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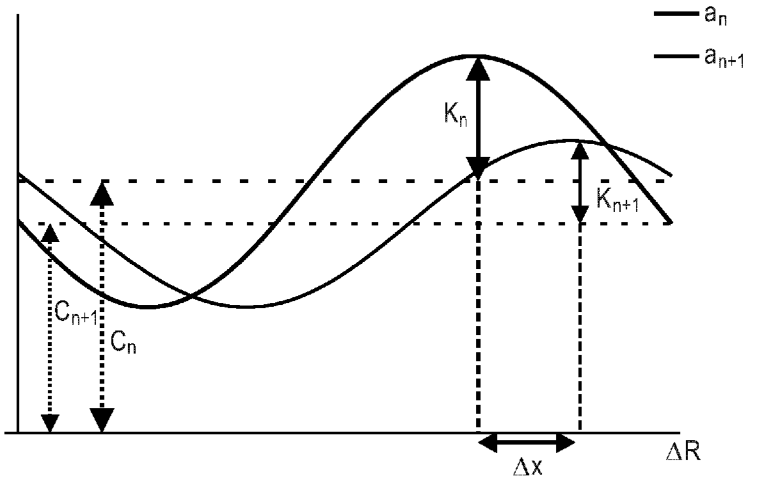

Fig. 3

(57) Abstract: A method of operating a radar sensor system (10) for monitoring a breathing motion of a subject (24). The radar sensor system (10) includes one radar transmitting antenna (12) and one radar receiving antenna (16) and an evaluation and control unit (22) for evaluating Doppler information from the received radar waves (18). The method comprises transmitting radar waves (14) towards a chest (26) and an abdominal region (28) of the subject (24), receiving radar waves (18) reflected by the subject (24), calculating (38) the autocorrelation function of the received radar signals, calculating (40) the Fourier transform A(y) of the calculated autocorrelation function, determining and recording (42) values of at least two peaks of the calculated Fourier transform A(y), and, from the recorded determined values of the at least two peaks, determine (46, 48) at least one breathing-characteristic parameter of the breathing motion of the subject (24).

[Continued on next page]

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System and Method for Breathing Monitoring using Radar-Based Sensor Systems and the Signal Autocorrelation Function

Technical field

[0001] The invention relates to a method of operating a radar sensor system for monitoring a breathing motion of a subject, and to a radar sensor system automatically executing such method.

Background of the Invention

[0002] In the technical field of supporting medical diagnostics of certain breathing diseases or disorders of human beings, such as bronchopulmonary dysplasia, obstructive sleep apnea or upper or lower airway obstruction, it is known to monitor both the chest and the abdomen mechanics. Chest and abdomen undergo periodic motion during breathing but not necessarily in a synchronous manner, a fact that can be characterized by a phase lag ϕ. A phase lag $\phi = 0$ indicates completely synchronicity, while a phase lag of $\phi = \pi$ indicates that both motions are completely asynchronous. Knowledge about a degree of asynchronicity represented by the phase lag ϕ can be exploited for supporting diagnostics. For instance, prematurely born infants or patients with certain neuromuscular diseases can display a rather large asynchronicity between a chest motion and an abdominal motion.

[0003] State of the art experimental methods for monitoring breathing and chest-abdomen mechanics are various types of plethysmography. Plethysmography methods, in particular for infants, are described in textbooks, by way of example in *"Infant Respiratory Function Testing*" by Janet Stocks, Peter D. Sly, Robert S. Tepper and Wayne J. Morgan (editors), John Wiley & Sons, 1996 (ISBN: 978-0-471-07682-7).

[0004] Plethysmography methods, in particular when applied to infants and children, may suffer from quite large uncertainties and errors in the phase lag ϕ between the chest and abdominal motion.

[0005] Further, it has been proposed to measure the degree of a chest-abdomen asynchronicity using radar Doppler measurements as a contactless method.

[0006] In the article “Non-contact diagnostic system for sleep apnea-hypopnea syndrome based on amplitude and phase analysis of thoracic and abdominal Doppler radars” by Masayuki Kagawa et al., a non-contact sleep apnea-hypopnea syndrome (SAHS) diagnostic system is described that can detect apneic events without inducing stress in monitored individuals. Two Doppler radars are installed beneath the mattress to measure the vibrations of the chest and abdomen, respectively. The SAHS determines apnea and hypopnea events when the radar output amplitude decreases by <20 and 70%, respectively, of the amplitude of a normal breath (without SAHS events). Additionally, a technique is proposed that detects paradoxical movements by focusing on phase differences between thoracic and abdominal movements, and are able to identify three types of sleep apnea: obstructive, central, and mixed. Respiratory disturbance indexes obtained showed a higher correlation (r = 94%) with full-night polysomnography (PSG), the recognized gold standard test, than with pulse oximetry (r = 89%). When predicting the severity of SAHS with an apnea-hypopnea index (AHI) of >15/h or >30/h using PSG as a reference, the radar system achieved a sensitivity of 96 and 90%, and a specificity of 100 and 79% with an AHI of >15/h and >30/h, respectively.

[0007] International application WO 2015/140333 A1 describes a method for ascertaining whether an unattended child is present within an automotive vehicle, using a radar sensor system comprising a transmitter and at least one sensor and processing circuitry and exploiting a breathing motion detected by radar signals, for instance by applying autocorrelation and peak finding. The method comprises: illuminating at least one occupiable position within the vehicle with radiation, the radiation exhibiting multiple frequencies; generating radar sensor signals from radiation reflected as a result of the transmitted radiation, a plurality of the radar sensor signals corresponding to different frequencies; operating the processing circuitry for generating, based on the radar sensor signals, a first indicator value, the first indicator value indicating a degree of motion associated with the occupiable position; determining whether the first indicator value satisfies a first predetermined criteria; if the first indicator value satisfies the first predetermined criteria, generating, based on radar sensor signals, a second indicator value, the second indicator value indicating a degree of repetitive pattern within the radar sensor signals; and determining that an unattended child is present within the automotive vehicle if the second indicator value satisfies a second predetermined criteria. The second indicator value may comprise a breathing signature indicative of the extent to which the sensor signals indicate that motion indicative of infant breathing child is detected.

[0008] In the article "*Non-Contact Estimation at 60 GHz for Human Vital Signs Monitoring Using a Robust Optimization Algorithm*" by Ting Zhang et al., Conference IEEE APS 2016, Jun 2016, Fajardo (Porto-Rico), United States, 2016, AP-S/URSI 2016. <hal-01340613>, an approach to estimate body movements related to vital activities by means of a 60 GHz Doppler radar is described, using robust optimization algorithms including signal autocorrelation analysis in order to extract heart-rate and breathing information from the radar signals.

Object of the invention

[0009] It is desirable to provide a non-contact method for reliably and quantitatively monitoring a breathing motion of a subject, particularly a human being.

[0010] It is therefore an object of the invention to provide a method for monitoring a breathing motion of a subject, particularly of a human being, that is capable of extracting and evaluating a quantity of one or more breathing-characteristic parameters from signals that are acquired from the subject by sensors operating in a contactless manner.

General Description of the Invention

[0011] The present invention is particularly useful as a supporting tool for medical purposes such as diagnostics, as a monitoring device for automotive applications such as advanced driver assistance systems (ADAS), or as a monitoring device in sports.

[0012] In one aspect of the present invention, the object is achieved by a method of operating a radar sensor system for monitoring a breathing motion of a subject. The radar sensor system includes a radar transmitting unit having one radar transmitting antenna and being configured for transmitting radar waves towards the subject, a radar receiving unit having one radar receiving antenna and being configured for receiving radar waves that have been transmitted by the radar transmitter unit and have been reflected by the subject, and an evaluation and control unit that is at least configured for evaluating Doppler information from the radar waves received by the radar receiving unit.

[0013] The method comprises at least steps of

- operate the radar transmitting unit for at least once transmitting radar waves of a predetermined radar carrier frequency for a specified time towards a chest and an abdominal region of the subject,
- operate the radar receiving unit at least once for a specified time for receiving radar waves that have been transmitted by the radar transmitting unit and that have been reflected by the chest and the abdominal region of the subject, and for generating received radar signals from the received radar waves,
- calculate the autocorrelation function of the received radar signals,
- calculate the Fourier transform of the calculated autocorrelation function,
- determine and record values of at least two peaks of the calculated Fourier transform, and
- from the recorded determined values of the at least two peaks, determine at least one breathing-characteristic parameter of the breathing motion of the subject.

[0014] The phrase “being configured to”, as used in this application, shall in particular be understood as being specifically programmed, laid out, furnished or arranged.

[0015] The phrase “evaluating Doppler information”, as used in this application, shall in particular be understood as evaluating received radar waves for ranging purposes.

[0016] The at least one breathing-characteristic parameter of the breathing motion of the subject may be given by, without being limited to, a chest breathing amplitude and an abdominal region breathing amplitude.

[0017] One advantage of the proposed method lies in that a non-contact measurement is provided that does not disturb the subject and avoids to potentially influence a result of the desired measurement.

[0018] Another advantage lies in that only one radar transmitter unit and only one radar receiving unit is required, resulting in a part and cost saving solution, which moreover reduces any necessary synchronization effort.

[0019] Further, by using the signal autocorrelation function, random noise beneficially cancels out, enabling more precise measurements in suitable embodiments, for instance of the phase lag between breathing motions of the chest and the abdominal region of the subject. This means an improvement in particular compared to the well-known in-phase or quadrature signal processing in this technical field.

[0020] By using the proposed method, diagnostics of patients with certain neuromuscular diseases and prematurely born infants can be supported. Moreover, the proposed method can enable to identify if a person is undergoing pulmonary or diaphragmatic breathing, which may be useful for many applications.

[0021] Preferably, the evaluation and control unit comprises a processor unit and a digital data memory unit to which the processor unit has data access. In this way, the steps of recording received radar signals and the calculating steps can be executed within the radar sensor system to enable a fast and undisturbed signal processing and evaluation.

[0022] In some embodiments, the radar transmitting unit and the radar receiving unit may be designed as distinct units. In other embodiments, the radar transmitting unit and the radar receiving unit may be designed as a transceiver unit, having common electronic circuitry and/or a common housing.

[0023] Preferably, the method further comprises steps of

- after the step of determining and recording values of at least two peaks, change the number of radar wavelengths in the path between the radar transmitting antenna, the subject and the radar receiving antenna at least once by a predetermined amount, and
- iteratively carry out at least the steps of operating the radar transmitter unit, of operating the radar receiving unit, of determining and recording values of at least two peaks and of changing the number of radar wavelengths, until at least one extreme value is detected for the determined values of each one the at least two peaks.

[0024] In this way, a chest breathing amplitude and/or an abdominal region breathing amplitude can be determined with low error of measurement. This benefit can in particular be also achieved if the breathing-characteristic parameter is formed by a phase lag between breathing motions of the chest and the abdominal region of the subject.

[0025] In some preferred embodiments of the method, the step of changing the number of radar wavelengths in the path includes carrying out a predetermined displacement along a predetermined direction of at least one out of the radar transmitting antenna and the radar receiving antenna relative to the subject. In this way, the number of radar wavelengths in the path can be changed in a constructively simple manner. For instance, the predetermined direction may be chosen as a straight line pointing essentially towards the subject and forming an acute angle with an angle bisector of an angle formed by the chest, the radar sensor system as the vertex and the abdominal region of the subject.

[0026] In some preferred embodiments of the method, the step of changing the number of radar wavelengths in the path includes changing a radar carrier frequency of the radar sensor system by a predetermined amount. By that, a fast, simple and precise change of the number of radar wavelengths in the path can be enabled, for instance by tuning a control voltage at a control input line of a voltage controlled oscillator (VCO) of the radar transmitting unit.

[0027] For such embodiments of the method, the step of operating the radar transmitting unit for transmitting radar waves preferably includes transmitting a plurality of consecutive radar wave trains, each wave train comprising a plurality of radar waves of predetermined duration, wherein radar carrier frequencies of each radar wave of the plurality of radar waves differ by an integral multiple of the predetermined amount. This feature is a variation of a concept commonly known as Frequency Shift Keying Radar. Further, the step of operating the radar receiving unit for receiving radar waves includes receiving radar waves that have been reflected by the chest and abdominal region of the subject for each radar wave of the plurality of radar waves and for each radar wave train of the plurality of radar wave trains, and includes generating and recording received radar signals for each one of the received radar waves. In a suitable embodiment, the method can thus allow for a shortened total measurement time.

[0028] The consecutive radar wave trains of the plurality of consecutive radar wave trains may be separated by a time gap. Alternatively, the consecutive radar wave trains of the plurality of consecutive radar wave trains may directly follow each other without any time gap.

[0029] Preferably, the step of changing the number of radar wavelengths in the path is carried out until at least one minimum value and one maximum value is recorded for the determined values of each one of the at least two peaks of the calculated Fourier transform. In this way, the phase lag between breathing motions of the chest and the abdominal region of the subject and/or the chest breathing amplitude and/or the abdominal region breathing amplitude can be determined from the determined values of each one of the at least two peaks with a smaller error of measurement.

[0030] The step of determining a chest breathing amplitude or an abdominal region breathing amplitude can further include correcting the at least one extreme value for the determined values of one of the at least two peaks by an offset value determined from the recorded determined values of the one of the at least two peaks. In this context it should be noted that the offset alone (as well as the size of the oscillation) carries information (i.e. depends on) the breathing amplitude. To get the size of the oscillation, it is preferable to subtract the offset. But in addition, the offset itself carries info about the breathing amplitudes. It follows that the step of determining a chest breathing amplitude or an abdominal region breathing amplitude can further include evaluating information contained in said offset value.

