# MORE ABOUT FLEXIBLE COILS

Rocoil
PRECISION ROGOWSKI COILS

## 1) General Construction.

Flexible coils are wound on a silicone rubber former. In most cases the winding is a single layer. The winding at one end of the coil 'returns' along the length of the coil through a conductor along the axis of the former. This arrangement reduces magnetic pick-up and conveniently ensures that the connections to the coil are both at the same end. The output of the coil depends on its mutual inductance (M). The output voltage is given by

$$V = M\frac{di}{dt}$$

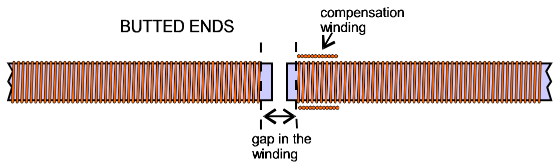
where *i* is the current threading the coil. Mutual inductances can vary from about 0.3µH for coils used in general-purpose applications to less than 0.02µH for coils which are designed to measure very fast current changes. The mutual inductance depends on the pitch of the winding and the cross-sectional area of the former but is independent of the length of the coil.

For an ideal Rogowski coil, (ie having an exactly uniform winding with no gaps) the mutual inductance is independent of the path the coil takes when it encircles the conductor provided the ends are brought together correctly. Also, under ideal conditions no voltage is induced in the coil by magnetic fields from adjacent conductors that do not thread the coil (see "Rogowski Coils and Ampères Law " later on).

In most cases a Rogowski coil is used in conjunction with an electronic integrator to provide a current waveform. The combination of a coil and an integrator is referred to as a 'current transducer'.

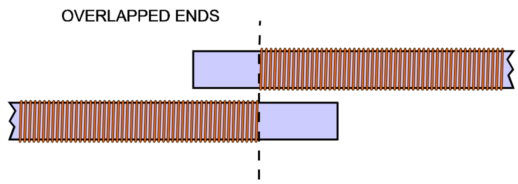
## 2) Aligning The Ends.

Flexible coils come in two basic types which are distinguished by the way their ends are aligned. The importance of end alignment arises because it is difficult to bring the ends together round the conductor without leaving a gap in the winding. A gap in the winding means that the coil is more liable to be affected by cross-talk or pick-up from adjacent conductors or other sources of magnetic fields. It also means that the coil output will be more sensitive to the position of the conductor within the coil loop. An 'ideal' coil, having a uniform winding with no gaps should not be sensitive to external magnetic fields or conductor position. Most flexible coils have plastic end fittings to ensure that the ends are aligned correctly




Type 1000 series coils have ends which are butted together and they incorporate an additional winding in the end fitting to compensate for the gap. This is the best way to cope with the gap problem but fitting and adjusting the compensation coil is time consuming.

Type 4000 series coils use a simpler method in which the ends are overlapped so that the ends of the winding are in line. This method ensures that the output from the coil is not excessively sensitive to the position of the conductor within the coil loop provided that the plane of the coil is perpendicular to the conductor. This method also gives good rejection of cross-talk from adjacent conductors which are parallel to the conductor being measured but is less good for more complex magnetic fields. The method works best with thin cross-section coils. Type 4000 coils have a simple end fitting to locate the ends. They can often be made to a length that is a comfortable fit round the conductor.




## 3) Screening.

Flexible coils can be supplied in screened or un-screened versions. Screening helps to make the coil less sensitive to pick-up from electrostatic fields. It will not make the coil less sensitive to magnetic pickup; this is done by winding the coil accurately and taking care with the end alignment as described above.

It is difficult to give definite rules as to whether screening is necessary or not for a given situation. A system with a screened coil has a less noisy output. Screening is advised where high frequencies are involved at any frequency. For most measurements at power frequencies it is probably not necessary except for low-current measurements (e.g. less than 10A).

Even when the coil itself is not screened, a screened cable is normally used for the output lead. The cable screen should be earthed to the enclosure of the integrator or connected to the earthy side of the electronics.

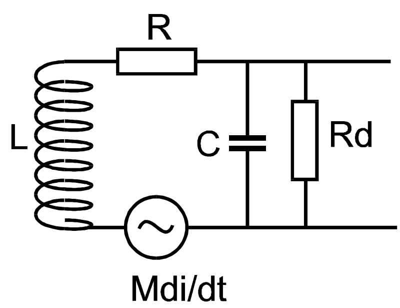
The current being measured by the coil will also induce circulating currents in the screen. We design the screen to ensure that the induced currents are not large enough to cause significant measurement errors. The magnitude of the circulating currents increases in proportion to the frequency. One way we minimise circulating currents is to use a screening braid made from a resistive material. With a resistive braid, circulating currents do not have a significant effect for frequencies less than about 100kHz. An alternative method is to wrap a strip of foil helically round the coil in such a way that adjacent turns do not touch. This provides a good screen with no possibility of circulating currents. A foil screen is used where the coil is likely to be used at frequencies above 100kHz but it has the disadvantage that it makes the coil les flexible.

