

CAPACITANCE MICROMETER

This invention relates to variable capacitance transducers and particularly though not exclusively to a capacitance micrometer.

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A convenient way of measuring small distance changes is through the use of a capacitance micrometer. In a simple parallel plate capacitor, the capacitance is given by

$$C = \frac{\epsilon \epsilon_0 A}{d} \quad 1$$

10 where ϵ is the relative permittivity (dielectric constant) of the medium between the plates, ϵ_0 is the permittivity of free space, A is the plate area, and d is the distance between the plates. The displacement of interest is allowed to vary either A or d , and the resultant capacitance change is measured. Generally, greater sensitivity is provided by varying the distance d between the plates of the capacitor.

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There is a number of ways in which the capacitance C is measured in practical capacitance micrometers. Most commonly, the impedance of the capacitor is measured by passing an alternating current of constant amplitude through the capacitor, and measuring the resultant voltage developed across it. If a current I is
20 passed through the capacitor, a voltage V will be developed given by

$$V = \frac{Id}{j\omega \epsilon \epsilon_0 A} \quad 2$$

Thus, if the current I is held constant, V is directly proportional to d - that is, V is a linear function of d . The book "The Nanopositioning Book" by Thomas Hicks and
25 Paul Atherton, ISBN number 0 9530658 0 4 describes the technique in further detail.

Although the technique described above is advantageous in that the measured voltage is a linear function of the distance between the capacitance micrometer plates, there is a number of disadvantages, particularly the frequency response. If the displacement d to be measured is varying rapidly, such as when attempting to
5 measure high frequency vibration or the eccentricity of a rapidly rotating shaft, then the carrier frequency ω must also be high. It then becomes difficult to generate a suitable constant current and measure the voltage V accurately. Typically, ω will be limited to $2\pi \times 30$ kHz or lower, limiting the vibration frequency to about half this at best, that is about 15 kHz. With this sort of carrier frequency, the nominal
10 capacitance of the micrometer capacitor must be high enough to give a sensibly large current, otherwise the accuracy is limited by electron shot-noise. A typical value would be between 2 and 10 picofarads (pF), although less than 1 pF is possible. This in turn gives a typical micrometer capacitor plate dimension of 10 mm diameter, with a nominal spacing of around 100 μ m also.

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In order to monitor vibrations, it is advantageous to have a small diameter sensor that operates at a relatively large nominal distance from the article generating the vibrations. The small diameter gives high spatial resolution, enabling small diameter shafts etc. to be monitored. The large nominal spacing makes the apparatus easier to
20 set up.

A different way of measuring capacitance is to let the capacitance determine the frequency of an oscillator circuit and then measure that frequency. The technique is described in "The ultra-micrometer; an application of the thermionic valve to the
25 measurement of very small distances", by R. Whiddington, in Phil. Mag. 1920, Volume 40, pages 634 - 639. The micrometer capacitor described in that paper is part of an inductance-capacitance (LC) oscillator operating at about 1 MHz. Changing the distance between the capacitor plates changes the resonant frequency

of the circuit (since $\omega_0 = (LC)^{-1/2}$). In this example the change in frequency was detected by beating the output of the oscillator with the output of another oscillator operating at a fixed frequency, and listening to the tone produced via a loudspeaker. A change in distance generates a change in tone. The "musical note" produced by
5 the beats can be compared with a fixed reference tone to enable very small gap changes to be detected.

FR-A-2334089 discloses a capacitance micrometer comprising a variable capacitance diode connected in a Clapp oscillator, whereby the frequency of oscillation varies in
10 accordance with the variation in capacitance of the diode and a micrometer capacitance in parallel with the inductor. The output of the oscillator is provided to a converter which converts the frequency of oscillation to a voltage whose value is proportional to the frequency. In Rev. Sci. Instrum. 54(5), May 1983 page 552
15 "Accurate insitu Measurement of Near-Surface Volume Dilatation in Radiated Silica through Capacitance Monitoring of Counterlever deflection" Norris *et al*, there is described in Figure 2 a variable capacitance device incorporated in a Clapp oscillator, and providing a variable oscillator output signal to a buffer amplifier and counter. A counter is an accurate means of frequency determination, but is
20 inherently slow as time must be allowed to count sufficient pulses to give the required resolution.

It is an object of the present invention to provide an improved capacitance micrometer which alleviates the problems of the prior art, and is capable of
25 measuring displacements over a large range of frequencies with lower noise levels.

According to a first aspect of the present invention, there is provided a variable capacitance transducer comprising variable oscillator means, including a variable capacitance means for varying the oscillator output frequency, and discriminator

means responsive to the oscillator output signal, including means for assessing the oscillator frequency in relation to a predetermined frequency value, to provide an output voltage signal whose value varies in relation to the frequency of the oscillator output signal.

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In a second aspect, the invention provides a method of measuring a desired parameter of an object, comprising providing a probe and measuring a capacitance between the object and the probe by providing a variable frequency from an oscillator which includes the capacitance and whose frequency varies with the capacitance, and converting the variable frequency to a voltage signal by assessing the variable frequency in relation to a predetermined frequency value.