[0031] In such embodiments of the method, in which at least one extreme value is detected for the determined values of each one of the at least two peaks, the step of determining and recording values of the at least two peaks of the calculated Fourier transform includes determining and recording values of a peak of order n and values of a peak of order -n of the calculated Fourier transform, and the step of determining at least one breathing-characteristic parameter of the breathing motion of the subject includes determining a phase lag between breathing motions of the chest and the abdominal region of the subject by determining a difference of the radar carrier frequencies at which extreme values of the peak of order n and the peak of order -n occur.

[0032] The phrase “peak of order ±n”, as used in this application, shall in particular be understood as a signal peak of the Fourier transform that is located at Fourier frequency $\pm n \cdot f_b$, wherein f_b denotes the breathing frequency.

[0033] This is based on the insight that extreme values of the peak of order n and the peak of order -n will only occur for the same value of the radar carrier frequency if the phase lag equals zero. A measured radar carrier frequency difference between extreme values of the peak of order n and the peak of order -n can thus be exploited for determining the phase lag.

[0034] Preferably, the step of determining and recording values of at least two peaks of the calculated Fourier transform comprises determining and recording a plurality of at least two additional peaks of the calculated Fourier transform representing higher order harmonics with respect to the at least two peaks, and the step of determining comprises determining at least one out of determining a chest breathing amplitude and an abdominal region breathing amplitude, and further comprises determining a standstill of the at least one out of a chest breathing amplitude and an abdominal region breathing amplitude by comparing recorded values of the plurality of at least two additional peaks with predetermined threshold values for the plurality of at least two additional peaks, and by detecting that recorded values of the plurality of at least two additional peaks exceed the predetermined threshold values for a predetermined period of time.

[0035] This embodiment of the proposed method is particularly beneficial for the application of apnea detection. Apnea is a sudden stop in breathing, in which case a received radar signal will suddenly drop to zero. As a result, higher order frequency harmonics will arise in the Fourier transform of the signal autocorrelation function, which would normally not be present for any realistic values of observable breathing displacement amplitudes. Mathematically speaking, a sharp breathing stop produces step-like signatures in in-phase and quadrature radar signals, which is equivalent to a larger number of higher order frequency harmonics in the Fourier space. A detected occurrence of higher order frequency harmonics in the Fourier space can thus be used as an apnea alarm trigger.

[0036] Preferably, a smallest gap between the at least two peaks and the plurality of at least two additional peaks of the calculated Fourier transform is equivalent to at least two orders, more preferably to at least three orders, and, most preferably, to at least four orders. In this way, an especially robust apnea detection can be achieved.

[0037] In preferred embodiments of the method, the step of determining and recording values of peaks comprises determining and recording values of at least three peaks of the calculated Fourier transform, and the step of determining at least one breathing-characteristic parameter of the breathing motion of the subject includes determining one out of a plurality of predetermined breathing amplitude intervals based on carrying out a ranking of the determined values of the at least three peaks of the calculated Fourier transform.

[0038] This is based on the insight that by ranking the determined values of the at least three peaks of the calculated Fourier transform it can be exploited that specific rankings of the values of the at least three peaks can exist in disjoint intervals, by which a chest breathing amplitude and/or an abdominal region breathing amplitude can be determined within specified limits.

[0039] Preferably, the at least three peaks of the calculated Fourier transform are of consecutive order. In this way, suitable intervals for breathing amplitudes can be achieved.

[0040] Preferably, the step of determining and recording values of peaks comprises determining and recording values of all peaks of the calculated Fourier transform that are larger than a predetermined value. In this way, an especially robust method of estimating a chest breathing amplitude and/or an abdominal region breathing amplitude can be provided.

[0041] Preferably, the method further comprises steps of

- comparing the determined at least one out of phase lag, chest breathing amplitude and abdominal region breathing amplitude with at least one predetermined threshold value, and
- generating an output signal representing a breathing status of the subject.

[0042] By that, a fast evaluation of the measurement can be accomplished that can be exploited for alarm purposes.

[0043] In another aspect of the invention, a radar sensor system is provided for monitoring a breathing motion of a subject. The radar sensor system comprises

- a radar transmitting unit having one radar transmitting antenna and being configured for transmitting radar waves of a predetermined radar carrier frequency towards a chest and an abdominal region of the subject,
- a radar receiving unit having one radar receiving antenna and being configured for receiving radar waves that have been transmitted by the radar transmitter unit and have been reflected by the subject, and
- an evaluation and control unit that is at least configured for evaluating Doppler information from the radar waves received by the radar receiving unit, and that is further configured to automatically execute steps of the method as disclosed herein.

[0044] The benefits described in context with the method of operating a radar sensor system for monitoring a breathing motion of the subject apply to the proposed radar sensor system automatically executing such method to the full extent.

[0045] Preferably, the predetermined radar carrier frequency lies in the frequency range between 15 GHz and 130 GHz, and more preferably in the frequency range between 57 GHz and 64 GHz. This can enable that the bandwidth of components of the radar sensor system is sufficiently large to ensure that at least one extreme value is detected for the determined values of each one of the at least two peaks of the calculated Fourier transform. What is beneficial for, for example a 60 GHz system, is that a rather large bandwidth of 8 GHz is available. Compared to lower radar carrier frequencies, the proposed frequency range can further have the advantage that higher order peaks of the calculated Fourier transform become more pronounced, which can result in a lower error of measurement.

[0046] If the radar transmitting antenna is configured to have a main lobe that is able to cover a major part of the chest and the abdominal region of the subject, a radar sensor system for monitoring a breathing motion of a subject with an especially simple construction and operation can be provided. The phrase “major part”, as used in this application, shall in particular be understood as more than 30%, preferably more than 50% and, more preferably, more than 60% of an outer surface of the respective region.

[0047] In yet another aspect of the invention, a software module for controlling automatic execution of the method disclosed herein is provided.

[0048] The method steps to be conducted are converted into a program code of the software module, wherein the program code is implementable in a digital memory unit of the radar sensor system or a separate control unit and is executable by a processor unit of the radar sensor system or a separate control unit. Preferably, the digital memory unit and/or processor unit may be a digital memory unit and/or a processing unit of the control and evaluation unit of the radar sensor system. The processor unit may, alternatively or supplementary, be another processor unit that is especially assigned to execute at least some of the method steps.

[0049] The software module can enable a robust and reliable automatic execution of the method and can allow for a fast modification of method steps.

[0050] These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

[0051] It shall be pointed out that the features and measures detailed individually in the preceding description can be combined with one another in any technically meaningful manner and show further embodiments of the invention. The description characterizes and specifies the invention in particular in connection with the figures.

Brief Description of the Drawings

[0052] Further details and advantages of the present invention will be apparent from the following detailed description of not limiting embodiments with reference to the attached drawing, wherein:

Fig. 1 schematically illustrates a configuration of an embodiment of the radar sensor system in accordance with the invention while executing an operating method for monitoring a breathing motion of a subject,

Fig. 2a shows the calculated Fourier transform of the autocorrelation function of radar waves received in the configuration pursuant to Fig. 1, Fig 2b shows another calculated Fourier transform of an autocorrelation function of radar waves received during an apnea event in the configuration pursuant to Fig. 1,

Fig. 3 shows a plot of the variation of amplitudes of two adjacent peaks of the calculated Fourier transform pursuant to Fig. 2a as a result of predetermined displacements of the radar sensor system pursuant to Fig. 1,

Fig. 4 shows a plot of the variation of amplitudes of two adjacent peaks of the calculated Fourier transform pursuant to Fig. 2a as a result of predetermined changes of the radar carrier frequency of the radar sensor system pursuant to Fig. 1,

Fig. 5 shows a plot of values of the first five peaks of another calculated Fourier transform of an autocorrelation function of other received radar waves vs. a breathing amplitude for a fixed radar carrier frequency,

Fig. 6 shows a plot of the variation of values of a peak of order n and values of a peak of order -n of the calculated Fourier transform of an autocorrelation function of other received radar waves for two distinct values of a phase lag,

Fig. 7 is a flowchart of an embodiment of the method in accordance with the invention of operating the radar sensor system pursuant to Fig. 1 for monitoring a breathing motion of a subject,

Fig. 8 is a flowchart of an alternative embodiment of the method in accordance with the invention of operating the radar sensor system pursuant to Fig. 1 for monitoring a breathing motion of a subject,

Fig. 9 is a flowchart of another alternative preferred embodiment of a method in accordance with the invention of operating the radar sensor system pursuant to Fig. 1 for monitoring a breathing motion of a subject,

Fig. 10 illustrates the plurality of consecutive radar wave trains of the fast frequency sweep of the radar carrier frequency as executed in a step of the method pursued to Fig. 7, and

Fig. 11 shows the simulated Fourier transform of the autocorrelation function of yet another possible embodiment.

Description of Preferred Embodiments

[0053] Fig. 1 schematically illustrates a configuration of an embodiment of the radar sensor system 10 in accordance with the invention while executing an operating method for monitoring a breathing motion of a subject 24.

[0054] The radar sensor system 10 comprises a radar transmitting unit having one radar transmitting antenna 12 and being configured for transmitting radar waves 14 of a predetermined radar carrier frequency towards a chest 26 and an abdominal region 28 of the subject 24. The radar transmitting antenna 12 is directed towards the subject 24 and is designed to have a main lobe that is able to cover a major part of more than 50% of the chest 26 and the abdominal region 28 of the subject 24. The predetermined radar carrier frequency is controllable within a frequency range between 15 GHz and 130 GHz, and more preferably in a frequency range between 57 GHz and 64 GHz, corresponding to wavelengths λ in air between 5.3 mm and 4.7 mm.

[0055] The radar sensor system 10 further includes a radar receiving unit having one radar receiving antenna 16 and being configured for receiving radar waves 18 that have been transmitted by the radar transmitter unit and have been reflected by the subject 24.

[0056] The radar transmitting antenna 12 and the radar receiving antenna 16 are co-located in a monostatic arrangement, which is indicated in Fig. 1 by use of a combined symbol. In this specific embodiment, the radar transmitter unit and the radar receiving unit form an integral part of a transceiver unit 20, sharing common electronic circuitry and a common housing. In other embodiments, the radar transmitter unit and the radar receiving unit may be designed as separate units.

[0057] Moreover, the radar sensor system 10 comprises an evaluation and control unit 22 that is configured for evaluating Doppler information from the radar waves 18 received by the radar receiving unit. The evaluation and control unit 22 is connected to the radar transmitting unit for controlling operation of the radar transmitting unit. The evaluation and control unit 22 is also connected to the radar receiving unit for receiving radar signals generated by the radar receiving unit. The evaluation and control unit 22 comprises a processor unit and a digital data memory unit (not shown) to which the processor unit has data access. The evaluation and control unit 22 is configured for recording the received radar signals generated by the radar receiving unit in the digital data memory unit.

[0058] The radar sensor system 10 is mechanically connected to a mechanism (not shown) that allows, by control of the control and evaluation unit 22, for a predetermined displacement of the radar sensor system 10 along the predetermined direction relative to the subject 24. A maximum displacement of the mechanism is 10.0 mm.

[0059] In a modeling approach, the configuration illustrated in Fig. 1 can mathematically be described as follows.

[0060] For simplicity, sinusoidal motion of the chest 26 and the abdominal region 28 of the subject 24 is assumed, although the analysis is applicable for an arbitrary continuous and periodic breathing pattern on grounds of the Fourier theorem, as will be readily acknowledged by those skilled in the art. The chest 26 and the abdominal region 28 undergo periodic sinusoidal motion about some equilibrium positions R_1 and R_2, which are respective distances to the radar sensor system 10 as shown in Fig. 1. As described before, the abdominal region 28 does not necessarily undergo the identical oscillatory motion as the chest 26. Rather, its motion can be characterized by some phase lag ϕ with respect to that of the chest 26. The frequency of the motion of the chest 26 and abdominal region 28 is denoted by f_b, and the radial projections of the amplitude of the motion of the chest 26 and the abdominal region 28 by x_1^0 and x_2^0, respectively. Then, their respective distances $r_1(t), r_2(t)$ to the radar sensor system 10 change with time t according to

$$r_1(t) = R_1 + x_1(t),$$

$$r_2(t) = R_2 + x_2(t), \qquad \text{Eq. (1)}$$

with

$$x_1(t) = x_0^1 \ \mathrm{g}(2\pi f_b t + \phi),$$

$$x_2(t) = x_0^2 \ \mathrm{g}(2\pi f_b t), \qquad \text{Eq. (2)}$$

wherein g denotes an arbitrary continuous and periodic function with period f_b^{-1}, representing the breathing pattern. This reduces to

$$x_1(t) = x_0^1 \sin(2\pi f_b t + \phi),$$

$$x_2(t) = x_0^2 \sin(2\pi f_b t),$$

in the case of a sinusoidal breathing pattern.

[0061] The reflected radar signal is now given by the superposition

$$u_r = A_1 e^{-i(2\pi f t + \frac{4\pi}{\lambda} r_1(t))} + A_2 e^{-i(2\pi f t + \frac{4\pi}{\lambda} r_2(t))}, \qquad \text{Eq. (3)}$$

wherein A_1 and A_2 denote the power amplitudes, which depend on

- the equilibrium distances $R_{1/2}$ in the limit of $x_{1/2}^0 \ll R_{1/2}$, which is always the case for any practical set-up,
- the antenna gain pattern, and
- the radar cross sections of the chest 26 and the abdominal region 28, respectively.

