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(54) APPARATUS, METHOD, AND COMPUTER PROGRAM FOR COMPARING AUDIO SIGNALS

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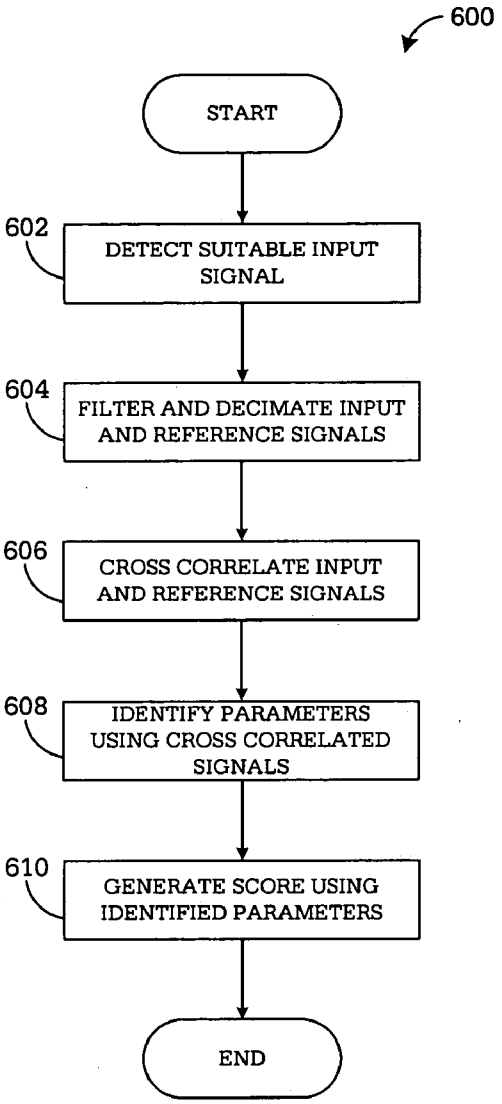
(57) **ABSTRACT**

An apparatus, method, and computer program are capable of receiving and cross-correlating a first audio signal and a second audio signal. This produces a cross-correlated signal, which is used to identify a plurality of parameters associated with at least one of the first and second audio signals. The parameters are used to generate an indicator identifying an extent to which the first and second audio signals match.



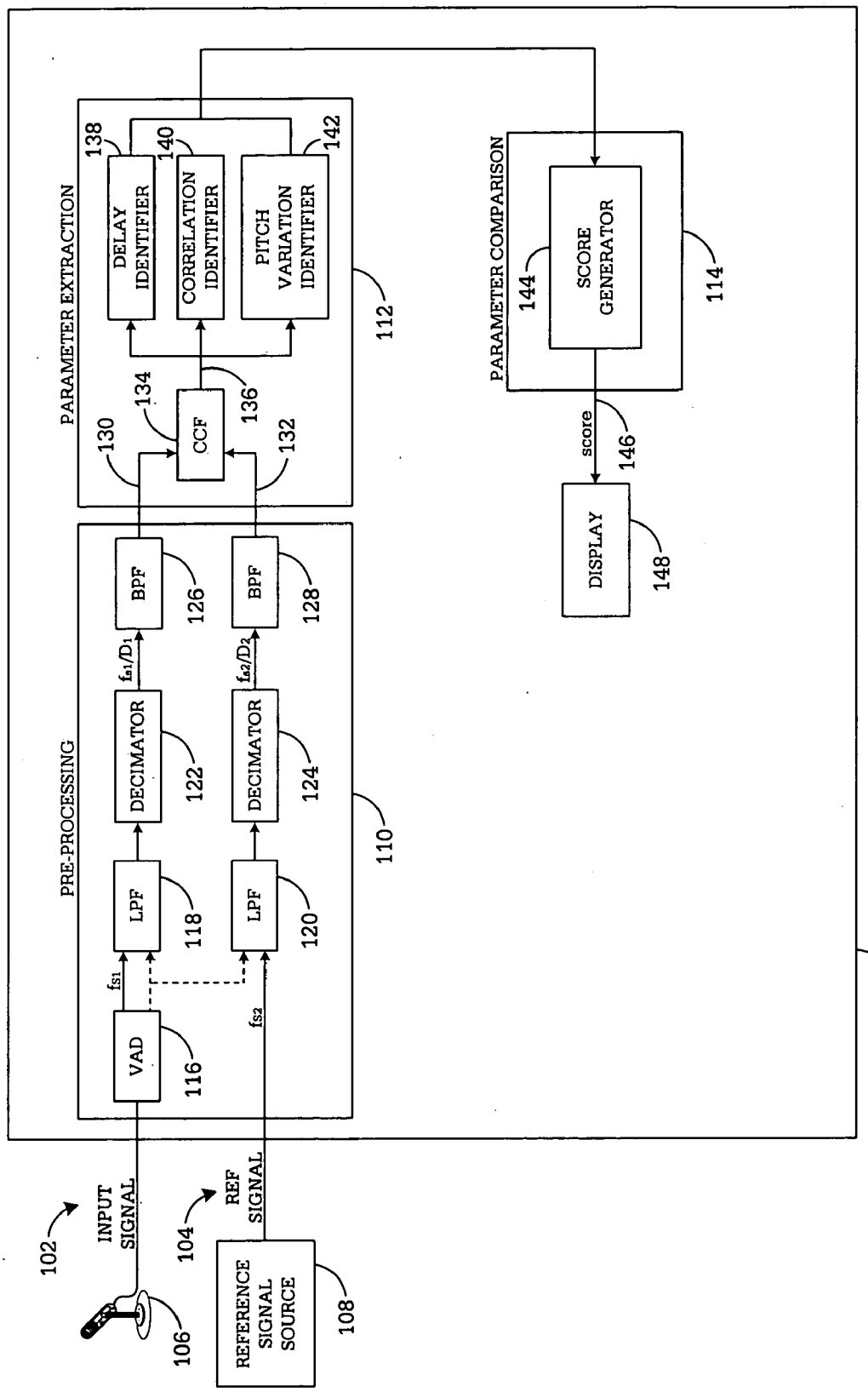

PARAMETER EXTRACTION
DELAY IDENTIFIER
CORRELATION IDENTIFIER
PITCH VARIATION IDENTIFIER
CCF
138
140
142
134
136
130
132
112
PARAMETER COMPARISON
SCORE GENERATOR
144
114
score
146
DISPLAY
148
PRE-PROCESSING
BPF
BPF
126
128
f_{s1}/D_1
f_{s2}/D_2
DECIMATOR
DECIMATOR
122
124
LPF
LPF
118
120
110
f_{s1}
f_{s2}
VAD
116
100
INPUT SIGNAL
REF SIGNAL
102
104
106
REFERENCE SIGNAL SOURCE
108

