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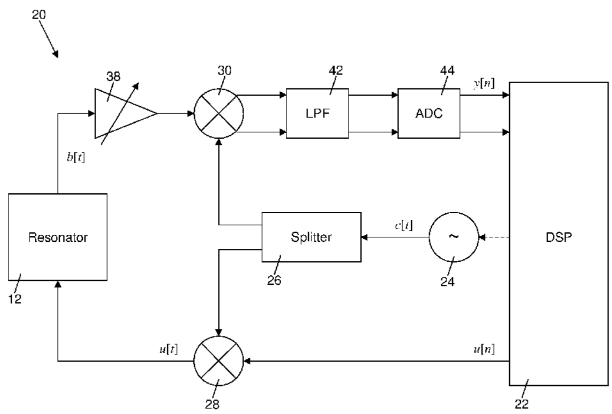

Figure 2

(57) Abstract: The present application relates to an apparatus (20) and method for estimating a characteristic, such as resonant frequency, bandwidth or insertion loss, of a microwave resonant device (12), that is to say a device that resonates in response to an excitation signal in the microwave frequency range. A broadband excitation signal is applied to the microwave resonant device (12) and a response signal output by the microwave resonant device (12) in response to the excitation signal is received. The response signal is compared to the output of an adaptive filter (14) to which the excitation signal is input, and a filter weight update algorithm calculates revised filter weights to match an output of the adaptive filter (14) to the response signal output by the microwave resonant device (12). The filter weights so calculated are used to calculate an estimate of the spectral response of the microwave resonant device (12), and this spectral response estimate is used to calculate an estimate of the desired characteristic.

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APPARATUS AND METHOD FOR ESTIMATING A CHARACTERISTIC OF A MICROWAVE RESONANT DEVICE

Technical Field

The present application relates to an apparatus and a method for estimating a characteristic of a microwave resonant device.

Background to the Invention

Certain sensors used in applications such as the measurement of density, moisture content, dielectric constant, and in industrial quality control, fluid identification and other applications, measure resonance in the microwave region of the electromagnetic spectrum (the wavelength range 1m to 1mm). Many such sensors are known, and these sensors measure a change in the resonant frequency and/or bandwidth of an electromagnetic or electromechanical resonator. The measured change in the resonant frequency or bandwidth is used to estimate the parameter of interest, e.g. density, moisture content, dielectric constant etc.

Known sensors of this type use a number of different techniques to estimate characteristics of an electromagnetic or electromechanical resonator, such as the resonant frequency, bandwidth, quality factor (Q) and insertion loss. Such techniques typically require the use of instruments such as vector network analysers or scalar network analysers, which, in addition to the high cost of the instruments, tend to be slow, as the instruments use a single frequency swept source which has a finite tuning time.

A faster and less costly method for estimating characteristics of an electromagnetic or electromechanical resonator uses a lock-in amplifier, but this method only permits accurate measurement of the amplitude and phase response at a single frequency. Additionally, the lock-in amplifier based method suffers from greatly reduced dynamic range, since it cannot use a broadband spectral characteristic of the resonator response.

A further method employs feedback to make the resonator into an oscillator. The resonant frequency of the resonator can be estimated by frequency counting of the resulting oscillations. However, this method is unable to measure resonator bandwidth, and suffers from a poor accuracy/measurement time trade off, since a large number of cycles of oscillation must be counted if fine frequency resolution is required, which inherently takes a long time and requires a stable clock.

Thus, all of the known methods of estimating characteristics of a microwave resonator suffer from disadvantages, in terms of measurement speed, accuracy, cost or limitations in the characteristics that can be measured.

Summary of Invention

The present application relates to an apparatus and method for estimating a characteristic, such as resonant frequency, bandwidth or insertion loss, of a microwave resonant device, that is to say a device that resonates in response to an excitation signal in the microwave frequency range. A broadband excitation signal is applied to the microwave resonant device and a response signal output by the microwave resonant device in response to the excitation signal is received. The response signal is compared to the output of an adaptive filter to which the excitation signal is input, and a filter weight update algorithm calculates revised filter weights to match an output of the adaptive filter to the response signal output by the microwave resonant device. The filter weights so calculated are used to calculate an estimate of the spectral response of the microwave resonant device, and this spectral response estimate is used to calculate an estimate of the desired characteristic.

According to a first aspect of the present invention there is provided apparatus for estimating a characteristic of a microwave resonant device, the apparatus comprising: means for generating a broadband excitation signal to be applied to the microwave resonant device to the excite the microwave resonant device, the apparatus further comprising: means for comparing a response signal received from the microwave resonant device with the broadband excitation signal to produce an estimate of a spectral response of the microwave resonant device; and means for generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device.

The apparatus permits fast and accurate estimation of the characteristics describing the spectral response of a resonator at a lower cost than known systems.

The means for generating the broadband excitation signal may be configured to generate a maximum length binary sequence.

The apparatus may further comprise a local oscillator for generating a carrier signal to be modulated by the broadband excitation signal.

The apparatus may further comprise a modulator for modulating the carrier signal.

The modulator may be a digital on-off keying modulator for generating an on-off keying modulated broadband excitation signal.

The means for comparing the output signal received from the microwave resonant device to the broadband excitation signal may comprise an adaptive filter which receives as an input the broadband excitation signal and outputs a filtered version of the broadband excitation signal.