**4) High-Frequency Response.**

The high-frequency performance of a coil is determined by its resonant frequency. The self-inductance of the coil and its self capacitance form a resonant circuit. The resonant frequency depends on the design of coil and is usually in the range from a few hundred kHz to several MHz. The higher the resonant frequency the better the high-frequency performance of the coil.

To get the best high-frequency performance the coil should be as short as possible and have a low mutual inductance (such as a low-output coil). It should also have a short output lead. If the coil is fitted with a long output lead this adds extra capacitance and reduces the resonant frequency. Screening a coil also reduces the resonant frequency.

A coil can be modelled mathematically by using a simple resonant circuit. By fitting a damping resistance across the output of the coil (including the output lead) the resonance can be damped to give a smooth roll-off at high frequency. As a rough rule, with a correctly damped coil, the -3dB roll-off point is at about the same frequency as the resonant frequency. In most cases we design the integrator so that the input impedance is equal to the optimum damping resistance. Unfortunately, damping a coil to give a flat amplitude response also has the effect of making the phase accuracy worse.




The parameters in the resonant circuit differ widely for different designs of coil. The capacitance is difficult to calculate reliably from first principles and in practice the best way to determine the parameters is by measurement.

When a coil is used in conjunction with an integrator the high-frequency characteristics of the complete transducer will also depend on the components (especially operational amplifiers) used in the integrator.

**5) Low-frequency Response**

The low-frequency response is determined by the design of the integrator used with the coil. Typically a response that is flat to within a few percent down to 1Hz is achievable. Coils with a low mutual inductance are not suitable for very low frequency measurements.

**6) Measuring Low Currents**

Low currents are difficult to measure because the output of the coil is very low. Typically for a standard cross-section coil the measurement starts to get difficult below about 10A. There are various design techniques which can be used to make successful low-current measurements but it may become necessary to trade-off some or all of the of the following features of the integrator.

(i) The output may have to roll off faster at low frequencies.
(ii) The low frequency phase accuracy may not be so good.
(iii) The transducer may have a less good transient response and only be suitable for steady currents.
(iv) The power supply consumption may be larger - a problem with battery-powered equipment.
(v) The transducer may be 'tuned' to a specific frequency.

By using these techniques it is possible to make a transducer using a flexible coil that can resolve currents down to a few milliamps at power frequency.

**7) Temperature Effects**

Increasing the temperature of the coil will cause the resistance of the winding to increase and will also cause thermal expansion. When the coil is used with an integrator the effect of increasing the winding resistance is to reduce the output of the transducer. The temperature coefficient depends on the ratio of the resistance of the coil winding to the input impedance of the integrator and can be calculated accurately.

The effect of thermal expansion is complex. Up to a certain 'critical' temperature the mutual inductance is not affected significantly. Above the critical temperature the mutual inductance usually (but not always!) falls. When the temperature is reduced to ambient there can be a permanent change in the mutual inductance because part of the winding has stretched. Next time the coil is heated it can be taken to a higher temperature before the mutual inductance changes. Where coils are to be used at a high temperature they can be heated to a temperature above the expected operating temperature to 'pre-condition' them and stabilise their output.

The critical temperature depends on the design of the coil. Coils with thin winding wire and a large cross-section former have a low critical temperature (about 60°C). Thick winding wire and a small cross-section former give a higher critical temperature.

## 8) Interchangeable Coils

Individual coils, even if they are made to the same specification, will differ slightly in their mutual inductances. This is not a problem when a coil and integrator are calibrated together as a unit but in some cases it would be convenient to be able to replace a coil without the need to re-calibrate the whole transducer. We have now developed an interchangeable coil system where each coil has a calibration resistor which is built into the output cable or the connector. Interchangeable coils must be used with an integrator having a specified input resistance. For example with the wall-mounted series of integrators the input resistance is 2.5kΩ (2K5).

Coils which have been calibrated for interchangeability will normally have a resistance value marked on them near the connector. Compatible integrators will be marked with the same resistance value. The most widely used input resistances are 2K5 and 820R. Interchangeable coils do not necessarily have to be the same length.

Interchangeability has only recently been introduced and the marking system has not yet been fully implemented. We can advise where necessary if the serial numbers of the coil and integrator are known.