FIGURE 1

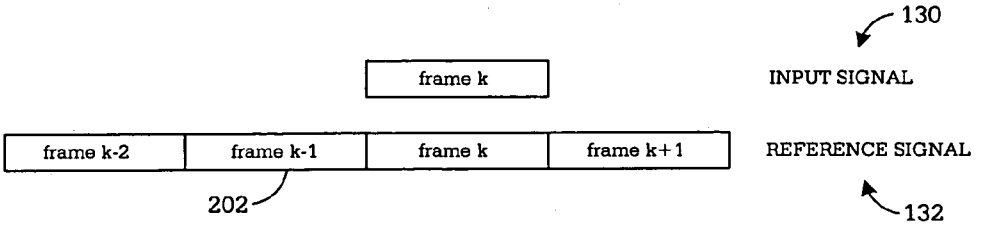


FIGURE 2

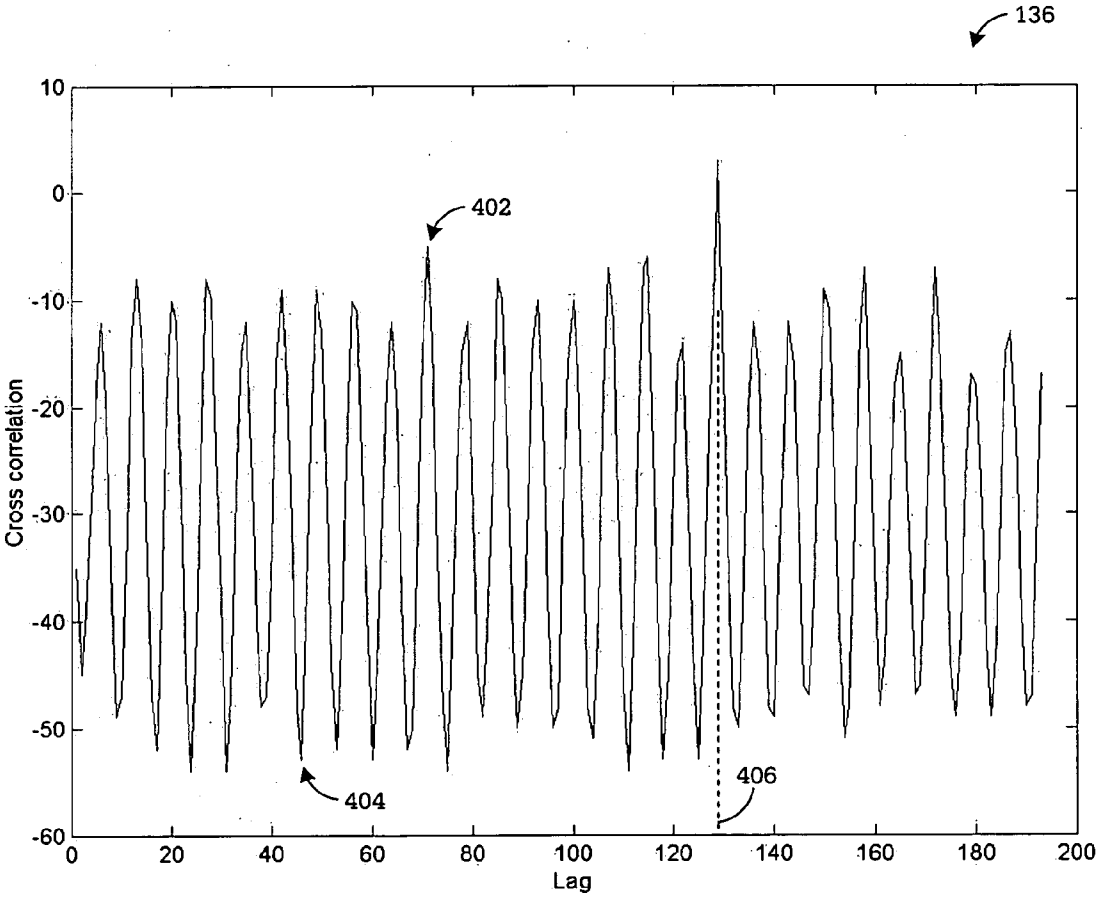


FIGURE 4

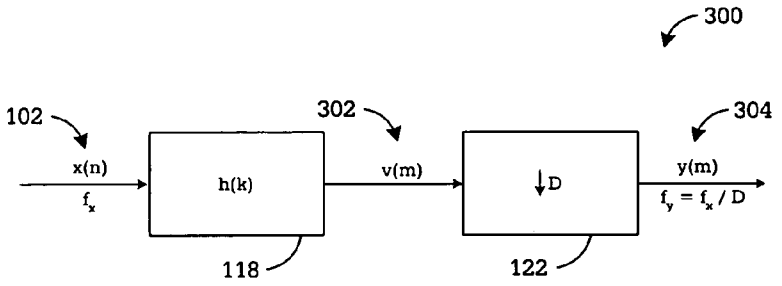


FIGURE 3

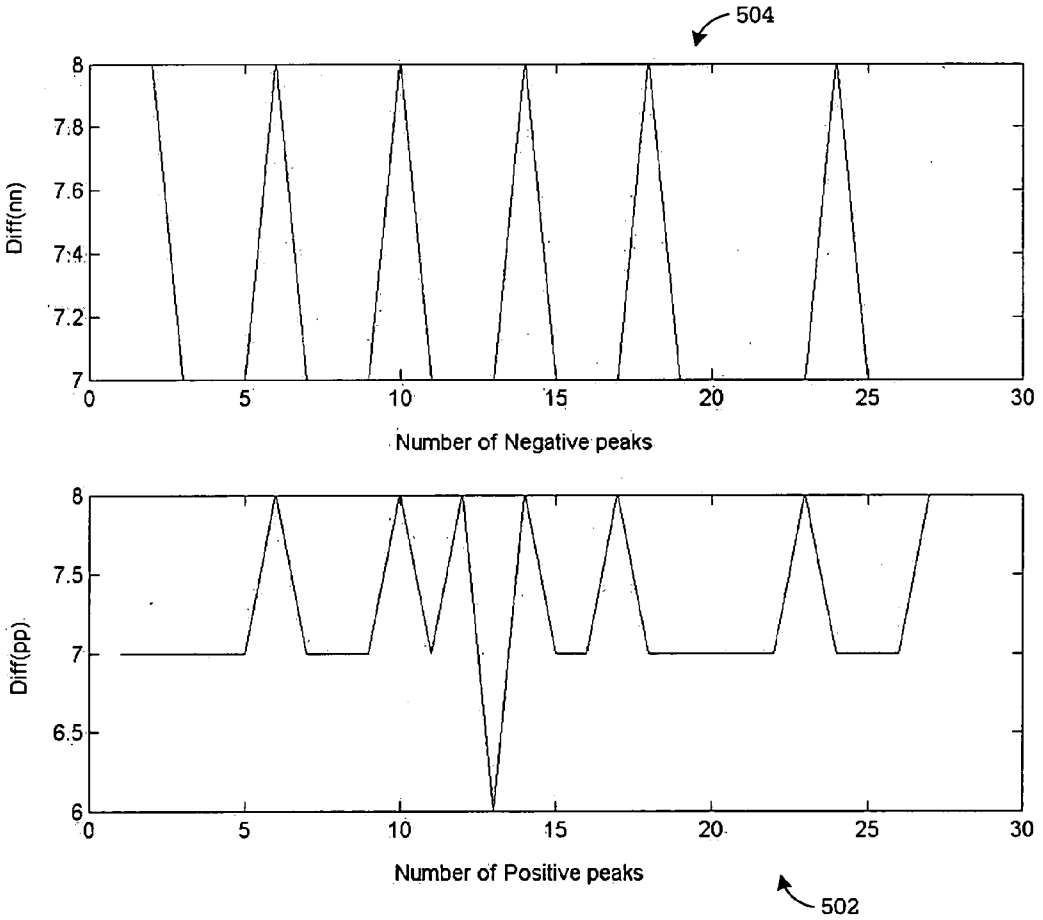


FIGURE 5

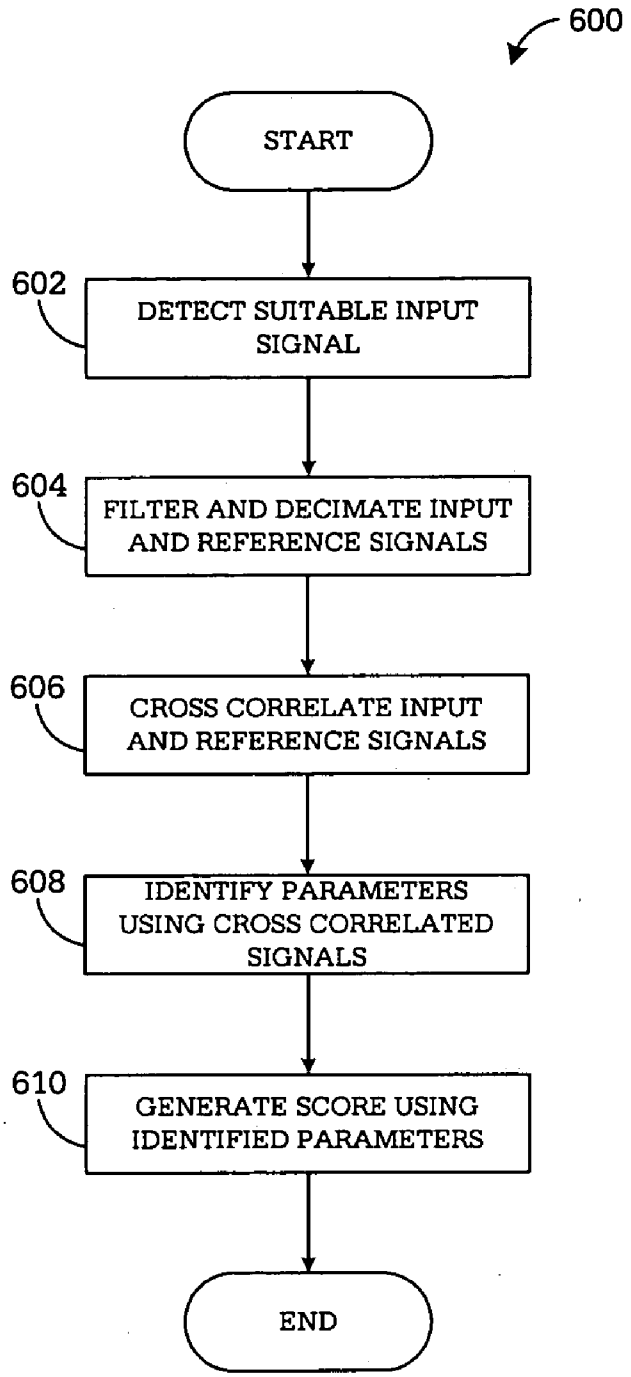

600
START
602
DETECT SUITABLE INPUT SIGNAL
604
FILTER AND DECIMATE INPUT AND REFERENCE SIGNALS
606
CROSS CORRELATE INPUT AND REFERENCE SIGNALS
608
IDENTIFY PARAMETERS USING CROSS CORRELATED SIGNALS
610
GENERATE SCORE USING IDENTIFIED PARAMETERS
END

