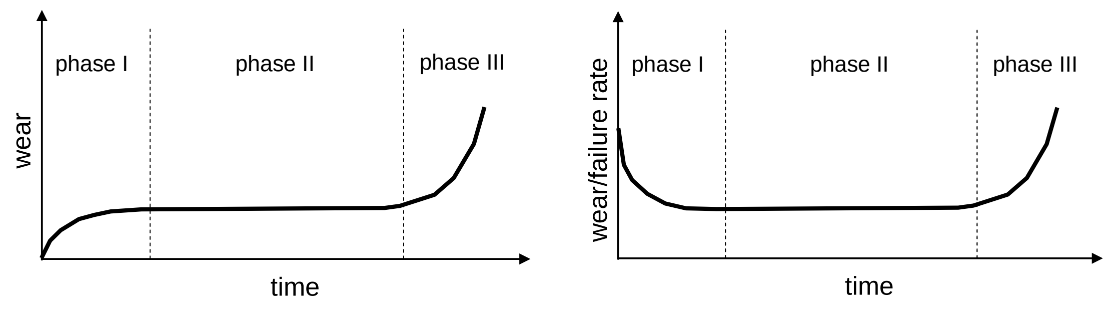

Figure 1: Typical wear/failure rate over lifetime

Through a wear respectively particle monitoring a severe breakdown with unplanned downtime can be avoided and maintenance actions can be triggered depending on the real condition of a machine. Within the following two chapters the state of the art methods and a new approach are described.

2. State of the art - particle monitoring

The monitoring of oil deterioration, water intrusion, oil type detection, etc. can be covered by different sensors as described in /3/. For particle and wear monitoring various types of sensors with different measurement principles are available. Most common standard today is the optical particle measurement, by means of the light extinction principle according to ISO11500:2008. The particle contamination respectively cleanliness level is expressed as a contamination grade according to ISO4406:1999.

A special application is the detection of metallic contaminations for which sensors are available. Recent sensors can detect ferromagnetic particles as well as non ferromagnetic particles within the main stream down to a size of 100 µm for ferromagnetic particles and 200µm for non ferromagnetic particles /4/.

One of the oldest methods of detecting ferromagnetic wear is the magnetic plug. It is mainly used in gearboxes, however also in hydraulic circuits. The following picture shows an early state magnetic plug of 1951.

Figure 2: Picture of magnetic plug / year 1951

The magnetic plug is placed in the main line or a reservoir, e.g. the drain line, and collects ferromagnetic debris over a certain period of time throughout operation. A service employee optically checks the collected amount of debris in a defined time interval to assess the current wear status of the system and cleans the sensor afterwards.

A more scientific approach is the magnetic debris switch that gives an electrical signal, as soon as the particles form a short circuit between two electrodes. However, due to the in figure 1 shown typical wear characteristic, with a high wear rate at the run in phase, these magnetic plugs tend to alarm early.

	advantages	**disadvantages**
optical particle sensor	▪ standardized ▪ covers a wide contamination range ▪ very sensitive	▪ sensible to air and water ▪ limited to homogeneous fluids ▪ limitation for some highly additivated fluids ▪ no information on the material
metal scan sensor	▪ information on metal content ▪ hardly any influence by air and water ▪ covers all types of metals	▪ expensive ▪ low sensitivity ▪ only big diameters can be detected
magnetic debris switch	▪ low price ▪ cumulative detection of the wear rate ▪ simple and robust	▪ cumulative measurement, no counting of single particles ▪ low sensitivity

Table 1: Advantages and disadvantages of different wear sensors

In order to overcome these disadvantages the magnetic plug approach has been extended. One idea is an automated assessment of the amount of debris not only by means of a switch but by a continuous measurement, in order to avoid manual inspections on site. The other idea is an automated cleaning of the sensor. Thus the sensor can measure repetitive cycles, without the need for a manual cleaning.

