US006896658B2

(12) **United States Patent**
Ji et al.

(10) **Patent No.: US 6,896,658 B2**
(45) **Date of Patent: May 24, 2005**

(54) **SIMULTANEOUS MULTI-MODE AND MULTI-BAND ULTRASONIC IMAGING**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 460 days.

(21) Appl. No.: **10/039,862**

(22) Filed: **Oct. 20, 2001**

(65) **Prior Publication Data**

US 2003/0078497 A1 Apr. 24, 2003

(51) **Int. Cl.**[7] **A61B 8/00**
(52) **U.S. Cl.** **600/440**
(58) **Field of Search** 600/443, 447, 600/454–459, 458, 440–441, 437; 128/916; 73/602, 625–626

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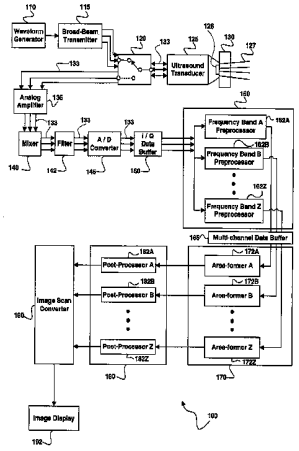
Primary Examiner—Francis J. Jaworski
(74) *Attorney, Agent, or Firm*—Carr & Ferrell LLP

(57) **ABSTRACT**

An ultrasound imaging method and system configured to simultaneously acquire and process multi-mode and multi-band echo information from a single set of pulse firings is provided. Raw ultrasound signals are digitized and stored in an I/Q data buffer. The stored data are then parallel preprocessed as a function of frequency band or alternative encoding. Parallel preprocessing optionally includes manipulating the data in respect to different imaging modes. Outputs of the parallel preprocessors are coupled to separate echo formers used to simultaneously reconstruct various desired echo information to form a multi-mode or multi-band image. The echo formation process is optionally performed in parallel.

19 Claims, 6 Drawing Sheets



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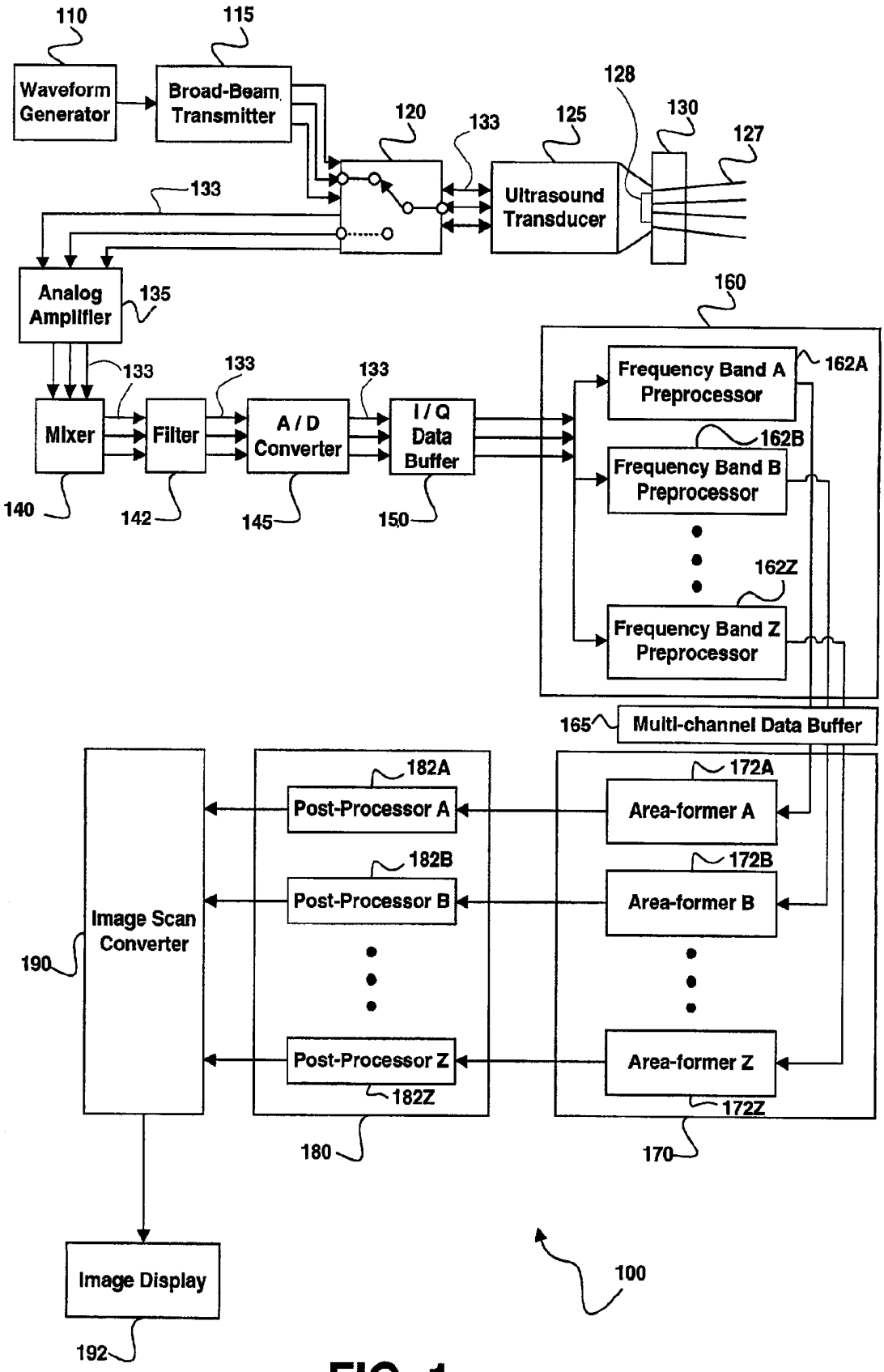

110
115
Waveform Generator
Broad-Beam Transmitter
120
133
125
128
130
127
Ultrasound Transducer
133
Analog Amplifier
135
160
133
133
133
Mixer
Filter
A / D Converter
I / Q Data Buffer
Frequency Band A Preprocessor
162A
Frequency Band B Preprocessor
162B
Frequency Band Z Preprocessor
162Z
140
142
145
150
165
Multi-channel Data Buffer
182A
Post-Processor A
182B
Post-Processor B
Post-Processor Z
182Z
172A
Area-former A
172B
Area-former B
Area-former Z
172Z
Image Scan Converter
190
180
170
Image Display
192
100