FIGURE 6

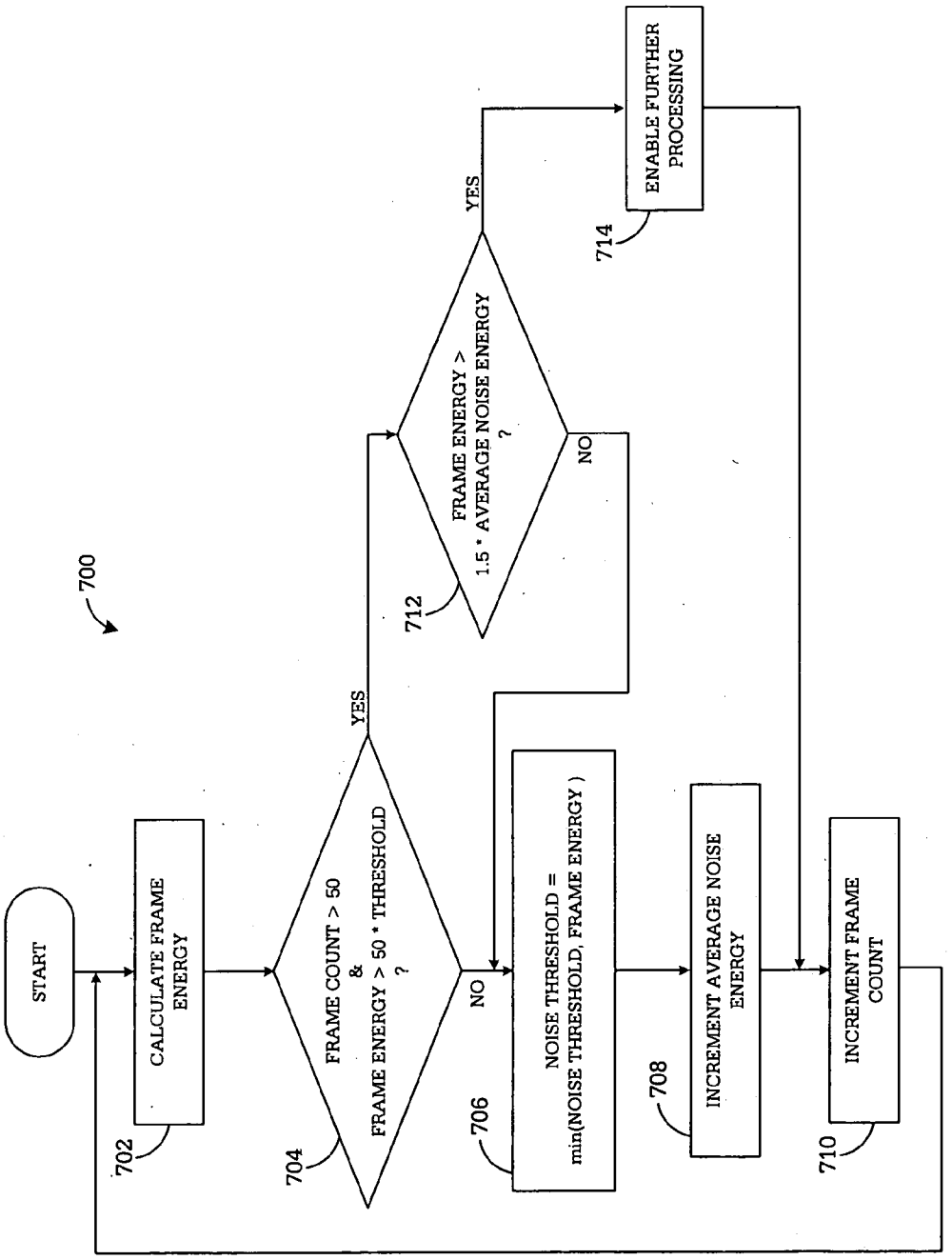

700
START
CALCULATE FRAME ENERGY
702
FRAME COUNT > 50 & FRAME ENERGY > 50 * THRESHOLD ?
704
YES
NO
FRAME ENERGY > 1.5 * AVERAGE NOISE ENERGY ?
712
YES
NO
ENABLE FURTHER PROCESSING
714
NOISE THRESHOLD = min(NOISE THRESHOLD, FRAME ENERGY)
706
INCREMENT AVERAGE NOISE ENERGY
708
INCREMENT FRAME COUNT
710

FIGURE 7

APPARATUS, METHOD, AND COMPUTER PROGRAM FOR COMPARING AUDIO SIGNALS

TECHNICAL FIELD

[0001] This disclosure is generally directed to audio systems and more specifically to an apparatus, method, and computer program for comparing audio signals.

BACKGROUND

[0002] Many conventional audio systems process and compare audio signals. For example, conventional karaoke systems compare an audio signal representing a singer's voice to an audio signal representing an original song. This allows the karaoke systems to identify how well a singer sings the original song. As another example, language-learning software typically compares a signal representing a speaker's voice to a signal representing the proper pronunciation of words. This allows the language-learning software to identify how well the speaker pronounces words in a particular language.

[0003] Some of these audio systems use simplistic algorithms for comparing audio signals. For example, some audio systems simply compare the frame energies of the audio signals. In effect, these systems compare the loudness of the audio signals, which does not provide an accurate comparison of the actual contents of the signals. Other audio systems use overly complex algorithms, such as fast Fourier transformation techniques. These techniques are often computationally intensive and do not compare the actual contents of the audio signals.

SUMMARY

[0004] This disclosure provides an apparatus, method, and computer program for comparing audio signals.

[0005] In one aspect, an apparatus includes a cross correlator operable to receive a first audio signal and a second audio signal and to cross correlate the first and second audio signals, producing a cross-correlated signal. The apparatus also includes at least one parameter identifier operable to receive the cross-correlated signal and to identify a plurality of parameters associated with at least one of the first and second audio signals. In addition, the apparatus includes a score generator operable to receive the plurality of parameters and generate an indicator identifying an extent to which the first and second audio signals match.

[0006] In another aspect, a method includes receiving a first audio signal and a second audio signal and cross-correlating the first and second audio signals to produce a cross-correlated signal. The method also includes identifying a plurality of parameters associated with at least one of the first and second audio signals using the cross-correlated signal. In addition, the method includes generating an indicator identifying an extent to which the first and second audio signals match using the plurality of parameters.

[0007] This has outlined rather broadly several features of this disclosure so that those skilled in the art may better understand the DETAILED DESCRIPTION that follows. Additional features may be described later in this document. Those skilled in the art should appreciate that they may readily use the concepts and the specific embodiments disclosed as a basis for modifying or designing other structures for carrying out the same purposes of this disclosure. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the invention in its broadest form.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] For a more complete understanding of this disclosure and its features, reference is now made to the following description taken in conjunction with the accompanying drawings, in which:

[0009] **FIG. 1** illustrates an example audio apparatus according to one embodiment of this disclosure;

[0010] **FIG. 2** illustrates example audio signals according to one embodiment of this disclosure;

[0011] **FIG. 3** illustrates an example model of a filter and a decimator in the audio apparatus according to one embodiment of this disclosure;

[0012] **FIG. 4** illustrates an example cross correlation of two audio signals according to one embodiment of this disclosure;

[0013] **FIG. 5** illustrates an example mechanism for identifying a pitch variation between two audio signals according to one embodiment of this disclosure;

[0014] **FIG. 6** illustrates an example method for comparing audio signals according to one embodiment of this disclosure; and

[0015] **FIG. 7** illustrates an example method for detecting a voice in an input signal according to one embodiment of this disclosure.