The apparatus may further comprise means for modifying filter weights of the adaptive filter.

The use of an adaptive filter and means for modifying its filter weights permits rapid estimation of the spectral response of the microwave resonant device, as new filter weights are calculated for each sample or block of samples of the response signal received from the microwave resonant device, meaning that the new spectral estimates can be generated as quickly as new samples or blocks of samples can be input to the adaptive filter.

The apparatus may further comprise an IQ demodulator for demodulating the response signal received from the microwave resonant device.

The IQ demodulator may receive the carrier signal from the local oscillator such that the apparatus operates in a homodyne manner.

Using the same carrier signal for modulation and demodulation in this way helps to minimise the effects of fluctuations or variations in the frequency of the local oscillator and variations in the amplitude and phase of the modulated and demodulated signals, thereby increasing the signal to noise ratio of the demodulated signal and improving overall system performance.

The apparatus may further comprise an analogue to digital converter for converting the demodulated response signal into a digital signal.

The analogue to digital converter may be configured to operate in an equivalent time sampling or undersampling mode.

The means for generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device may be configured to implement a digital iterative curve fitting algorithm.

A digital iterative curve fitting algorithm provides highly accurate estimates of the characteristic of the microwave resonant device.

Alternatively, the means for generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device may be configured to implement an artificial neural network.

An artificial neural network is not as accurate as a digital curve fitting algorithm, but at high sampling rates is not as computationally intensive as a digital curve fitting algorithm, and thus for high sampling rates may provide an acceptable compromise of slightly reduced accuracy but also reduced computational requirements.

According to a second aspect of the present invention, there is provided a sensor system comprising apparatus according to the first aspect.

According to a third aspect of the present invention there is provided a method for estimating a characteristic of a microwave resonant device, the method comprising: generating a broadband excitation signal to be applied to the microwave resonant device to excite the microwave resonant device, the method further comprising: comparing a response signal received from the microwave resonant device with the broadband excitation signal to produce an estimate of a spectral response of the microwave resonant device; and generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device.

Generating the broadband excitation may comprise generating a maximum length binary sequence.

The method may further comprise using a local oscillator to generating a carrier signal to be modulated by the broadband excitation signal.

The method may further comprise modulating the carrier signal with the broadband excitation signal.

The carrier signal may be modulated using a digital on-off keying modulator to generate an on-off keying modulated broadband excitation signal.

Comparing the output signal received from the microwave resonant device to the broadband excitation signal may comprise generating, using an adaptive filter, a filtered version of the broadband excitation signal.

The method may further comprise modifying filter weights of the adaptive filter.

The method may further comprise demodulating the response signal received from the microwave resonant device using an IQ demodulator.

The IQ demodulator may receive the carrier signal from the local oscillator such that the method is performed in a homodyne manner.

The method may further comprise converting the demodulated response signal into a digital signal.

Converting the demodulated response signal into a digital signal may be performed using an analogue to digital converter configured to operate in an equivalent time sampling or undersampling mode.

Generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device may be performed using a digital iterative curve fitting algorithm.

Alternatively, generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device may be performed using an artificial neural network.

According to a fourth aspect of the invention there is provided a computer program which, when executed by processing means, performs the method of the third aspect.

Brief Description of the Drawings

Embodiments of the invention will now be described, strictly by way of example only, with reference to the accompanying drawings, of which:

Figure 1 is a schematic diagram illustrating operating principles of an apparatus for estimating characteristics of a microwave resonant device;

Figure 2 is a schematic representation of an apparatus for estimating characteristics of a microwave resonant device; and

Figure 3 is a schematic representation of a microwave sensor system incorporating the apparatus of Figure 2.

Description of the Embodiments

Figure 1 shows, generally at 10, a block diagram illustrating the principle of operation of an apparatus and method for estimating characteristics of a resonator 12 made of a microwave resonant device.

The resonator 12 is excited by a broadband modulated excitation signal $u[n]$, which is also input to an adaptive filter 14.

In response to the excitation signal $u[n]$, the resonator produces an output signal, which is demodulated and digitised to generate a digital response signal $y[n]$. It will be appreciated that the digital response signal $y[n]$ can be regarded as a version of the input excitation signal that has been subject to a filtering operation due to the characteristics of the resonator 12, i.e.

$$y[n] = h[n]u[n],$$

where $h[n]$ is a digital approximation of the RF transfer function of the resonator 12, centred around the carrier frequency of the modulated excitation signal.

In response to the excitation signal $u[n]$, the adaptive filter produces an output signal $\hat{y}[n]$, which can be regarded as a version of the input excitation signal that has been subject to a filtering operation due to the characteristics of the adaptive filter, i.e.

$$\hat{y}[n] = \hat{h}[n]u[n],$$

where $\hat{h}[n]$ is the transfer function of the adaptive filter 14.