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In a further aspect, the invention provides a variable capacitance transducer comprising a Clapp oscillator including a variable capacitance means in series with an inductor whereby to determine the frequency of oscillation of the Clapp oscillator, the oscillator frequency varying with change in capacitance of the capacitance means, and discriminator means responsive to the oscillator frequency to provide an output voltage signal whose value varies in relation to the frequency of the oscillator frequency.

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In accordance with the invention, said output signal provides a direct measure of the value of said variable capacitance. This provides a far more sensitive measuring system. The output signal means may comprise any suitable means, for example a frequency discriminator or a phase comparator for comparison with a reference clock signal. As preferred, a phase discriminator is provided comprising means for multiplying the intermediate signal with a delayed version of itself, and employing a D.C. component of the multiplied signal, whose magnitude is proportional to the intermediate frequency, as the output signal. As preferred, the discriminator is

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implemented digitally with a crystal controlled clock, which is inherently a very stable arrangement. Further, the local oscillator is preferably a digital frequency synthesiser, which is inherently very stable with a very fast response.

- 5 A number of well known oscillators may be used to generate the oscillator output signal, including Clapp oscillators, tunnel diode oscillators, and resonant cavity or transmission line oscillators.

- 10 Problems may arise with the usual operating frequency of the variable oscillator, around 200 MHz. This places very high demands on the stability of the circuit and it is therefore preferred in accordance with the invention to mix the output signal of the variable oscillator with a fixed frequency "local oscillator" to give an intermediate frequency, preferably of around 10 MHz.

- 15 In accordance with a further aspect of the invention therefore there is provided a variable capacitance transducer comprising variable oscillator means, including a variable capacitance means for varying the oscillator output signal frequency, local oscillator means for generating a signal for mixing with the oscillator output signal to produce an intermediate frequency signal, and discriminator means responsive to
20 the intermediate frequency signal to provide an output voltage signal whose value varies in relation to the frequency of the intermediate frequency signal.

- 25 The variable capacitance may comprise a single electrode to be positioned adjacent an object, a parameter of which, e.g. position, is to be measured. Alternatively, the variable capacitance may be a parallel plate capacitor. Relative movement between the capacitor plates causes a change in the capacitance of the capacitor. For some applications, however, a change in the relative area of the plates or the dielectric may be desirable instead. It will be appreciated that the capacitance micrometer is a

form of transducer in which the measured variable causes a change in capacitance which is turned into a frequency output that can be monitored. It is equally possible to measure variables other than distance by the same technique. For example, variation of the dielectric will also cause a change in capacitance. Thus, variables of
5 fluid are susceptible to the same transducer technique.

It is common to house the capacitor in a probe assembly, commonly as a cylindrical housing with the variable capacitor positioned at the tip of the housing. In addition signal processing circuitry is included in the probe assembly, and in particular an
10 inductor providing with the capacitor a resonance circuit for oscillation. Since the probe assembly will commonly be used for measuring eccentricity in rotating machinery, it is likely there will be large variations in operating temperature. In order therefore to achieve the object of the invention of measuring displacements over a large range of frequencies with lower noise levels, it is desirable to provide
15 an arrangement for cancelling out or at least reducing variations in capacitance due to changes in temperature.

Accordingly, in a further aspect of the invention there is provided a variable capacitance transducer formed as a probe comprising a body having at one end a
20 capacitor arrangement for forming with an object to be measured a variable capacitance, and connected to an inductor mounted in the body for forming there with a resonance circuit wherein the dimensions of the inductor and/or materials forming the capacitor arrangement and the inductor are chosen such that over the likely temperature differentials experienced in use, the change in inductance of the
25 inductor is compensated by the change in capacitance of the capacitance arrangement.

As an alternative in a further aspect of the invention, the inductor which is a significant factor in temperature variation, has a configuration which is inherently more stable under temperature changes, and in particular is formed as a flat coil on a substrate, preferably in the form of a rectangular spiral.

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Accordingly, in a further aspect of the invention there is provided a variable capacitance transducer formed as a probe including a capacitance arrangement formed at one end of the probe for forming with an object which is to be measured a variable capacitance, the capacitance arrangement being connected to an inductor
10 mounted within the probe assembly to form a resonant circuit, the inductor comprising a flat coil mounted on a substrate in the form of a spiral.

As preferred, the resonant circuit formed by the inductor and variable capacitance is connected in an oscillator circuit, preferably a Clapp oscillator, all the components
15 being mounted within the probe assembly housing to ensure stray capacitance etc. are reduced to a minimum. Further, in accordance with the invention power is provided to the probe assembly via a coaxial cable, and the central conductor of the coaxial cable is employed both for conducting power to the probe assembly and for carrying the variable frequency signal output by the oscillator. To this end, power is
20 supplied at the remote end of the coaxial cable via an impedance matching arrangement which serves as a load from which a voltage signal can be derived representing the variable frequency of the oscillator. This provides a very convenient and noise-resistant arrangement.