DETAILED DESCRIPTION

[0016] **FIG. 1** illustrates an example audio apparatus **100** according to one embodiment of this disclosure. The apparatus **100** shown in **FIG. 1** is for illustration only. Other embodiments of the apparatus **100** may be used without departing from the scope of this disclosure.

[0017] In one aspect of operation, the apparatus **100** receives audio signals, such as an input signal **102** and a reference signal **104**. The apparatus **100** cross-correlates the audio signals and uses the cross correlation to identify various characteristics or parameters of the audio signals. For example, the cross correlation may be used to identify a variation of pitch between the signals **102**, **104**. The cross correlation may also be used to identify a delay between the signals **102**, **104**. In addition, the cross correlation may be used to identify an amount of correlation between the signals **102**, **104**. Using the identified characteristics, the apparatus **100** generates a score or other indicator identifying the extent to which the signals **102**, **104** match.

[0018] In the illustrated example, the apparatus **100** receives an input signal **102** and a reference signal **104**. The input signal **102** and the reference signal **104** represent audio signals to be compared by the apparatus **100**. In this example, the input signal **102** is supplied by a microphone **106**, and the reference signal **104** is supplied by a reference signal source **108**. In a particular embodiment, the input signal **102** is produced by a microphone **106** used by a singer, and the reference signal **104** represents an original song provided by a compact disc (CD) player. In another

particular embodiment, the input signal **102** is produced by a microphone **106** used by a student, and the reference signal **104** represents a proper pronunciation of words to be spoken by the student. This represents two possible uses of the apparatus **100**. However, the illustrated input signal **102** and reference signal **104** could be replaced by any suitable audio signals provided by any suitable source or sources.

[**0019**] The signals **102, 104** may have any suitable format. For example, in some embodiments, the signals **102, 104** represent Pulse Code Modulated (PCM) signals. In particular embodiments, the input signal **102** includes 12,000 samples per second, while the reference signal **104** includes 48,000 samples per second. Other formats and sampling rates could also be used.

[**0020**] As shown in **FIG. 1**, the apparatus **100** includes a pre-processing section **110**, a parameter extraction section **112**, and a parameter comparison section **114**. In general, the pre-processing section **110** prepares the signals **102, 104** for comparison, the parameter extraction section **112** identifies characteristics of the signals **102, 104**, and the parameter comparison section **114** uses the characteristics to generate a score.

[**0021**] In the illustrated example, the pre-processing section **110** includes a voice activity detector (VAD) **116** coupled to the microphone **106**. In this document, the term "couple" and its derivatives refer to any direct or indirect communication between two or more elements, whether or not those elements are in physical contact with one another.

[**0022**] In this example, the voice activity detector **116** detects when the input signal **102** received from the microphone **106** contains audio information representing a voice. For example, when the microphone **106** is activated, a speaker may or may not begin speaking into the microphone **106**. The voice activity detector **116** analyzes the information in the input signal **102** and determines whether the input signal **102** represents a voice. If a voice is detected, the voice activity detector **116** signals other components in the apparatus **100** to begin processing the input signal **102** and the reference signal **104**. One technique for determining whether an input signal **102** represents a voice is shown in **FIG. 7**, which is described below. The voice activity detector **116** includes any hardware, software, firmware, or combination thereof for detecting a voice in an audio signal.

[**0023**] In the pre-processing section **110**, the input signal **102** is supplied to a filter **118**, and the reference signal **104** is supplied to a filter **120**. The filters **118, 120** filter the signals **102, 104** before the signals **102, 104** are processed further. Each filter **118, 120** includes any hardware, software, firmware, or combination thereof for filtering a signal. As an example, the filters **118, 120** may represent anti-aliasing low pass filters. As a particular example, the filters **118, 120** may represent anti-aliasing low pass filters having a cut-off frequency of 3 kHz. In some embodiments, the filters **118, 120** do not process the signals **102, 104** until the voice activity detector **116** detects a voice in the input signal **102**.

[**0024**] The filter **118** is coupled to a decimator **122**, and the filter **120** is coupled to a decimator **124**. The decimators **122, 124** decimate the input signal **102** and the reference signal **104**, which lowers the sampling frequency of the signals **102, 104**. For example, the decimator **122** may decimate the input signal **102** by selecting and outputting every other sample in the input signal **102**. In some embodiments, the decimator **122** decimates the input signal **102** by a first factor D_1, and the decimator **124** decimates the reference signal **104** by a second factor D_2. In these embodiments, if the input signal **102** has a frequency of f_{S1}, the decimated input signal **102** has a frequency of f_{S1}/D_1. Similarly, if the reference signal **104** has a frequency of f_{S2}, the decimated reference signal **104** has a frequency of f_{S2}/D_2. The decimators **122, 124** may decimate the signals **102, 104** by any suitable factors. In particular embodiments, the decimators **122, 124** decimate the signals **102, 104** so that the decimated signals **102, 104** have a frequency of 6 kHz. As an example, the input signal **102** and reference signal **104** may have sampling rates of 12,000 samples per second and 48,000 samples per second, respectively. If the decimated signals should have a frequency of 6 kHz, the decimator **122** has a decimation factor D_1 of two, and the decimator **124** has a decimation factor D_2 of eight. Each decimator **122, 124** includes any hardware, software, firmware, or combination thereof for decimating a signal **102, 104**.

[**0025**] A filter **126** is coupled to the decimator **122**, and a filter **128** is coupled to the decimator **124**. The filters **126, 128** filter the decimated input signal **102** and decimated reference signal **104**. The filters **126, 128** filter the decimated signals **102, 104** before the decimated signals **102, 104** are processed further. Each filter **126, 128** includes any hardware, software, firmware, or combination thereof for filtering a signal. As an example, the filters **126, 128** may represent band pass filters. As a particular example, the filters **126, 128** may represent infinite impulse response (IIR) filters that band limit the decimated signals **102, 104** to 1 kHz, which helps to attenuate frequencies above 1.5 kHz.

[**0026**] The filters **126, 128** produce two pre-processed signals, a pre-processed input signal **130** and a pre-processed reference signal **132**. The pre-processed signals **130, 132** are supplied to the parameter extraction section **112**.

[**0027**] The parameter extraction section **112** includes a cross correlator (CCF) **134**. The cross correlator **134** receives the pre-processed signals **130, 132** and cross-correlates the pre-processed signals **130, 132**. This produces a cross-correlated signal **136**. The cross correlator **134** may use any suitable technique to cross correlate the pre-processed signals **130, 132**. The cross correlator **134** includes any hardware, software, firmware, or combination thereof for cross-correlating two or more signals.

[**0028**] The cross-correlated signal **136** is provided to a delay identifier **138**, a correlation identifier **140**, and a pitch variation identifier **142**. The identifiers **138-142** use the cross-correlated signal **136** to identify various characteristics associated with the input signal **102** and/or the reference signal **104**.

[**0029**] The delay identifier **138** estimates the delay between the signals **102, 104** using the cross-correlated signal **136**. For example, the input signal **102** could represent a singer's voice, and the reference signal **104** could represent an original song. The singer may sing words before or after the words occur in the original song, and the delay identifier **138** identifies this difference or delay. The delay identifier **138** uses any suitable technique for identifying a delay between two signals. As described below, in

some embodiments, the delay identifier **138** identifies the maximum value in the cross-correlated signal **136**, and the delay is associated with that maximum value. The delay identifier **138** includes any hardware, software, firmware, or combination thereof for identifying a delay between signals.

[**0030**] The correlation identifier **140** identifies the amount of correlation between the signals **102**, **104** using the cross-correlated signal **136**. For example, the reference signal **104** could represent a song, and the amount of correlation between the signals **102**, **104** represents whether a singer sung the correct lyrics in the song. In some embodiments, the correlation identifier **140** identifies the amount of correlation between the signals **102**, **104** in the form of a percentage. The correlation identifier **140** uses any suitable technique for identifying the amount of correlation between signals. The correlation identifier **140** includes any hardware, software, firmware, or combination thereof for identifying the amount of correlation between two or more signals. As a particular example, the correlation identifier **140** may include a normalizer that normalizes the cross-correlated signal **136**. The normalized value of the cross-correlated signal **136** represents an indication of the percentage match between the signals **102**, **104**.