The output $y[n]$ of the resonator 12 and the output $\hat{y}[n]$ of the adaptive filter 14 are input to a subtractor 16, which subtracts the output $\hat{y}[n]$ of the adaptive filter 14 from the output $y[n]$ of the resonator 12 to generate an error signal $e[n]$ indicative of the difference between the output $y[n]$ of the resonator 12 and the output $\hat{y}[n]$ of the adaptive filter 14, i.e.

$$e[n] = y[n] - \hat{y}[n].$$

The error signal $e[n]$ is input into a processor 18, such as a digital signal processor (DSP) or general purpose computer, executing an algorithm which generates a filter weight update vector $\Delta\mathbf{w}[n]$ to modify the weights of the adaptive filter 14 such that output $\hat{y}[n]$ of the adaptive filter 14 and the output $y[n]$ of the resonator 12 are identical, i.e.

$$\hat{y}[n] = y[n].$$

When this condition is satisfied (which may require a number of iterations to refine the filter weight update vector $\Delta\mathbf{w}[n]$) the transfer function $\hat{h}[n]$ of the adaptive filter 14 is identical to the transfer function $h[n]$ of the resonator 12, since the input excitation signal $u[n]$ is identical for the resonator 12 and the adaptive filter 14. The filter weights associated with the transfer function $\hat{h}[n]$ of the adaptive filter 14 can then be used to estimate characteristics such as the resonant frequency, bandwidth, quality factor (Q) and insertion loss of the resonator 12, using techniques that will be described in more detail below.

Figure 2 is a schematic block diagram illustrating an implementation of the principle described above and illustrated in Figure 1. It is to be appreciated that the functional blocks shown in Figure 2 do not necessarily represent physical components of a hardware implementation, but are merely for illustrative purposes to aid understanding. Those skilled in the art will appreciate that the system illustrated in Figure 2 can be implemented in a number of different ways in hardware, or as software for execution on appropriately configured processing hardware such as a DSP, general purpose computer, application specific integrated circuit (ASIC) or field programmable gate array (FPGA).

In the system illustrated generally at 20 in Figure 2, a digital signal processor 22 implements an adaptive digital filter (which is the adaptive filter 14 shown in Figure 1) and an algorithm to generate the filter weight update vector $\Delta\mathbf{w}[n]$ which is used to modify the adaptive filter 14.

The DSP 22 may also control a local oscillator 24 that is used to generate a carrier signal $c(t)$ onto which the excitation signal $u[n]$ is modulated to generate a broadband modulated excitation signal $u(t)$ that is used to excite the resonator 12. The excitation signal may be, for example, a digital maximum length binary signal.

The frequency of the local oscillator 24 should be chosen such that the broadband modulated excitation signal can cover the entirety of the anticipated range of resonator characteristic over the course of a measurement. This avoids the need for adjustment of the frequency of the carrier signal. In some embodiments the frequency of the local oscillator 24 may be fixed, but the local oscillator frequency may also be variable to permit tuning of the system to suit different resonators 12 when performing other measurements.

A splitter 26 splits the carrier signal $c(t)$ generated by the local oscillator 24 and passes it to an excitation modulator 28 and to a response demodulator 30. The excitation modulator 30 modulates the excitation signal $u[n]$ onto the carrier signal $c(t)$ to generate a broadband modulated excitation signal $u(t)$ which is used to excite the resonator 12. The excitation modulator 28 may be an analogue modulator or may be a digital on-off keying modulator implemented using an electronic switch such as a PIN diode or another modulator architecture which generates an on-off keying modulated excitation signal.

The DSP 22 generates the excitation signal $u[n]$, which in some embodiments is a maximum length binary sequence, using a linear feedback shift register or similar method, or by repeating a sequence stored in memory. The sequence is replayed continuously in order to provide a repetitive excitation signal in the time domain.

The modulated excitation signal is input to the resonator 12 to excite the resonator 12, and is altered (effectively filtered) by the resonator 12, which outputs a response signal $y(t)$. This response signal $y(t)$ is passed to the response demodulator 30 for demodulation.

The response demodulator 30 may be an analogue demodulator, or may be a digital demodulator such as an IQ demodulator which may be implemented, for example, using digital signal processing (digital downconversion) preceded by a simple analogue mixer frequency translation stage. An amplifier 38 may be provided in the “receive” path between the resonator 12 and the response demodulator 30 to amplify the signal output by the resonator 12.

The response demodulator 30 receives the carrier signal generated by the local oscillator 24 from the splitter 26 and demodulates the response signal $y(t)$ received from the resonator 12. For this reason, the “receive” side of the system 20 may be regarded as a homodyne receiver architecture.

The demodulated signal is passed, via an anti-aliasing low pass filter 42 to a high-speed, high bandwidth two-channel analogue to digital converter (ADC) 44, which samples the demodulated signal to generate a digital version $y[n]$ of the demodulated received signal, which is output to the DSP 22 for subsequent processing. In some embodiments a variable gain amplifier is provided in the baseband path between the response demodulator 30 and the anti-aliasing low pass filter 42 to (further) amplify the demodulated response signal.

The bandwidth of the ADC 44 should be sufficient to cover the expected bandwidth of the microwave resonant device, and may be several times the bandwidth of the resonator 12, such that the multi tone signal has spectral components covering several times the resonator bandwidth. Thus, a broadband ADC may be required.

The sampling rate of the ADC 44 may be equal to this bandwidth, or may be lower, in which case the ADC 44 operates in an under-sampled configuration in which aliasing is deliberately introduced, and subsequently removed digitally using knowledge of the relationship between the maximum length sequence clock frequency and the sampling frequency of the ADC 44. This is known as equivalent time sampling. Sampling in this way is valid because the excitation signal is repetitive in a known interval. This has the advantage that an ADC 44 with a lower sampling rate can be used, which may reduce costs and power consumption. However, for this equivalent time sampling method to be applicable the resonator characteristic must change slowly; equivalent time sampling is not effective for fast changing resonator characteristics.