In Eq. (3), f denotes the predetermined radar carrier frequency.

[0062] After mixing and going through the low-pass filter, which removes the high radar carrier frequency component f, the complex radar signal Y reads

$$Y(t) = B_1 e^{-i(\frac{4\pi}{\lambda} r_1(t))} + B_2 e^{-i(\frac{4\pi}{\lambda} r_2(t))}, \qquad \text{Eq. (4)}$$

wherein $B_k,\ k = 1, 2$ represents the signal amplitudes after mixing and the low-pass filter.

[0063] In the following, various possible embodiments of a method in accordance with the invention of operating the radar sensor system 10 pursuant to Fig. 1 for monitoring a breathing motion of the subject 24 will be presented. The individual alternative embodiments are identified by a prefix cipher of the particular embodiment, starting with cipher 1. Steps whose function is the same or basically the same in all embodiments are identified by reference numbers made up of the prefix cipher of the embodiment to which it relates, followed by the numeral of the feature.

[0064] A first embodiment of the method of operating the radar sensor system 10 pursuant to Fig. 1 for monitoring a breathing motion of the subject 24 will be described with reference to Fig. 1. A flowchart of the method is provided in Fig. 7. In preparation of operating the radar sensor system 10, it shall be understood that all involved units and devices are in an operational state and configured as illustrated in Fig. 1.

[0065] In order to be able to carry out the method automatically and in a controlled way, the evaluation and control unit 22 comprises a software module. The method steps to be conducted are converted into a program code of the software module. The program code is implemented in the digital data memory unit of the evaluation and control unit 22 and is executable by the processor unit of the evaluation and control unit 22.

[0066] With the radar sensor system 10 arranged at a fixed predetermined position relative to the subject 24, the radar transmitting unit is controlled by the control of evaluation unit 22 for transmitting radar waves of the predetermined radar carrier frequency for a specified duration towards the chest 26 and the abdominal region 28 of the subject 24 in a step 134 of the method.

[0067] The radar receiving unit receives radar waves that have been transmitted by the radar transmitting unit and that have been reflected by the chest 26 and the abdominal region 28 of the subject 24, and the radar receiving unit generates received radar signals from the received radar waves. In another step 136, the generated received radar signals are received and recorded by the control and evaluation unit 22.

[0068] In another step 138 of the method, the autocorrelation function of the received radar signal is calculated.

[0069] The autocorrelation function of the complex radar signal Y given by Eq. (4) is defined as

$$A(\tau) = \int_{-\infty}^{\infty} Y(t)\, Y^{*}(t+\tau)\, dt, \qquad \text{Eq. (5)}$$

wherein Y^{*} denotes the complex conjugate of the complex radar signal Y. The complex signal Y is given by $Y = I + iQ$, where I is the in-phase signal, and Q the quadrature signal, and i the imaginary unit.

[0070] In a next step 140, the Fourier transform $A(\nu)$ of the calculated autocorrelation function $A(\tau)$ is calculated. The letter ν denotes the Fourier transform frequency.

[0071] The autocorrelation function $A(\tau)$ is a convolution of the complex radar signal Y with itself; therefore the convolution theorem can be applied to calculate the Fourier transform $A(\nu)$ of the autocorrelation function $A(\tau)$ from

$$A(\nu) = Y(\nu)\, Y^{*}(\nu), \qquad \text{Eq. (6)}$$

wherein $Y(\nu)$ is the Fourier transform of the complex radar signal $Y(t)$ given by Eq. (4), i.e.

$$Y(\nu) = \int_{-\infty}^{\infty} e^{-i2\pi\nu t}\, Y(t)dt \qquad \text{Eq. (7)}$$

[0072] Evaluating the following Fourier transform:

$$\int_{-\infty}^{\infty} e^{-i2\pi\nu t} e^{-i\frac{4\pi x_0^1\, g(2\pi f_b t+\phi)}{\lambda}} dt$$

yields

$$= \int_{-\infty}^{\infty} e^{-i2\pi\nu(\tilde{t}-\frac{\phi}{2\pi f_b})} e^{-i\frac{4\pi x_0^1\, g(2\pi f_b \tilde{t})}{\lambda}} d\tilde{t}$$

$$= e^{-i\frac{\nu}{f_b}\phi} \int_{-\infty}^{\infty} e^{-i2\pi\nu\tilde{t}} e^{-i\frac{4\pi x_0^1\, g(2\pi f_b \tilde{t})}{\lambda}} d\tilde{t}, \qquad \text{Eq. (8)}$$

wherein a change of variables $\tilde{t} = t + \frac{\phi}{2\pi f_b}$ has been performed in the second line of the above.

[0073] Further, one can make the following decomposition according to Eq. (9), which in more detail is described in W. A. Gardner, "*Statistical Spectral Analysis: A Nonprobabilistic Theory*", Prentice-Hall, Englewood Cliffs, NJ, 1987, and in the cited article "*Non-Contact Estimation at 60 GHz for Human Vital Signs Monitoring Using a Robust Optimization Algorithm*" by Ting Zhang et al. Both these documents shall hereby be incorporated by reference in their entirety with effect for those jurisdictions permitting incorporation by reference.

$$\int_{-\infty}^{\infty} e^{-i2\pi\nu\tilde{t}} e^{-i\frac{4\pi x_0^1\, g(2\pi f_b \tilde{t})}{\lambda}} d\tilde{t} = \sum_{n=-\infty}^{\infty} J_n\left(\frac{4\pi}{\lambda} x_0^1\right) \delta(\nu - n f_b). \qquad \text{Eq. (9)}$$

[0074] Herein, J_n is a basis function, which in principle depends on the shape of the breathing signal (e.g. sinusoidal, triangular, etc.). In case that the function g is the sinus function (i.e. breathing pattern has sinusoidal shape), the function J_n is the nth order spherical Bessel function of the first kind.

[0075] Thus, the Fourier transform $Y(\nu)$ of the complex radar signal $Y(t)$ in Eq. (4) reads

$$Y(\nu) = B_1 e^{-i\frac{4\pi}{\lambda}R_1} \sum_{n=-\infty}^{\infty} J_n\left(\frac{4\pi}{\lambda}x_0^1\right) e^{-i\frac{\nu}{f_b}\phi} \delta(\mathrm{v} - nf_b) + B_2 e^{-i\frac{4\pi}{\lambda}R_2} \sum_{n=-\infty}^{\infty} J_n\left(\frac{4\pi}{\lambda}x_0^2\right) \delta(\mathrm{v} - nf_b)$$

Eq. (10)

[0076] Using Eq. (6) in combination with the result of Eq. (10), the following can be obtained:

$$A(\nu) = \textstyle\sum_{n=-\infty}^{\infty} a_n \; \delta(\mathrm{v} - nf_b), \qquad \text{Eq. (11a)}$$

with

$$a_n(f) = C_n(f) + K_n(\mathrm{f})\cos\left(n\phi + \frac{4\pi}{c} f (R_1 - R_2)\right), \qquad \text{Eq. (11b)}$$

$$C_n(f) = B_1^2 J_n^2\left(\tfrac{4\pi x_1^0}{c} f\right) + B_2^2 J_n^2\left(\tfrac{4\pi x_2^0}{c} f\right), \text{ and}$$

$$K_n(f) = 2B_1 B_2 J_n\left(\tfrac{4\pi x_1^0}{c} f\right) J_n\left(\tfrac{4\pi x_2^0}{c} f\right),$$

wherein f denotes the radar carrier frequency. Thereby, it is proven that Eq. (11a) is applicable for an arbitrarily shaped periodic signal, which is also confirmed by simulations, as will be described thereinafter.

[0077] According to Eq. (11a), the Fourier transform $A(\nu)$ of the autocorrelation function $A(\tau)$ is given by a series of peaks of different heights, separated by f_b, the frequency of the motion of the chest and abdominal region of the subject. This is exemplarily illustrated in Fig. 2a. A height a_n of the nth peak, given by Eq. (11b), depends on the power amplitudes B_1, B_2 received from the chest 26 and the abdominal region 28, respectively, on the chest and abdominal region displacement amplitudes x_0^1 and x_0^2, on the difference $\Delta R = R_1 - R_2$ in the average distances from chest 26 and abdominal region 28 to the radar sensor system 10, and on the phase lag ϕ.

[0078] It is obvious from Eq. (11b) that in this specific embodiment of the radar sensor system 10, in which a predetermined displacement along the predetermined direction relative to the subject 24 is enabled, the maximum displacement of the mechanism of 10.0 mm is sufficient to make the height a_n of the nth peak undergo a full oscillation.

[0079] The predetermined direction for the predetermined displacement is chosen such that a displacement results in a change of the equilibrium distances R_1 and R_2 of the chest 26 and the abdominal region 28, respectively, as well as in a change of the quantity $\Delta R = R_1 - R_2$. In general, the power amplitudes also scale like $B_1 \sim \frac{1}{R_1^2}$, but if small displacements of the radar sensor system 10 are implemented in the order of magnitude of the radar carrier wavelength $\lambda \ll R_i, i = 1, 2$, the amplitude change will be negligible, while the cosine function term in Eq. (11b) can vary substantially.

[0080] Values of a plurality of peaks of the calculated Fourier transform $A(\nu)$ are determined and recorded by the control and evaluation unit 22 in another step 142 of the method.

[0081] In an alternative embodiment of the method, values of a plurality of four additional peaks of the calculated Fourier transform $A(\nu)$ that represent higher order harmonics (n = 9 to 12) with respect to the plurality of peaks (n = 1 to 7) of the calculated Fourier transform $A(\nu)$ can be determined and recorded. A smallest gap between the plurality of peaks and the plurality of four additional peaks of the calculated Fourier transform is equivalent to two orders. A standstill of at least one out of a chest breathing amplitude and an abdominal region breathing amplitude can be detected by comparing the recorded values of the plurality of four additional peaks with predetermined threshold values for the plurality of four additional peaks, and by detecting that the recorded values of the plurality of four additional peaks exceed the predetermined threshold values for a predetermined period of time. The smaller the breathing amplitude, the less pronounced are any higher order frequency harmonics in the Fourier transform of the signal autocorrelation function. As an example, for a child breathing with an amplitude of 2 to 3 mm, there will be only one or two higher order harmonics visible in the Fourier transform of the signal autocorrelation function for a 24 GHz radar carrier frequency. During an apnea event, 5 to 6 additional peaks will be emerging (Fig. 2b), an observation which can be exploited as an alarm trigger, as at least one of the higher order peaks may exceed the predetermined threshold value.

[0082] Referring again to the first embodiment of the method, in another step 144, the number of radar wavelengths in the path between the radar transmitting antenna 12, the subject 24 and the radar receiving antenna 16 is changed by a predetermined amount by carrying out a predetermined displacement of the radar sensor system 10 relative to the subject 24 along the predetermined direction. The steps 134 to 144 are iteratively carried out until two extreme values, namely a maximum and a minimum value, are detected for the determined values of each one the plurality of peaks.

[0083] Fig. 3 exemplarily shows a plot of the variation of the recorded values of two adjacent peaks of the calculated Fourier transform $A(\nu)$ pursuant to Fig. 2a, namely a value of the nth peak a_n and a value a_{n+1} of the (n+1)th peak, as a result of a series of predetermined displacements of the radar sensor system 10 pursuant to Fig. 1.

[0084] From the plot of Fig. 3, a phase lag ϕ between the breathing motions of the chest 26 and the abdominal region 28 of the subject 24 is derived in another step 146. The phase lag ϕ can be determined by looking at the distance between the maxima of the nth and (n+1)th peak in Fig. 3. The phase lag ϕ is given by

$$\phi = 2k\pi - \frac{2\pi}{\lambda}\Delta x,$$

wherein Δx is the distance between the maximum of the nth peak and the maximum of the (n+1)th peak, and k is an integer that is chosen to fulfil $0 \leq \phi \leq \pi$.

[0085] The constants C_n and K_n are also extracted from the plot of amplitudes of two peaks of the calculated Fourier transform in another step 148 of the method. Constant C_n represents the constant offset in Fig. 3, while constant K_n represents the amplitude of the oscillation. This is carried out for a plurality of different values for n, e.g. n = 1, 2, 3 ...for reduced error of measurement. The constants C_n and K_n provide information about amplitudes of the displacements of the chest 26 and abdominal region 28 of the subject 24. It should be emphasized at this point that the constants C_n and K_n depend on quantities such as a particular shape of the breathing displacement (e.g. sinusoidal, triangular, etc.), breathing amplitudes, radar cross sections of chest and the abdomen, and an antenna gain pattern. However, for determining the degree of chest/abdomen asynchronicity none of these quantities (radar cross sections, antenna gain pattern, etc.) need to be known *a priori*. The constants C_n and K_n can be extracted from the experimentally measured variation, such as the offset and the size of the oscillation, respectively.

[0086] As optional steps of the method (not shown in Fig. 7), the determined phase lag ϕ, chest breathing amplitude and abdominal region breathing amplitude can be compared with predetermined threshold values for each one of these determined quantities. Also, an output signal representing a breathing status of the subject 24 can be generated and provided to an external unit for further signal processing.

[0087] All predetermined, predefined, calculated or recorded values and threshold values mentioned herein reside in the digital data memory unit of the evaluation and control unit 22 and can readily be retrieved by the processor unit of the evaluation and control unit 22.

