



Ultrasound Flow Imaging

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(54) **ULTRASOUND FLOW IMAGING**

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(57) **ABSTRACT**

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An ultrasound imaging system includes a transducer array (102) with a plurality of transducer elements (106) configured to transmit an ultrasound signal, receive echo signals produced in response to the ultrasound signal interacting with stationary structure and flowing structure, and generate electrical signals indicative of the echo signals. The system further includes a beamformer (112) configured to process the electrical signals and generate sequences, in time, of beamformed data. The system further includes a filter (118) configured to process the beamformed data, and remove or replace a set of frequency components based on a threshold, producing corrected beamformed data. The system further includes a flow processor (120) configured to estimate a velocity of flowing structure from the corrected beamformed data. The system further includes a rendering engine (224) configured to display the flow velocity estimate on a display (124).

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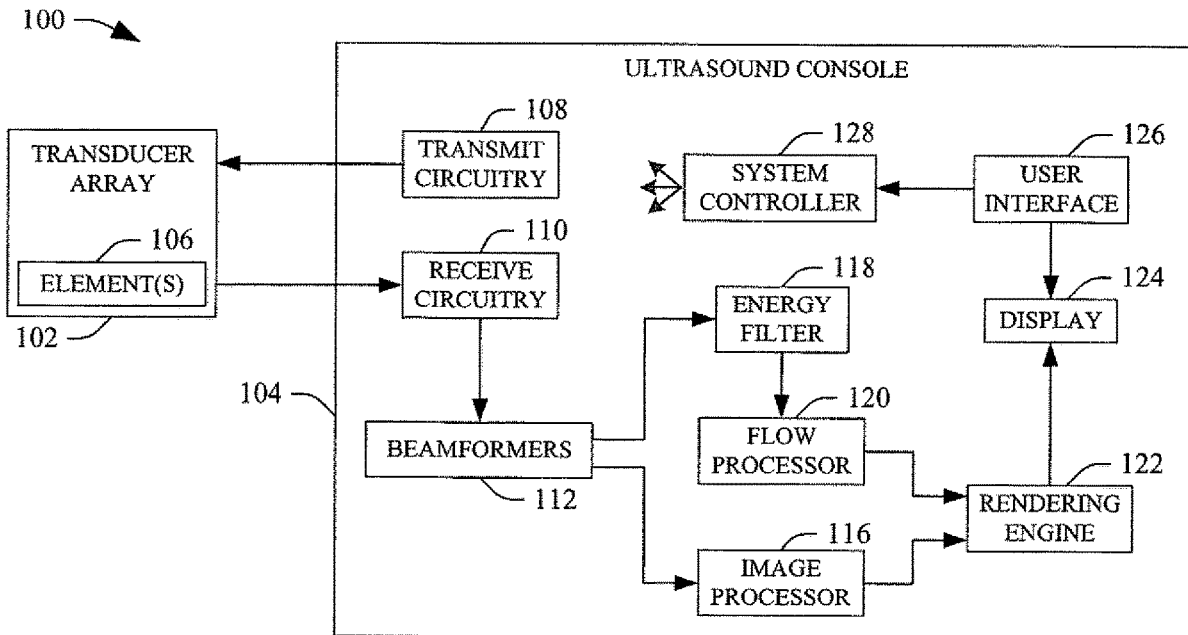
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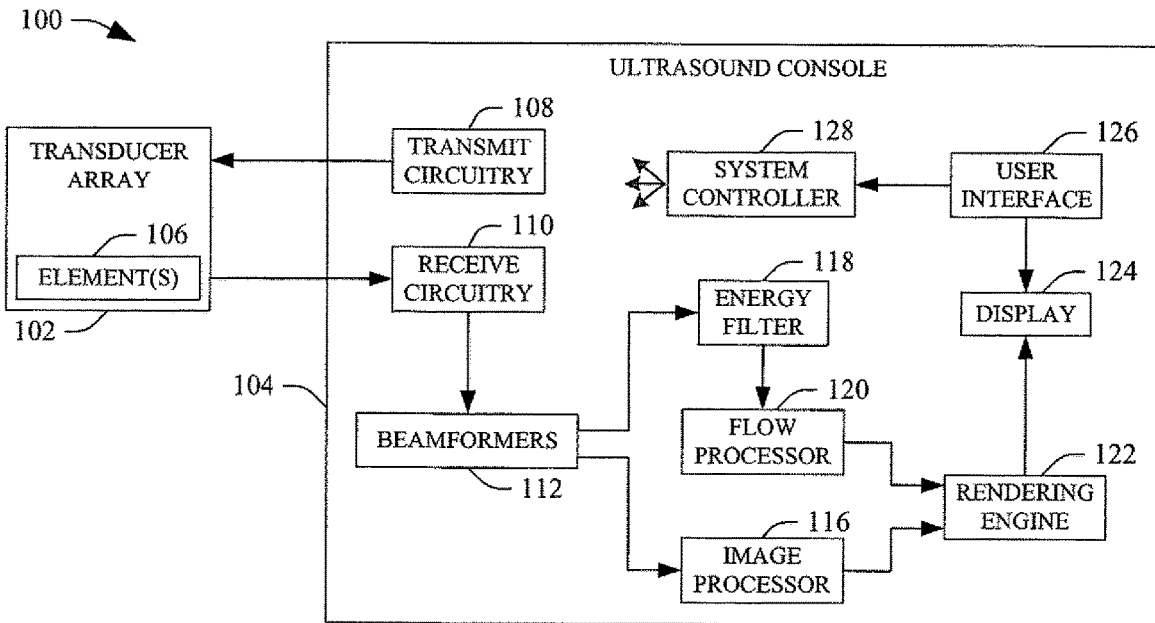