3. Approach of an automated magnetic plug

3.1. Sensor concept

The schematic of the sensor can be seen in the following cross-sectional drawing.

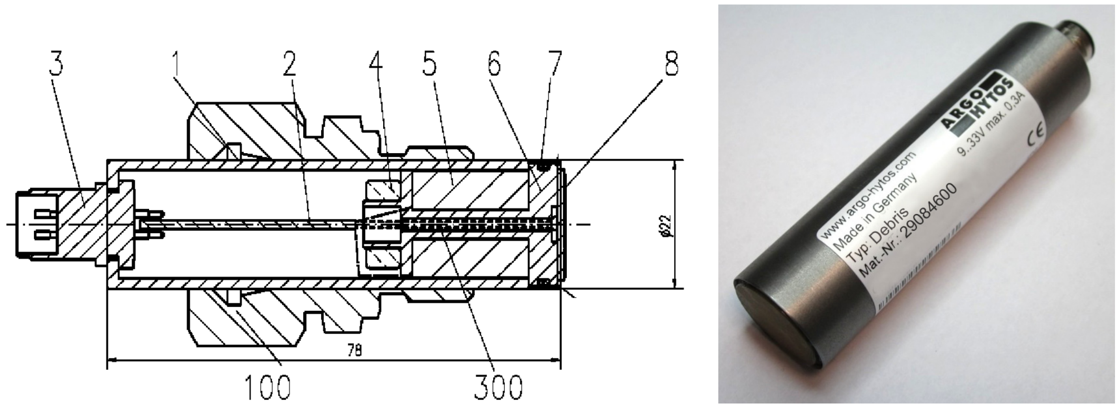

Figure 3: Cross-section of the automated magnetic plug

Passing ferromagnetic particles are attracted and accumulated on top of the debris transducer (8) by means of the permanent magnet (4). The magnetic flux is guided through the field-guide (6) to the debris transducer. The magnetic loop is closed via the sensor housing (1).

The detection of the collected debris is performed by an inductive coil transducer (8). The planar coil is integrated into an oscillating circuit that oscillates at 27,12 MHz ±0,5% centre frequency (2), which is appropriate for industrial purposes. An alternative frequency band is 13,56 MHz. If metallic debris is collected on top of the planar coil the frequency is detuned, which is sampled respectively processed by the controller on the electronic board (2). The electronic circuit design for the evaluation of this frequency shift can be seen in **figure 4**.

During the start-up phase of the sensor the transducer is automatically cleaned and the current frequency is stored as a base line. All further frequency changes resulting from the debris accumulation are referred to this base.

The frequency shift is converted into a PWM-output, filtered, converted into a 4…20mA output and then given out via the connector (3).