[0088] In an alternative embodiment of the method, the step of determining and recording values of at least two peaks of the calculated Fourier transform $A(\nu)$ includes determining and recording values of a peak of order n and values of a peak of order -n of the calculated Fourier transform $A(\nu)$. Fig. 6 shows a plot of the variation of values of the peak of order n and values of the peak of order -n of the calculated Fourier transform $A(\nu)$ of the autocorrelation function for two distinct values of a phase lag ϕ.

[0089] By carrying out the Fourier transform $A(\nu)$ of the autocorrelation function, both the negative and the positive frequency spectrum is obtained, which, depending on the signal shape and the phase lag ϕ, do not necessarily have to be mirror images of one another. From Eq. (11b) and since $J_n = J_{-n}$, it follows that $C_n = C_{-n}$, and $K_n = K_{-n}$, and further that

$$a_{-n}(f) = C_n(f) + K_n(f)\cos\left(-n\phi + \frac{4\pi}{c} f(R_1 - R_2)\right) \qquad \text{Eq. (11c)}$$

[0090] From Eq. (11b) and Eq. (11c) it is obvious that minima of $a_n(f)$ and $a_{-n}(f)$ will not occur for the same value of the carrier frequency f unless the phase lag ϕ equals zero.

[0091] The step of determining a phase lag ϕ between breathing motions of the chest 26 and the abdominal region 28 of the subject 24 therefore includes determining the phase lag ϕ by determining a difference $\overline{\Delta f_n}$ of the radar carrier frequency f at which extreme values of the peak of order n and the peak of order -n occur. The phase lag ϕ can then be determined from

$$\phi = \pi \frac{\overline{\Delta f_n}}{\Delta f_{bw}} + \frac{m\pi}{n} \qquad \text{Eq. (12)}$$

[0092] Herein, m is an integer which should be chosen such that the phase lag ϕ lies between 0 and π, and Δf_{bw} denotes the radar carrier frequency sweep that is necessary to drive the peaks $a_n(f)$ and $a_{-n}(f)$ of the Fourier transform $A(\nu)$ through an entire oscillation.

[0093] Fig. 6 shows a plot of simulation results of a variation of values of a peak of order 1 and values of a peak of order -1 of the calculated Fourier transform of an autocorrelation function of other received radar waves for two distinct values of a phase lag ϕ, namely for $\phi = \frac{\pi}{6}$ (left hand side) and $\phi = \frac{\pi}{3}$ (right hand side), respectively, with same other parameters. The value of the phase lag ϕ as determined by the above-described method was found to exactly match the phase lag ϕ that was entered in the simulations.

[0094] This method of determining the phase lag ϕ from the features of positive and negative Fourier spectra is especially useful in the case of breathing amplitudes that are small compared to the radar carrier wavelength, when only the peaks of order 1 and -1 are visible in the Fourier spectrum, whereas any higher order peaks with n = ±2, ±3, … might not exist.

[0095] Fig. 8 shows a flowchart of an alternative embodiment of the method in accordance with the invention, of operating the radar sensor system 10 pursuant to Fig. 1 for monitoring a breathing motion of the subject 24.

[0096] With the radar sensor system 10 arranged at a fixed position relative to the subject 24, the radar transmitting unit is controlled by the control and evaluation unit 22 for transmitting radar waves of a predetermined initial radar carrier frequency f_0 for a specified duration towards the chest 26 and the abdominal region 28 of the subject 24 in a step 234 of the method.

[0097] The radar receiving unit receives radar waves that have been transmitted by the radar transmitting unit and that have been reflected by the chest 26 and the abdominal region 28 of the subject 24, for example for a duration of 10 s, and the radar receiving unit generates received radar signals from the received radar waves. In the next step 236, the generated received radar signal is received and recorded by the control and evaluation unit 22.

[0098] In another step 238 of the method, the autocorrelation function of the received radar signal is calculated. In a next step 240, the Fourier transform or a similar transformation of the calculated autocorrelation function is calculated.

[0099] Values of a plurality of peaks of the calculated Fourier transform are determined and recorded by the control an evaluation unit 22 in another step 242 of the method.

[0100] In another step 244, the number of radar wavelengths in the path between the radar transmitting antenna 12, the subject 24 and the radar receiving antenna 16 is changed by a predetermined amount by changing the radar carrier frequency of the radar sensor system by a predetermined frequency amount. The steps 234 to 244 are iteratively carried out until two extreme values, namely a maximum and a minimum value, are detected for the determined values of each one the plurality of peaks.

[0101] Fig. 4 exemplarily shows a plot of the variation of the recorded values of two adjacent peaks of the calculated Fourier transform $A(\nu)$ pursuant to Fig. 2a, namely a value of the nth order peak a_n and a value a_{n+1} of the (n+1)th order peak, as a result of predetermined changes of the radar carrier frequency of the radar sensor system 10 pursuant to Fig. 1. The predetermined changes of the radar carrier frequency are performed by tuning a control voltage at a control input line of a voltage controlled oscillator (VCO, not shown) of the radar transmitting unit, as is commonly known in the art.

[0102] From the plot of Fig. 4, a phase lag ϕ between the breathing motion of the chest 26 and the abdominal region 28 of the subject 24 is derived in another step 246. The phase lag ϕ can be determined from an observed difference Δy of the radar carrier frequencies at which the maxima of the nth and (n+1)th order peak are located. The phase lag ϕ is then given by

$$\phi = 2\pi \frac{\Delta y}{\Delta f_{bw}},$$

wherein Δf_{bw} corresponds to the frequency sweep bandwidth that is necessary to observe a full oscillation of the term a_n.

[0103] The constants C_n and K_n are also extracted from the plot of amplitudes of two peaks of the calculated Fourier transform $A(\nu)$ in another step 248 of the method. Constant C_n represents the constant offset in Fig. 4, while constant K_n represents the amplitude of the oscillation. This is carried out for a plurality of different values for n, e.g. n = 1, 2, 3 ...for reduced error of measurement. The constants C_n and K_n provide information about amplitudes of the chest and abdominal region displacement.

[0104] The behavior of the determined and recorded values of the plurality of peaks of the calculated Fourier transform $A(\nu)$ is checked for periodicity in another step 250 as the carrier frequency is varied. If it is observed that the determined and recorded values of the plurality of peaks of the calculated Fourier transform $A(\nu)$ do not show a periodic behavior, then the configuration of the radar sensor system 10 and the subject 24 is such that $R_1 - R_2 \ll \lambda$. From Eq. (11b) one can obtain that the second term in the argument of the cosine function becomes negligible, which is more apparent if the term is rephrased, using the relation $\frac{1}{\lambda} = \frac{f}{c}$ for electromagnetic waves, to $4\pi \frac{R_1 - R_2}{\lambda}$.

[0105] Thus, a_n can be approximated by

$$a_n(f) \approx C_n(\bar{f}) + K_n(\bar{f})\cos(n\phi), \qquad \text{Eq. (12)}$$

wherein $\bar{f} = f_0 + \Delta f_{bw}/2$ is the mean value of the radar carrier frequency during the frequency sweep. In this case, the constants C_n and K_n and, by that, amplitudes of the chest and abdominal region displacements can directly be determined from Eq. (12), using the values of a_n for different values of n.

[0106] In the flowchart shown in Fig. 8, m_{th} denotes a predetermined threshold value for a maximum number of stepwise increases of the radar carrier frequency, that is necessary for a_n to undergo at least one full oscillation.

[0107] In another alternative embodiment of the method, values of at least three peaks of a calculated Fourier transform of an autocorrelation function of other received radar waves are determined and recorded. Fig. 5 shows a plot of values of the first five peaks of consecutive order of another calculated Fourier transform of an autocorrelation function of other received radar waves vs. a breathing amplitude (i.e. parameter $y = \frac{4\pi x_0}{\lambda}$) for a fixed radar carrier frequency. A chest breathing amplitude or an abdominal region breathing amplitude can be estimated by carrying out a ranking of the determined values of the peaks of the first three orders.

[0108] Considering a sinusoidal breathing pattern for demonstration purposes, the valuea_n of the nth order peak (i.e. the peak located at nf_b, wherein n is an integer and f_b the breathing frequency) is proportional to $J_n^2(4\pi\frac{x_0}{\lambda})$, with x_0 denoting the breathing displacement amplitude, λ the wavelength and J_n the nth order Bessel function of the first kind (for a sinusoidal breathing pattern). If, for a given wavelength and breathing amplitude, there are multiple peaks present in the Fourier transform of the autocorrelation function, one can carry out a ranking of the peaks according to their value. For example $a_2 > a_1 > a_3$, means that the value of peak of order $n = 2$ is the largest, followed by the value of the peak of order $n = 1$, which is the second largest, and then the third largest value is that of the peak of order $n = 3$. To verify this ranking in the plot of Fig. 5, the conditions of $J_2^2\left(4\pi\frac{x_0}{\lambda}\right) > J_1^2\left(4\pi\frac{x_0}{\lambda}\right) > J_3^2\left(4\pi\frac{x_0}{\lambda}\right)$ have to be met, and this only holds for the predetermined interval $2.5 < 4\pi\frac{x_0}{\lambda} < 3.05$ (other potential intervals are excluded by plausibility considerations). Thus, an estimate of the breathing displacement amplitude can be determined by identifying one out of a plurality of predetermined breathing amplitude intervals assigned to rankings of the peaks of the first three orders of the Fourier transform of the autocorrelation function.

[0109] Fig. 9 shows a flowchart of another alternative embodiment of a method in accordance with the invention of operating the radar sensor system 10 pursuant to Fig. 1 for monitoring a breathing motion of the subject 24.

[0110] In this embodiment of the method, the step 334 of operating the radar transmitting unit for transmitting radar waves includes transmitting a plurality of N+1 consecutive radar wave trains 30 as illustrated in Fig. 8. Each wave train 30 has a duration Δt and comprises a plurality of M+1 radar waves 32 of predetermined equal duration $\frac{\Delta \mathrm{t}}{M+1}$, wherein radar carrier frequencies f of each radar wave 32 of the plurality of M+1 radar waves 32 differ by an integral multiple of the predetermined frequency amount $\frac{\Delta f_{bw}}{M}$.

[0111] Time $t(m,n)$ and radar carrier frequency $f(m)$ of the mth radar wave 32 of the nth radar wave train 30 are given by

$$t(m,n) = n\Delta t + m\frac{\Delta t}{M}, m = 0,1,\ldots,M; n = 0,1,\ldots,N$$

$$f(m) = f_o + m\frac{\Delta f_{bw}}{M}, m = 0,1,\ldots,M, \qquad \text{Eq. (13)}$$

wherein f_0 denotes an initial radar carrier frequency. Thus, the step 334 of operating the radar transmitting unit includes a step 344 of changing the number of radar wavelengths in the path between the radar transmitting antenna 12, the subject 24 and the radar receiving antenna 16 by predetermined amounts by changing the radar carrier frequency of the radar sensor system. In the exemplary embodiment shown in Fig. 8, M equals 5.

[0112] Further, a step 336 of operating the radar receiving unit for receiving radar waves includes receiving radar waves 18 that have been reflected by the chest 26 and abdominal region 28 of the subject 24 for each radar wave 32 of the plurality of radar waves 32 and for each radar wave train 30 of the plurality of radar wave trains 30, i.e. at each point of time $t(m,n)$ as given in Eq. (13), and includes generating and recording received radar signals for each one of the received radar waves 32.

[0113] After the plurality of N+1 consecutive radar wave trains 30 has been transmitted and the radar signals recorded, which takes a measurement time T_{rec} of

$$T_{rec} = (N+1)\Delta t,$$

the autocorrelation function of the received radar signal is calculated in another step 338 of the method as a function of time t and radar carrier frequency f.

[0114] While in the embodiment of the method pursuant to Fig. 8, the radar signal needs to be recorded for every radar carrier frequency $f \in (f_0, f_0 + \Delta f_{bw})$ for a duration of e.g. 10 s, and thus may require a somewhat longer total measurement time, which is equal to the number of possible radar carrier frequencies times 10 s, in the embodiment of the method pursuant to Fig. 9, the total measurement time can be reduced to $T_{rec} \approx 10$ s, and, nevertheless, the radar signal values at different values of the radar carrier frequency $f \in (f_0, f_0 + \Delta f_{bw})$ and for the times $t(m,n) \in (0, T_{rec})$ have been recorded. In order to accomplish this shorter measurement time, the radar carrier frequency sweep shall be suitably and sufficiently fast in this embodiment.

[0115] In a next step 340, the Fourier transform or a similar transformation of the calculated autocorrelation function is calculated. A plurality of peaks of the calculated Fourier transform $A(\nu)$ is determined and recorded in another step 342.

[0116] In another step 350, the periodicity of the determined and recorded values of the plurality of peaks of the calculated Fourier transform $A(\nu)$ is checked either during a carrier frequency sweep or during radar displacement. If a periodic behavior is detected, a phase lag ϕ between the breathing motion of the chest 26 and the abdominal region 28 of the subject 24 is derived in another step 346 as described for the embodiment pursuant to Fig. 6. Also, constants C_n and K_n are extracted from the plot of amplitudes of two peaks of the calculated Fourier transform $A(\nu)$ in another step 348 of the method as described for the embodiment pursuant to Fig. 8.

[0117] If it is observed that the determined and recorded values of the plurality of peaks of the calculated Fourier transform $A(\nu)$ do not show a periodic behavior, the constants C_n and K_n and, by that, amplitudes of the chest and abdominal region displacements can directly be determined from Eq. (12), using the values of a_n for different values of n.