FIG. 1

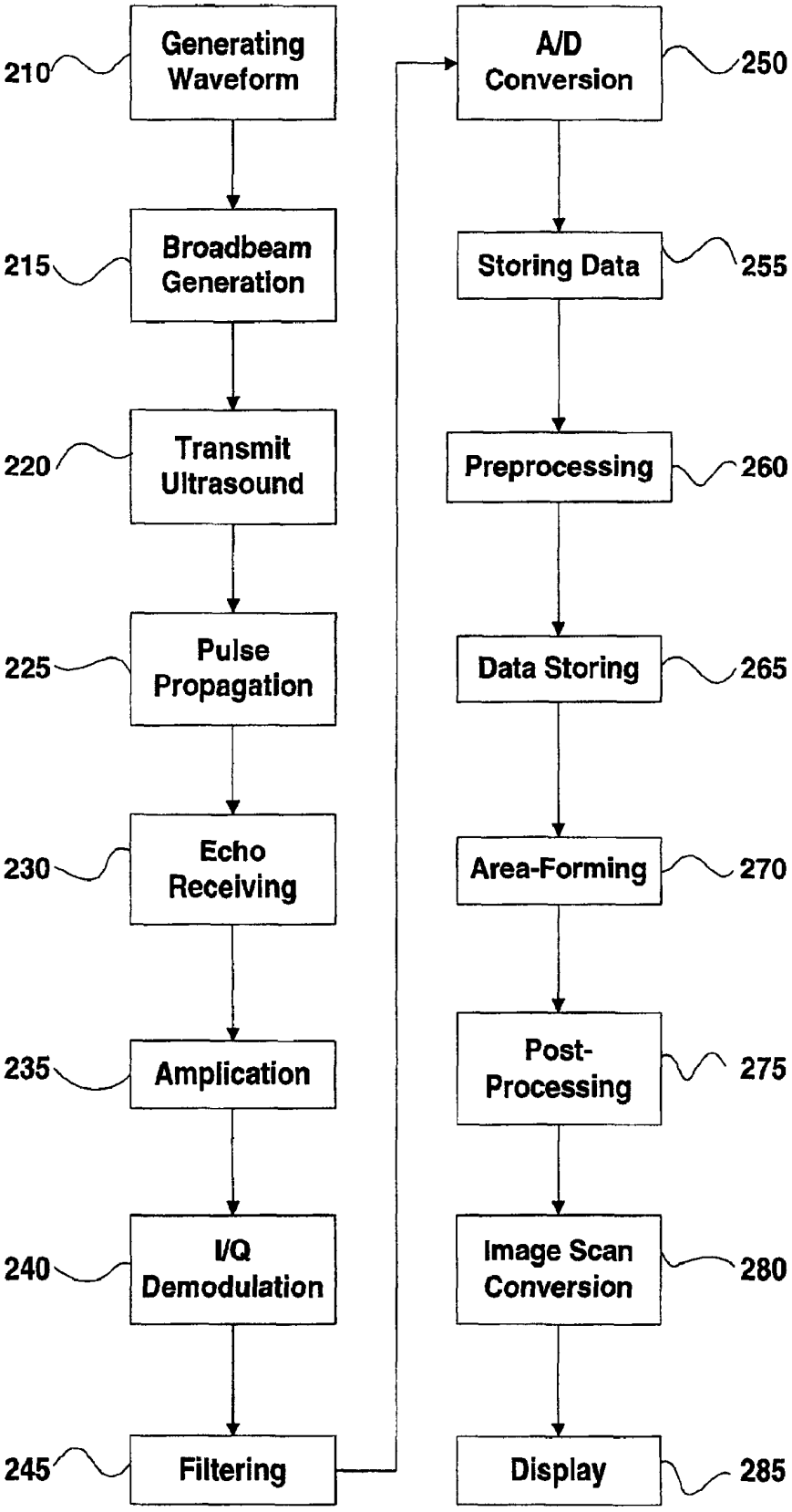

210
Generating Waveform
215
Broadbeam Generation
220
Transmit Ultrasound
225
Pulse Propagation
230
Echo Receiving
235
Amplication
240
I/Q Demodulation
245
Filtering
250
A/D Conversion
255
Storing Data
260
Preprocessing
265
Data Storing
270
Area-Forming
275
Post-Processing
280
Image Scan Conversion
285
Display

FIG. 2

FIG. 3

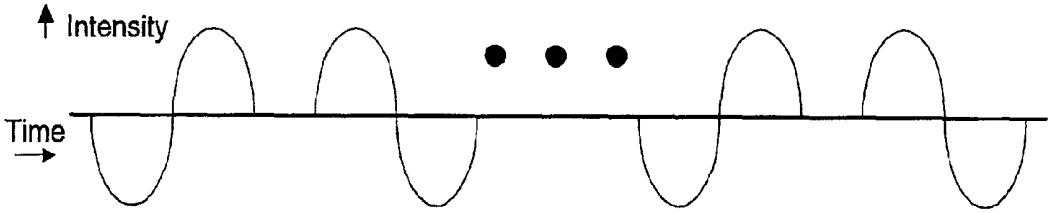


FIG. 4A

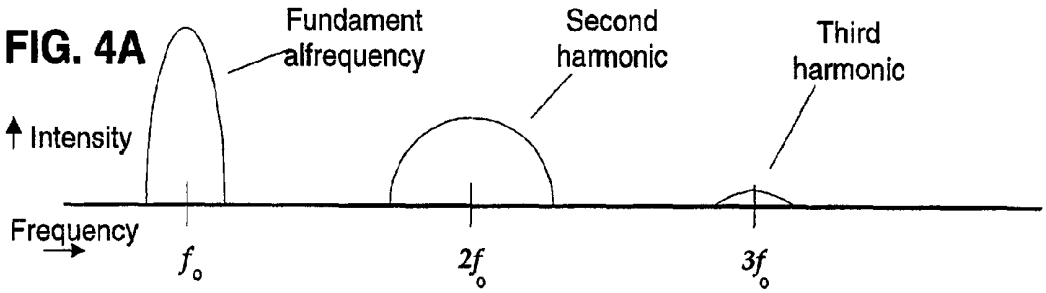
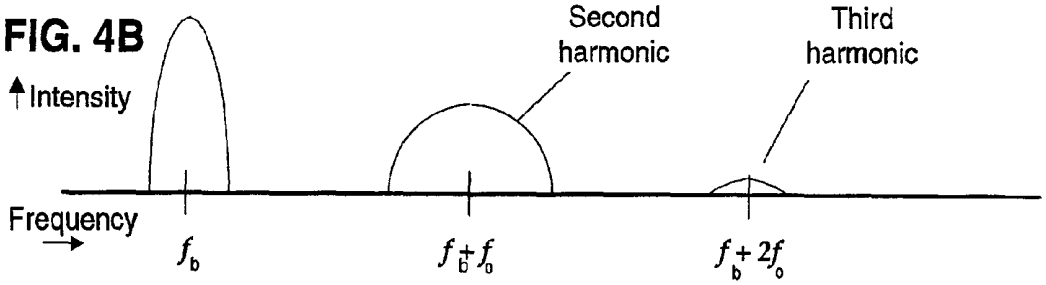