[**0031**] The pitch variation identifier **142** identifies the amount of pitch variation between the signals **102**, **104** using the cross-correlated signal **136**. For example, the reference signal **104** could represent a song, and a singer may sing at a different pitch than the original song. The pitch variation identifier **142** identifies the variation in pitch between the original song and the singer's voice. The pitch variation identifier **142** uses any suitable technique for identifying the pitch variation between signals. As described below, in some embodiments, the pitch variation identifier **142** uses the periodicity of the cross-correlated signal **136** to identify the pitch variation. The pitch variation identifier **142** includes any hardware, software, firmware, or combination thereof for identifying the amount of pitch variation between two or more signals.

[**0032**] The identified delay, amount of correlation, and pitch variation are supplied to the parameter comparison section **114**. The parameter comparison section **114** includes a score generator **144**. The score generator **144** processes the identified delay, correlation, and pitch variation and generates a score **146** using these values. The score **146** represents an indicator identifying an extent to which the signals **102**, **104** match. The score **146** could, for example, represent a value between 0 and 100. In some embodiments, the input signal **102** and the reference signal **104** may be divided into frames, and a score **146** may be produced for each frame. The score generator **144** may also dynamically adjust the score **146** for one frame based on previous frames. The score generator **144** uses any suitable technique for generating a score **146**. One technique for generating a score **146** is described below with respect to **FIG. 6**. The score generator **144** includes any hardware, software, firmware, or combination thereof for generating a score **146** using the information generated by the parameter extraction section **112**. Although this has described the score generator **144** using the identified delay, correlation, and pitch variation to generate a score **146**, other or additional characteristics could also be used to generate a score **146**.

[**0033**] The score **146** produced by the score generator **144** is presented to a user or other person or people on a display **148**. The display **148** represents any suitable device or structure for presenting a score **146**. Although **FIG. 1** illustrates the display **148** as forming part of the apparatus **100**, the display **148** could reside external to the apparatus **100**. Also, the score **146** could be used in other ways, such as by storing the score **146** in a database or other storage medium.

[**0034**] The various components shown in **FIG. 1** may represent any suitable hardware, software, firmware, or combination thereof. As an example, the components in the pre-processing section **110**, parameter extraction section **112**, and parameter comparison section **114** may represent software routines executed by one or more processors in the apparatus **100**.

[**0035**] Although **FIG. 1** illustrates one example of an audio apparatus **100**, various changes may be made to **FIG. 1**. For example, the functional division of the apparatus **100** is for illustration only. Various components can be omitted or combined and additional components can be added according to particular needs. As particular examples, the voice activity detector **116** could be omitted, and the reference signal source **108** could form part of the apparatus **100**. Also, the filters **118**, **126** may be combined, and the filters **120**, **128** may be combined. Further, the input signal **102** and reference signal **104** could represent analog or digital signals. If one or both signals **102**, **104** are analog signals, one or more amplifiers and/or one or more analog-to-digital converters could be used to convert the signals **102**, **104** into a digital format. In addition, the apparatus **100** could form part of a larger apparatus or system, such as a karaoke system or a computer system.

[**0036**] **FIG. 2** illustrates example audio signals according to one embodiment of this disclosure. In particular, **FIG. 2** illustrates the pre-processed input signal **130** and the pre-processed reference signal **132** used by the parameter extraction section **112** of **FIG. 1**. The signals **130**, **132** shown in **FIG. 2** are for illustration only. Other signals **130**, **132** having other formats may be used by the audio apparatus **100** of **FIG. 1** without departing from the scope of this disclosure.

[**0037**] In the illustrated example, each signal **130**, **132** is divided into one or more frames **202** of audio information. Each frame **202** may represent any suitable amount of audio information. For example, in some embodiments, each frame **202** represents **64** samples. Any other frame size could be used by the apparatus **100**.

[**0038**] As described above, the apparatus **100** decimates the input signal **102** and the reference signal **104** to produce the pre-processed signals **130**, **132**. As a result, the samples in a frame **202** of the pre-processed input signal **130** correspond to a larger number of samples in the input signal **102**. If the decimator **122** decimates the input signal **102** by a factor of D_1 and a frame **202** has N samples, the frame **202** represents $N*D_1$ samples in the input signal **102**. Similarly, the samples in a frame **202** of the pre-processed reference signal **132** correspond to a larger number of samples in the reference signal **104**. If the decimator **124** decimates the reference signal **104** by a factor of D_2, the frame **202** represents $N*D_2$ samples in the reference signal **104**.

[**0039**] Even though **FIG. 2** shows that the frames **202** labeled "frame k" are synchronized (same starting and

ending positions), the information contained in the frames **202** may not be. For example, if the apparatus **100** is used to score a karaoke singer's performance, the singer may not be singing in synchronization with the original song. In other words, the singer might sing the lyrics before or after he or she is supposed to sing them. This leads to a difference or delay between the contents of the signals **130**, **132**, which means that the lyrics sung by the singer may not overlap the lyrics in the original song.

[**0040**] This delay may cause problems in conventional systems. For example, the singer could sing all lyrics of a song perfectly but sing them two frames **202** early or late. If a conventional system attempted to cross-correlate the signals **130**, **132** frame by frame, the information in the frames would not be synchronized, and the correlation may indicate that the singer sung incorrect lyrics.

[**0041**] The cross correlator **134** helps to compensate for this delay by correlating samples from the pre-processed input signal **130** within a certain window of time and samples from the pre-processed reference signal **132** within a larger window of time. For example, as shown in **FIG. 2**, the cross correlator **134** correlates 64 samples (one frame) from the pre-processed input signal **130** and 256 samples (four frames) from the pre-processed reference signal **132**. This produces a cross-correlated signal **136** associated with the frame **202** ("frame k") in the pre-processed input signal **130**, and the cross-correlated signal **136** is used to generate a score **146** for that frame **202**. Another cross-correlated signal **136** could then be generated for another frame **202** ("frame k+1") in the pre-processed input signal **130** using four frames **202** ("frame k−1" through "frame k+2") in the pre-processed reference signal **132**.

[**0042**] This allows the cross correlator **134** to take into account the fact that the input and reference signals **102**, **104** may not be synchronized. Even if a singer sings lyrics of a song two frames early or late, the cross correlator **134** can process the signals **102**, **104** correctly. A larger or smaller window could also be used during the correlation, such as when the cross correlator **134** correlates one frame **202** from the pre-processed input signal **130** and two frames **202** from the pre-processed reference signal **132**. Although this has described the use of a particular number of samples by the cross correlator **134**, any suitable number of samples from the input signal **130** and reference signal **132** may be correlated.

[**0043**] Although **FIG. 2** illustrates one example of audio signals processed by the apparatus **100**, various changes may be made to **FIG. 2**. For example, each signal **130**, **132** could include any number of frames **202** having any number of samples. Also, other signals with other formats could be processed by the apparatus **100**.

[**0044**] **FIG. 3** illustrates an example model **300** of a filter **118** and a decimator **122** in the audio apparatus **100** according to one embodiment of this disclosure. The model **300** shown in **FIG. 3** is for illustration only. Embodiments of the apparatus **100** operating under any other model may be used without departing from the scope of this disclosure. Also, the same or similar model may be used to represent the filter **120** and the decimator **124** in the apparatus **100**.

[**0045**] As shown in **FIG. 3**, the filter **118** receives an input signal **102** and produces an intermediate filtered signal **302**. The filter **118** has a filter coefficient of h(k). In this example, x(n) represents the time domain input signal **102**, where the input signal **102** has a frequency of f_x. Also, v(m) represents the time domain intermediate filtered signal **302**.

[**0046**] The decimator **122** receives the intermediate filtered signal **302** and produces a decimated input signal **304**. In this example, y(m) represents the time domain decimated input signal **304**. The decimator **122** decimates the intermediate filtered signal **302** by a factor of D. This may include, for example, the decimator **122** selecting and outputting every Dth value from the intermediate filtered signal **302**. This gives the decimated input signal **304** a frequency f_y of f_x/D. The operation of the decimator **122** may be represented by the following equation:

$$y(m) = v(mD) = \sum_{k=0}^{\infty} h(k)x(mD-k). \tag{1}$$

[**0047**] Reducing the sampling rate of the input signal **102** by selecting every Dth value may result in an aliased version of the input signal **102** with a folding frequency of $f_S/2D$. In some embodiments, to avoid aliasing, the bandwidth of the input signal **102** is reduced to a maximum of $f_S/2D$ by the filter **118**. Ideally, the filter **118** (and filter **120**) satisfies the following condition:

$$H(w) = \begin{cases} 1, & |f| \le f_s/2D \\ 0, & \text{otherwise} \end{cases}. \tag{2}$$

[**0048**] Although **FIG. 3** illustrates one example of a model **300** of a filter **118** and a decimator **122** in the audio apparatus **100**, various changes may be made to **FIG. 3**. For example, the filter **118** could have any suitable response.