FIGURE 1

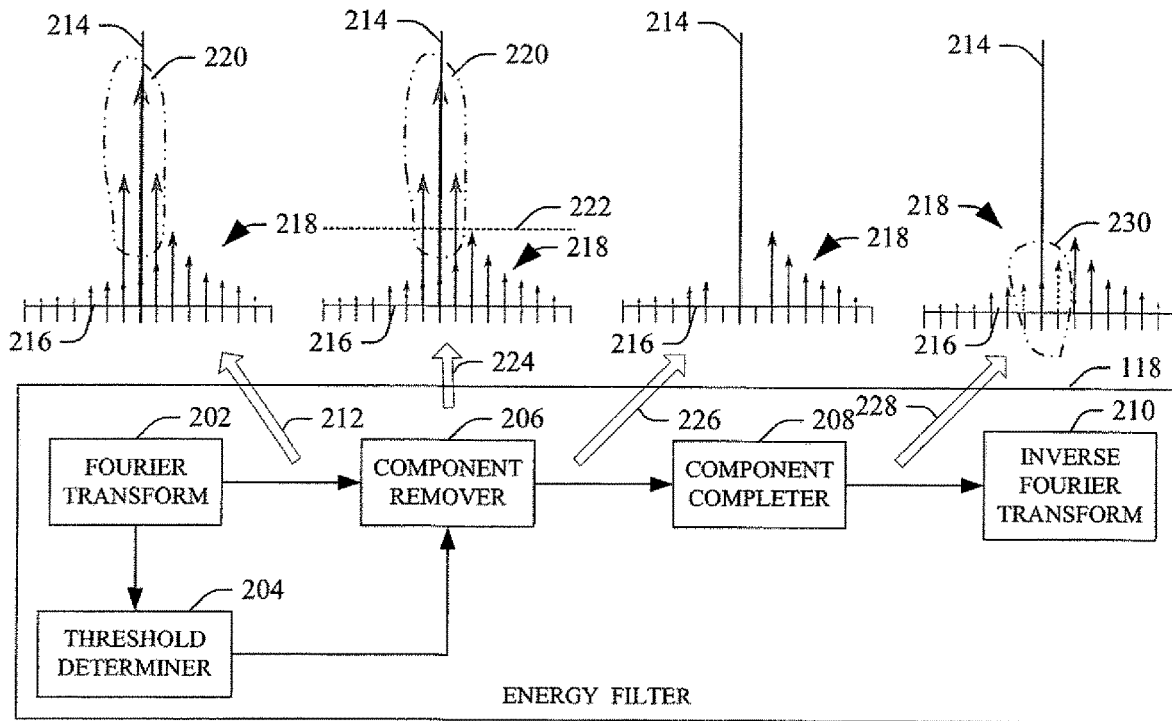


FIGURE 2

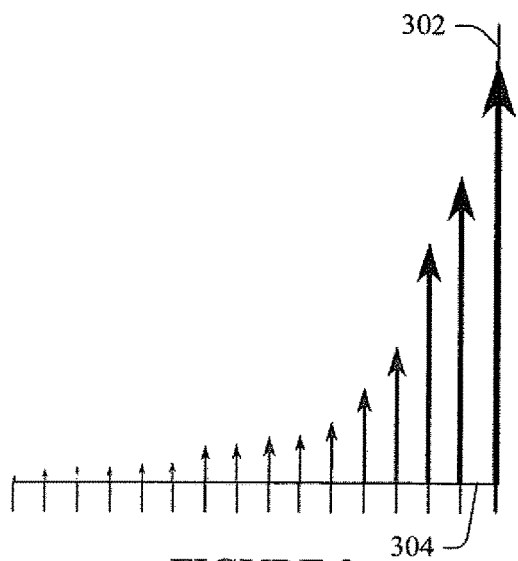


FIGURE 3

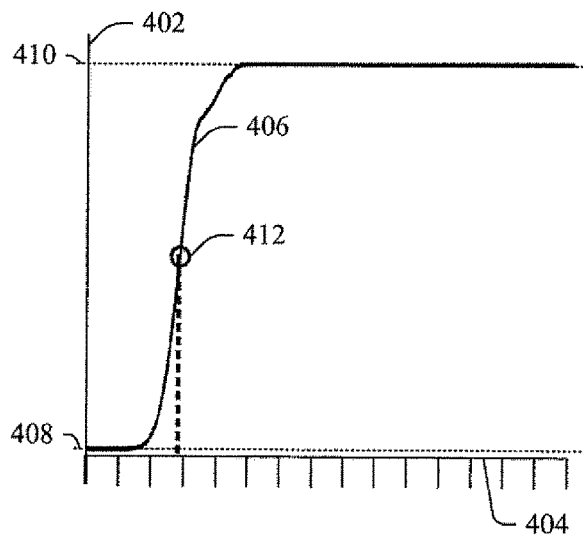


FIGURE 4

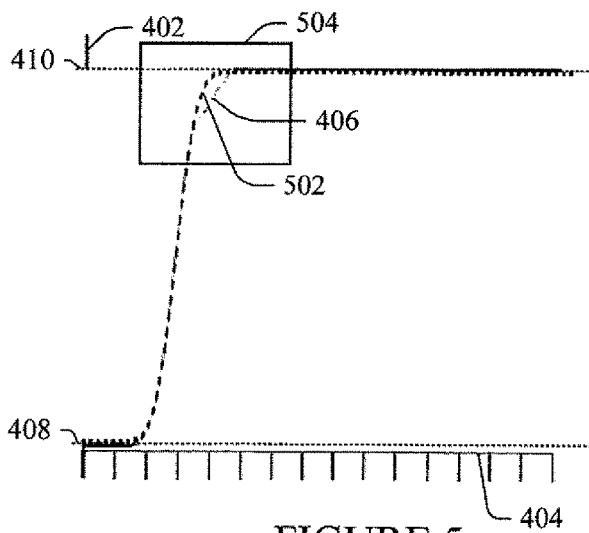


FIGURE 5

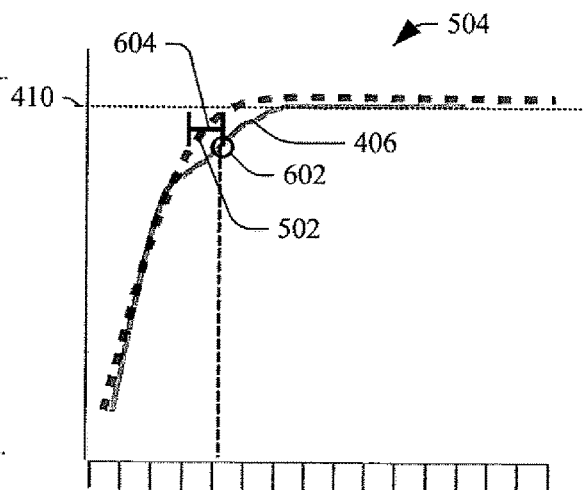


FIGURE 6

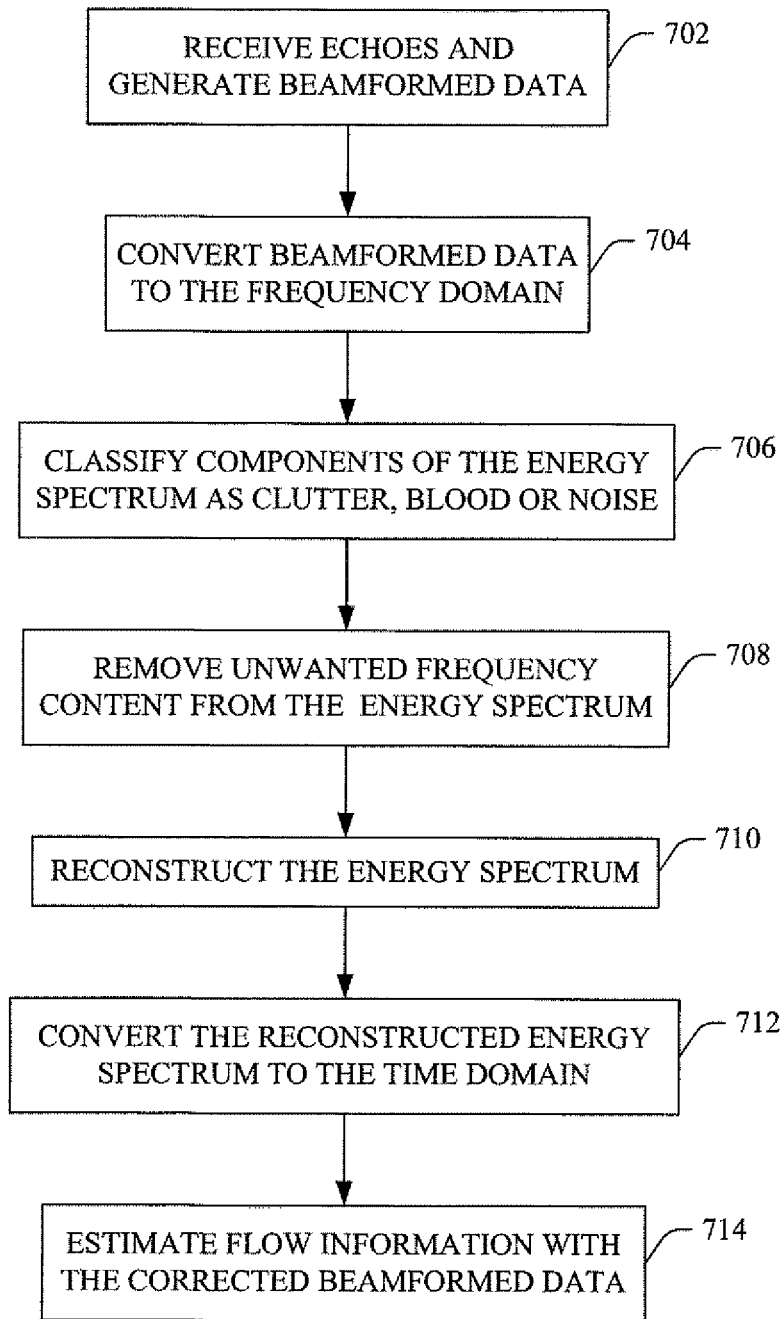


FIGURE 7

ULTRASOUND FLOW IMAGING

TECHNICAL FIELD

[0001] The following generally relates to ultrasound imaging and more particularly to ultrasound flow imaging.

BACKGROUND

[0002] Ultrasound imaging provides a real-time image of information about the interior of a subject such as organs, tissue, etc. Ultrasound imaging also allows for estimating flow, e.g., of flowing or moving structure such as blood cells. Flow estimation approaches allow for flow estimation at a time-resolution near the pulse repetition frequency (e.g., on the order of milliseconds). Synthetic aperture imaging flow allows for continuous data sets that enables the use of more advanced filtering methods, motion