25 Accordingly in a further aspect of the invention there is provided a variable capacitance transducer formed as a probe assembly, comprising a probe body, a variable capacitance means formed at one end of the body for co-operating with an object which is to be measured, an oscillator circuit formed in the probe body and

including an inductance which together with the variable capacitance forms a resonant circuit, a cable coupled to the probe having a conductor for supplying power to the oscillator circuit and for transmitting from the oscillator a variable frequency signal over the same conductor, and an impedance matching arrangement
5 disposed at the remote end of the coaxial cable for providing power to the coaxial cable and for providing a voltage signal representing the variable frequency signal.

Brief Description of the Drawings

10 The present invention can be put into practice in various ways which will now be described by way of example with reference to the accompanying drawings in which:-

Figure 1 shows an oscillator circuit suitable for use in the variable capacitance
15 transducer of the invention;

Figure 2 shows the output frequency of the oscillator of Figure 1 as a function of transducer plate spacing;

20 Figure 3 shows a resonant discriminator for use in a first embodiment of the variable capacitance transducer of the present invention;

Figure 4 shows the voltage response of the discriminator circuit as a function of the discriminator circuit's input frequency;
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Figure 5 shows a block diagram of the variable capacitance transducer;

Figure 6 shows the output of the resonant discriminator circuit as a function of the plate spacing of the transducer in the oscillator;

5 Figure 7 is a block diagram of a digital version of a discriminator as a second embodiment of the variable capacitance transducer of the present invention;

Figure 8 is a more detailed block diagram of the Digital Phase Locked Loop of the discriminator circuit of Figure 7;

10 Figures 9 and 10 are sectional views at right angles to one another of a cylindrical probe incorporating the variable capacitance transducer of the present invention;

Figures 11 to 15 represent different configurations of probe, and inductor and capacitor for use therein; and

15 Figure 16 is a schematic view of a preferred version of inductor and end capacitance electrode for use in a probe.

Description of the Preferred Embodiment

20 Referring to Figure 1, an oscillator circuit is shown. A transistor TR1, which is a BFY90 or any other suitable small signal vhf transistor, is connected at its base between two resistors R1 and R2. The resistors R1 and R2 are connected between the supply rail +Vcc via R6, and ground. By connecting the base of the transistor TR1
25 in this manner, the transistor is biased.

A capacitor C1 is connected to ground in parallel with the resistor R2, and thus decouples the transistor TR1's base.

The collector of the transistor TR1 is connected via a load resistor R3 and R6 to supply power + Vcc.

5 The collector is also connected to ground via a resonant circuit consisting of a capacitor Cmic, and an inductor L1 linked in series. Feedback to the resonant circuit is provided by two series-connected capacitors C2 and C3, which are connected in parallel with the resonant circuit between the transistor TR1's collector and ground.

10 The emitter of the transistor TR1 is connected to ground via a further resistor R5. To complete the feedback, and to sustain oscillation a further resistor R4 is connected between the transistor emitter and two capacitors C2 and C3.

As shown in Figure 1 the oscillator circuit is mounted within a probe assembly P
15 (indicated in dotted lines). Power is conveyed to the oscillator by the central conductor W1 of a coaxial cable W. The outer braid of the cable is grounded as shown at the probe and in addition at the remote end of the cable in a discriminator circuit D. The output of the oscillator is transmitted to the discriminator along the central conductor of the coaxial cable. Thus the discriminator and the probe are
20 joined by a length of coaxial cable, W, which may be several metres long. Power for the probe is provided down this line from the discriminator power supply line, +Vcc, via resistor R6. The value of R6 is chosen to match the impedance of the coaxial line and typically may be 50 to 100 . The probe oscillator previously described superimposes an oscillating current which could be between 100 MHz and
25 1 GHz, but is typically at around 200 MHz, on the supply current. This oscillating current is converted to a voltage by the resistor R6 and is passed to discriminator circuitry. The capacitor C4 blocks the dc supply voltage. As has been described, variations in the value of Cmic caused by variations of its distance from a conducting

target cause the oscillator frequency to vary and this variation is converted into a measure of the mechanical displacement by the discriminator.

5 The circuit of Figure 1 is generally called a Clapp oscillator. This oscillator configuration is preferred, as the resonant frequency is determined mainly by the one capacitor, C_{mic} , and by the inductor L_1 . The resonant frequency is largely unaffected by other component values. The capacitor C_{mic} is the micrometer capacitor which comprises two conducting plates, one of which is the target to which distance is to be measured, and the other which is typically formed from a material similar to that of the other components in the system. Suitable substances are aluminium, copper, Invar™ and gold patterned onto Zerodur™. The probe plate is typically 1 mm in diameter used at a nominal spacing of 1 mm from the target. The displacement to be measured will typically vary the micrometer plate spacing between 0.5 and 1.5 mm.

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Using the dimensions suggested above, the capacitance of C_{mic} is around 7fF, but there will typically be stray capacitance in parallel with this, of the order of 0.9 pF.

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Figure 2 shows the output frequency as a function of capacitor plate spacing using the nominal dimensions listed above. The parallel stray capacitance, considered to be a constant 0.9 pF, has been included. As will be seen, the frequency of the output voltage is around 200 MHz and the sensitivity of the device is approximately 1 Hz.nm⁻¹. It will be noted, however, that the frequency change is a non-linear function of the capacitor plate spacing.