[**0049**] **FIG. 4** illustrates an example cross correlation of two audio signals according to one embodiment of this disclosure. In particular, **FIG. 4** illustrates a cross-correlated signal **136** produced by the cross correlator **134** using one frame **202** representing an input signal and four frames **202** representing a reference signal. The cross-correlated signal **136** shown in **FIG. 4** is for illustration only. Other cross-correlated signals could be produced by the apparatus **100** without departing from the scope of this disclosure.

[**0050**] As shown in **FIG. 4**, the cross-correlated signal **136** is highly periodic in nature with a large number of positive peaks **402** and negative peaks **404**. In this example, the cross-correlated signal **136** is produced using audio signals representing a human voice and a reference voice. The periodic nature of the cross-correlated signal **136** is at least partially due to the harmonic nature of human voices. When there is a match in the harmonic frequencies of the input voice and the reference voice, there is a corresponding peak **402**, **404** in the cross-correlated signal **136**.

[**0051**] The cross-correlated signal **136**, which represents the cross correlation Y(τ) of two independent signals **130**, **132**, can be expressed by the equation:

$$Y(\tau) = \frac{1}{N}\sum_{n=0}^{N-1} y_1(n) * y_2(n+\tau), \quad (3)$$

[0052] where N represents the size of the frames **202**, τ represents the lag or delay between the signals **130**, **132**, and $y_1(n)$ and $Y_2(n)$ represent the signals **130**, **132**. In some embodiments, the value of τ varies between 0 and (w−1)*N+1, where w represents the number of frames **202** from the pre-processed reference signal **132** cross-correlated with one frame **202** from the pre-processed input signal **130**. For example, if 256 samples (four frames **202**) from the pre-processed reference signal **132** are used during the cross-correlation, the value of τ varies between 0 and (4−1)*N+1, or 3N+1.

[0053] To remove the dependency of the score **146** on the loudness of the signals **102**, **104**, the cross-correlated signal **136** may be normalized. In some embodiments, the cross-correlated signal **136** is normalized using the root mean square of the energies of both the input signal **102** and the reference signal **104**. The root mean square of the energy may be defined using the following equation:

$$E_y = \sqrt{\sum_{n=0}^{N-1} y^2(n)} \quad (4)$$

[0054] where E_y represents the root mean square energy and y(n) represents one of the signals **130**, **132**.

[0055] The cross-correlated signal **136** in **FIG. 4** is provided to the delay identifier **138**, correlation identifier **140**, and pitch variation identifier **142** in the apparatus **100**. The identifiers **138-142** use the cross-correlated signal **136** to identify different parameters or characteristics of the input signal **102** and reference signal **104**.

[0056] As an example, the delay identifier **138** identifies a delay between the pre-processed signals **130**, **132**. In some embodiments, the delay identifier **138** identifies the delay by identifying the maximum value in the cross-correlated signal **136**. As shown in **FIG. 4**, the maximum value is shown by a line **406**.

[0057] In this example, the maximum value occurs at a lag of **128**. However, this does not necessarily mean that the input signal **102** is lagging behind the reference signal **104**. In fact, in this example, a lag of 128 indicates that the signals **102**, **104** are synchronized. To produce the cross-correlated signal **136** shown in **FIG. 4**, the cross correlator **134** correlated the samples in one frame **202** of an input signal with the samples in four frames **202** of a reference signal. As shown in **FIG. 2**, if the frames **202** labeled "frame k" are synchronized, the synchronization would begin at the beginning of the third frame **202**. Assuming each frame **202** has 64 samples, the synchronization begins 128 samples into the reference signal shown. In this example, a lag of 128 indicates synchronization, and a lag that varies from 128 indicates a lack of synchronization.

[0058] The correlation identifier **140** also processes the cross-correlated signal **136** to identify the amount of correlation between the signals **102**, **104**. In some embodiments, the correlation identifier **140** identifies the normalized value of the cross-correlated signal **136**, where the normalized value represents the percentage match between the two signals **130**, **132**.

[0059] The pitch variation identifier **142** identifies the amount of variation in the pitch of the signals **102**, **104** using the cross-correlated signal **136**. The periodicity of the cross-correlated signal **136** acts as an indicator of the pitch variation in the signal **102** with respect to the signal **104**. A constant period may indicate that the variation is at a minimum, and fluctuations in the period may indicate variations in the input signal **102**.

[0060] In some embodiments, the pitch variation identifier **142** measures the periodicity of the cross-correlated signal **136** over successive frames **202**. In particular embodiments, the pitch variation identifier **142** identifies the periodicity of the cross-correlated signal **136** by measuring the distance between positive peaks **402** and the distance between negative peaks **404** in the cross-correlated signal **136**. This technique is described below with respect to **FIG. 5**.

[0061] Although **FIG. 4** illustrates one example of a cross correlation of two audio signals, various changes may be made to **FIG. 4**. For example, any cross-correlated signal **136** could be produced and used by the apparatus **100** of **FIG. 1**.

[0062] **FIG. 5** illustrates an example mechanism for identifying a pitch variation between two audio signals according to one embodiment of this disclosure. In particular, **FIG. 5** illustrates a technique for identifying the periodicity of a cross-correlated signal **136** using distances **502** between positive peaks **402** and distances **504** between negative peaks **404**. The distances **502**, **504** shown in **FIG. 5** are for illustration only. Other distances could be identified using any cross-correlated signal **136** without departing from the scope of this disclosure.

[0063] The cross-correlated signal **136** shown in **FIG. 4** is highly periodic. The periodicity of the cross-correlated signal **136** is an indicator of the pitch variation between the signals **102**, **104**. The periodicity of the cross-correlated signal **136** is estimated by measuring the distance **502** ($Diff_{pp}$) between positive peaks **504** and the distance **504** ($Diff_{nn}$) between negative peaks **404**.

[0064] Using the distances **502** as an example, **FIG. 5** shows that the distances between positive peaks **402** in **FIG. 4** vary from six and eight lags. When the distances **502** remain constant (at seven lags), the periodicity of the positive peaks **402** is also constant. This indicates that the pitch variation between the signals **130**, **132** is at a minimum. When the distances **502** between positive peaks **402** fluctuate (to six or eight lags), this indicates that the pitch variation between the signals **130**, **132** has increased.

[0065] The peaks **402**, **404** in the cross-correlated signal **136** may be identified using any suitable technique. In some embodiments, the positive peaks **402** are identified by locating points in the cross-correlated signal **136** where $Y(\tau-1)<Y(\tau)>Y(\tau+1)$, and the negative peaks **404** are identified by locating points in the cross-correlated signal **136** where $Y(\tau-1)>Y(\tau)<Y(\tau+1)$. Using these criteria, the peaks **402**, **404** in the cross-correlated signal **136** of **FIG. 4** are identified, and the distances between them are shown in **FIG. 5**.

[0066] The pitch variation identifier **142** may use the information in **FIG. 5** to identify the estimated pitch variation. In some embodiments, the pitch variation identifier **142** uses the following equation to identify the estimated variation in pitch:

$$Pitch^{l}_{est} = \frac{\sum Diff_{pp}}{k_p} + \frac{\sum Diff_{nn}}{k_n} \quad (5)$$

[0067] where k_p represents the number of positive peaks **402**, k_n represents the number of negative peaks **404**, l represents the lth frame **202**, and $Pitch_{est}$ represents the estimated coincidental harmonic frequency (or pitch variation) for the lth frame **202**.

[0068] Although **FIG. 5** illustrates one example of a mechanism for identifying a pitch variation between two audio signals, various changes may be made to **FIG. 5**. For example, the specific distances **502**, **504** are for illustration only.

[0069] **FIG. 6** illustrates an example method **600** for comparing audio signals according to one embodiment of this disclosure. For ease of explanation, the method **600** is described with respect to the audio apparatus **100** of **FIG. 1**. The method **600** could be used by any other suitable apparatus or system.