FIG. 4B



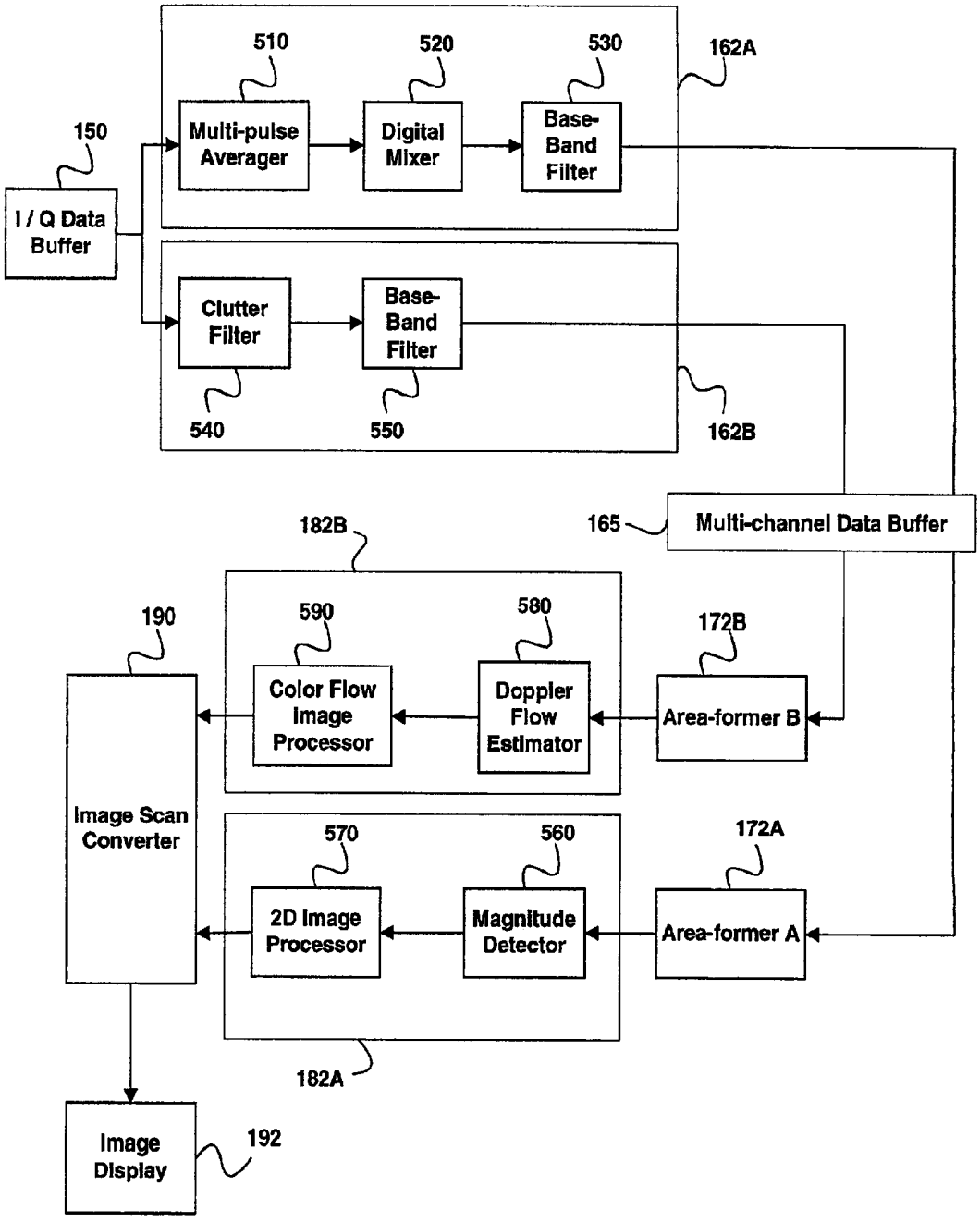

510
520
530
162A
150
Multi-pulse Averager
Digital Mixer
Base-Band Filter
I / Q Data Buffer
Clutter Filter
Base-Band Filter
540
550
162B
165
Multi-channel Data Buffer
182B
190
590
580
172B
Color Flow Image Processor
Doppler Flow Estimator
Area-former B
Image Scan Converter
570
560
172A
2D Image Processor
Magnitude Detector
Area-former A
182A
Image Display
192

FIG. 5

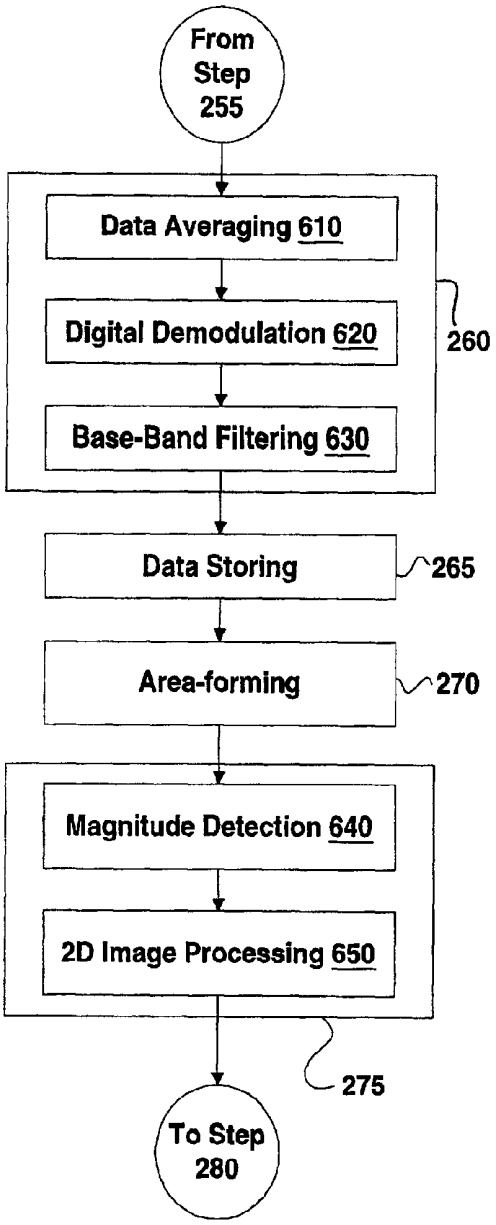

From Step 255
Data Averaging 610
Digital Demodulation 620
Base-Band Filtering 630
260
Data Storing
265
Area-forming
270
Magnitude Detection 640
2D Image Processing 650
275
To Step 280

FIG. 6A

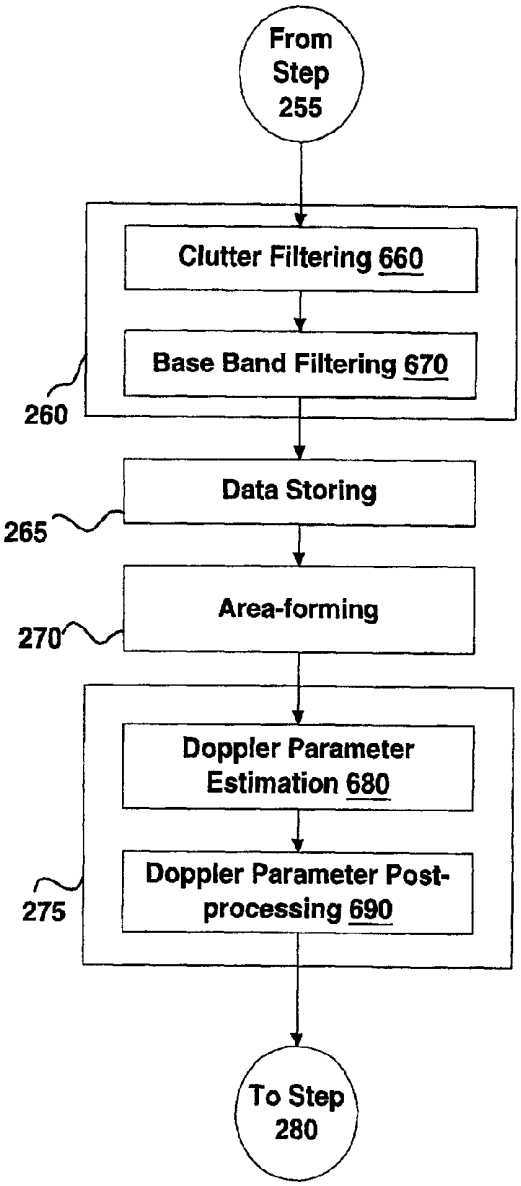

From Step 255
Clutter Filtering 660
Base Band Filtering 670
260
Data Storing
265
Area-forming
270
Doppler Parameter Estimation 680
Doppler Parameter Post-processing 690
275
To Step 280