compensation algorithms, and high frame rate imaging. This leads the way for a wider application range of medical ultrasound, including for instance: perfusion imaging of the kidneys, studying flow in vascularized tumors, or measuring blood velocities in the coronary arteries without any contrast agent.

[0003] However, such applications can be affected by the movement of stationary tissue, which dominates the signal from the smaller vasculatures. Unfortunately, a challenge in velocity estimation is the cancellation of stationary tissue signal (clutter) to enhance the low signal from blood cells. For example, the literature states that since the frequency content of the signal from blood is strongly dependent on the flow angle, it is in general not possible to choose a single cut off frequency that discriminates between stationary tissue and slow flowing structure. Furthermore, low flow velocities result in a Doppler frequency spectrum that is similar to tissue.

SUMMARY

[0004] Aspects of the application address the above matters, and others.

[0005] In one aspect, an ultrasound imaging system includes a transducer array with a plurality of transducer elements configured to transmit an ultrasound signal, receive echo signals produced in response to the ultrasound signal interacting with stationary structure and flowing structure, and generate electrical signals indicative of the echo signals. The system further includes a beamformer configured to process the electrical signals and generate sequences, in time, of beamformed data. The system further includes a discriminator configured to process the beamformed data, and remove and replace a set of frequency components based on a threshold, producing corrected beamformed data. The system further includes a flow processor configured to estimate a velocity of flowing structure from the corrected beamformed data. The system further includes a rendering engine configured to display the flow velocity estimate on a display.