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Figure 3 shows a resonant discriminator. The discriminator is a passive circuit which takes an input voltage V_{in} relative to a ground rail. The input voltage is

generated from the output voltage V_{out} of the oscillator in Figure 1, but is suitably amplified and buffered.

5 The discriminator includes a resistor R6 in series with the input. Connected between the resistor R6 on the input voltage rail, and the ground rail, is an inductor L4 in series with a capacitor C4. The capacitor C4 and inductor L4 are arranged to be similar to L1 and Cmic, of the oscillator circuit, except that the plate spacing of C4 is held stationary. In parallel with these two components is a further capacitor C5. The capacitor C5 helps match the temperature coefficients of series-connected capacitors
10 C2 and C3 in the oscillator Figure 1, and is not essential.

The components R6, C4, L4 and C5 together form a resonant circuit. The output of this circuit is a vhf signal which is rectified by a diode D1. A resistor R8 and a capacitor C6 are connected between the output voltage rail and ground, in order to
15 smooth the rectified vhf signal.

A typical time constant (RC) of R8 and C6 is around 3 μ s, which gives a frequency response for the thus demodulated signal of between dc and 50 kHz.

20 Figure 4 shows the frequency response of the resonant discriminator of Figure 3, using the above quoted values and a vhf input. As can be seen, the voltage rises rapidly as the input frequency varies between 199 and just over 200 MHz. It is useful to ensure that L4 and C4 in the discriminator are similar to L1 and Cmic, so that the temperature drifts in the inductance and stray capacitance can cancel. That
25 is, a temperature-induced drift in frequency in the oscillator will be cancelled by a corresponding drift of the discriminator operating frequency.

Figure 5 shows a block diagram of a capacitance micrometer constructed using the oscillator of Figure 1 and the resonant discriminator of Figure 3. The capacitance micrometer 10 takes an input which is a regulated d.c. voltage supply +Vcc. The output of the oscillator 20 is a vhf signal which is amplified and buffered by a vhf operational amplifier 30. The output of the operational amplifier 30 is connected to the resonant discriminator 40 which generates a d.c. output voltage related to the frequency of the input signal, as shown in Figure 4.

By employing the oscillator and resonant discriminator combination described above, the micrometer of this embodiment of the invention is capable of measuring displacements at frequencies between dc and 50 kHz or above, whilst using a sensor diameter of 1 mm and a nominal spacing of 1 mm, the noise level is no more than 1 nm.Hz^{-1/2}. This corresponds to a nominal capacitance of 7 femtofarad (7 fF) with a resolution of 7 zeptofarad (7 zF).

By combining the response curves of the oscillator 20 and the discriminator 40, a plot of d.c. output voltage/capacitor C_{mic} plate spacing can be obtained. This is shown in Figure 6. The device of the present invention can be improved still further however by flattening the generally S-shaped output voltage/capacitor C_{mic} plate spacing curve of Figure 6. Conveniently, this is done using a digital signal processor. With the performance criteria outlined above, a 16-bit analogue to digital converter, sampling at 100 kHz is preferable. This provides a 50 kHz frequency response, with a resolution of around 1 in 65,000. The stated noise level of 1 nm.Hz^{-1/2} converts to 223 nm over the range 0 to 50 kHz. The analogue to digital converter has a resolution of 16 bits over a range of 1 mm, which converts to a resolution of 15 nm. Thus, the system is not limited by the analogue to digital conversion.

Once the output voltage has been digitised, a linearising power series such as

$$d = a_0 + a_1V + a_2V^2 + a_3V^3 + a_4V^4 + \dots \quad 3$$

can be applied to it to give the displacement. The coefficients $a_0, a_1, a_2, \dots$ are determined by calibration of the micrometer against a laser interferometer.

5 It will be appreciated that the non-linear voltage/micrometer plate spacing shown in Figure 5 is usable as such, and may provide suitable accuracy for many applications. However, for the highest accuracy measurements, it is preferable to linearise the output.

10 The invention is, of course, susceptible to a number of variations. The Clapp oscillator is only one of a number of different oscillators which may be employed, such as a tunnel diode oscillator, or a resonant cavity oscillator. If a resonant cavity oscillator is employed, it is convenient to use a second resonant cavity rather than a resonant discriminator, although the general principles of operation of the
15 capacitance micrometer are similar.

The arrangement described above with reference to Figures 1-6 operates satisfactorily and has the advantage of tracking the oscillator in terms of frequency drift and thus compensating for temperature variations but the resonant circuit of the
20 discriminator has to be tuned precisely to a frequency just a little different to the nominal frequency of the oscillator. This may be difficult to do in a stable fashion.

The need to be able to tune the discriminator, requires a variable capacitor or inductor, either of which can drift. To get an idea of the stability required, consider
25 the case where the nominal operating frequency is around 200 MHz, varying by 1 MHz over the full displacement range of 1mm. A change of 1 part in 200 is all that is required to tune over the full operating range; this is a sensitive adjustment.