FIG. 6B

FIG. 7A

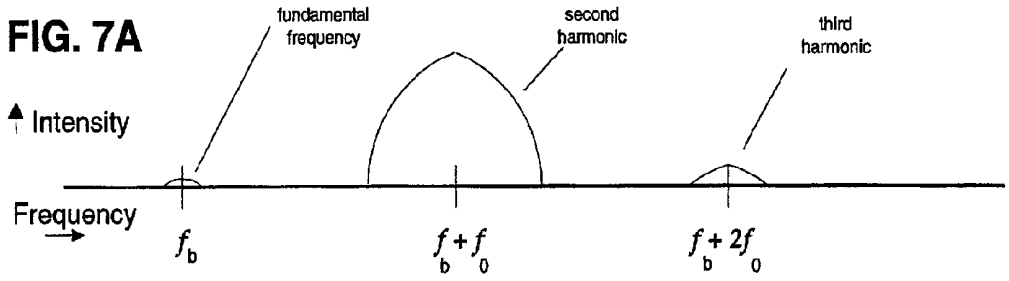
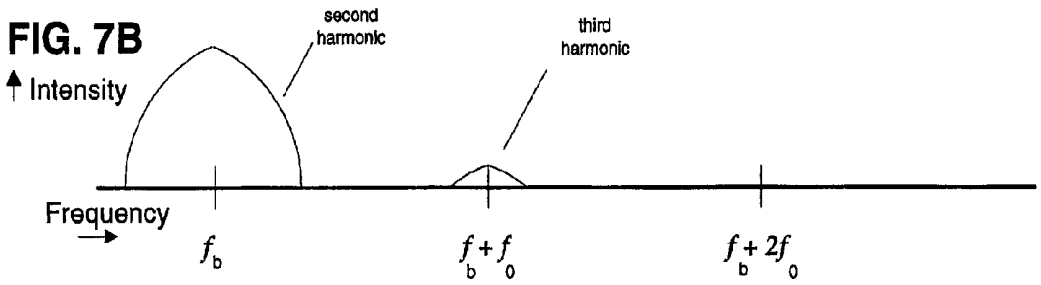

fundamental frequency
second harmonic
third harmonic
Intensity
Frequency
f_b
$f_b + f_0$
$f_b + 2f_0$

FIG. 7B


second harmonic
third harmonic
Intensity
Frequency
f_b
$f_b + f_0$
$f_b + 2f_0$

SIMULTANEOUS MULTI-MODE AND MULTI-BAND ULTRASONIC IMAGING

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is related to U.S. patent application Ser. No. 10/039,922 entitled "Block Switching in Ultrasound Imaging," filed on Oct. 20, 2001. The subject matter of this related application is incorporated herein by reference. The related application is commonly owned and assigned.

BACKGROUND

1. Field of the Invention

The invention is in the field of imaging devices and more particularly in the field of ultrasonic imaging.

2. Description of the Prior Art

Ultrasonic imaging is a frequently used method for examining a wide range of materials. The method is especially common in medicine because of its relatively non-invasive nature, low cost, and fast diagnostic cycles. Typically, ultrasound imaging is accomplished by generating and directing ultrasonic sound waves into a material under investigation and then observing reflections generated at the boundaries of dissimilar materials. The reflections are converted to electrical signals by receiving devices (transducers) and then processed, using beam-forming techniques known in the art, to determine the locations of echo sources. The resulting data is displayed using a display device such as a monitor.

Typically, the ultrasonic signal transmitted into the material under investigation is generated by applying continuous or pulsed electronic signals to a transducer. The transmit frequency of medical ultrasound is most commonly in the range of 1 MHz to 15 MHz. The ultrasound propagates through the material under investigation and reflects off of structures such as boundaries between adjacent tissue layers. As it travels, the ultrasonic energy may be scattered, resonated, attenuated, reflected, or otherwise modified. Portions of the reflected signals are returned to the transducers and detected as echoes. The detecting transducers convert the echo signals to electronic signals and furnish them to a beamformer. The beamformer calculates locations of echo sources and typically includes simple filters and signal averagers. Calculated positional information, produced through a serial series of beam-forming operations, is used to generate two-dimensional data that can be presented as an image. In prior art systems, the rate at which images are formed (the frame rate) is limited by at least the pulse return time. The pulse return time is the time between the transmission of ultrasonic sound into the media of interest and the detection of the last reflected signals.

As an ultrasound pulse propagates through a material under investigation, additional harmonic frequency components are generated. These additional harmonic frequency components continue to propagate and, in turn, reflect off of or interact with other structures in the material under investigation. Both fundamental and harmonic signals are detected. The analysis of harmonic signals is generally associated with the visualization of boundaries or image contrast agents designed to re-radiate ultrasound at specific harmonic frequencies.

Several modes of ultrasonic imaging are established in the prior art. These prior art modes include analyzing signals at the fundamental (base-band) or harmonic frequencies for studying static structures in the material under investigation, and detecting movement using spectral Doppler or color

Doppler imaging modes. These imaging modes are either sequentially or alternatively executed and the results combined in a single image. For example, in one prior art system a first series of ultrasound pulses is first fired to facilitate tissue harmonic imaging that is utilized to examine a human heart. A second series of ultrasound pulses is fired to generate color Doppler imaging signals at a fundamental frequency. These signals measure the velocity of blood flow through the heart. The first series and second series of ultrasound pulses are alternated in a line-interleaved or frame-interleaved manner. The signals generated by each series are analyzed separately and the resulting two-dimensional data is combined in a single data set for display to the user. In the display it is common to use color to differentiate and characterize the combined data sets. Since the data are recorded using two different sets of ultrasound pulses, generated at different times, the displayed image may contain undesirable temporal anomalies. For example, such an anomaly could indicate blood flow through a closed heart valve. Also, using multiple series of pulses exposes the material under investigation to additional ultrasound energy. This additional energy may be considered undesirable.

BRIEF DESCRIPTION OF THE VARIOUS VIEWS OF THE DRAWING

FIG. **1** is a block diagram of an embodiment of the invention;

FIG. **2** is a flow diagram showing steps of an embodiment of the invention;

FIG. **3** shows illustrative waveforms representing signals found at a step in the execution of an embodiment of the invention;

FIG. **4**A shows an example of a demodulated signal spectrum from a single channel associated with a single receiving transducer;

FIG. **4**B shows an illustrative spectrum representing signals found after demodulation by an I/Q mixer;

FIG. **5** is a block diagram showing an embodiment of the invention wherein harmonic signals for 2D imaging and fundamental signals for Doppler imaging are processed in parallel;

FIG. **6**A shows steps involved in a method of the invention wherein harmonic signals are processed for 2D imaging;

FIG. **6**B shows steps involved in a method of the invention wherein fundamental signals are processed for Doppler imaging;

FIG. **7**A shows an illustrative spectrum representing signals found after processing using a multi-phase averager; and

FIG. **7**B shows an illustrative spectrum representing signals found after demodulating the signal shown in FIG. **7**A using a digital mixer.