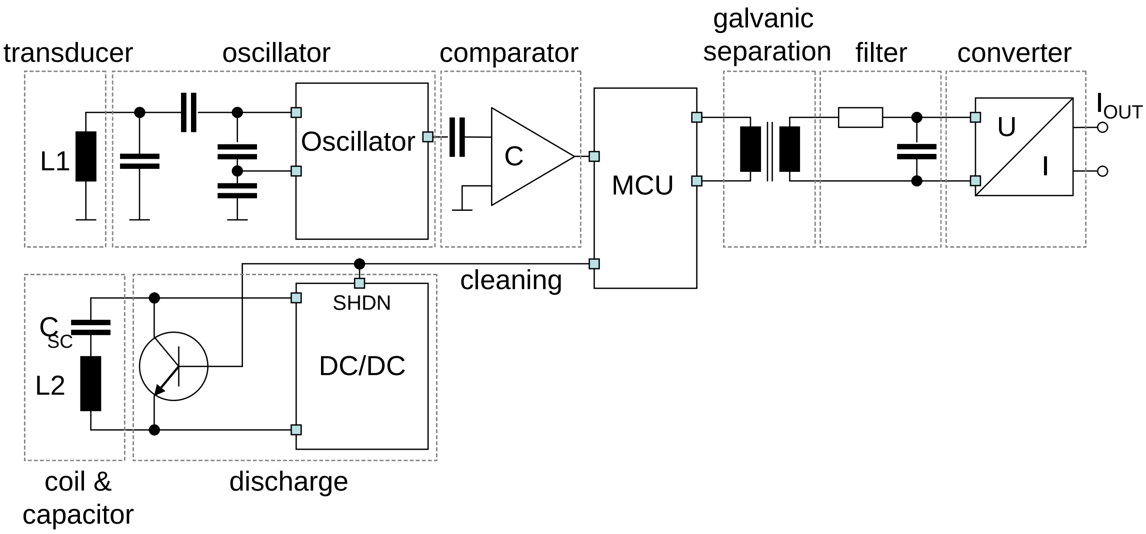

Figure 4: Electrical principle of the debris sensor

3.2. Demagnatization principle

The collected debris can be released by means of a cylindrical compensation coil (5) with inductivity L_2 (ref. figure 4). This process is activated as soon as a certain amount of debris is collected and thus a predefined frequency shift is exceeded. For the activation the stored energy W_{SC}

$$W_{SC} = \frac{1}{2} \cdot C_{SC} \cdot U^2 \quad (1)$$

of a charged super cap is completely discharged and conducted over the coil /5/, /6/. The coil and the capacitor in row form an oscillator that exchanges the energy, until it is completely consumed by the internal losses.

The flux within the coil can be estimated by means of the theoretical stored energy W_{Coil}

$$W_{Coil} = \frac{1}{2} \cdot L_2 \cdot I^2 = \frac{1}{2} \cdot B \cdot H \cdot V \quad (2)$$

and the theoretical value for the inductance L_2 of the cylindrical coil.

$$L_2 = N_{Coil}^2 \cdot \frac{\mu_r \cdot \mu_0 \cdot A_{Coil}}{l_{Coil}} \quad (3)$$

The compensation is repeated five times in order to ensure a complete removal of the debris during the cleaning process. Afterwards the remaining energy in the capacitor is insufficient for another compensation and the capacitor needs to be charged again.

The oscillation frequency and thus the time for the cleaning process can be calculated by means of the Thomson equation /6/.

$$f_0 = \frac{1}{2 \cdot \pi \cdot \sqrt{L_2 \cdot C_{SC}}} \tag{4}$$

The time for one period according to this equation is approximately one second.

By means of the following parameters of the cylindrical coil, the geometry of the coil, the numbers of windings and the current the magnetic field strength respectively the magnetic induction results.

$$B_{Coil} = \mu_r \cdot \mu_0 \cdot H_{Coil} = \mu_r \cdot \mu_0 \cdot \frac{I \cdot n}{\sqrt{l^2 + D^2}} \tag{5}$$

The resulting magnetic field strength H_{Coil} compensates the remanence field density $B_{rPM} = \mu_0 M_R$ of the permanent magnet. Therefore the magnetic field strength at the magnet $H_{Coil-PM}$ has to be calculated, considering the different cross sections.

$$H_{Coil-PM} \cdot \mu_0 \cdot \mu_r \cdot A_{PM} = H_{Coil} \cdot \mu_0 \cdot \mu_r \cdot A_{Coil} \tag{6}$$

The field strength is reduced by the factor of two, due to the geometric design.

$$B_{rPM} = \mu_0 \cdot \left(M_R + H_{Coil-PM}\right) \tag{7}$$

For the magnetic field strength of the permanent magnet two threshold limits can be distinguished, the coercive field strength H_{cB} and H_{CJ} of the demagnetisation curve, which are both crucial parameters of permanent magnets. H_{cB} indicates the field strength at which the magnetic induction of the permanent magnet is completely compensated ($B_{rPM}=0$). On the other hand side H_{cJ} must not be exceeded in order to not permanently loose the magnetization.