[0006] In another aspect, a method includes transmitting, with elements of a transducer array, an ultrasound signal, receiving, with the elements of a transducer array, a set of echo signals generated in response to the ultrasound signal interacting with stationary and moving structure, generating, with the elements of a transducer array, electrical signals indicative of the received set of echo signals, and beamforming the electrical signals to generate RF data. The method further includes removing a subset of frequency

components from the RF data based on an energy level of the frequency components. The method further includes determining flow information for the moving structure based on the RF data with the removed subset of frequency components and visually presenting the flow information.

[0007] In another aspect, apparatus includes a transducer array that receives ultrasound echoes produced in response to a pressure field interacting with moving structure and generates signals indicative thereof and a console in electrical communication with the transducer array. The console includes a beamformer configured to process the signals and generate ultrasound data in the time domain, an energy filter configured to remove, in the frequency domain and based on an energy threshold, signals from the time domain data, wherein the removed signals correspond to stationary tissue, and a flow processor configured to estimate, in the time domain, a velocity of flowing structure from the filtered ultrasound data.

[0008] Those skilled in the art will recognize still other aspects of the present application upon reading and understanding the attached description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The application is illustrated by way of example and not limited by the figures of the accompanying drawings, in which like references indicate similar elements and in which:

[0010] FIG. 1 schematically illustrates an example ultrasound imaging system with an energy filter;

[0011] FIG. 2 schematically illustrates example of the energy filter;

[0012] FIGS. 3, 4, 5 and 6 illustrate a non-limiting approach determining an energy threshold for the energy filter; and

[0013] FIG. 7 illustrates an example method in accordance with an embodiment herein.

DETAILED DESCRIPTION

[0014] FIG. 1 illustrates an example imaging system **100** such as an ultrasound imaging system. The imaging system **100** includes a transducer array **102** and an ultrasound console **104**, which interface through suitable complementary hardware and/or wireless interfaces (not visible).

[0015] The transducer array **102** includes one or more transducer elements **106**. Examples of suitable one-dimensional arrays include 64, 128, 192, 256, etc. Two-dimensional arrays can be square, rectangular, circular, irregular, etc. The transducer array **102** can include linear, curved, etc. arrays, which are fully populated, sparse and/or a combination thereof, etc.

[0016] The elements **106** convert an excitation electrical (e.g., pulsed) signal to an ultrasound pressure field, and at least a sub-set of the elements **106** are excited to transmit. The elements **106** also receive echo signals and generate analog electrical signals indicative thereof. The echo signals, in one instance, are generated in response to the transmitted pressure field interacting with structure, stationary and/or moving (e.g., flowing blood cells).

[0017] Transmit circuitry **108** is configured to generate the excitation electrical signal and convey the excitation electrical signal to the elements **106** of the transducer array **106**. Receive circuitry **110** is configured to receive and condition the analog electrical signals. The conditioning may include

at least amplifying the signals with an amplifier. Other processing includes digitizing the signals with an analog-to-digital converter.

[0018] The one or more transducer elements **106** can be selectively excited such that at least a sub-set of the transducer elements **106** transmit an ultrasound signal into an examination or scan field of view. The ultrasound signal may be in a hard-focused ultrasound beam, a soft-focused beam, a plane wave or a defocused (spherical) wave, and/or other ultrasound signal. In general, any known or other acquisition scheme can be used.

[0019] A beamformer **112** is configured to beamform the signals from the receive circuitry **110**. The beamformer **112** can include conventional, synthetic aperture, plane wave, row-column, and/or one or more other beamformers. For B-mode imaging, the beamforming may include delay and summing signals for a plurality of processing channels that correspond to the elements **106** and generating and outputting receive-beams of radiofrequency (RF) data. The RF-data may be converted to the complex-value I/Q-data domain, e.g., for flow estimations.

[0020] An image processor **116** processes the beamformed RF-data and generates one or more images.

[0021] The beamformed RF-data is filtered. In one instance, an energy filter **118** is used and configured to dampen tissue motion that otherwise overrules the signal from flowing structure such as slowly moving blood scatterers where the scatterers and tissue move on a same order of velocity. As described in greater detail below, this may include adaptively modifying, based at least on the energy of the RF data, the Doppler spectrum components. The energy filter **118** may also filter based on frequency. The approach described herein can improve discrimination between stationary tissue movement and flowing structure relative to a configuration in which the energy filter **118** is omitted. Where continuous data is available, the energy filter **118** is well-suited for synthetic aperture applications.