The digital signal processor 22 implements an adaptive filter (which is the adaptive filter 14 shown in Figure 1) and an algorithm to generate the filter weight update vector $\Delta\mathbf{w}[n]$ which is used to modify the adaptive filter 14.

The adaptive filter 14 may be, for example, a Normalised Least Mean Squares (NLMS) filter, and the adaptive filter 14 should be configured by the DSP 22 to be equal in length to the number of samples in the excitation signal (e.g. the adaptive filter 14 may be equal in length to the number samples in a maximum length sequence that is used as the excitation signal), as the excitation signal will be precisely periodic in this number of samples. The adaptive filter 14 may be implemented in the frequency domain or in the time domain. It will be apparent to those skilled in the art that the frequency resolution of the spectral measurement of the resonator will therefore be equal to the length of the digital excitation signal.

The DSP 22 compares the magnitude and phase of the demodulated received signal to those of the excitation signal to generate an estimate of the spectral response of the resonator 12. To do this, the DSP 22 retrieves the excitation signal $u[n]$ from an internal storage structure such as a linear feedback shift register or a circular buffer and filters this signal using the adaptive filter 14 to generate a filter output signal $\hat{y}[n]$. This filter output signal is subtracted by the DSP 22 from the digital version $y[n]$ of the demodulated received signal to generate an error signal $e[n]$, which is used by the DSP 22 in the algorithm to generate the filter weight update vector $\Delta\mathbf{w}[n]$ which is used to modify the adaptive filter 14. The algorithm iteratively generates the filter weight update vector $\Delta\mathbf{w}[n]$ which is used to modify the weights of the adaptive filter 14. New filter weights are generated for every sample received from the ADC 44 (or block of N samples if a frequency domain algorithm is used).

When the error signal $e[n]$ is reduced to a level comparable to the noise floor, the filter output signal $\hat{y}[n]$ is an optimum approximation of the digital version $y[n]$ of the demodulated received signal, and the transfer function $\hat{h}[n]$ of the adaptive filter 14 is an optimum approximation of the transfer function $h[n]$ of the resonator 12. The filter weights associated with the resulting transfer function $\hat{h}[n]$ of the adaptive filter 14 are then used by the DSP 22 to generate estimates of the characteristics of the resonator 12, as is described below.

The adaptive NMLS filter 14 used in the "system identification" mode described above can be described by the equation

$$\hat{\mathbf{w}}[n+1] = \hat{\mathbf{w}}[n] + \mu \frac{(u[n] - \hat{\mathbf{w}}^H[n]\mathbf{x}[n])\mathbf{x}[n]}{\mathbf{x}^H[n]\mathbf{x}[n]}$$

where $\hat{\mathbf{w}}[n]$ are the filter weights at the nth iteration, μ is the learning rate, $\mathbf{x}[n]$ are the last N samples from the ADC 44 (N being the length of the adaptive filter 14), $u[n]$ is the last transmitted sample and $(.)^H$ denotes the Hermitian transpose of a complex vector.

The spectral response of the resonator 12 can be estimated by the DSP 22 using the Fourier transform

$$\widehat{\mathbf{W}}(n) = \mathcal{F}\{\widehat{\mathbf{w}}(n)\}$$

to produce an estimate of the entire microwave resonant device spectral response for each iteration n. This estimate may be generated up to the maximum sampling rate of the ADC 44, thus permitting a very high maximum estimation rate of the characteristics of the resonator 12. Time-domain smoothing of successive spectral response estimates may be controlled by the learning rate μ, which may typically have a value being of 0.001 to

0.01, which is much lower than in other applications of this technique. This is possible because the anticipated rate of change of the spectral response of the microwave resonant device is much slower than the sampling rate used.

This spectral response is then converted by the DSP 22 into an estimate of characteristics of the resonator 12 such as resonant frequency, bandwidth and insertion loss. This conversion may be performed, for example, using a digital iterative curve-fitting algorithm such as the Gauss-Newton method, or using an interpolating artificial neural network (ANN) in feed-forward mode, or using a similar interpolation method such as radial basis functions. Iterative curve-fitting methods typically offer greater accuracy than interpolating ANNs, but at the expense of limited processing rates, due to the requirement for matrix algebra. Thus, for the highest output sampling rates the interpolating ANN may provide acceptable accuracy with the benefit of reduced computational demands.