Setting up can be eased by mixing the 200 MHz signal with a fixed frequency 'local oscillator' to give an intermediate frequency of around 10 MHz. The 10 MHz intermediate frequency will still vary by 1 MHz per millimetre of mechanical displacement, so the full range now represents a change of 1 part in 10, which is far less sensitive.

Stability can be improved further by using a fixed frequency discriminator (no variable components) and tuning the local oscillator to give the correct intermediate frequency. The local oscillator may be a frequency synthesiser based on a crystal oscillator and therefore very stable. Mixing the signal down to a lower intermediate frequency thus gives advantages in setting up and stability.

In accordance with a second embodiment of the invention, a digital discriminator is provided that is digital in nature and capable of operating over a wide range of input frequencies with no added drift, using a crystal controlled RF synthesiser as a local oscillator and a Digital Phase Locked Loop (DPLL) as the frequency detector.

The DPLL is a closed loop feedback scheme that uses a phase detector to lock a Direct Digital Synthesiser (DDS) onto the input FM signal. The control input to the DDS is then a measure of the input frequency.

The phase detector and DDS determine the accuracy of the system. Since the DDS can be used to produce very stable sine waves with digital frequency control, the accuracy of the system then depends upon the phase detector.

The advantages of a digital phase locked loop are that it is immune to amplitude variations in the input signal and because of its closed loop nature its accuracy is

limited only by the phase detector. It is immune to component value changes, temperature variations and power supply variations.

Figure 7 shows a block diagram of the digital discriminator system with typical frequencies marked.

The probe 70 in this embodiment comprises a Clapp oscillator circuit previously described with a typical nominal frequency of 200 MHz, which typically varies by 1 MHz·mm⁻¹ of displacement. This is combined in a 1st mixer 72 with the fixed frequency signal from a crystal-controlled RF synthesiser 74. The frequency of the synthesiser can be set digitally at 76 to be 10 MHz higher than the probe frequency. Being digital, the set-up value cannot drift and stability is determined by the crystal used to control the synthesiser. The output from the 1st mixer is a 10 MHz intermediate frequency signal whatever the centre frequency of the probe. Typically this signal will vary by 1 MHz·mm^{-1/2} of displacement, depending on the probe.

As an alternative, the 200 MHz signal can be divided down to 10 MHz using a programmable divider. This is a simpler approach, which retains digital stability, but sensitivity is lost as frequency variations due to displacement changes are also divided down. The loss of sensitivity, however, is not necessarily a problem as the noise introduced by the DPLL is very low, so the overall signal to noise ratio of the probe is not affected unduly.

The 10 MHz intermediate frequency is passed to a DPLL block 78 which typically produces 14 bit words representing the input frequency. As described below, the word update rate is 4 MHz. Although the output word from the DPLL 78 represents the probe frequency, the relationship is not linear. To linearise the output a linearising function must be applied. This is conveniently done by means of a look-

up table stored in an Erasable Programmable Read Only Memory (EPROM) 80. The look-up table values are determined by direct calibration of the probe displacement against a standard measuring device, for example a laser interferometer. Alternatively a digital signal processor and linearisation algorithm such as equation 3
5 could be used.

After the look-up table 80, the stream of words is a direct linear function of the displacement of the probe. The update rate of 4 MHz means that in principle mechanical displacement frequencies up to 2 MHz (the Nyquist frequency) could be
10 catered for. In practice however the frequency response of the DPLL will limit the actual frequency response to around 125 kHz, so it is prudent to filter the 4 MHz signal down to 125 kHz to limit the system noise. This is done as shown with a digital filter 82, which may be for example a third order Finite Impulse Response (FIR) Bessel filter. Obviously other filter functions could be implemented. The
15 filtered word stream is then conveniently decimated down to 250 kHz as at 84 to simplify interfacing with a recording computer (not shown in this figure). Alternatively the digital information at 4 MHz could be applied to a Digital to Analogue Converter (DAC) 88 and then filtered with an analogue filter 89. This would give a voltage proportional to mechanical displacement.

20 The DPLL block 78 is shown expanded in Fig. 8. The 10 MHz intermediate frequency is mixed in a second mixer 90 with the output of a Direct Digital Synthesiser (DDS) 92. A DDS produces a sine wave output, the frequency of which depends on an applied digital word. The function is thus very similar to that of the
25 frequency synthesiser used as the first local oscillator. The difference is that the operating frequency regime is different and the DDS is very frequency agile: it changes output frequency virtually instantaneously with the input digital word. It is the aim of the DPLL to keep the output of the DDS at 1 MHz less than the 10 MHz

intermediate frequency, even as the intermediate frequency varies due to probe displacement changes. The nominal DDS frequency will be 9 MHz. Other difference frequencies than 1 MHz could be chosen by suitable choice of the delay in the phase detector 100 that follows.

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The output from the mixer 90 is a sine wave at the difference frequency of 1 MHz plus a sine wave at the sum of the frequencies, i.e. 11 MHz. The 11 MHz signal is of no interest and is filtered out by a 4 MHz low pass analogue filter 94. A cut off frequency of 4 MHz gives adequate rejection of the 11 MHz component without unduly shifting the phase of the 1 MHz component.