The needed design parameters of the super cap can be estimated by using equation (1), (2) and (8)

$$C_{SC} = \frac{\mu_r \cdot \mu_0 \cdot H_{cB}^2 \cdot A_{Coil} \cdot l_{Coil}}{U_{SC}^2} \tag{8}$$

This capacitance is needed to compensate the magnetic field of the permanent magnet.

Since the current varies throughout discharging it is made sure that the magnetic field of the coil and the remanence of the permanent magnet will equalize a certain point and the holding force reaches a minimum. At that point the sensor will be cleaned by gravity or flow forces.

3.3. Wear-rate measurement

One approach for the wear measurement is to simply look at the amount of accumulated debris. As soon as the amount of debris exceeds a preset limit, corresponding with a certain analogue output of the sensor, the PLC will give an alarm.

Another approach is to not only look at the current contamination, but to measure the wear rate instead, by evaluating the variation of the debris accumulation time intervals. The faster the signal changes and the shorter the time between two cleaning processes gets the higher the wear rate and thus the contamination of the system.

Through the repetitive measurement and the evaluation the time intervals a more accurate monitoring of the change of the particle concentration can be performed.

4. Frequency shift

The base frequency of the empty transducer is shown in the following figure.

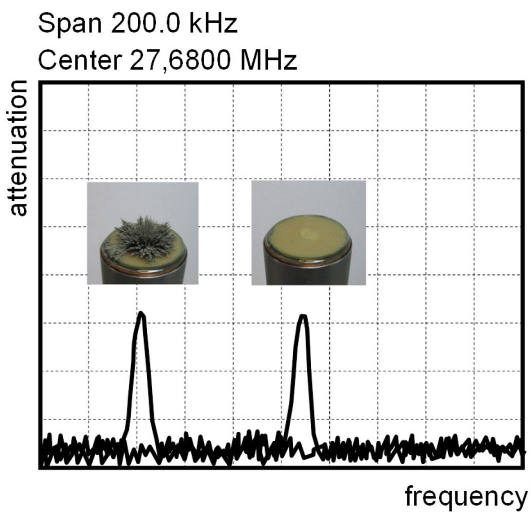

Figure 5: Base frequency and frequency at the upper limit before cleaning

While loading the transducer with ferromagnetic debris a frequency shift will result. In the following figure the frequency measurement at different debris loads is given.

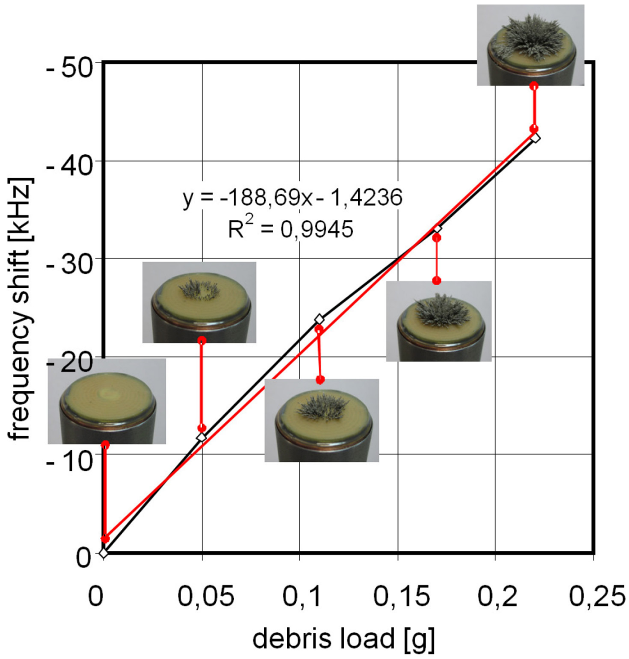

Figure 6: Frequency versus debris load

The curve shows an almost linear frequency drop with an increasing debris load.