The Gauss-Newton algorithm for the fitting of a simple Lorentzian function P(β) to the resonator's output power transmission function $\left|\hat{\mathbf{W}}[n]\right|^2$ can be described by the equation

$$\beta[n+1] = \beta[n] - \gamma(\mathbf{J}^T\mathbf{J})^{-1}\mathbf{J}^T\mathbf{P}(\beta[n])$$

where β[n] are the fitted coefficients at the *n*th iteration, γ is the learning rate (which is typically 0.001 – 0.1 in the system 20 to provide smoothing), and $\mathbf{J}$ is the Jacobian matrix of the residual, $r[n] = \left|\hat{\mathbf{W}}[n]\right|^2 - \mathbf{P}(\beta[n])$, with respect to the coefficients. The function is given by the (computationally) simplified Lorentzian

$$\mathbf{P}(\beta[n]) = \frac{\beta_0[n]}{1 + \beta_1[n]x + \beta_2[n]x^2}, \forall x = \frac{\{0...(N-1)\}}{N-1}$$

Conversion from these parameters to the resonant frequency, bandwidth and insertion loss, can then be achieved by means of the following equations:

$$\text{insertion loss [n]} = k_0 \frac{|4\beta_0[n]\beta_1[n]|}{\beta_2^2[n] - 4\beta_0[n]}$$

$$\text{bandwidth [n]} = \frac{\sqrt{f_s^{\,2}\left(|4\beta_0[n]\beta_1^{\,2}[n]|\right)}}{\beta_2[n]}$$

$$\text{resonant frequency [n]} = \frac{|\beta_2[n]|(2f_{LO} - f_s) - f_s|\beta_1[n]|}{2|\beta_2[n]|}$$

where f_{LO} is the local oscillator frequency, f_s is the Nyquist frequency (equal to the sampling frequency in an IQ system), and k_0 is a correction factor to account for the loss in the cables, etc.

These estimates are decimated to the desired output measurement rate, which is typically several kHz. This decimation also improves the SNR of the estimates as the decimation factor increases, since decimation involves low-pass filtering.

Where an ANN is used to convert the spectral response estimate to estimates of the resonator parameters, the ANN is trained from a large number of simulations of a numerical resonator with many different combinations of characteristics, so that it learns the relationship between each point in the spectral response estimate (its input) and the resonator characteristics to which that point corresponds (the outputs of the ANN).

As an alternative, the following ANN equation may be used

$$\beta[n] = \mathbf{A}^T f\left(\mathbf{B}^T f(\mathbf{C}^T \mathbf{W}[n])\right)$$

where the weight matrices **A**, **B** and **C** are previously 'taught' to the ANN from mathematical simulations of resonator frequency response over a large, fully-sampled grid over the anticipated range of parameters. The functions $f(.)$ are the neural network activation functions and may be of the 'sigmoid' type; $y = 2/(1 + e^{-2x}) - 1$, or some more computationally-efficient function such as a Look Up Table (LUT) or a truncated power series representation of the same. The neural network can also be implemented as a radial basis function network, or indeed any other form of non-parametric interpolating network.

The system described above with reference to Figures 1 and 2 permits highly accurate estimation of resonator characteristics at high speed without requiring costly and physically large instruments such as vector or scalar network analysers, and therefore offers a more compact and less expensive option than known techniques. Indeed, the use of high speed digital to analogue converters and high bandwidth digital signal processing permits estimation speed that may be several orders of magnitude higher than techniques which use network analysers.

To adjust the system 20 to suit a different resonator the resonator 12 is replaced by a "thru" line (effectively a short circuit) and the amplitude or gain error of each tone in the multi tone excitation signal is corrected by the DSP 22. Another method is to empty the resonator 12 of any sample and ensure it is unchanging then run the DSP procedure as normal. The spectral results should be averaged over many samples. The 'residual' of the curve fit (i.e., the result of subtracting the averaged spectrum from that given by the equation used for the curve fit) is then used to correct the gain error of each excitation tone. Further crest factor optimisation may then be performed on the corrected excitation signal by the DSP 22 if required, and IQ phase equalisation may then also be performed by the DSP 22 if required. The resulting corrections may be added to the excitation signal input to the adaptive filter 14, so no additional computation is required.

In one exemplary application, illustrated schematically in Figure 3, the system described above with reference to Figures 1 and 2 may be used in a microwave sensor system to detect changes in microwave resonator characteristics such as resonant frequency, bandwidth and insertion loss and thereby to measure parameters such as density, moisture content, dielectric constant, and the like.

In the application illustrated generally at 60 in Figure 3, one or more microwave sensors 62 are used to test a sample, for example blood, that is introduced into the sensor(s) 62 or into the vicinity of the sensor(s) 62. The resulting change in a characteristic such as resonant frequency, bandwidth or insertion loss of the microwave sensor(s) 62 is detected and measured or estimated by the system 20 and reported to a computer system 64, which uses the measured or estimated change in the characteristic to calculate a desired measurement, such as a blood glucose level, which is then displayed on a display 66 of the computer system 64.

Although the system 20 is described above as being implemented by processing blocks and a digital signal processor, it will be appreciated that it could equally be implemented in software running on an appropriately configured general purpose computer connected to suitable analogue components, or in one or more appropriately configured application specific integrated circuits (ASICs) or field programmable gate arrays (FPGAs).

CLAIMS

1. Apparatus for estimating a characteristic of a microwave resonant device, the apparatus comprising:

means for generating a broadband excitation signal to be applied to the microwave resonant device to the excite the microwave resonant device, the apparatus further comprising:

means for comparing a response signal received from the microwave resonant device with the broadband excitation signal to produce an estimate of a spectral response of the microwave resonant device; and

means for generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device.

2. Apparatus according to claim 1 wherein the means for generating the broadband excitation signal is configured to generate a maximum length binary sequence.

3. Apparatus according to claim 1 or claim 2 further comprising a local oscillator for generating a carrier signal to be modulated by the broadband excitation signal.