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The 1MHz output of the filter 94 is now sampled and digitised by an Analogue to Digital Converter (ADC) 96. In this implementation of the invention, the sampling rate is 16 MHz, generated by a crystal controlled clock 98, and the number of bits is 10. The digitised signal now passes to the Phase Detector 100, comprising a fixed time delay 102 and a digital multiplier 104. It is the aim of the Phase Detector to give zero output when the input frequency is 1 MHz, a positive output when the input frequency is above 1 MHz and a negative output when the input frequency is below 1 MHz.

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Consider a sine wave multiplied by a time-delayed version of itself

$$N_{out} = N_0 \sin(\omega t) N_0 \sin(\omega(t - t_{delay})) \quad 4$$

$$N_{out} = -\frac{N_0^2}{2} [\cos(\omega t + \omega(t - t_{delay})) + \cos(\omega t - \omega(t - t_{delay}))] \quad 5$$

$$N_{out} = -\frac{N_0^2}{2} \cos(2\omega t - \omega t_{delay}) - \frac{N_0^2}{2} \cos \omega t_{delay} \quad 6$$

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where N_0 represents the amplitude of the input sine wave of angular frequency ω .

The first term is a phase-shifted signal at twice the input frequency (more of this later) and the second is a dc component dependent on the input angular frequency ω and the time delay t_{delay} . This wanted component will be zero when

$$\omega t_{\text{delay}} = \frac{n\pi}{2} \quad 7$$

5 or

$$f t_{\text{delay}} = \frac{n}{4} \quad 8$$

where n is an integer. To get zero output at 1 MHz, t_{delay} will be 250 ns (n=1). Note that an accurate 250 ns delay is easy to achieve as the signal is digitised at 16 MHz and 250 ns thus represents four samples. A four sample long shift register clocked at the 16 MHz sample frequency will thus provide a consistent and accurate delay. Note that the input frequency at which the output dc component is zero is independent of the amplitude N_0 of the input signal. The performance of the phase detector is thus dependent only on the 16 MHz clock stability 98 which, being crystal controlled, can be very stable indeed.

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If the frequency is a little higher than 1 MHz, then ωt_{delay} will be a bit higher than $\pi/2$ and $\cos(\omega t_{\text{delay}})$ will be negative. The appropriate cosine term of equation 6 is negative so the result will be a positive dc component as required. Similarly a frequency less than 1 MHz will give a negative dc output.

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The aim of the DPLL is to keep the 2nd mixer 90 output at 1 MHz. The output of the Phase Detector 100 is passed to an accumulator 106. The accumulator output at a given clock cycle is determined by adding its previous output to its current input, it thus integrates its input signal. If the input to the accumulator is zero, then its output will be constant at some value, which would be zero at switch-on. If its input is positive its output will ramp up and similarly if its input is negative its output will ramp down. Ignoring blocks 108, 110, 112 for the time being, the output of the

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accumulator is used to control the frequency of the DDS 92. The output frequency of the DDS will thus change until the input to the accumulator is zero, i.e. until the phase detector 100 output is zero. As has been shown, this occurs when the DDS output frequency is 1 MHz different from the DPLL input frequency. The digital
5 input to the DDS is thus a measure of the DPLL input frequency. The 1 MHz offset is simply a constant offset on the input number, which gets calibrated out.

Equation 6 shows that the output of the phase detector also contains a sinusoidal component at twice the input frequency, i.e. at 2 MHz. This component will appear
10 as an unwanted ripple on the accumulator output. This ripple is removed by resampling the waveform at 4 MHz at 108, delaying the signal by one period at 110 and adding the delayed signal to the current signal at 112. In this way, the 2 MHz component will be eliminated, leaving only the wanted dc component. This is achieved by blocks 108, 110, 112. Alternatively a low pass FIR filter could be used.

15 Referring back to Figure 1, the oscillator and variable capacitance transducer arrangement is mounted in a probe assembly, and the physical form of the probe assembly is shown in Figures 9 and 10, wherein the inductor L1 of Figure 1 comprises a coil 120. This is wound on an insulating former 122 which is
20 conveniently a machinable glass ceramic, Macor™ (Macor is the registered trademark of Corning Inc.). Other materials could be used, especially fused silica, or low expansion glass ceramics (for example zerodur™) for low thermal drift applications. The core material has low rf losses so as not to reduce the Q of the inductor. The wire end of the coil is brought out to form a tip 24 which is used
25 as a sensing capacitor electrode. Alternatively other larger electrodes (not shown) may be attached to this for greater sensitivity.

An end cap 126 is narrower than the main body 4 to enable sensing in confined spaces. The wire end tip 124 is insulated from the narrow part of the body by an insulating tube 128, again conveniently Macor™ but which could be another material such as fused silica, zerodur or PTFE. It is important that the material has low dielectric losses to maintain high Q for the resonant circuit.

The main body of the probe is a stainless steel tube 130, though other materials could be used such as aluminium or brass. The coil core is machined to a half-cylinder 132 to house the printed circuit board 134 on which the remaining components of the circuit of Fig.1 are mounted. The end of the cylindrical body 130 houses a coaxial connector 136 which carries power to the probe and the signal back to the discriminator.