[0070] The apparatus **100** detects a suitable input signal at step **602**. This may include, for example, the voice activity detector **116** receiving an input signal **102** and determining that the input signal **102** contains audio information representing a voice. This may also include the voice activity detector **116** instructing the filters **118**, **120** to begin processing the input signal **102** and a reference signal **104**.

[0071] The apparatus **100** filters and decimates the input and reference signals at step **604**. This may include, for example, the filters **118**, **120** performing low pass filtering on the signals **102**, **104**. This may also include the decimators **122**, **124** decimating the filtered input signals **102**, **104**. This may further include the filters **126**, **128** band pass filtering the decimated input signals **102**, **104**, which produces two pre-processed signals **130**, **132**.

[0072] The apparatus **100** cross-correlates the processed signals at step **606**. This may include, for example, the cross correlator **134** correlating the pre-processed input and reference signals **130**, **132** to produce a cross-correlated signal **136**. The cross correlator **134** may correlate an equal number of samples from the pre-processed signals **130**, **132**. The cross correlator **134** could also correlate an unequal number of samples from the pre-processed signals **130**, **132**.

[0073] The apparatus **100** identifies a plurality of parameters using the cross-correlated signals at step **608**. This may include, for example, the identifiers **138-142** using the cross-correlated signal **136** to identify a delay between the signals **130**, **132**, an amount of correlation between the signals **130**, **132**, and a pitch variation between the signals **130**, **132**. Other or additional parameters could also be identified.

[0074] The apparatus **100** uses the identified parameters to generate a score at step **610**. The score identifies the extent to which the signals **102**, **104** match. This may include, for example, the score generator **144** receiving the identified parameters from the identifiers **138-142** and generating the score using the parameters.

[0075] The score generator **144** may use any suitable technique to generate a score using the parameters. In some embodiments, the score generator **144** assigns different weights or levels of importance to the values produced by the identifiers **138-142**. For example, when used in a karaoke system, the operator of the apparatus **100** may want a singer who incorrectly sings the lyrics of a song to receive a lower score **146** than a singer who sings at a variable pitch. In this example, a higher weight is assigned to singing the correct words, which can be determined using the delay and correlation values produced by the identifiers **138-140**. The weights can be assigned in any suitable manner, such as having default values and allowing a user to assign custom values as desired.

[0076] In particular embodiments, the score generator **144** uses a two-stage scoring algorithm to determine a score **146**. For example, the score generator **144** may generate a first score using the delay value and correlation value produced by the delay identifier **138** and correlation identifier **140**. The score generator **144** may then generate a second score using the pitch variation value produced by the pitch variation identifier **142**. The final score **146** may represent a sum of the first and second scores.

[0077] The following represents one example way in which the score generator **144** may generate a score **146**. Various values used in this example are for illustration and explanation only. First, the score generator **144** generates a value α using the information from the delay identifier **138** and the correlation identifier **140**. The value of α is determined using the formula:

$$\text{local_maxout/max_out.} \quad (6)$$

[0078] In this embodiment, local_maxout identifies the largest value of the cross-correlated signal within a certain range centered at the 128th lag, such as within a range of **125-131** (±3 lags from 128). Also, max_out identifies the largest value in the cross-correlated signal. In this example, the correlation identifier **140** outputs two values, one identifying a value for max_out and another identifying a value of local_maxout. Using the value of α, the score generator **144** selects a first score ($Score_1$) using Table 1.

TABLE 1

Range	$Score_1$
$\alpha \geqq 0.75$	60
$0.75 > \alpha \geqq 0.5$	50
$0.5 > \alpha \geqq 0.25$	40
$0.25 > \alpha$	30

[0079] After that, the score generator **144** uses the information from the pitch variation identifier **142** to select a second score, which is added to the first score to produce the final score **146**. In particular, the score generator **144** produces two values β_1 and β_2, which uses the estimated coincidental harmonic frequency for three successive frames **202** calculated using Equation 5. The score generator **144** uses the following equations to identify values for β_1 and β_2:

$$\beta_1 = \left| \frac{Pitch_{est}^{l-1} - Pitch_{est}^{l-2}}{Pitch_{est}^{l-2}} \right| \quad (7)$$

$$\beta_2 = \left| \frac{Pitch_{est}^{l} - Pitch_{est}^{l-1}}{Pitch_{est}^{l-1}} \right|. \quad (8)$$

[0080] Ideally, if the input signal **102** has a constant pitch, the deviation of the estimated coincidental harmonic frequency across the frames **202** should be small. Using the values of β_1 and β_2, the score generator **144** assigns a final score using Table 2. In Table 2, if both the "Range 1" condition and "Range 2" condition in the same line are satisfied, the final score is computed using the formula on that line. The formula adds the first score to a second score and produces the final score **146**. In Table 2, the symbol denotes the logical OR operation.

TABLE 2

Range 1	Range 2	Final Score
$\beta_1 < 0.2$	$\beta_2 < 0.2$	$Score_1 + 40$
$\beta_1 \parallel \beta_2 < 0.2$	$\beta_1 \parallel \beta_2 < 0.3$	$Score_1 + 20$
$\beta_1 \parallel \beta_2 < 0.3$	$\beta_1 \parallel \beta_2 < 0.6$	$Score_1$
$\beta_1 \parallel \beta_2 \geqq 0.3$	$\beta_1 \parallel \beta_2 < 0.6$	$Score_1 - 10$
$\beta_1 \geqq 0.6$	$\beta_2 \geqq 0.6$	$Score_1 - 30$

[0081] By considering the two previous frames **202** in the computation of the final score **146**, the score generator **144** averages out fluctuations in short time periods and provides a more reliable estimate of the quality of the input signal **102**.

[0082] This represents one way to generate a score **146** for a single frame **202** in the pre-processed input signal **130**. The score **146** for multiple frames could be used in any suitable manner. For example, the scores **146** could be averaged to produce an overall score for the input signal **102**.

[0083] Although **FIG. 6** illustrates one example of a method **600** for comparing audio signals, various changes may be made to **FIG. 6**. For example, the apparatus **100** could always process audio signals and not wait to detect a suitable input signal **102** at step **602**.

[0084] **FIG. 7** illustrates an example method **700** for detecting a voice in an input signal according to one embodiment of this disclosure. In particular, the method **700** is used by the voice activity detector **116** to determine when an input signal **102** suitable for processing has been received. For ease of explanation, the method **700** is described with respect to the audio apparatus **100** of **FIG. 1**. The method **700** could be used by any other suitable apparatus or system.

[0085] The voice activity detector **116** calculates the energy contained in a frame of an input signal at step **702**. The frame in the input signal could have a size of $N*D_1$, where N represents the size of a frame **202** in the pre-processed input signal **102**. In particular embodiments, the frame energy is determined using the formula:

$$E^l = \sum_{n=(l-1)*D_1 N+1}^{l*D_1 N} x(n)^2 \quad (9)$$

[0086] where l represents the lth frame of size D_1*N, and E^l represents the frame energy of the lth frame.

[0087] The voice activity detector **116** determines whether the calculated frame energy represents a possible voice at step **704**. This may include, for example, the voice activity detector **116** determining whether 50 frames of the input signal **102** have been received and whether the calculated frame energy is at least 50 times greater than a noise threshold. In this example, the first 50 frames of the input signal **102** are used to identify the noise threshold, and a decision as to whether a voice is present in the input signal **102** is not made during those 50 frames. While this example uses 50 frames, any other suitable number of frames could be used.

[0088] If either of the conditions at step **704** is not met, the voice activity detector **116** updates the noise threshold at step **706**. This may include, for example, the voice activity detector **116** setting the noise threshold equal to the smaller of the previous noise threshold and the current frame energy.

[0089] The voice activity detector **116** increments an average noise energy value at step **708**. In particular embodiments, the average noise energy value is determined using the formula:

$$E_n^a = \frac{1}{k} \sum_{l=1}^{k} E^l \quad (10)$$

[0090] where E^a_n represents the average noise energy over k frames of the input signal **102**.

[0091] The voice activity detector **116** increments a frame count at step **710**. The frame count allows the voice activity detector **116** to determine when it has processed a threshold number (such as 50) of frames in the input signal **102**. The voice activity detector **116** returns to step **702** to process another frame in the input signal **102**.

[0092] Eventually, the voice activity detector **116** detects that the conditions at step **704** are satisfied. When that occurs, the voice activity detector **116** determines whether the frame energy for the current frame in the input signal exceeds the average noise energy value by a specified amount at step **712**. This may include, for example, the voice activity detector **116** determining whether the frame energy for the current frame of the input signal **102** is greater than 1.5 times the average noise energy value.