SUMMARY OF THE INVENTION

The present invention includes systems and methods for performing parallel and multi-mode processing of ultrasound signals. For example, one method of parallel processing ultrasound signals is ultrasonic imaging including the steps of transmitting ultrasound pulses into a media of interest that modifies the ultrasound pulses, receiving the modified ultrasound pulses at a sensor, generating signals responsive to the received ultrasound pulses using the sensor, processing the signals using a plurality of imaging modes; interpreting the processed signals to generate

responsive positional data; and generating image data with no visible temporal anomalies using the positional data. Such an image is said to be visibly temporally synchronized.

This method can be performed using an ultrasonic imaging system including an ultrasound transducer for transmitting ultrasound pulses into a media of interest that modifies the ultrasound pulses, a sensor (which is optionally the same transducer used for transmitting) for receiving the modified ultrasound pulses and generating analog signals responsive to the modified ultrasound pulses, an A/D converter for converting the analog signals to digital data, a plurality of frequency band preprocessors for preprocessing the digital data in parallel, and an echo-forming system for interpreting the preprocessed digital data and generating positional data responsive to the preprocessed digital data. The echo-forming system optionally includes an area-forming system, a volume-forming system, or a multidimensional-forming system.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. **1** is a block diagram showing an embodiment of the invention generally designated system **100**. System **100** includes a waveform generator **110** that produces waveforms having a plurality of pulses. These pulses are optionally of differing or multiple frequencies. The output of waveform generator **110** is coupled to a broad-beam transmitter **115**. Broad-beam transmitter **115** splits the input waveform into multiple channels, amplifies the signal, and/or applies the delays required to form a broad-beam ultrasound wave. Broad-beam technology reduces the number of transmitted pulses required to image an area and enables use of area-forming techniques in place of prior art beam-forming methods. In an alternative embodiment broad-beam transmitter **115** is replaced by a prior art beam transmitter. The output of broad-beam transmitter **115** is coupled through a multi-channel transmit/receive switch **120** and used to drive an ultrasound transducer **125**. Ultrasound transducer **125** sends ultrasound pulses **127** into a media of interest **130**. These ultrasound pulses **127** are modified through attenuation, scattering, reflection, harmonic generation, or the like. Returning echoes are received by transducer elements **128**. Transducer elements **128**, which are used to detect echoes, may be a part of ultrasound transducer **125**, used to generate ultrasound pulses **127**. The detected signals include ultrasound with frequencies near the original transmitting frequency as well as with other harmonic frequencies. Each of transducer elements **128** converts the received ultrasound pulses into electrical signals and couples these electrical signals to a distinct data channel **133**.

After conversion to electrical signals, pulses are coupled to multi-channel transmit/receive switch **120** from distinct data channels **133**. Transmit/receive switch **120** directs the electrical signals to a multi-channel analog amplifier **135**. Analog amplifier **135** amplifies the signals and couples them to a mixer **140** for demodulation. Mixer **140** can be an analog mixer, a multi-channel mixer, a phase modulator, a time signal multiplier and/or any other signal modulator known in the art. The demodulated signals are made up of in-phase and quadrature (I/Q) components. Each distinct data channel **133** is independently coupled through a filter **142**.

In one embodiment filter **142** includes a multi-channel band-pass filter that selectively impedes specific frequency ranges. In this embodiment, the resulting signals are digitized using a multi-channel A/D (analog to digital) converter **145** and are stored in an I/Q data buffer **150**. I/Q data buffer **150** is multi-channel and can optionally be programmed to individually sum digitized signals received from each distinct data channel **133**. I/Q data buffer **150** makes the stored data available to a preprocessing module **160**. In an alternative embodiment, a digital mixer **140** and/or digital filter **142** are optionally placed after A/D converter **145**.

An embodiment of preprocessing module **160** includes a plurality of frequency band preprocessors **162**A–Z. These labels are arbitrary designations and not intended to limit the number of frequency band preprocessors **162** to twenty-six. Each frequency band preprocessor **162** can process multiple data sets, from several or all of the distinct data channels **133**, stored in I/Q data buffer **150**. The frequency band preprocessors are optionally differentiated by one or more characteristics. These differentiating characteristics include, for example, the processing frequency range (frequency band), specific encoding within the processed signal, the mode of processing preformed, or the like. Signals, resulting from one or more transmit/receive cycles, are optionally combined, filtered, decoded, and/or modulated, prior to image formation. In one embodiment of the present invention, each frequency band preprocessor **162**A–Z within preprocessing module **160** can access all or part of the data within I/Q data buffer **150**. The frequency band preprocessors **162**A–Z may each take selected data and process it in parallel such that all of the data passed by band-pass filter **142** is optionally processed by at least one frequency band preprocessor **162**A–Z. The preprocessed, multi-band, multi-channel signals are optionally stored in multi-channel data buffer **165** and made available to a series of area-formers **172** within an area-forming module **170**. In FIG. **1** area-formers **172** are individually designated **172**A–Z. These labels are arbitrary designations and not intended to limit the number of area-former **172**A–Z to twenty-six.

Embodiments of area-forming module **170** processes data stored in multi-channel data buffer **165**, or delivered directly from preprocessing module **160**. The processing performed by area-forming module **170** includes calculating positional information regarding the source of signals within the media of interest **130**. Each of area-former **172**A–Z is capable of forming positional information covering an area using broad-beam technology, rather than just positional information along a line. Because preprocessing module **160** preprocesses the data, each of area-formers **172** optionally operates on a data set restricted to a specific criterion or processed to accentuate a specific aspect of the data. For example, in one embodiment area-former **172**A receives data preprocessed to identify moving components within media of interest **130**. Area-former **172**A, therefore, may operate on Doppler components of the total signal received by preprocessing module **160**. In the same embodiment, area-former **172**B is disposed to process data combined after processing by frequency band preprocessors **162**A and **162**B, each of which preprocesses data with a specific encoding. When input data is processed in parallel, each area-former **172**A–Z generates output data with the same time zero and temporal characteristics and the output data is temporally synchronized. Because preprocessing module **160** optionally reduces the total amount of data, area-forming module **170** may operate on only part of the data received by preprocessing module **160** and calculations may, thus, be performed more rapidly. Data prepared by preprocessing module **160** are parallel processed by area-forming module **170**. The parallel aspect of the processing eliminates temporal delays between the outputs of the area-forming module **170** and allows different types of imaging modes to

be simultaneously executed. For example, data accentuating motion can be processed in one imaging mode at the same time that data representing static structures is processed in another imaging mode.

In an embodiment output of area-forming module **170** is combined, or further processed, in a post-processor system **180**. Since the outputs of area-forming module **170** can be based on signals recorded at substantially the same time, the output data, which can result from several imaging modes, are combined without introducing temporal jitter. In various aspects of the invention post-processor system **180** also combines data from multiple broad-beam zones and prepares a single data set for delivery to an image scan converter **190** for output on an optional image display **192**.

FIG. **2** is a flow diagram showing steps of an embodiment of the invention utilizing the system illustrated by FIG. **1**. In a waveform generation step **210** waveform generator **110** is used to produce a waveform having a series of pulses. These pulses are grouped as singlets, pairs, or larger combinations of pulses. The waveform generated in waveform generation step **210** optionally includes a plurality of characteristics such as frequencies, amplitudes, pulse widths, phases, or variation thereof. These characteristics are optionally used to encode the waveform. As an example, FIG. **3** illustrates the waveform including a series of pulse pairs having opposite phase.