The oscillation frequency of the probe depends on the inductance of the coil 120, the stray capacitance between the coil and the housing (C_{coil}), the stray capacitance of the probe tip (C_{tip}), and of course the capacitance between the tip and the target, (C_{mic}). In fact stray capacitances dominate the capacitance contribution. The oscillation frequency is given by

$$f = \frac{1}{2\pi} \sqrt{\frac{1}{L(C_{\text{coil}} + C_{\text{tip}} + C_{\text{mic}})}}$$

Where L is the inductance of the coil. As temperature rises, the coil will expand and thus its inductance will increase. This will reduce the oscillation frequency. It can be shown that the effective coil capacitance is given by

$$C_{\text{coil}} = \frac{2\epsilon_{\text{air}} l_{\text{coil}}}{\pi \ln \frac{r_{\text{house}}}{r_{\text{coil}}}}$$

where ϵ_{air} is the permittivity of the medium between the coil and the housing (typically air), l_{coil} is the length of the coil r_{house} is the internal radius of the housing tube and r_{coil} is the external radius of the coil. Also

$$C_{\text{tip}} = \frac{2\pi\epsilon_{\text{ins}} l_{\text{tip}}}{\ln \frac{r_{\text{cap}}}{r_{\text{tip}}}}$$

- 5 Where ϵ_{ins} is the permittivity of the tip insulator, r_{cap} the end cap radius, l_{tip} is the length of the tip and r_{tip} is the radius of the wire end.

If the material of the housing is chosen to have a greater thermal expansion coefficient than that of the coil former, the denominator of the last equation can be made to increase faster than the numerator with increasing temperature. This
10 capacitance term can thus be made to decrease with temperature, balancing the inductance increase. Similarly C_{tip} can be made to decrease with increasing temperature helping the balance. Further compensation can be achieved if required by choice of tip insulating material. Most ceramic materials have permittivity that
15 increases with temperature, but some ceramics and polymers such as PTFE, have a permittivity that decreases with temperature. Frequency compensation can thus be tailored to requirements by making all or part of the tip insulator out of such a ceramic, or PTFE, or similar material with negative permittivity temperature coefficient.

20

The design of Figures 9 and 10 can be modified in a variety of ways for differing measurement applications. For example the measuring tip may be offset from the body 128 as shown at 150 in Figure 11. A mounting block can be clamped at a convenient point along the probe body. The offset configuration is particularly
25 useful for monitoring radial motions (run-out) of a rotating platter 152 attached close

to a motor body 154, as illustrated in Fig. 11. Fig 12 shows yet another variation in which the tip 150 is radial to the probe body 128 rather than axial.

5 When the sensing tip area can be large, for example when monitoring the displacement of a large object, a spiral 'pancake' coil arrangement can be used to produce a flatter disk-like probe. Fig. 13 shows a suitable coil.

10 The coil pattern 230 is conveniently formed by photo-chemical etching or vacuum deposition of gold or other metal on an insulating substrate 232. Fused silica is preferable as a substrate giving very good thermal stability. The sensing capacitor electrode 234 is formed on the other face of the substrate 232 by similar means and is conveniently connected to the outer end of the spiral by a conducting track 236. The centre of the spiral connects to the rest of the electronics. Obviously the capacitor electrode could connect to the centre of the spiral via a hole and the electronics to the edge.

15 Fig 14 shows a probe arrangement using the pancake coil. An insulating substrate 240, which again is preferably fused silica, is bonded to the spiral side of the coil substrate 232. The PCB 242 carrying the rest of the probe electronic components is bonded to the insulating substrate. This sub-assembly is mounted in a metal housing 244 which also carries a coaxial connector 246. The connector is shown mounted axially but could equally well be mounted radially or be a flying lead.

25 In an alternative form of construction the 'spiral' coil is composed of straight-line segments in triangular, rectangular or higher order irregular or regular polygonal form. This approach could ease photo-chemical etching mask production. Also a square or rectangular form of sensor may be advantageous in some applications.

The square form of coil is shown in Fig. 15. Its application is the same as the circular spiral coil.

5 Figure 16 shows a rectangular coil 260 mounted on an elongated substrate 262 with a lead 264 terminated at a tapered end 266 of the substrate. A disc-like capacitor electrode 268 has a central conductor to contact lead 264. The substrate 262 and electrode 268 are dimensioned so as to fit within housing 128 of Figure 9.