[0118] In yet another possible embodiment the carrier frequency does not need to be changed and the chest and abdomen displacement amplitudes can be pre-determined (e.g. by pulse radar, ultrasound etc.). In this specific embodiment the phase lag between the chest and abdominal motion is then extracted by comparing the pattern of the Fourier transform of the autocorrelation function to the library of patterns for different values of phase lag, until the best match is found, see for example illustrated in Fig. 11.

[0119] Fig. 11 shows the simulation of the Fourier transform of the autocorrelation function for the chest-abdomen phase lag of $\phi = \pi/4$ and unequal chest and abdomen amplitudes. Herein, f_b denotes the breathing frequency. We have taken equal chest and abdomen equilibrium distances $R_1 = R_2$, equal chest and abdomen radar cross sections and $x_0^1 = 4.68mm$ and $x_0^2 = 3.12mm$ for the displacement amplitudes. The carrier frequency was chosen to be 24 GHz. As expected from theory, see Eq. (11b), the ratio of peaks is $\frac{a_2}{a_1} = 5.45$, and $\frac{a_3}{a_1} = 1.79$, $\frac{a_4}{a_1} = 1.02$, and $\frac{a_5}{a_1} = 0.778$. There is an excellent agreement between the analytics and simulations.

[0120] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments.

[0121] Other variations to be disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, the disclosure, and the appended claims. In the claims, the word “comprising” does not exclude other elements or steps, and the indefinite article “a” or “an” does not exclude a plurality, which is meant to express a quantity of at least two. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage. Any reference signs in the claims should not be construed as limiting scope.

List of Reference Symbols

10	radar sensor system	22	evaluation and control unit
12	radar transmitting antenna	24	subject
14	transmitted radar waves	26	chest
16	radar receiving antenna	28	abdominal region
18	reflected radar waves	30	wave train
20	transceiver unit	32	radar wave

Steps of

34	transmit radar waves
36	receive radar waves and record radar signals
38	calculate autocorrelation function of received radar signal
40	calculate Fourier transform of autocorrelation function
42	record values of peaks of calculated Fourier transform
44	change number of radar wavelengths in path to subject
46	derive phase lag
48	extract breathing amplitudes
50	check for periodicity
$\mathrm{A}(\nu)$	Fourier transform of autocorrelation function
ν	Fourier frequency component
$\mathrm{a_n}$	height of nth peak of Fourier transform $\mathrm{A}(\nu)$
$\mathrm{C_n}$	constant offset
$\overline{\Delta f_n}$	radar carrier frequency difference between extrema of a_n and a_{-n}
$(\mathrm{f_0}), \mathrm{f}$	(initial) radar carrier frequency
$\mathrm{f_b}$	chest and abdominal region motion frequency
$\Delta \mathrm{f_{bw}}$	frequency sweep bandwidth for full oscillation
ϕ	phase lag between breathing motions of chest and abdominal region of subject
$\mathrm{K_n}$	amplitude of oscillation
$\Delta \mathrm{R}$	difference of average distances between chest and abdominal region to radar sensor system
$\Delta \mathrm{x}$	distance between maximum of nth peak and (n+1)th peak
$\Delta \mathrm{y}$	difference $\Delta \mathrm{y}$ of radar carrier frequencies between maximum of nth peak and (n+1)th peak

Claims

1. A method of operating a radar sensor system (10) for monitoring a breathing motion of a subject (24), the radar sensor system (10) including a radar transmitting unit having one radar transmitting antenna (12) and being configured for transmitting radar waves (14) towards the subject (24), a radar receiving unit having one radar receiving antenna (16) and being configured for receiving radar waves (18) that have been transmitted by the radar transmitter unit and have been reflected by the subject (24), and an evaluation and control unit (22) that is at least configured for evaluating Doppler information from the radar waves (18) received by the radar receiving unit,
   the method comprising at least steps of

   - operate (34) the radar transmitting unit for at least once transmitting radar waves (14) of a predetermined radar carrier frequency (f) for a specified time towards a chest (26) and an abdominal region (28) of the subject (24),
   - operate (36) the radar receiving unit at least once for a specified time for receiving radar waves (18) that have been transmitted by the radar transmitting unit and that have been reflected by the chest (26) and the abdominal region (28) of the subject (24), and for generating received radar signals from the received radar waves (18),
   - calculate (38) the autocorrelation function of the received radar signals,
   - calculate (40) the Fourier transform $A(\nu)$ of the calculated autocorrelation function,
   - determine and record (42) values of at least two peaks of the calculated Fourier transform $A(\nu)$, and
   - from the recorded determined values of the at least two peaks, determine (46, 48) at least one breathing-characteristic parameter of the breathing motion of the subject (24).

2. The method as claimed in claim 1, further comprising steps of

   - after the step of determining and recording (42) values of at least two peaks, change (44) the number of radar wavelengths in the path between the radar transmitting antenna (12), the subject (24) and the radar receiving antenna (16) at least once by a predetermined amount, and

- iteratively carry out at least steps (34, 36, 42, 44) until at least one extreme value is detected for the determined values of each one the at least two peaks.

3. The method as claimed in claim 1 or 2, wherein the step (44) of changing the number of radar wavelengths in the path includes carrying out a predetermined displacement along a predetermined direction of at least one out of the radar transmitting antenna (12) and the radar receiving antenna (16) relative to the subject (24).

4. The method as claimed in any one of the preceding claims, wherein the step (44) of changing the number of radar wavelengths in the path includes changing a radar carrier frequency (f_0, f) of the radar sensor system (10) by a predetermined amount.

5. The method as claimed in claim 4, wherein

   - the step (34) of operating the radar transmitting unit for transmitting radar waves (14) includes transmitting a plurality of consecutive radar wave trains (30), each wave train (30) comprising a plurality of radar waves (32) of predetermined duration, wherein radar carrier frequencies (f_0, f) of each radar wave (32) of the plurality of radar waves (32) differ by an integral multiple of the predetermined amount, and
   - the step (36) of operating the radar receiving unit for receiving radar waves includes receiving radar waves (18) that have been reflected by the chest (26) and abdominal region (28) of the subject (24) for each radar wave (32) of the plurality of radar waves (32) and for each radar wave train (30) of the plurality of radar wave trains (30), and includes generating and recording received radar signals for each one of the received radar waves (32).

6. The method as claimed in any one of the preceding claims, wherein the step (44) of changing the number of radar wavelengths in the path is carried out until at least one minimum value and one maximum value is recorded for the determined values of each one of the at least two peaks of the calculated Fourier transform $A(\nu)$ of the autocorrelation function $A(\tau)$.

7. The method as claimed in any one of the preceding claims, wherein the step (48) of determining a chest breathing amplitude or an abdominal region breathing amplitude includes correcting the at least one extreme value for the determined values of one of the at least two peaks by an offset value determined from the recorded determined values of the one of the at least two peaks and/or evaluating information contained in said offset value.

8. The method as claimed in any one claims 2 to 6, wherein the step of determining and recording (42) values of at least two peaks of the calculated Fourier transform $A(\nu)$ includes determining and recording values of a peak of order n and values of a peak of order -n of the calculated Fourier transform $A(\nu)$, and wherein the step of determining at least one breathing-characteristic parameter of the breathing motion of the subject (24) includes determining a phase lag (ϕ) between breathing motions of the chest and the abdominal region of the subject by determining a difference of the radar carrier frequencies at which extreme values of the peak of order n and the peak of order -n occur.

9. The method as claimed in claim 1, wherein the step of determining and recording (42) values of at least two peaks of the calculated Fourier transform $A(\nu)$ comprises determining and recording a plurality of at least two additional peaks of the calculated Fourier transform $A(\nu)$ representing higher order harmonics with respect to the at least two peaks, wherein the step of determining (46, 48) comprises determining at least one out of determining a chest breathing amplitude and an abdominal region breathing amplitude, and further comprises determining a standstill of the at least one out of a chest breathing amplitude and an abdominal region breathing amplitude by comparing recorded values of the plurality of at least two additional peaks of the calculated Fourier transform $A(\nu)$ with predetermined threshold values for the plurality of at least two additional peaks of the calculated Fourier transform $A(\nu)$, and by detecting that recorded values of the plurality of at least two additional peaks of the calculated Fourier transform $A(\nu)$ exceed the predetermined threshold values for a predetermined period of time.

10. The method as claimed in claim 1, wherein the step of determining and recording (42) comprises determining and recording values of at least three

peaks of the calculated Fourier transform $A(\nu)$, and wherein the step of determining (46, 48) includes determining one out of a plurality of predetermined breathing amplitude intervals based on carrying out a ranking of the determined values of the at least three peaks.

11. The method as claimed in any one of the preceding claims, further comprising steps of

    - comparing the determined at least one out of phase lag (ϕ), chest breathing amplitude and abdominal region breathing amplitude with at least one predetermined threshold value, and
    - generating an output signal representing a breathing status of the subject (24).

12. A radar sensor system (10) for monitoring a breathing motion of a subject (24), the radar sensor system (10) comprising

    - a radar transmitting unit having one radar transmitting antenna (12) and being configured for transmitting radar waves (14) of a predetermined radar carrier frequency (f_0, f) towards a chest (26) and an abdominal region (28) of the subject (24),
    - a radar receiving unit having one radar receiving antenna (16) and being configured for receiving radar waves (18) that have been transmitted by the radar transmitter unit and have been reflected by the subject (24), and
    - an evaluation and control unit (22) that is at least configured for evaluating Doppler information from the radar waves (18) received by the radar receiving unit, and that is further configured to automatically execute steps of the method as claimed in any one of the preceding claims.

13. The radar sensor system (10) as claimed in claim 12, wherein the predetermined radar carrier frequency (f_0, f) is lying in a frequency range between 15 GHz and 130 GHz and more preferably in a frequency range between 57 GHz and 64 GHz.

14. The radar sensor system (10) as claimed in claims 12 or 13, wherein the radar transmitting antenna (12) is configured to have a main lobe that is able to cover a major part of the chest (26) and the abdominal region (28) of the subject (24).

15. A software module for controlling automatic execution of the method as claimed in any one of claims 1 to 11, wherein method steps to be conducted are converted into a program code of the software module, wherein the program code is implementable in a digital data memory unit of the radar sensor system or a separate control unit and is executable by a processor unit of the radar sensor system or a separate control unit.