5. Assessment of Wear Rate

Since the sensor continuously measures until the preset accumulation limit is reached and the cleaning process starts, information about the wear rate can be derived from the time intervals.

As long as the wear rate is low the period between the cleaning processes is long. As soon as the wear rate increases the period becomes shorter. Thus the wear rate can be determined by means of a simple and precise time measurement. The measurement of an increasing wear rate can be seen in the following diagram.

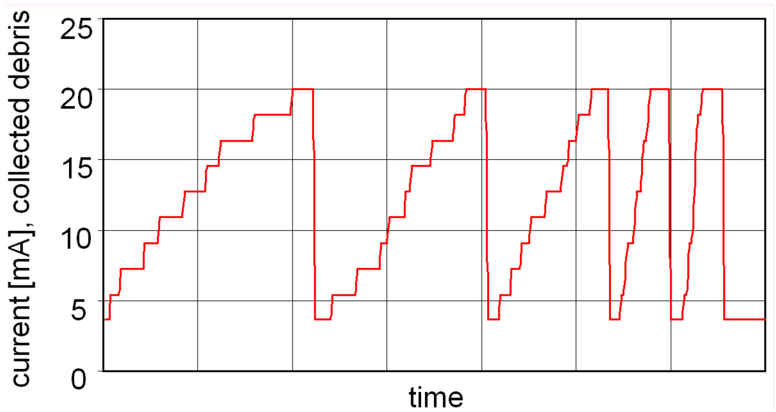

Figure 7: Wear rate measurement

6. Cross talk/ Influencing parameters

Under real conditions the sensor has to work at a wide temperature range (-40°C…120°C) without being influenced significantly.

Two options are appropriate to obtain a low temperature cross talk. Either the electronic has to be designed robustly. For example the controller can be operated with a temperature stable oscillator. Temperature cross talk can also be compensated by using electronic parts with certain temperature characteristic TK. Or the temperature compensation can be conducted within the controller.

Within the scope of the investigation another approach was followed. Therefore the temperature influence of the electronic and the transducer is given in order to be integrated into the controller. The final solution however will comprise both approaches, using a robust electronic and compensating the final influence by means of a look up table within the controller.

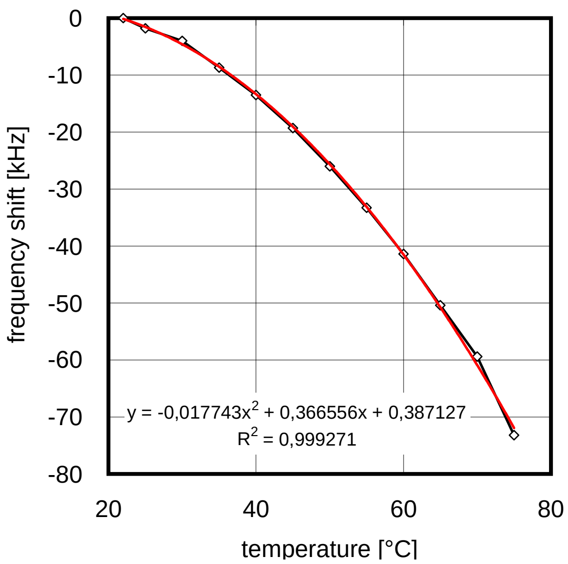

Figure 8: Temperature cross talk

7. Clamping force

One crucial point with regard to the sensor function is the holding force. In order to simply test the holding force, the following test procedure has been set up. As test specimen a cylindrical mass with a defined diameter of 15 mm was used. The specimen was placed underneath the transducer in a hanging position. Afterwards the mass was continuously reduced, until the magnetic holding force could compensate the gravity force. The final weight of the specimen was 22g. According to the following equation

$$F_{magnet} = m_{specimen} \cdot g \tag{9}$$

this corresponds to a magnet force of F_{magnet} = 0,22 N. With a medium friction coefficient μ_H of 0,1 the sticking force F_H is 0,022 N.