4. Apparatus according to claim 3 further comprising a modulator for modulating the carrier signal.

5. Apparatus according to claim 4 wherein the modulator is a digital on-off keying modulator for generating an on-off keying modulated broadband excitation signal.

6. Apparatus according to any one of the preceding claims wherein the means for comparing the output signal received from the microwave resonant device to the broadband excitation signal comprises an adaptive filter which receives as an input the broadband excitation signal and outputs a filtered version of the broadband excitation signal.

7. Apparatus according to claim 6 further comprising means for modifying filter weights of the adaptive filter.

8. Apparatus according to any one of claims 1 to 7 further comprising an IQ demodulator for demodulating the response signal received from the microwave resonant device.

9. Apparatus according to claim 8, where dependent upon claim 3, wherein the IQ demodulator receives the carrier signal from the local oscillator such that the apparatus operates in a homodyne manner.

10. Apparatus according to claim 8 or claim 9 further comprising an analogue to digital converter for converting the demodulated response signal into a digital signal.

11. Apparatus according to claim 10 wherein the analogue to digital converter is configured to operate in an equivalent time sampling or undersampling mode.

12. Apparatus according to any one of the preceding claims wherein the means for generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device is configured to implement a digital iterative curve fitting algorithm.

13. Apparatus according to any one of claims 1 to 12 wherein the means for generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device is configured to implement an artificial neural network.

14. A sensor system comprising apparatus according to any one of the preceding claims.

15. A method for estimating a characteristic of a microwave resonant device, the method comprising:

generating a broadband excitation signal to be applied to the microwave resonant device to excite the microwave resonant device, the method further comprising:

comparing a response signal received from the microwave resonant device with the broadband excitation signal to produce an estimate of a spectral response of the microwave resonant device; and

generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device.

16. A method according to claim 15 wherein generating the broadband excitation comprises generating a maximum length binary sequence.

17. A method according to claim 15 or claim 16 further comprising using a local oscillator to generating a carrier signal to be modulated by the broadband excitation signal.

18. A method according to claim 17 further comprising modulating the carrier signal with the broadband excitation signal.

19. A method according to claim 18 wherein the carrier signal is modulated using a digital on-off keying modulator to generate an on-off keying modulated broadband excitation signal.

20. A method according to any one of claims 15 to 19 wherein comparing the output signal received from the microwave resonant device to the broadband excitation signal comprises generating, using an adaptive filter, a filtered version of the broadband excitation signal.

21. A method according to claim 20 further comprising modifying filter weights of the adaptive filter.

22. A method according to any one of claims 15 to 21 further comprising demodulating the response signal received from the microwave resonant device using an IQ demodulator.

23. A method according to claim 22, where dependent upon claim 17, wherein the IQ demodulator receives the carrier signal from the local oscillator such that the method is performed in a homodyne manner.

24. A method according to claim 22 or claim 23 further comprising converting the demodulated response signal into a digital signal.

25. A method according to claim 24 wherein converting the demodulated response signal into a digital signal is performed using an analogue to digital converter configured to operate in an equivalent time sampling or undersampling mode.

26. A method according to any one of claims 15 to 25 wherein generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device is performed using a digital iterative curve fitting algorithm.

27. A method according to any one of claims 15 to 25 wherein generating, from the estimate of the spectral response of the microwave resonant device, an estimate of the characteristic of the microwave resonant device is performed using an artificial neural network.

28. A program which, when executed by processing means, performs the method of any one of claims 15 to 27.

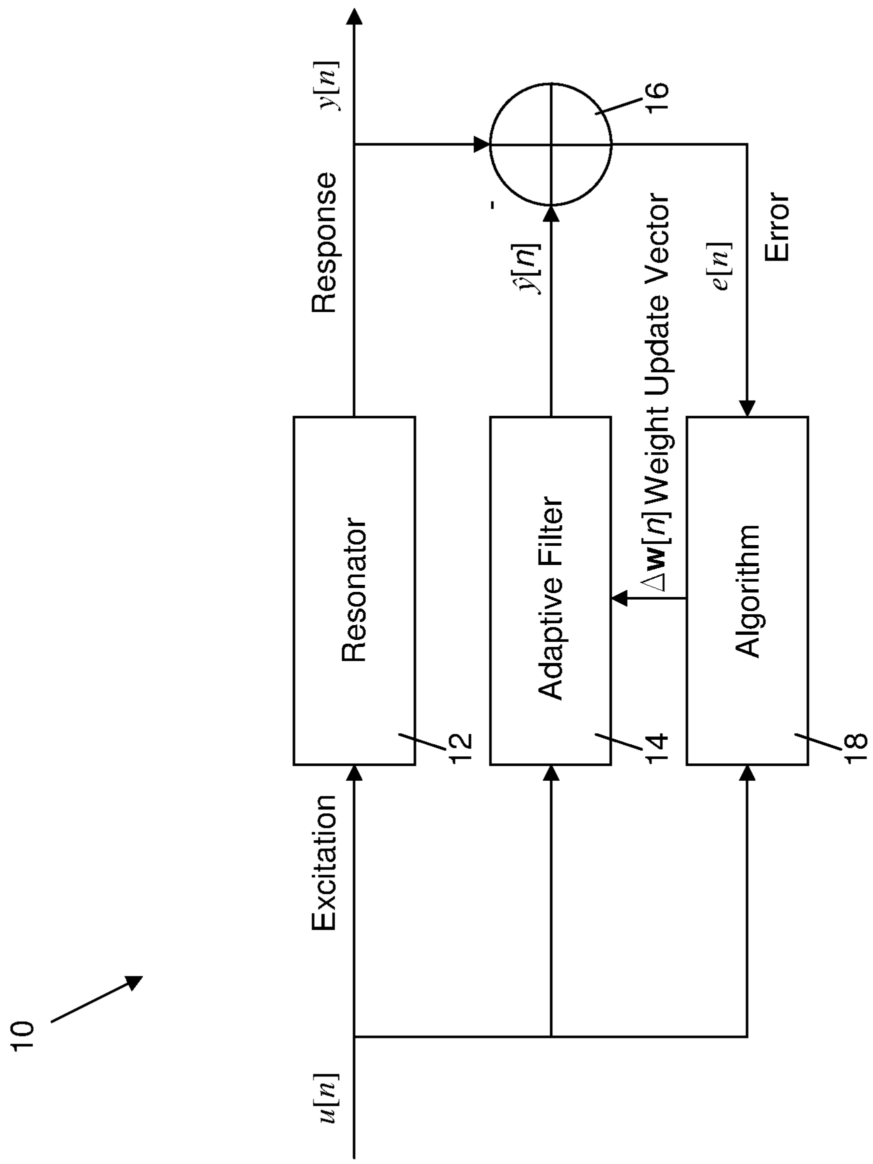
10
$u[n]$
Excitation
Resonator
12
Response
$y[n]$
Adaptive Filter
14
$\hat{y}[n]$
-
16
$\Delta\mathbf{w}[n]$ Weight Update Vector
Algorithm
18
$e[n]$
Error