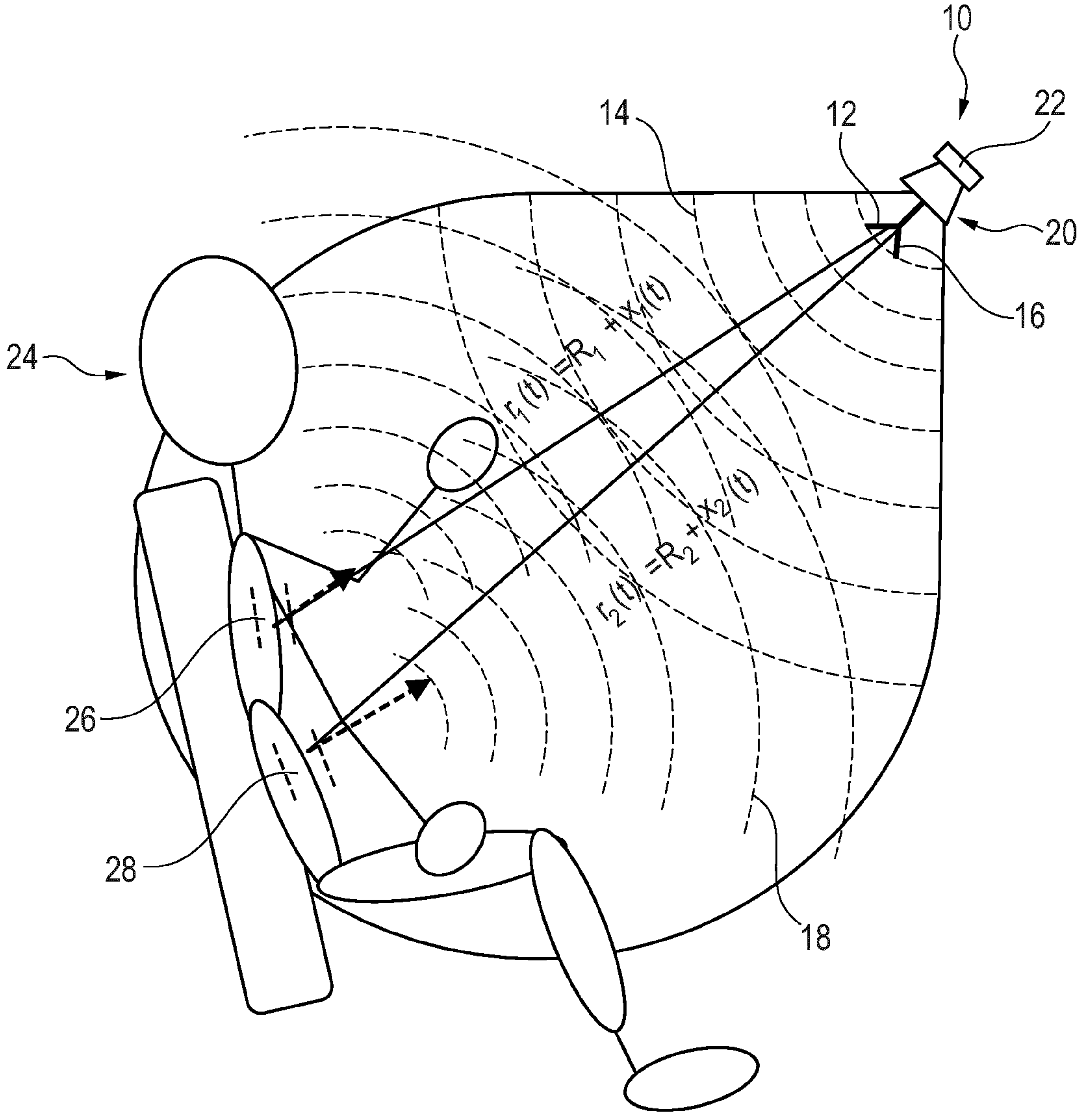

Fig. 1

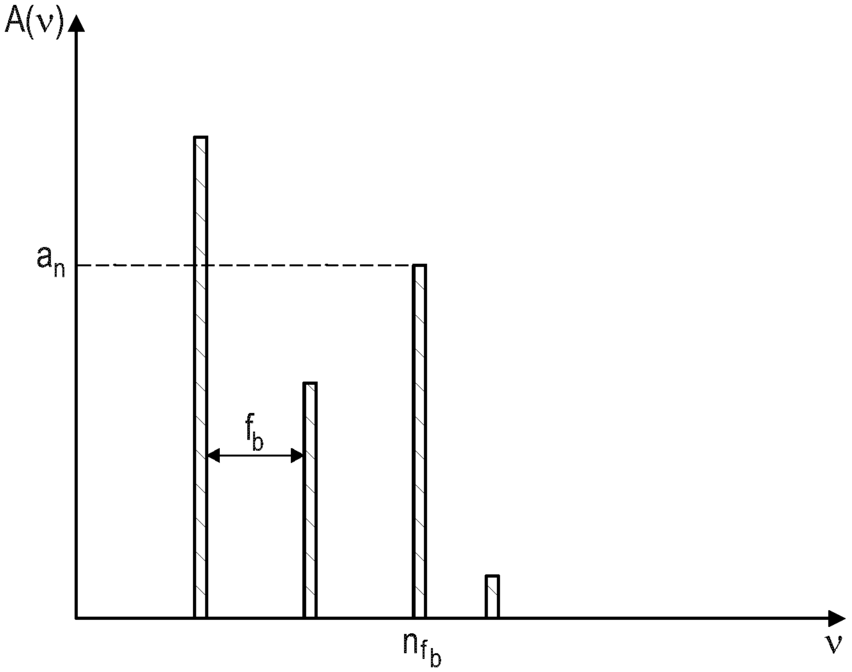
A(ν)
a_n
f_b
n_{f_b}
ν

Fig. 2a

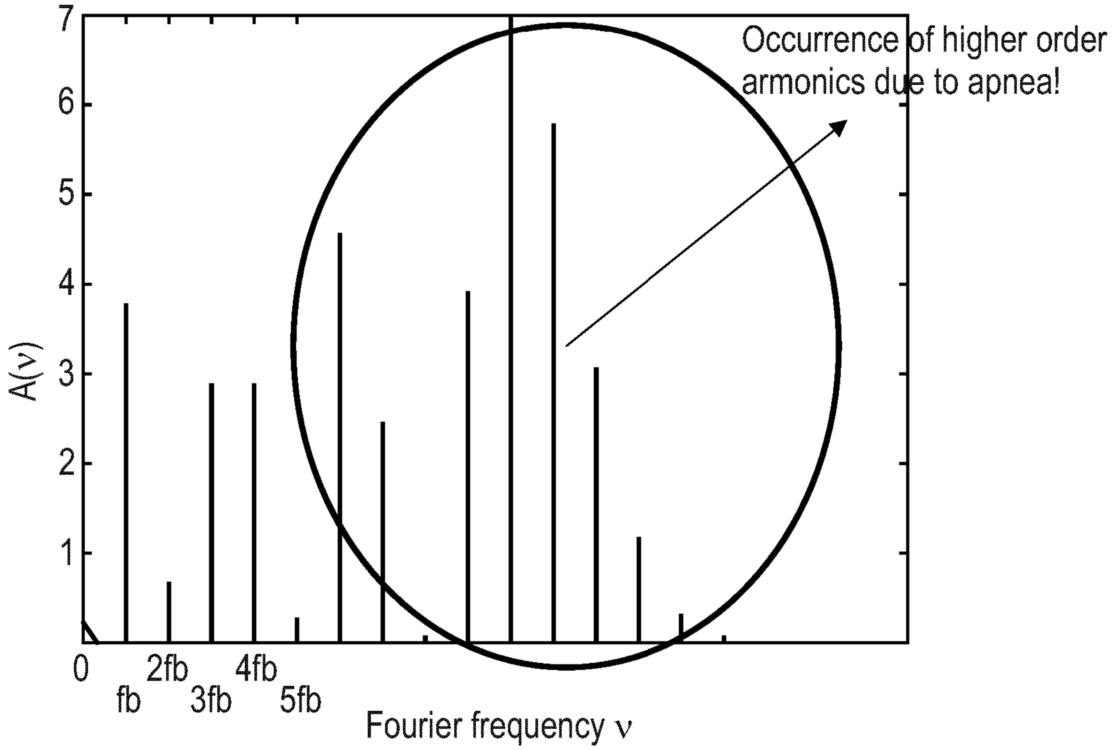
7
6
5
4
3
2
1
0
fb
2fb
3fb
4fb
5fb
A(ν)
Fourier frequency ν
Occurrence of higher order armonics due to apnea!

Fig. 2b

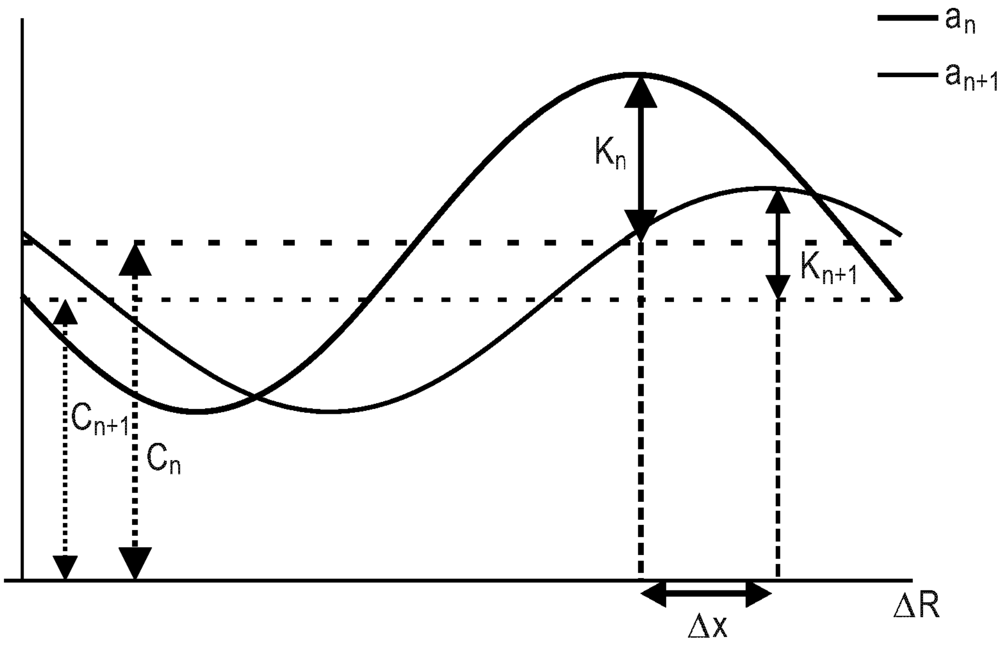
a_n
a_{n+1}
K_n
K_{n+1}
C_{n+1}
C_n
Δx
ΔR

Fig. 3

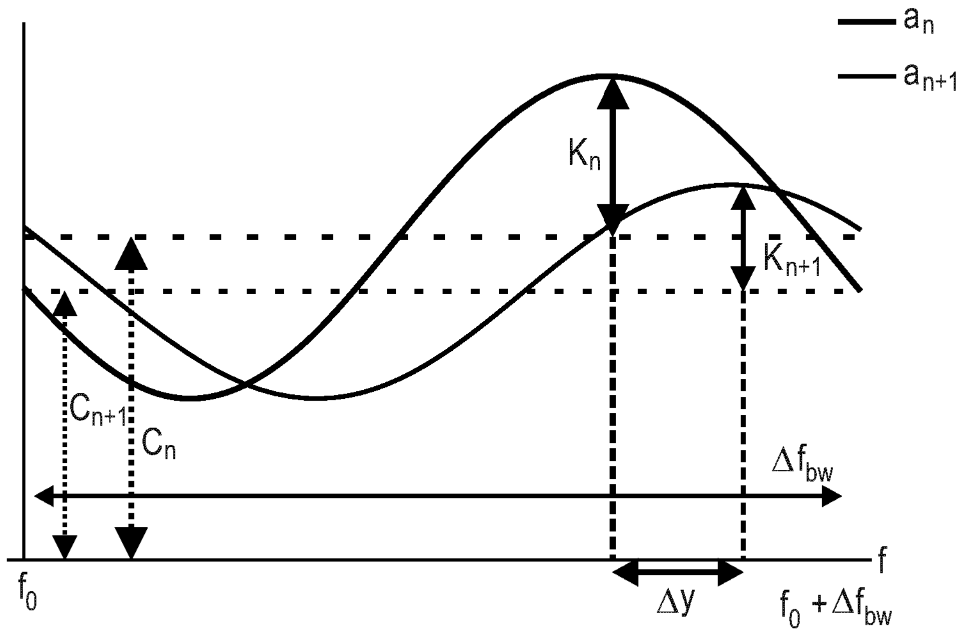
a_n
a_{n+1}
K_n
K_{n+1}
C_{n+1}
C_n
Δf_{bw}
f
f_0
Δy
$f_0 + \Delta f_{bw}$

Fig. 4

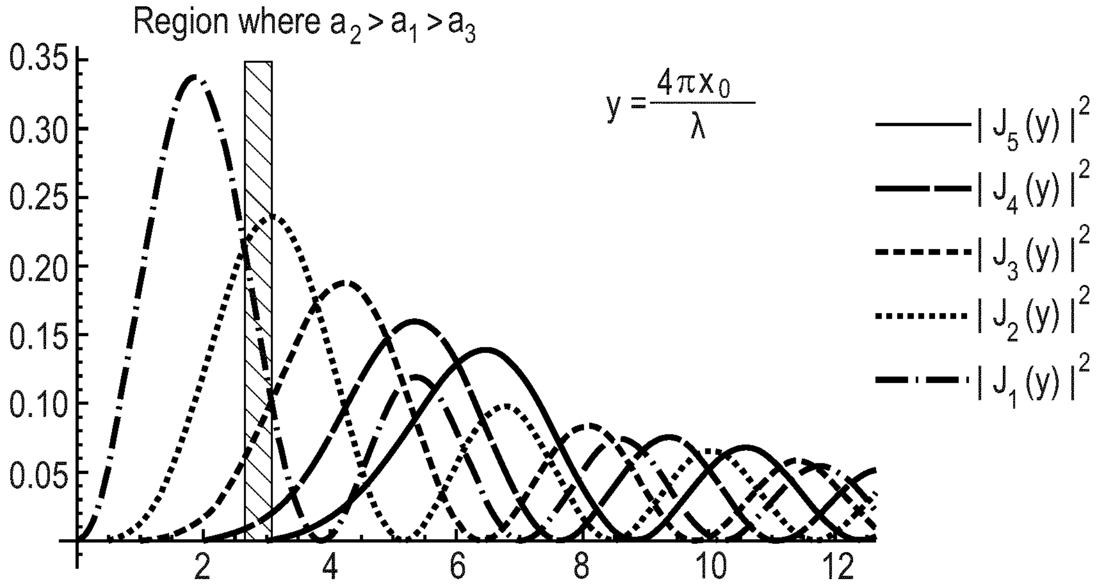
Region where $a_2 > a_1 > a_3$
$y = \frac{4\pi x_0}{\lambda}$
$|J_5(y)|^2$
$|J_4(y)|^2$
$|J_3(y)|^2$
$|J_2(y)|^2$
$|J_1(y)|^2$
0.35
0.30
0.25
0.20
0.15
0.10
0.05
2
4
6
8
10
12

Fig. 5

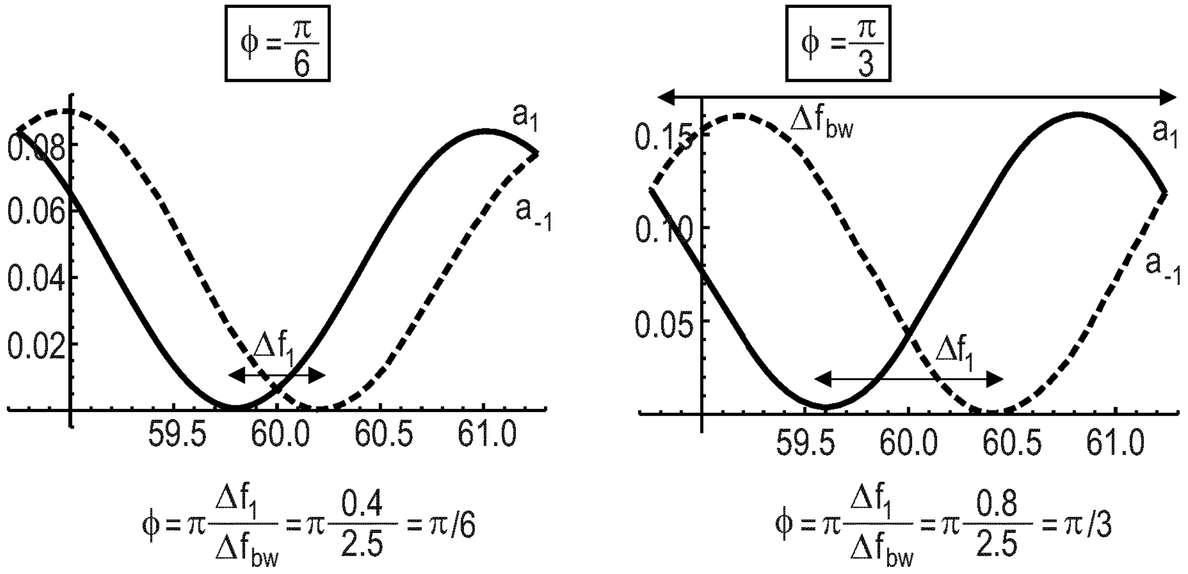
$\phi = \frac{\pi}{6}$
a_1
a_{-1}
0.08
0.06
0.04
0.02
Δf_1
59.5
60.0
60.5
61.0
$\phi = \pi\frac{\Delta f_1}{\Delta f_{bw}} = \pi\frac{0.4}{2.5} = \pi/6$
$\phi = \frac{\pi}{3}$
Δf_{bw}
a_1
a_{-1}
0.15
0.10
0.05
Δf_1
59.5
60.0
60.5
61.0
$\phi = \pi\frac{\Delta f_1}{\Delta f_{bw}} = \pi\frac{0.8}{2.5} = \pi/3$