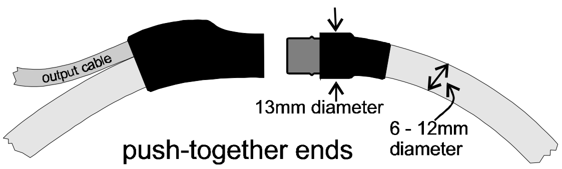
## 9) Coil Types and Characteristics

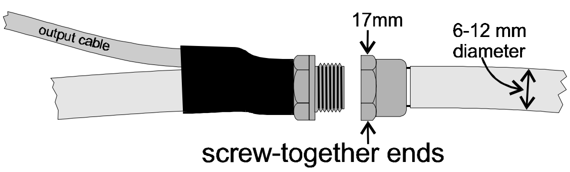
Coils are characterised by a four digit number

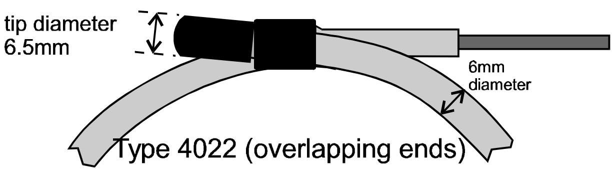
1st digit 1 - butted together ends, 4 - overlapping ends (see section 2), X - unspecified
2nd digit 0 - no screen, 1 - braid screen, 2 - foil screen, X - unspecified
3rd digit 1 - standard cross-section, 2 - small cross-section, 3 - low output. X - unspecified
4th digit 0 - no insulation, 1 - single layer of insulation, 2 - double insulation X - unspecified

| Type | Description | OD including insulation | Typical mutual inductance |
|---|---|---|---|
| X012 | no screen / standard cross-section / double insulation | 10mm | 0.20 - 0.31μH |
| X112 | screened / standard cross-section / double insulation | 12mm | 0.20 - 0.31μH |
| X022 | no screen / small cross-section / double insulation | 6mm | 0.10μH |
| X122 | screened / small cross-section / double insulation | 6.5-7mm | 0.10μH |
| X232 | foil screen / low output / double insulation | 7.5mm | 20nH |

Coils with butted-together ends can have either push-together end fittings, which are more suitable when coils are repeatedly opened and closed, or screw-together end fittings which are better for permanent installations. At the moment the same end fittings are used for all coils with butted-together ends irrespective of their cross-section.




This drawing shows the end joining arrangement for a Type 4022 coil with overlapping ends. With this style the tip diameter is half that for the butted-together coils. This makes it easier to thread the coil through a small gap.

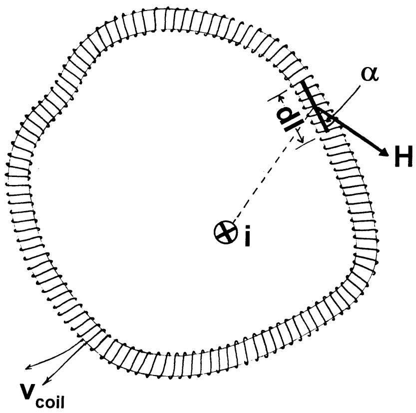
For cases where space is severely limited we can make thinner coils but it may also be necessary to reduce the thickness of the insulation.

## 10) Rogowski Coils and Ampère's Law

The theory of a Rogowski coil illustrates very well how a coil can be considered as an embodiment of Ampère's Law. A Rogowski coil works by sensing the magnetic field in the space around the conductor; Ampère's Law provides the relationship between the current flowing and the magnetic field around it.

If a line is drawn in a loop which totally encircles the current then, according to Ampère's Law, the line integral of the magnetic field around the loop is equal to the net current enclosed by it no matter what path the loop takes. If the loop encloses no net current the line integral is zero. This is expressed mathematically as

$$\oint H \cos\alpha \, dl = i. \qquad - \quad - \quad -(1)$$




Where dl is a small element of length along the loop, H is the magnetic field and α is the angle between the direction of the field and the direction of the element.

The figure shows a long, thin helical coil, with n turns per metre and cross-sectional area, A, which encircles a conductor carrying a current, i. In a section of length dl the number of turns is ndl and the magnetic flux linking the section is

$$d\Phi = \mu_o H \, A \, ndl \, \cos\alpha.$$

Where H is the magnetic field. The flux linking the entire coil is given by integrating along the coil:

$$\Phi = \oint d\Phi = \mu_o nA \oint H \cos\alpha \, dl = \mu_o nAi.$$

Where Ampère's Law (eq. 1) has been used to evaluate the integral.

For an alternating current the voltage output from the coil is given by the rate of change of flux:

$$V_{coil} = -\frac{d\Phi}{dt} = -\mu_0 nA \frac{di}{dt}$$

A thin, flexible, Rogowski coil can be used to provide an elegant experimental demonstration of Ampère's Law because, according to this equation, the voltage output from the coil is independent of the way the coil is placed round the conductor provided only that the ends of the coil are brought together.

Ampère's Law makes a thin Rogowski coil ideal for use as a transducer for alternating currents since it responds only to currents which thread the loop and rejects currents and fields from external sources. Also the output of the transducer does not depend on the exact path taken by the loop or the position of the conductor within the loop. It can be shown that similar considerations apply to coils with a large cross section, provided that they are circular.

For practical purposes the coupling between a coil and the conductors threading it is described in terms of a mutual inductance, M, where

$$M = \mu_o \, nA.$$

Mutual inductance is the quantity which is measured when a coil is calibrated.