[0022] A flow processor **120** processes the filtered beamformed RF-data and/or other data (e.g., I/Q data) and generates flow information. This may include processing the data for velocity imaging, vector-velocity imaging (e.g., based on Transverse Oscillation (TO), plane wave, synthetic aperture, etc.), Doppler imaging, and/or other flow imaging.

[0023] A rendering engine **122** visually presents, via a display **124**, the image generated by the image processor **116** and/or flow information generated by the flow processor **120**, e.g., superimposed or overlaid over the image and/or otherwise. Indicia such as color, arrows, etc. can be used to show magnitude and/or direction.

[0024] A user interface (UI) **126** includes one or more input devices (e.g., a button, a knob, a slider, a touch pad, a mouse, a trackball, a touch screen, etc.) and/or one or more output devices (e.g., a display screen, a light, an audio generator, etc.), which allow for interaction between a user and the ultrasound imaging system **100**.

[0025] A controller **128** is configured to control one or more of the components of the console **104**, the transducer array **102**, and/or other device.

[0026] One or more of the components of the console **204** can be implemented via one or more processors (CPU, microprocessor, controller, etc.) executing one or more computer readable instructions encoded or embedded on computer readable storage medium, which is a non-transitory medium such as physical memory or other non-transi-

tory medium, and excludes transitory medium. Additionally or alternatively, at least one of the instructions can be carried by a carrier wave, a signal, or other transitory medium.

[0027] The ultrasound imaging system **100** can be part of a portable system on a stand with wheels, a system residing on a tabletop, and/or other system in which the transducer array **102** is housed in a probe or the like, and the console **104** is housed in an apparatus separate therefrom. In another instance, the transducer array **102** and the console **104** can be housed in a same apparatus such as within a single enclosure hand-held ultrasound scanning device.

[0028] FIG. 2 illustrates an example of the energy filter **118**.

[0029] In this example, the energy filter **118** includes a Fourier processor **202**, a threshold determiner **204**, a component remover **206**, a component completer **208**, and an inverse Fourier processor **210**. In this example, frequency components with magnitudes above a threshold are classified as tissue and removed, and new values are inserted to replace removed flowing structure components to match the behavior of the signal.

[0030] The Fourier processor **202** applies a Fourier transform to transform the RF data to the frequency domain and outputs a Doppler spectrum. An example of the Doppler spectrum is shown at **212**, wherein a y-axis **214** represents power (e.g., in units of decibel, dB) and an x-axis **216** represents frequency (e.g., in units of Hertz, or Hz). This spectrum is composed of a flowing structure signal **218** and stationary tissue signal **220**.

[0031] The threshold determiner **204** determines energy thresholds, e.g., for at least one of clutter (tissue), flowing structure (e.g., blood), or noise. In one instance, the threshold determiner **204** does this based on analyzing characteristics of the energy spectrum. This can be achieved based on modeling a Gaussian distribution and determining when it deviates from this model, using a priori knowledge of the operating conditions, dynamically computing through adaptive and recursive techniques, and/or otherwise. An example is provided in detail below in connection with FIG. 3.

[0032] The component remover **206** removes components of the spectrum based on the threshold. An example of an energy threshold **222** is shown at **224**, and an example of the resulting signal after thresholding is shown at **226**. In this example, the components having energy above the energy threshold **222** are removed. Note that this removes both the flowing structure contribution and the stationary tissue contribution. A DC component is also included, and therefore no cut frequency exists in the filter, removing the limit on the minimum detectable velocity.

[0033] The component completer **208** completes or reconstructs the spectrum by adding back an estimate of the removed flowing structure contribution based on the characteristics of the flowing structure signal **218**. This can be achieved by analyzing the characteristics of the signal **218** classified as flowing structure, e.g., using a Gaussian and/or other model to replace the amplitude. Alternatively, this can be achieved through a priori knowledge, e.g., using amplitude and phase characteristics of the already known flowing structure signal spectrum **218** to reconstruct the parts of the spectrum that were removed. An example is shown at **228**, wherein the signal **218** includes new flowing structure components **230**.

[0034] The inverse Fourier processor 210 applies an inverse transform to transform the data back to the time domain.

[0035] FIGS. 3, 4, 5 and 6 illustrates an example approach for the threshold determiner 204 to estimates the threshold 222 (FIG. 2).

[0036] This example describes a down to top approach. However, other approaches are also contemplated herein. In this example, the threshold determiner 204 first determines a noise floor limit and then adds a margin to cover tissue signal. For this, the spectrum is first sorted as a function of energy level. This is shown in FIG. 3, where a y-axis 302 represents power (e.g., in units of dB) and an x-axis 304 represents the components.