Fig. 6

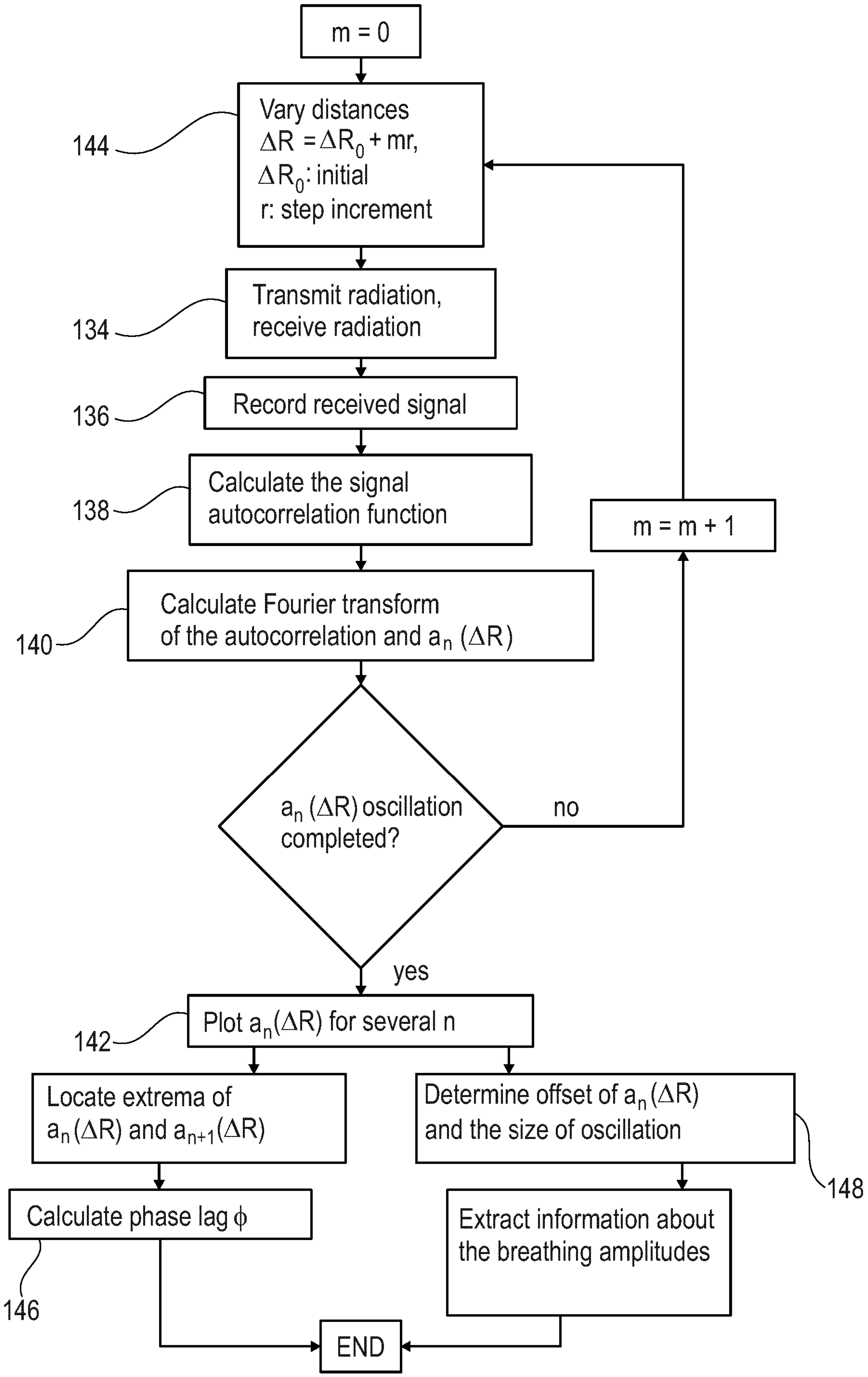
m = 0
Vary distances
$\Delta R = \Delta R_0 + mr$,
ΔR_0: initial
r: step increment
144
Transmit radiation, receive radiation
134
Record received signal
136
Calculate the signal autocorrelation function
138
Calculate Fourier transform of the autocorrelation and $a_n(\Delta R)$
140
$a_n(\Delta R)$ oscillation completed?
no
m = m + 1
yes
Plot $a_n(\Delta R)$ for several n
142
Locate extrema of $a_n(\Delta R)$ and $a_{n+1}(\Delta R)$
Determine offset of $a_n(\Delta R)$ and the size of oscillation
148
Calculate phase lag ϕ
146
Extract information about the breathing amplitudes
END

Fig. 7

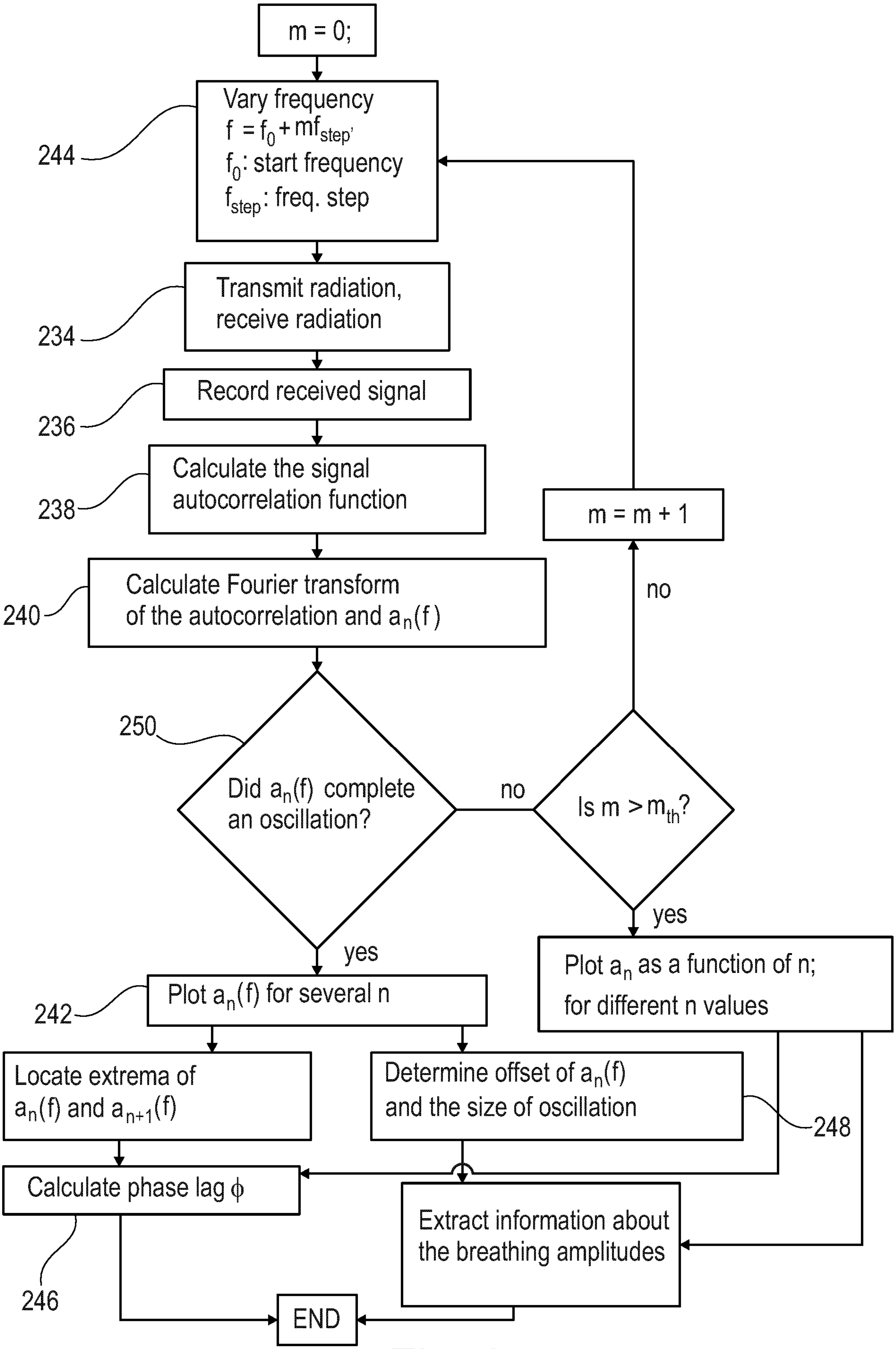
m = 0;
Vary frequency
$f = f_0 + mf_{step}$,
f_0: start frequency
f_{step}: freq. step
244
Transmit radiation, receive radiation
234
Record received signal
236
Calculate the signal autocorrelation function
238
Calculate Fourier transform of the autocorrelation and $a_n(f)$
240
250
Did $a_n(f)$ complete an oscillation?
no
Is $m > m_{th}$?
no
m = m + 1
yes
yes
Plot $a_n(f)$ for several n
242
Plot a_n as a function of n; for different n values
Locate extrema of $a_n(f)$ and $a_{n+1}(f)$
Determine offset of $a_n(f)$ and the size of oscillation
248
Calculate phase lag ϕ
246
Extract information about the breathing amplitudes
END

Fig. 8

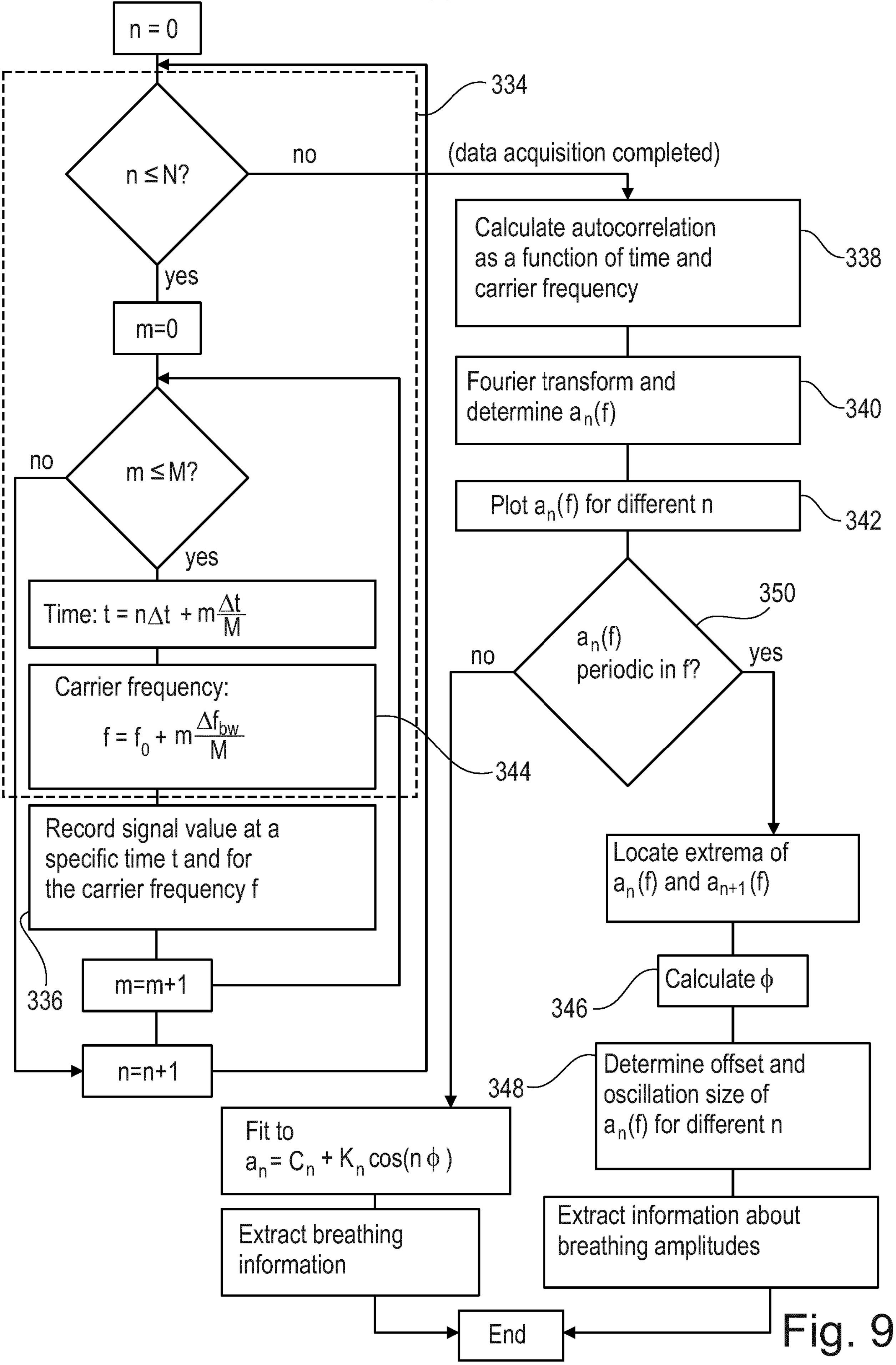
n = 0
334
n ≤ N?
no
(data acquisition completed)
yes
m=0
Calculate autocorrelation as a function of time and carrier frequency
338
Fourier transform and determine $a_n(f)$
340
Plot $a_n(f)$ for different n
342
no
m ≤ M?
yes
350
Time: $t = n\Delta t + m\frac{\Delta t}{M}$
$a_n(f)$ periodic in f?
no
yes
Carrier frequency: $f = f_0 + m\frac{\Delta f_{bw}}{M}$
344
Record signal value at a specific time t and for the carrier frequency f
Locate extrema of $a_n(f)$ and $a_{n+1}(f)$
336
m=m+1
Calculate ϕ
346
n=n+1
348
Determine offset and oscillation size of $a_n(f)$ for different n
Fit to $a_n = C_n + K_n \cos(n\phi)$
Extract breathing information
Extract information about breathing amplitudes
End