Figure 1

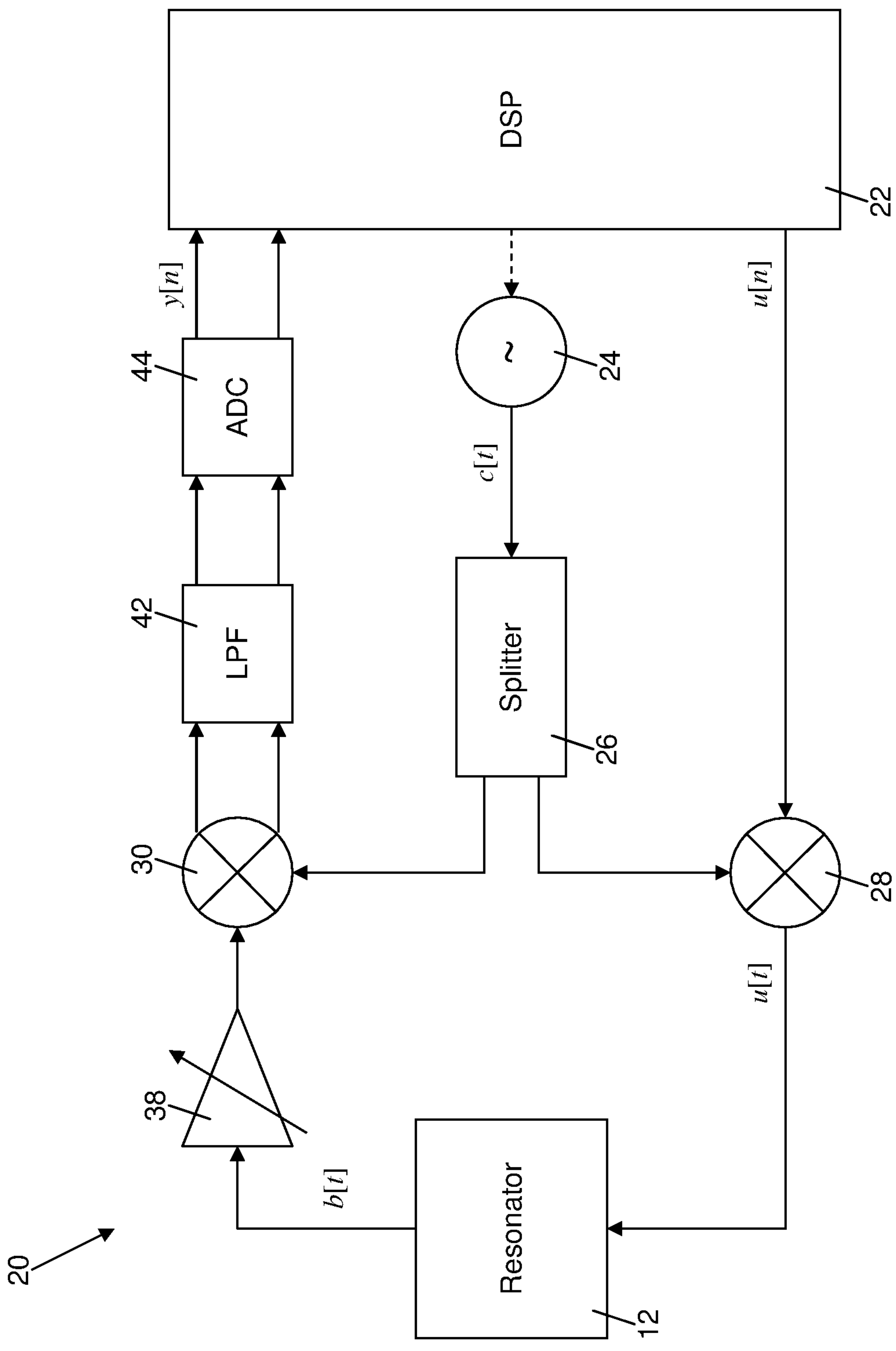
DSP
22
y[n]
u[n]
44
ADC
24
~
c[t]
42
LPF
Splitter
26
30
28
u[t]
38
b[t]
Resonator
12
20