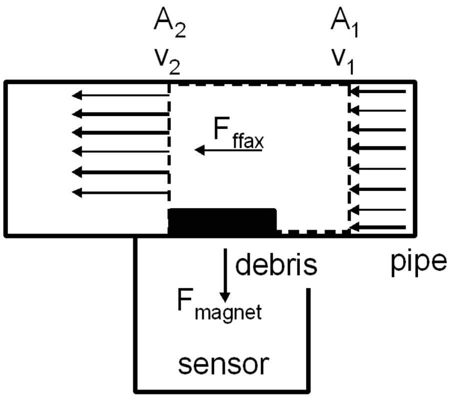

Figure 9: Calculation of the flow forces on the debris

On the other hand side the dimension of the axial flow force F_{ffax} can be estimated by means of the momentum equation.

$$F_{ffax} = \rho \cdot Q \cdot \left(\bar{v}_2 - \bar{v}_1\right) \tag{10}$$

For the calculation of the average flow velocity v_1 and v_2 the pipe diameter has to be known.

$$A_{pipe} = \frac{Q}{\bar{v}_{\max}} \tag{11}$$

For the example v_{max} = 4 m/s is assumed. The cross section of the debris reduces A_2 (assumption 1 mm²) and thus v_2 is higher than v_1.

The resulting axial flow force F_{ffax} = 0,014 N is independent to the flow rate Q and lower than the sticking force calculated above. So the debris will stick to the sensor.

8. Outlook

Within the scope of this paper the principle of an automated magnetic debris monitoring has been presented. The advantages are that on the one hand side the accumulation of debris at the sensor transducer can be observed continuously and on the other hand side the wear-rate measurement can be performed by means of a simple time measurement. Moreover the simple design will lead to a low cost sensor, compared to state of the art particle monitors.

Issues for the future are the improvement of the detection precision, the temperature compensation and the increase of the clamping force.

9. Reference list

/1/ Murrenhoff, H.; Meindorf, T.; Stammen, C.; „Online Condition Monitoring (OCM) in Fluid Power Technology“, Conference Proceedings 4th International Fluid Power Conference, Dresden, March 25-26, 2004, page 219ff

/2/ Gold, P.W. “Tribology”, Umdruck zur Vorlesung, RWTH-Aachen, 1998

/3/ Meindorf, T.; „Neue Wartungskonzepte durch kontinuierliche Online-Öl-Überwachung“, Oil Doc Ölsensoren Symposium, Brannenburg, 2011

/4/ Becker, E.; „Wear Monitoring in Oil-Lubricated Machines“, Oil Doc Ölsensoren Symposium, Brannenburg, 2011

/5/ Kallenbach, E. et al; „Elektromagnete“, Grundlagen, Berechnung, Entwurf und Anwendung, 3. Auflage, Vieweg + Teubner, 2008

/6/ Hering, E.; „Physik für Ingenieure“, 6. Auflage, Springer Verlag, ISBN 3-540-6244-2, 1997

/7/ N.N., „Filter Guideline“, ARGO-HYTOS, 2001

/8/ N.N., www.oilcheck.com, 01/2012

10. Nomenclature

W	energy	$m^2 \cdot kg \cdot s^{-3}$
C	capacity	$C \cdot V^{-1}$
L	inductivity	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
U	voltage	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
I	current	A
B	magnetic flux density	$kg \cdot s^{-2} \cdot A^{-1}$
H	magnetic field strength	$A \cdot m^{-1}$
N	number of turns per unit length	-

μ	permittivity	$F \cdot m^{-1}$
f	frequency	Hz
M	magnetization	$A \cdot m^{-1}$
A	surface	m^2
V	volume	m^3
F	force	N
g	gravity	$N \cdot m^{-1} s^{-1}$
v	Velocity	$m \cdot s^{-1}$
T	temperature	°C