Fig. 9

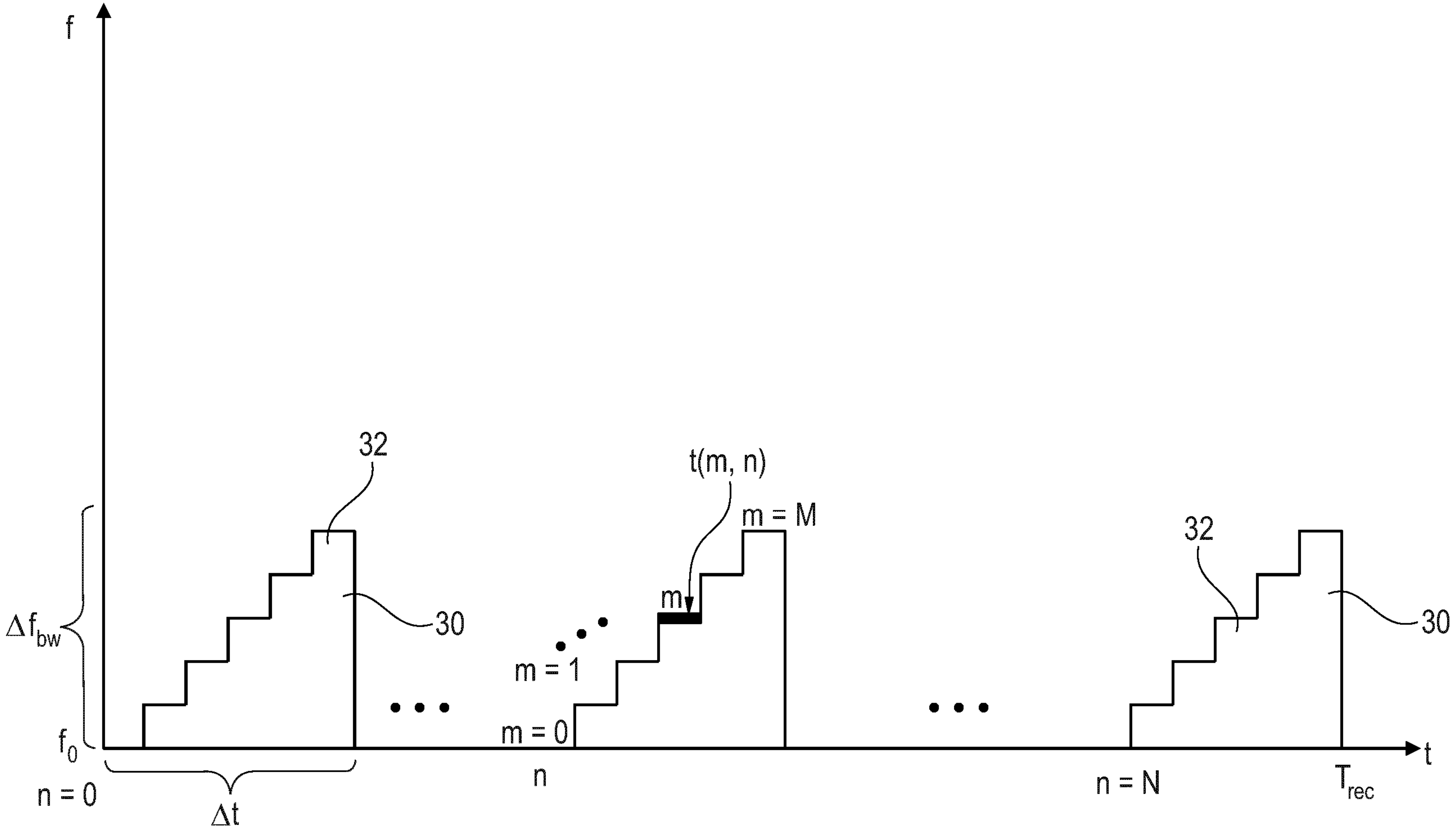

Fig. 10

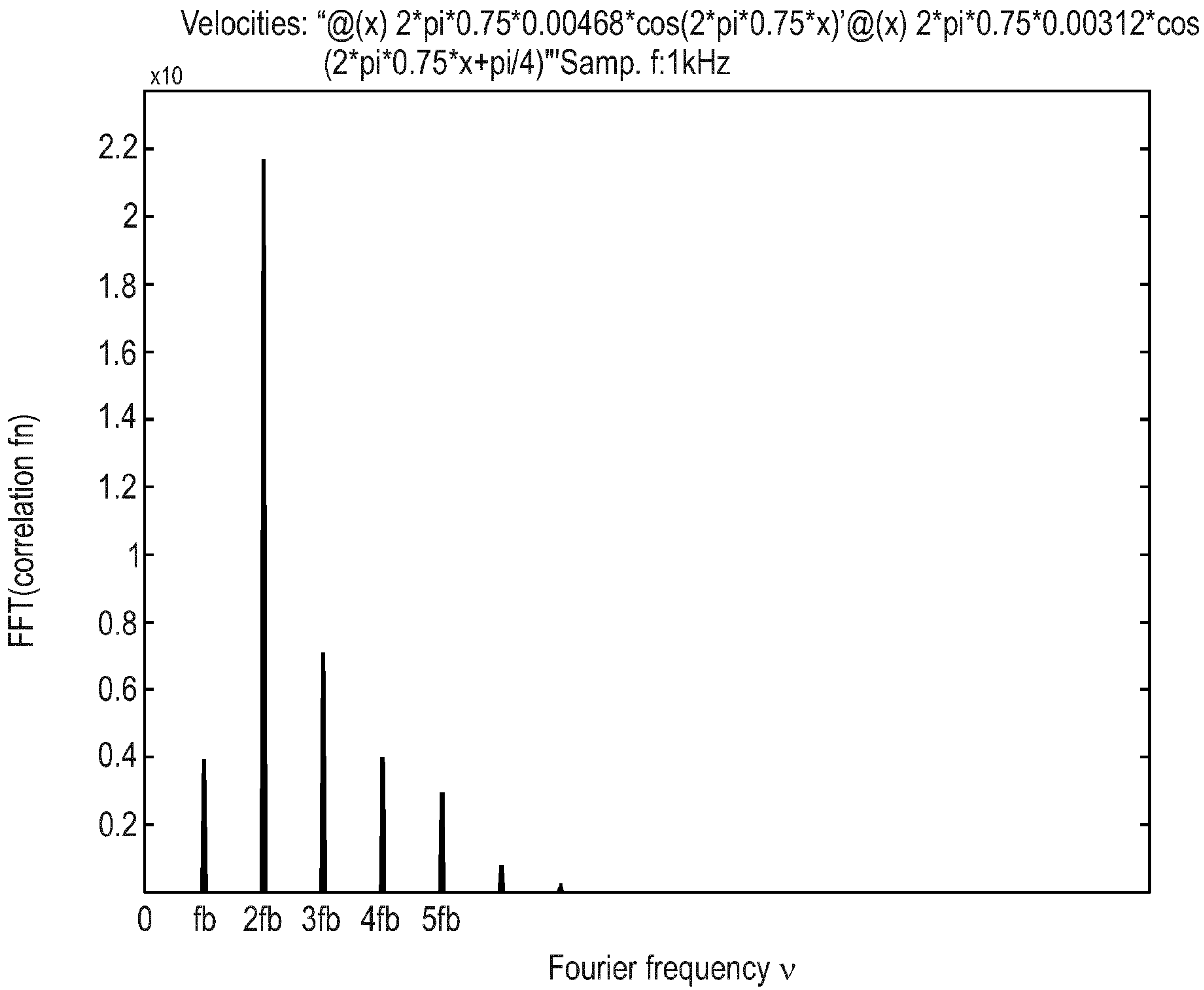
Velocities: “@(x) 2*pi*0.75*0.00468*cos(2*pi*0.75*x)’@(x) 2*pi*0.75*0.00312*cos
(2*pi*0.75*x+pi/4)”'Samp. f:1kHz
x10
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
FFT(correlation fn)
0
fb
2fb
3fb
4fb
5fb
Fourier frequency ν

Fig. 11

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2018/066456

A. CLASSIFICATION OF SUBJECT MATTER

INV. A61B5/18 A61B5/05 A61B5/08 A61B5/113 G01S13/88

ADD. A61B5/00

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)

A61B G01S

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 2010/152600 A1 (DROITCOUR AMY [US] ET AL) 17 June 2010 (2010-06-17) abstract; figure 1A paragraphs [0013], [0027], [0060], [0438] - [0440], [0502] the whole document -----	1,12-15 2-11
A	LEE YEE SIONG ET AL: "Detection of respiratory paradoxical movement via Doppler radar measurements", 7TH INTERNATIONAL CONFERENCE ON INFORMATION AND AUTOMATION FOR SUSTAINABILITY, IEEE, 22 December 2014 (2014-12-22), pages 1-5, XP032752810, DOI: 10.1109/ICIAFS.2014.7069602 the whole document ----- -/--	1-15

☒ 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

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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 13 August 2018	Date of mailing of the international search report 21/08/2018
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Furlan, Stéphane

1

International application No
PCT/EP2018/066456

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2016/200276 A1 (DIEWALD ANDREAS [DE]) 14 July 2016 (2016-07-14) paragraphs [0121] - [0135] abstract -----	1-15

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2018/066456

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2010152600 A1	17-06-2010	US 2010152600 A1	17-06-2010
		US 2010240999 A1	23-09-2010
		US 2010249630 A1	30-09-2010
		US 2010249633 A1	30-09-2010
		US 2010292568 A1	18-11-2010
		WO 2010132850 A1	18-11-2010
US 2016200276 A1	14-07-2016	CN 105452898 A	30-03-2016
		EP 3033634 A1	22-06-2016
		US 2016200276 A1	14-07-2016
		WO 2015022358 A1	19-02-2015

专利名称(译)	基于雷达的传感器系统和信号自相关功能进行呼吸监测的系统和方法		
公开(公告)号	EP3641649A1	公开(公告)日	2020-04-29
申请号	EP2018731115	申请日	2018-06-20
[标]申请(专利权)人(译)	IEE国际电子工程股份公司		
申请(专利权)人(译)	IEE国际电子与工程S.A.		
当前申请(专利权)人(译)	IEE国际电子与工程S.A.		
[标]发明人	KARAHASANOVIC UNA TATARINOV DIMITRI LAMESCH LAURENT KHAN MUHAMMAD ZEESHAN		
发明人	KARAHASANOVIC, UNA TATARINOV, DIMITRI LAMESCH, LAURENT KHAN, MUHAMMAD-ZEESHAN		
IPC分类号	A61B5/18 A61B5/05 A61B5/08 A61B5/113 G01S13/88 A61B5/00		
CPC分类号	A61B5/0507 A61B5/0816 A61B5/0826 A61B5/113 A61B5/18 A61B5/6893 A61B2503/045 A61B2503/22 G01S13/586 G01S13/88		
优先权	100324 2017-06-22 LU 100438 2017-09-11 LU 100633 2017-12-28 LU		
外部链接	Espacenet		

摘要(译)

一种用于监视对象（24）的呼吸运动的雷达传感器系统（10）的方法。雷达传感器系统（10）包括一个雷达发射天线（12）和一个雷达接收天线（16）以及评估和控制单元（22），用于评估来自接收到的雷达波（18）的多普勒信息。 该方法包括朝着对象（24）的胸部（26）和腹部区域（28）发射雷达波（14），接收由对象（24）反射的雷达波（18），计算（38）自相关函数 接收的雷达信号，计算（40）计算的自相关函数的傅立叶变换A（y），确定并记录（42）计算的傅立叶变换A（y）的至少两个峰值的值，并从记录的 确定至少两个峰值的值，确定（46、48）受试者的呼吸运动的至少一个呼吸特性参数（24）。