[0037] The threshold determiner 204 then determines a cumulative distribution function $F(E)$ of the energy of the spectra. This is shown in FIG. 4, where a y-axis 402 represents a percentage of the components, an x-axis 404 represents power (e.g., in units of dB), and a curve 406 represents $F(E)$. The y-axis 402 spans from zero (0) 408 to one hundred (100) 410 percentage. FIG. 4 also shows a mean energy value 412 (e.g., $F(E_{\text{mean}})=0.5$).

[0038] The threshold determiner 204 then generates and fits a theoretical Gaussian cumulative distribution using the mean energy value 412 and a standard deviation from a slope of the cumulative distribution function $F(E)$ 406 around the mean 412. This is shown in FIG. 5, where a theoretical Gaussian cumulative distribution 502 is fitted to the cumulative distribution function $F(E)$ 406. FIG. 6 shows a magnified view of a sub-portion 504 of the FIG. 5.

[0039] The threshold determiner 204 determines the noise floor limit as a point where the cumulative distribution function $F(E)$ 406 exceeds the theoretical value by a predetermined dB level (e.g., 2 dB). This point defines a starting point for the threshold, which is increased gradually until the point reaches a predetermined upper limit (e.g., $F(E)=0.85$, 20 dB, etc.). This is shown in FIG. 6, where a point 602 on the cumulative distribution function $F(E)$ 406 exceeds the fitted Gaussian cumulative distribution 502 by a value 604 which exceeds the predetermined upper limit.

[0040] Using $F(E)=0.85$, e.g., whenever the noise limit is found above 85% of the components, it is considered that the flowing structure signal is aliased or lacking and the threshold is kept at that level. Where each pixel spectrum is processed independently, a smoothing filter can be used to maintain a similar threshold in neighboring pixels. In one instance, this conserves more coherently the spatial phase information of the Fourier transform, and the spatial correlation of the signals is maintained. As such, vector velocity estimates also benefit and could be use in low blood velocities.

[0041] FIG. 7 illustrates an example method.

[0042] It is to be understood that the following acts are provided for explanatory purposes and are not limiting. As such, one or more of the acts may be omitted, one or more acts may be added, one or more acts may occur in a different order (including simultaneously with another act), etc.

[0043] At 702, echo signals are received and processed to generate sequences, in time, of beamformed ultrasound data.

[0044] At 704, the beamformed ultrasound data is converted to the frequency domain, producing an energy spectrum.

[0045] At 706, thresholds are used to classify components of the energy spectrum as either clutter, blood, or noise, as described herein and/or otherwise.

[0046] At 708, unwanted frequency content (e.g., clutter and noise) is removed from the energy spectrum based on the classification.

[0047] At 710, the energy spectrum is reconstructed, producing a corrected energy spectrum, as described herein and/or otherwise.

[0048] At 712, the reconstructed energy signal spectrum is converted back to the time domain, producing corrected beamformed ultrasound data.

[0049] At 714, the corrected beamformed ultrasound data is processed to estimate flow information for the blood.

[0050] At least a portion of one or more of the methods discussed herein may be implemented by way of computer readable instructions, encoded or embedded on computer readable storage medium (which excludes transitory medium), which, when executed by a computer processor (s), causes the processor(s) to carry out the described acts. Additionally or alternatively, at least one of the computer readable instructions is carried by a signal, carrier wave or other transitory medium.

[0051] The application has been described with reference to various embodiments. Modifications and alterations will occur to others upon reading the application. It is intended that the invention be construed as including all such modifications and alterations, including insofar as they come within the scope of the appended claims and the equivalents thereof.

1. An ultrasound imaging system, comprising:
 - a transducer array with a plurality of transducer elements configured to transmit an ultrasound signal, receive echo signals produced in response to the ultrasound signal interacting with stationary structure and flowing structure, and generate electrical signals indicative of the echo signals;
 - a beamformer configured to process the electrical signals and generate sequences, in time, of beamformed data;
 - a discriminator configured to process the beamformed data, and remove or replace a set of frequency components based on a threshold, producing corrected beamformed data;
 - a flow processor configured to estimate a velocity of flowing structure from the corrected beamformed data; and
 - a rendering engine configured to display the flow velocity estimate on a display.
2. The system of claim 1, further comprising:
 - an image processor configured to process the beamformed data and generate an image, wherein the rendering engine displays the image on the display.
3. The system of claim 1, wherein the threshold is an energy threshold and the discriminator includes an energy filter that comprises:
 - a Fourier processor that converts the beamformed data to an energy spectrum;
 - a component remover that removes energy components from the energy spectrum that exceed the energy threshold, wherein the removed energy components include contributions from noise, the stationary structure and the flowing structure;