In a broad-beam generation step **215**, broad-beam transmitter **115** processes the waveform generated by waveform generator **110**. In various aspects of the invention the processing by broad-beam transmitter **115** includes amplifying the waveform, separating the waveform among distinct data channels **133**, applying delays and weightings to each distinct data channel **133**, and the like. Broad-beam generation step **215** further effectuates coupling the processed waveform within each distinct data channel **133** to multi-channel transmit/receive switch **120** and to multi-element ultrasound transducer **125**. In a transmit ultrasound step **220** each element of ultrasound transducer **125** emits ultrasound pulses **127** using the processed waveforms. Since the present invention optionally includes broad-beam technology, the number of pulses required to cover the imaging area can be significantly fewer than the number required to cover a similar area using conventional beamforming methods known in the art.

In pulse propagation step **225**, ultrasound pulses **127** propagate through media of interest **130**. Variations in media of interest **130** cause echoes to be generated and ultrasound pulses **127** to be altered. In an echo receiving step **230**, returning ultrasound signals are received by ultrasound transducer **125** using transducer elements **128**. Transducer elements **128** receive the returning ultrasound signals at the frequency near or at the frequencies of ultrasound pulses **127** and/or at harmonics thereof. Each receiver generates signals in at least one of distinct data channel **133** and the signals of each distinct data channel **133** are coupled through transmit/receive switch **120** to analog amplifier **135**. From echo receiving step **230** through a post-processing step **275** all operations are optionally performed on distinct data sets, such as set distinguished by different analysis modes, in parallel.

An amplification step **235** uses a low-noise analog amplifier **135** to amplify distinct data channel **133** signals. In an I/Q demodulation step **240**, each channel is processed by mixer **140** that demodulates the signals. FIG. **4A** illustrates an example of a resulting demodulated signal spectrum from a single channel associated with a single receiver. Signal components can be found near the frequency (f_0) at which the ultrasound was transmitted and at harmonics of the transmitted frequency ($2f_0$, $3f_0$, or the like). In an embodiment of the invention, mixer **140** demodulates the components of the signal at the fundamental frequency (f_0) to a base-band frequency (f_b) and demodulates the 2^{nd} harmonic components of the signal to a new frequency (f_b+f_0). The result is illustrated in FIG. **4B**. In a filtering step **245** each signal is optionally coupled through filter **142**. Filter **142** applies a high-pass, low-pass, or band-pass filter to the signal. The type of filtering is selected as a function of the expected use of the signal.

In an A/D conversion step **250** the signal in each distinct data channel **133** is converted from the analog to the digital domain by A/D converter **145**. In an alternative embodiment A/D conversion step **250** occurs prior to demodulation step **240** or filtering step **245**. In a data storage step **255**, the digitized data from each channel is stored in I/Q data buffer **150**. I/Q buffer **150** optionally sums the digital signals resulting from a plurality of pulses. The summed, "raw," data is sampled at the output of the I/Q data buffer **150**. Under selected summation and phase conditions, the summation process results in an average approaching zero for some components of the signals.

In a data preprocessing step **260**, preprocessing module **160** reads data from I/Q data buffer **150** and processes it using one or more of frequency band preprocessors **162**A–Z Each frequency band preprocessor **162**A–Z can access all of the data available in I/Q data buffer **150**. However, depending on the type of imaging mode desired, each frequency band preprocessor **162**A–Z can also be operated to process only a segment of the data. In various aspects of the invention, these segments are divided by transducer channel, frequency range, or encoding. In various embodiments, frequency band preprocessors **162**A–Z apply a variety of processing routines to the data. In an illustrative example, half of the frequency band preprocessors **162**A–Z are configured to process data associated with Doppler signals while the other half are configured to process signals associated with static structures. Thus, in these embodiments, preprocessing module **160** processes the data stored in I/Q data buffer **150** in multiple modes, in multiple frequency bands, with multiple encodings, and/or in multiple independent data channels. Since preprocessing module **160** consists of multiple independent frequency band preprocessors **162**A–Z, processing can occur in parallel.

In an embodiment of the invention signals are processed by frequency band pre-processors **162**A–Z as a function of encoding included within the signal. For example, if waveform generator **110** produces pulses at two or more distinct frequencies, the returned (encoded) ultrasound echoes can be differentiated (decoded) by their frequency. This ability to differentiate allows pulses to be sent into the material under investigation at a rate faster than un-encoded pulses, since a second set of pulses can be sent before the first is received. Using this encoding the pulse transmit rate and the collection of data is not limited by the roundtrip time of a pulse. The pulse roundtrip time is the time between transmission of a pulse and the detection of all resulting echoes. Frequency band preprocessors **162**A–Z can be individually arranged to select and process signals resulting from one or more of distinct frequency bands.

After preprocessing, data is optionally stored in multi-channel data buffer **165** in a data storing step **265**. This step enables further data manipulation, such as averaging and synchronization between preprocessing module **160** and area-forming module **170**. If the product of the number of

preprocessing modes, frequency bands, and data channels is larger than the number of frequency band pre-processors then some of the channels can be preprocessed in parallel and the results are stored in multi-channel data buffer **165**. Following this preprocessing process, another set of channels is optionally preprocessed and stored. The preprocessing process can be repeated until all channels have been preprocessed and stored. The use of multi-channel data buffer **165** further enables the implementation of a larger number of parallel preprocessing modes, frequency bands, encoding, and the like.

In an area-forming step **270** preprocessed data is used to perform parallel area-forming calculations using area-forming module **170**. Area-forming module **170** includes a plurality of area-former **172**A–Z, Each area-former **172**A–Z can be enabled to identify locations of echo sources from data generated by an individual frequency band preprocessor **162**A–Z, For example, in an embodiment of the present invention, area-former **172**A is configured to process data preprocessed by frequency band preprocessor **162**A. In another embodiment of the invention, area-former **172**A is configured to process data combined in multi-channel data buffer **165** after parts of the data are separately preprocessed by frequency band preprocessor **162**B and frequency band preprocessor **162**A. Preprocessing the data potentially reduces noise, undesirable signal components, and the total amount of data within each data channel.

The existence of several area-former **172**A–Z within area-forming module **170** enables parallel processing of data associated with multiple imaging modes. For example, in one embodiment area-former **172**A is configured to process data associated with moving echo sources and area-formi er **172**B is configured to process data associated with static echo sources. In another embodiment area-former **172**A is configured to process data with encoding type A and area-former **172**B is configured to process data with encoding type B, where encoding types A and B are any two distinguishable encoding schemes.

In an optional post-processing step **275** the output of area-forming module **170** is post-processed by post-processing system **180**. Post-processing can include one or more elements such as encoding of data generated using different modes, sum and difference calculations between data generated using different modes, calculation of differences among data recorded at different times, differential and integral calculations, or the like. Post-processing system **180** can also combine data derived from multiple transmit zones to produce data sets covering an expanded area. Post-processing generates at least data representing some attribute of the signal as a function of a coordinate system.

In an optional image scan conversion step **280** an image is prepared using image scan converter **190**. The image optionally includes motion video and/or false color representations of the encoding developed in post-processing step **275**. For example, in one embodiment of the invention velocities of detected materials are calculated and colors are chosen so as to visually convey the range and distribution of velocities. In another embodiment of the invention static components of the material of interest are shown using a color scheme designed to show material ultrasound reflectivity.