CLAIMS

1. A variable capacitance transducer comprising variable oscillator means, including a variable capacitance means for varying the oscillator output signal frequency, and discriminator means responsive to the oscillator output signal, including means for assessing the oscillator frequency in relation to a predetermined frequency value, to provide an output voltage signal whose value varies in relation to the frequency of the oscillator output signal.
2. A transducer according to claim 1, wherein the assessing means comprises a resonant LC circuit having a predetermined resonant frequency.
3. A transducer according to claim 1, wherein the discriminator means includes analogue to digital conversion means for providing digital samples of the oscillator output signal, a delay means responsive to a clock signal having said predetermined frequency to provide a predetermined delay period, and multiplying means for multiplying the oscillator output signal with a version delayed in said delay means.
4. A transducer according to claim 1, including local oscillator means for generating a signal for mixing with the oscillator output signal to produce an intermediate frequency signal.
5. A variable capacitance transducer comprising variable oscillator means, including a variable capacitance means for varying the oscillator output signal frequency, local oscillator means for generating a signal for mixing with the oscillator output signal to produce an intermediate frequency signal, and



discriminator means responsive to the intermediate frequency signal to provide an output voltage signal whose value varies in relation to the frequency of the intermediate frequency signal.

5 6. A transducer according to claim 4 or 5, including first and second local oscillator means producing first and second intermediate frequencies.

7. A transducer according to claim 4 or 5, including phase or frequency locked
10 loop means for controlling the frequency of said local oscillator means, including
said discriminator means, and a variable frequency generator responsive to said
output signal for providing said local oscillator signal.

8. A transducer according to claim 7, wherein the output of the discriminator
15 means is coupled to a direct frequency synthesiser, serving as said local oscillator
means.

9. A transducer according to claim 7, wherein the output of the discrimination
means is coupled to low pass filter means to provide an output signal.

20 10. A transducer according to claim 1 or 5, wherein the variable oscillator means
comprises a Clapp oscillator, with said variable capacitance means in series with an
inductor whereby to determine the frequency of oscillation.

25 11. A variable capacitance transducer comprising a Clapp oscillator including a
variable capacitance means in series with an inductor whereby to determine the

frequency of oscillation of the Clapp oscillator, the oscillator frequency varying with change in capacitance of the capacitance means, and discriminator means responsive to the oscillator frequency to provide an output voltage signal whose value varies in relation to the frequency of the oscillator frequency.

5

12. A transducer according to claim 1, 5 or 11, including a probe assembly comprising a probe housing, said variable capacitance means being formed at one end of the housing for co-operating with an object whose position is to be measured, said variable oscillator means being formed within the probe housing and including
10 an inductance which together with the variable capacitance forms a resonant circuit, a cable coupled to the probe assembly having a conductor for supplying power to the oscillator circuit and for transmitting from the oscillator a variable frequency signal over the same conductor, and an impedance matching arrangement disposed at the remote end of the coaxial cable for providing power to the coaxial cable and for
15 providing a voltage signal representing the variable frequency signal.

13. A variable capacitance transducer formed as a probe assembly, comprising a probe body, a variable capacitance means formed at one end of the body for co-operating with an object which is to be measured, an oscillator circuit formed in the
20 probe body and including an inductance which together with the variable capacitance forms a resonant circuit, a cable coupled to the probe having a conductor for supplying power to the oscillator circuit and for transmitting from the oscillator a variable frequency signal over the same conductor, and an impedance matching arrangement disposed at the remote end of the coaxial cable for providing power to
25 the coaxial cable and for providing a voltage signal representing the variable frequency signal.



14. A variable capacitance transducer formed as a probe comprising a body having at one end a capacitor arrangement for forming with an object to be measured a variable capacitance, and connected to an inductor mounted in the body for forming there with a resonant circuit wherein the dimensions of the inductor and/or materials forming the capacitor arrangement and the inductor are chosen such that over the likely temperature differentials experienced in use, the change in inductance of the inductor is compensated by the change in capacitance of the capacitance arrangement.
15. A transducer according to claim 14, wherein a wire forming the inductor coil has one end extending to the one end of the housing to form with a probe housing a variable capacitance.
16. A transducer according to claim 15, wherein the probe housing at said one end is of a smaller diameter than the remainder of the housing.
17. A transducer according to claim 15 or 16, wherein a material providing the former of the inductance coil extends to the variable capacitance to define a capacitance dielectric.
18. A transducer according to any of claims 14-17 wherein the material of the probe housing has a greater temperature differential than that of the coil former.
19. A variable capacitor according to claim 14, wherein the inductor comprises a flat coil mounted on a substrate in the form of a spiral.



20. A variable capacitance transducer formed as a probe including a capacitance arrangement formed at one end of the probe for forming with an object which is to be measured a variable capacitance, the capacitance arrangement being connected to an inductor mounted within the probe assembly to form a resonant circuit, the inductor comprising a flat coil mounted on a substrate in the form of a spiral.
21. A transducer according to claim 19 or 20 wherein the variable capacitance comprises an electrode in the form of a flat disk parallel with the substrate.
22. A transducer according to claim 20, wherein the flat coil extends coaxially along the probe body, and the variable capacitance includes a disk electrode perpendicular to the flat coil.
23. A transducer according to claim 19 or 20, wherein said spiral is composed of straight line segments to define a triangular, rectangular or other polygonal configuration.
24. A method of measuring a desired parameter of an object, comprising providing a probe and measuring a capacitance between the object and the probe by providing a variable frequency from an oscillator which includes the capacitance and whose frequency varies with the capacitance, and converting the variable frequency to a voltage signal by assessing the variable frequency in relation to a predetermined frequency value.