- a component completer that reconstructs the processed energy spectrum by adding estimates for the removed flowing structure contributions; and
 an inverse Fourier processor that converts the reconstructed energy spectrum to the corrected beamformed data.
- 4.** The system of claim **3**, wherein the energy filter further comprises:
 a threshold determiner configured to generate the energy threshold.
- 5.** The system of claim **4**, wherein the energy threshold distinguishes clutter and noise from blood.
- 6.** The system of claim **4**, wherein the threshold determiner determines the energy threshold based on analyzing characteristics of the energy spectrum.
- 7.** The system of claim **4**, wherein the threshold determiner determines the energy threshold based on a priori knowledge of the operating conditions.
- 8.** The system of claim **4**, wherein the threshold determiner dynamically determines the energy threshold through adaptive and recursive techniques.
- 9.** The system of claim **4**, wherein the threshold determiner determines the energy threshold based on a Gaussian distribution.
- 10.** The system of claim **4**, wherein the threshold determiner determines the energy threshold by:
 sorting the energy spectrum based on energy level;
 determining a cumulative distribution function of the energy of the spectra based on the sorted energy spectrum;
 determining a mean and variance of the cumulative distribution function;
 generating a theoretical Gaussian cumulative distribution based on the mean and the variance;
 fitting the theoretical Gaussian cumulative distribution to the cumulative distribution function;
 determining a point on the cumulative distribution function where an energy value of the cumulative distribution function exceeds an energy value of the fitted theoretical Gaussian cumulative distribution by a predetermined level; and
 increasing the energy value by a predetermined amount.
- 11.** The system of claim **3**, wherein the component completer determines the estimates based on characteristics of the processed energy spectrum.
- 12.** The system of claim **11**, wherein the characteristics are analyzed using a Gaussian model to estimate replacement amplitudes.
- 13.** The system of claim **3**, wherein the component completer determines the estimates based on a priori knowledge.
- 14.** The system of claim **13**, wherein the a priori knowledge includes amplitude and phase characteristics of components of the processed energy spectrum.
- 15.** A method, comprising:
 transmitting, with elements of a transducer array, an ultrasound signal;
 receiving, with the elements of a transducer array, a set of echo signals generated in response to the ultrasound signal interacting with stationary and moving structure;
 generating, with the elements of a transducer array, electrical signals indicative of the received set of echo signals;
 beamforming the electrical signals to generate RF data;
 removing a subset of frequency components from the RF data based on an energy level of the frequency components;
 determining flow information for the moving structure based on the RF data with the removed subset of frequency components; and
 visually presenting the flow information.
- 16.** The method of claim **15**, wherein removing the subset of frequency components comprises:
 converting the RF data to frequency components in the frequency domain;
 computing a threshold based on amplitudes of the frequency components;
 removing frequency components having amplitudes greater than the threshold;
 adding an estimated set of frequency components to replace the removed frequency components; and
 converting the processed frequency components to the time domain, wherein the flow information is determined from processed frequency components converted to the time domain.
- 17.** The method of claim **16**, wherein the computing of the threshold comprises:
 sorting an energy spectrum of the frequency components based on energy level;
 determining a cumulative distribution function of the energy of the spectra based on the sorted energy spectrum;
 determining a mean and variance of the cumulative distribution function;
 generating a theoretical Gaussian cumulative distribution based on the mean and the variance;
 fitting the theoretical Gaussian cumulative distribution to the cumulative distribution function; and
 determining the threshold based on a point on the cumulative distribution function where an energy value of the cumulative distribution function exceeds an energy value of the fitted theoretical Gaussian cumulative distribution by a predetermined level.
- 18.** The method of claim **16**, further comprising:
 determining the estimated set of frequency components based on characteristics of the remaining frequency components using a Gaussian model to estimate replacement amplitudes.
- 19.** The method of claim **16**, further comprising:
 determining the estimated set of frequency components based on a priori knowledge of amplitude and phase characteristics of the remaining frequency components.
- 20.** An apparatus, comprising:
 a transducer array that receives ultrasound echoes produced in response to a pressure field interacting with moving structure and generates signals indicative thereof; and
 a console in electrical communication with the transducer array, wherein the console includes:
 a beamformer configured to process the signals and generate ultrasound data in the time domain;
 an energy filter configured to remove, in the frequency domain and based on an energy threshold, signals from the time domain data, wherein the removed signals correspond to stationary tissue; and

a flow processor configured to estimate, in the time domain, a velocity of flowing structure from the filtered ultrasound data.

* * * * *