The above process is optionally repeated for multiple transmit zones until an entire field of view is covered. For example, see co-pending U.S. patent application Ser. No. 10/039,922 entitled "Block Switching in Ultrasound Imaging" that published on Feb. 5, 2004 as U.S. Patent Publication No. US 2004-0024316 A1. The final images of multi-mode and/or multi-band signals are combined and scan-converted to an appropriate display format by image scan converter **190**.

In an optional display step **285** the image prepared in image scan conversion step **280** is displayed using image display **192**. The final images are displayed with little or no time delay or time lag between various components of the image that result from different imaging mode or frequency bands.

In the present invention more than one imaging mode is optionally performed on a single set of data produced from a single set of transmitted ultrasound pulses. In these embodiments a single set of ultrasound pulses, are used in parallel to generate echo location data based on multiple analysis modes. In several embodiments, parallel multi-mode imaging creates a visibly temporally synchronized image, thereby eliminating time jitter (temporal anomalies) associated with prior art methods of serial generation of echo data in multi-rode imaging. Multi-band preprocessing and area-forming enables the separation of signals based on encoding characteristics. For example, images, or other echo location data, produced from separate frequency bands can be formed in parallel and compounded together to decrease speckle noise without reduction of frame rate.

FIG. **5** is a block diagram showing an embodiment of the invention wherein harmonic signals for 2D imaging and fundamental signals for color Doppler imaging are produced and processed in parallel. This embodiment executes the two different data processing modes at the same time. In the illustrative example of FIG. **5**, one of the modes is designed to perform high-resolution 2D harmonic tissue imaging, while the other mode is designed to perform color Doppler flow imaging. Both modes use the same set of data that are produced from a series of pulse firings and collected at I/Q data buffer **150**. Alternative embodiments optionally include more than two different analysis modes executed in parallel.

In the 2D harmonic tissue imaging mode, data is copied from I/Q buffer **150** to frequency band preprocessor **162**A. In this mode, frequency band preprocessor **162**A is used to process harmonic signals to produce a high resolution 2D tissue image. Frequency band preprocessor **162**A is configured to include multi-pulse averager **510**, digital mixer **520**, and base-band filter **530**. The results of the preprocessing are optionally stored in multi-channel data buffer **165** and coupled to area-former **172**A to reconstruct echo location data (image). The echo location data (image) is coupled to post-processor **182**A. In this embodiment, post-processor **182**A includes a magnitude detector **560** and 2D image processor **570**.

In the Doppler flow imaging mode, data is copied from I/Q buffer **150** to frequency band preprocessor **162**B. In this embodiment, this data is the same data copied from I/Q buffer **150** for use in a parallel 2D harmonic tissue imaging mode. In the Doppler flow imaging mode, frequency band preprocessor **162**B is configured to include a clutter filter **540** and a base-band filter **550**. Using these elements, frequency band preprocessor **162**B processes the fundamental frequency signal to detect moving targets within media of interest **130**. After optional storage in multi-channel data buffer **165** and processing by area-former **172**B, the re-constructed echo location data is coupled to post-processor **182**B, which includes a Doppler flow estimator **580** and a color flow image processor **590**. Image scan converter **190** combines the echo location data generated using both processing modes and converts the combined

data into an appropriate display format to form the final image. The final image is optionally displayed using image display **192**.

The various elements **510** through **590** introduced in FIG. **5** are optionally implemented using software. Thus, while preprocessor **162**A includes multi-pulse averager **510**, digital mixer **520**, and base-band filter **530** in one instance of an embodiment, in a subsequent instance of the same embodiment preprocessor **162**A may be reconfigured via software to include instead clutter filter **540** and base-band filter **550**. Post-processor **182**A is optionally configurable through software in an analogous manner.

FIG. **6** includes two flowcharts showing processes enabling two different imaging modes that can be executed in parallel utilizing the elements shown in FIG. **5**. FIG. **6**A shows steps involved in a method of the invention wherein harmonic signals are processed for 2D imaging. FIG. **6**B shows steps involved in a method of the invention wherein fundamental signals are processed for Doppler imaging. Both flowcharts start from step **255** and conclude at step **280** of FIG. **2**.

In the method illustrated by FIG. **6**A, data preprocessing step **260** includes a data averaging step **610**, a digital modulation step **620**, and a base-band filtering step **630**. In data averaging step **610**, multi-pulse averager **510** (FIG. **5**) reduces or eliminates fundamental frequency components by averaging multiple received signals generated using multiple pairs of phase-inverted transmitting pulses. Since the 2^{nd} harmonic component of the received signals from these phase-inverted pulse sequence are in-phase, the signal-to-noise ratio of the 2^{nd} harmonic component is enhanced by the averaging process. An illustration of resulting signals is shown in FIG. **7**A. Signals at the fundamental frequency are essentially cancelled and the 2^{nd} harmonic signals are enhanced. In alternative embodiments wherein the transmitting pulse sequence is not phase-inverted, the signal average simply serves to improve signal-to-noise ratio. In digital demodulation step **620** the digital mixer **520** demodulates the 2^{nd} harmonic component down to base-band frequency. Possible resulting signals are illustrated in FIG. **7**B. In base-band filtering step **630**, base-band filter **530** is used to filter out any residual fundamental frequency component and other noise outside the base-band, while preserving the demodulated 2^{nd} harmonic signal.

After base-band filtering step **630**, the data are optionally stored, in a data storing step **265**, in multi-channel data buffer **165**. In an area-forming step **270** the pre-processed 2^{nd} harmonic components are coupled to area-former **172**A and echo location data is re-constructed for 2D tissue image.

In the method illustrated by FIG. **6**A, post-processing step **275** includes a signal magnitude detection step **640** and a 2D image processing step **650**. Magnitude detection step **640** includes I/Q signal-to-magnitude conversion and log-compression. 2D image processing step **650** optionally includes operations such as adjustment of gain and dynamic range, spatial and/or temporal filtering, and the like.

In the method illustrated by FIG. **6**B, preprocessing step **260** includes a clutter filtering step **660** and a base-band filtering step **670**. In clutter filtering step **660**, clutter filter **540** is applied to the same multiple signals collected for harmonic tissue imaging to remove signals resulting from stationary and slow-moving sources within the media of interest **130**. In base-band filtering step **670**, base-band filter **550** is used to extract the clutter filtered fundamental frequency component and remove any noise outside base-band. Preprocess data step **260** is followed by optional store data step **265** and area-forming step **270**.

In the method illustrated by FIG. **6**B a post-processing step **275** includes a Doppler parameter estimation step **680** and a Doppler parameter post-processing step **690**. In Doppler parameter estimation step **680**, Doppler flow estimator **580** calculates flow parameters such as Doppler velocity, Doppler velocity variance, Doppler energy, and the like. These calculations are optionally accomplished using auto-correlation methods known in the art. In Doppler parameter post-processing step **690** color flow image processor **590** can use thresholds, noise reduction, smoothing, color coding and/or other image processing techniques to generate a color image conveying information of the Doppler parameters of interest.

The methods illustrated by FIGS. **6**A and **6**B are optionally performed in parallel. The results of both processes are combined in a single image data set in image scan conversion step **280** (FIG. **2**). This single image data set is displayed in display step **285** using image display **192**. Since both imaging modes are executed in parallel and use the same set of received data the outputs are generated more quickly than serial execution and the images produced using each imaging mode are temporally synchronized with each other. Quicker image generation enables a higher frame rate. The synchronization of data collection for multiple imaging modes can eliminate or reduce temporal anomalies within a resulting composite image. Encoded data arising from multiple transmitted pulses are optionally added together to improve signal-to-noise ratios.