Figure 2

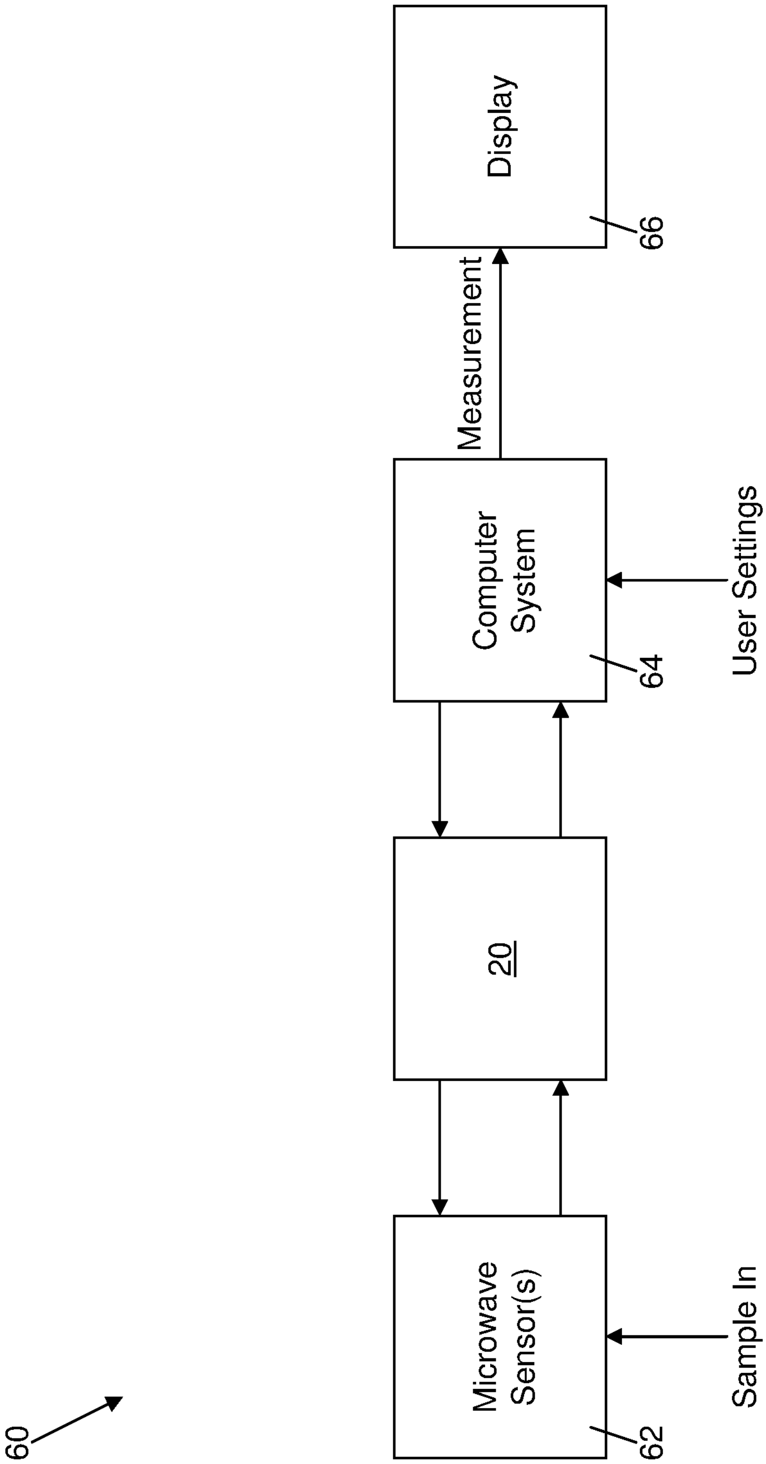
Display
66
Measurement
Computer System
64
User Settings
20
Microwave Sensor(s)
62
Sample In
60

Figure 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2013/052063

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R31/28
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01R

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, COMPENDEX, INSPEC, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CATTAFESTA L N ET AL: "Active control of flow-induced cavity oscillations", PROGRESS IN AEROSPACE SCIENCES, OXFORD, GB, vol. 44, no. 7-8, 1 October 2008 (2008-10-01), pages 479-502, XP025686453, ISSN: 0376-0421, DOI: 10.1016/J.PAEROSCI.2008.07.002 [retrieved on 2008-09-11] paragraphs [0004] - [04.4]; figures 9-12 -----	1-28
A	US 5 999 223 A (PATEL CHANDRAKANT B [US] ET AL) 7 December 1999 (1999-12-07) figures 1-12 -----	1-28

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 November 2013	05/12/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Binger, Bernard

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2013/052063

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5999223 A	07-12-1999	NONE	