Steps **260** through **275** optionally include additional and alternative imaging modes such as fundamental imaging, color Doppler imaging, harmonic imaging, spectral Doppler imaging, and/or any other ultrasound imaging mode. Combinations of three or more parallel modes are also possible in alternative embodiments. For example, one set of three parallel modes includes harmonic tissue imaging, color Doppler imaging, and spectral Doppler imaging. Alternatively, another set of three parallel modes includes harmonic tissue imaging, Doppler tissue imaging and color Doppler imaging.

In practice the above methods are optionally applied to a series of zones covering an image field of view within media of interest **130**. Each zone can be processed independently and an image of the combined zones can be constructed by image scan converter **190**. In each zone a set of N pulses is used to generate data using parallel processing. For K zones a total of K*N pulses are required to form a complete image. For some imaging modes the minimum value of N is two and for other imaging modes the minimum value of N is one. Increasing the number of processing modes does not necessarily increase the number of required pulses. Also, minimizing power consumption extends the lifetime of limited power sources, such as batteries, and enables the use of battery powered, single or multi-mode, instruments with increased operating times.

The parallel processing architecture described in this invention result in very fast data processing speeds. The pre-processing of raw I/Q data optimizes the input signal and improves signal to noise ratios prior to area formation. This optimized input signal improves the quality of area formation and precision of the resulting image data.

From the description of the preferred embodiments of the process and apparatus set forth herein, it will be apparent to one of ordinary skill in the art that variations and additions to the embodiments can be made without departing from the principles of the present invention. For example, preprocessing module **160** and area-forming module **170** can be

used for the processing of ultrasound data obtained through alternative means. In various embodiment area formers **172** are replaced by alternative echo-forming systems, such as series of parallel multi-line beamformers, individual examples of which are known in the art. Echo-forming systems include beam-forming systems, area-forming systems, volume-forming systems, and multidimensional-forming systems. The ultrasound system of the present invention may be used to image a wide range of materials.

We claim:

1. A method of using ultrasound to analyze a media of interest, comprising:

transmitting a single set of ultrasound pulse firings into the media of interest, the ultrasound pulse firings being modified by the media of interest;

receiving at a transducer the modified ultrasound pulse firings;

generating signals in response to the received modified ultrasound pulse firings;

parallel processing the signals using a plurality of imaging modes;

generating positional data responsive to the parallel processed signals; and

generating image data using the positional data, the image data having no visible temporal anomalies.

2. The method of claim **1**, wherein generating positional data includes area-forming.

3. A method of using ultrasound to analyze a media of interest, comprising:

transmitting a single set of ultrasound pulse firings into the media of interest, the ultrasound pulse firings being modified by the media of interest;

receiving at one or more transducers the modified ultrasound pulse firings;

generating analog signals in response to the received modified ultrasound pulse firings;

converting the analog signals to digital data using an A/D converter;

preprocessing the digital data using a plurality of frequency band pre-processors;

generating positional data responsive to the preprocessed digital data; and

generating image data using the positional data, the image data having no visible temporal anomalies.

4. The method of claim **3**, wherein digital data resulting from an individual member of the single set of ultrasound pulse firings is processed using a plurality of imaging modes.

5. The method of claim **3**, wherein preprocessing the digital data is preprocessed in parallel.

6. The method of claim **3**, wherein the positional data is generated using echo-forming.

7. The method of claim **3**, wherein the positional data is generated using echo-forming and the echo-forming uses an area-forming module that includes a plurality of area-formers.

8. The method of claim **3**, further comprising providing preprocessed digital data to one or more members of a plurality of area-formers from one or more members of the plurality of frequency band pre-processors.

9. The method of claim **3**, further comprising providing the positional data to an image scan converter, wherein the positional data is generated using a plurality of imaging modes.

10. The method of claim **9**, further comprising generating image data using the image scan converter and the positional data.

11. The method of claim **9**, further comprising generating image data using the image scan converter and the positional data, wherein the image data is visibly temporally synchronized.

12. The method of claim **3**, wherein preprocessing the digital data is performed using a plurality of imaging modes.

13. The method of claim **12**, wherein the plurality of imaging modes includes Doppler imaging.

14. The method of claim **12**, wherein the plurality of imaging modes includes imaging using harmonic frequencies.

15. The method of claim **3**, wherein preprocessing the digital data is done in parallel, and

the plurality of frequency band preprocessors are responsive to encoding within the digital data.

16. The method of claim **3**, further comprising post-processing the positional data in parallel using a plurality of post-processors.

17. An ultrasonic analysis system comprising:

an ultrasound transducer for transmitting a single set of ultrasound pulse firings into a media of interest such that the media of interest modifies the ultrasound pulse firings;

a transducer for receiving the modified ultrasound pulse firings and generating signals responsive to the modified ultrasound pulse firings;

a plurality of frequency band preprocessors for preprocessing the signals in parallel;

an echo-forming system for generating positional data responsive to the pre-processed signals; and

an image converter system for generating image data using the positional data, the image data having no visible temporal anomalies.

18. The system of claim **17**, wherein the echo-forming system includes a plurality of beamformers configured to receive signals preprocessed using a plurality of imaging modes.

19. The system of claim **17**, wherein the echo-forming system includes an area-forming module.

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专利名称(译)	同时多模和多波段超声成像		
公开(公告)号	US6896658	公开(公告)日	2005-05-24
申请号	US10/039862	申请日	2001-10-20
[标]申请(专利权)人(译)	姬廷局域网 MCLAUGHLIN GLEN		
申请(专利权)人(译)	姬廷-LAN MCLAUGHLIN GLEN		
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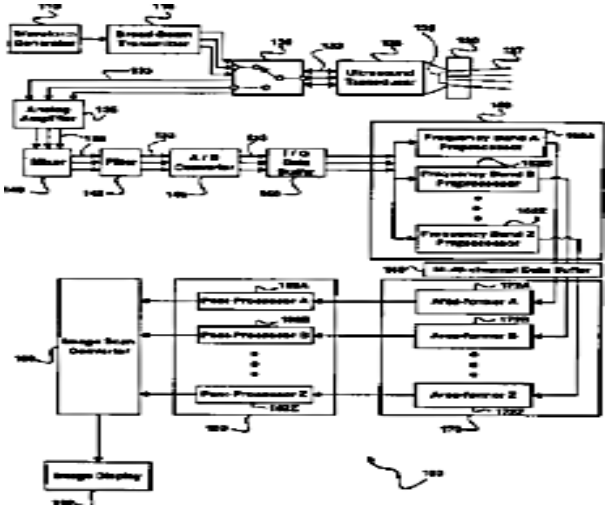
IPC分类号	G01N29/11 G01N29/06 G01N29/34 G01N29/04 G01S15/89 G03B42/00 G01S15/00 G03B42/06 G01S7/52 G01N29/44 A61B8/00		
CPC分类号	G01N29/06 G01N29/0609 G01N29/11 G01N29/348 G03B42/06 G01S7/52023 G01S15/8954 G01N2291/017 G01N2291/02416 G01N2291/02466 G01N2291/0228		
其他公开文献	US20030078497A1		
外部链接	Espacenet USPTO		

摘要(译)

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