[0093] If not, the voice activity detector **116** returns to step **706** to update the noise threshold. At this point, the apparatus **100** is still not processing the input signal **102**. For example, the voice activity detector **116** could output a value of zero to the filters **118**, **120**, which prevents the filters **118**, **120** from processing the input signal **102** and reference signal **104**. The apparatus **100** could also be outputting a default score **146**, such as a score of zero.

[0094] Otherwise, if the frame energy for the current frame in the input signal exceeds the average noise energy value by a specified amount, the voice activity detector **116** enables further processing of the input signal at step **714**. This may include, for example, the voice activity detector **116** outputting a value of one to the filters **118**, **120**, which allows the filters **118**, **120** to process the input signal **102** and reference signal **104**. At this point, the remaining components in the apparatus **100** process the signals **102**, **104** and output a score **146**.

[0095] Although **FIG. 7** illustrates one example of a method **700** for detecting an input signal, various changes may be made to **FIG. 7**. For example, the values of "50" in step **704** and "1.5" in step **712** are for illustration only. Other values could be used in these steps. Also, any other voice detection mechanism could be used in the apparatus **100**, and the voice activity detector **116** could be omitted.

[0096] It may be advantageous to set forth definitions of certain words and phrases used in this patent document. The terms "include" and "comprise," as well as derivatives thereof, mean inclusion without limitation. The term "or" is inclusive, meaning and/or. The phrases "associated with" and "associated therewith," as well as derivatives thereof, may mean to include, be included within, interconnect with, contain, be contained within, connect to or with, couple to or with, be communicable with, cooperate with, interleave, juxtapose, be proximate to, be bound to or with, have, have a property of, or the like. The term "controller" means any device, system, or part thereof that controls at least one operation. A controller may be implemented in hardware, firmware, or software, or a combination of at least two of the same. It should be noted that the functionality associated with any particular controller may be centralized or distributed, whether locally or remotely.

[0097] While this disclosure has described certain embodiments and generally associated methods, alterations and permutations of these embodiments and methods will be apparent to those skilled in the art. Accordingly, the above description of example embodiments does not define or constrain this disclosure. Other changes, substitutions, and alterations are also possible without departing from the spirit and scope of this disclosure, as defined by the following claims.

What is claimed is:

1. An apparatus, comprising:

a cross correlator operable to receive a first audio signal and a second audio signal, the cross correlator also operable to cross correlate the first and second audio signals to produce a cross-correlated signal;

at least one parameter identifier operable to receive the cross-correlated signal and identify a plurality of parameters associated with at least one of the first and second audio signals; and

a score generator operable to receive the plurality of parameters and generate an indicator identifying an extent to which the first and second audio signals match.

2. The apparatus of claim 1, wherein the at least one parameter identifier comprises:

a delay identifier operable to identify a delay between the first and second audio signals;

a correlation identifier operable to identify an amount of correlation between the first and second audio signals; and

a pitch variation identifier operable to identify a variation in pitch between the first and second audio signals.

3. The apparatus of claim 2, wherein:

the delay identifier is operable to identify the delay by identifying a maximum value in the cross-correlated signal;

the correlation identifier is operable to identify the amount of correlation by normalizing the cross-correlated signal; and

the pitch variation identifier is operable to identify the variation in pitch by identifying a coincidental harmonic frequency using the cross-correlated signal.

4. The apparatus of claim 2, wherein the score generator is operable to generate the indicator by:

generating a first score using the delay between the first and second audio signals and the amount of correlation between the first and second audio signals;

generating a second score using the variation in pitch between the first and second audio signals; and

combining the first and second scores to produce a final score.

5. The apparatus of claim 1, wherein the first audio signal is associated with an input signal and the second audio signal is associated with a reference signal; and

further comprising:

a plurality of decimators operable to receive and decimate the input signal and the reference signal; and

a plurality of filters operable to filter at least one of the input signal, the reference signal, a decimated input signal, and a decimated reference signal.

6. The apparatus of claim 5, wherein the plurality of filters comprise:

a first anti-aliasing low pass filter operable to filter the input signal, a first of the decimators operable to decimate the filtered input signal;

a second anti-aliasing low pass filter operable to filter the reference signal, a second of the decimators operable to decimate the filtered reference signal;

a first band pass filter operable to filter the decimated input signal to produce the first audio signal; and

a second band pass filter operable to filter the decimated reference signal to produce the second audio signal.

7. The apparatus of claim 1, further comprising a voice activity detector operable to detect a voice in the input signal;

wherein the score generator is operable to generate the indicator after the voice activity detector detects the voice in the input signal.

8. The apparatus of claim 1, wherein:

each of the first and second audio signals comprises a plurality of frames; and

the cross correlator is operable to correlate one frame from the first audio signal and multiple frames from the second audio signal to produce the cross-correlated signal.

9. The apparatus of claim 8, wherein the indicator identifies an extent to which the one frame from the first audio signal matches at least a portion of the multiple frames from the second audio signal.

10. A method, comprising:

receiving a first audio signal and a second audio signal;

cross-correlating the first and second audio signals to produce a cross-correlated signal;

identifying a plurality of parameters associated with at least one of the first and second audio signals using the cross-correlated signal; and

generating an indicator identifying an extent to which the first and second audio signals match using the plurality of parameters.

11. The method of claim 10, wherein the plurality of parameters comprise:

a delay between the first and second audio signals;

an amount of correlation between the first and second audio signals; and

a variation in pitch between the first and second audio signals.

12. The method of claim 11, wherein identifying the plurality of parameters comprises:

identifying the delay by identifying a maximum value in the cross-correlated signal;

identifying the amount of correlation by normalizing the cross-correlated signal; and

identifying the variation in pitch by identifying a coincidental harmonic frequency using the cross-correlated signal.

13. The method of claim 11, wherein generating the indicator comprises:

generating a first score using the delay between the first and second audio signals and the amount of correlation between the first and second audio signals;

generating a second score using the variation in pitch between the first and second audio signals; and

combining the first and second scores to produce a final score.

14. The method of claim 10, wherein the first audio signal is associated with an input signal and the second audio signal is associated with a reference signal; and

further comprising:

decimating the input signal and the reference signal; and

filtering at least one of the input signal, the reference signal, a decimated input signal, and a decimated reference signal.

15. The method of claim 14, wherein filtering at least one of the signals comprises:

anti-alias low pass filtering the input signal;

anti-alias low pass filtering the reference signal;

band pass filtering the decimated input signal to produce the first audio signal; and

band pass filtering the decimated reference signal to produce the second audio signal.

16. The method of claim 10, further comprising detecting a voice in the input signal;

wherein generating the indicator comprises generating the indicator after detecting the voice in the input signal.

17. The method of claim 10, wherein:

each of the first and second audio signals comprises a plurality of frames; and

cross-correlating the first and second audio signals comprises cross-correlating one frame from the first audio signal and multiple frames from the second audio signal to produce the cross-correlated signal.

18. A computer program operable to be executed by a processor, the computer program comprising computer readable program code for:

receiving a first audio signal and a second audio signal;

cross-correlating the first and second audio signals to produce a cross-correlated signal;

identifying a plurality of parameters associated with at least one of the first and second audio signals using the cross-correlated signal; and

generating an indicator identifying an extent to which the first and second audio signals match using the plurality of parameters,

19. The computer program of claim 18, wherein the plurality of parameters comprise:

a delay between the first and second audio signals;

an amount of correlation between the first and second audio signals; and

a variation in pitch between the first and second audio signals.

20. The computer program of claim 19, wherein the computer readable program code for identifying the plurality of parameters comprises computer readable program code for:

identifying the delay by identifying a maximum value in the cross-correlated signal;

identifying the amount of correlation by normalizing the cross-correlated signal; and

identifying the variation in pitch by identifying a coincidental harmonic frequency using the cross-correlated signal.

21. The computer program of claim 19, wherein the computer readable program code for generating the indicator comprises computer readable program code for:

generating a first score using the delay between the first and second audio signals and the amount of correlation between the first and second audio signals;

generating a second score using the variation in pitch between the first and second audio signals; and

combining the first and second scores to produce a final score.

22. The computer program of claim 18, wherein the first audio signal is associated with an input signal and the second audio signal is associated with a reference signal; and

further comprising computer readable program code for:

decimating the input signal and the reference signal; and

filtering at least one of the input signal, the reference signal, a decimated input signal, and a decimated reference signal.

23. The computer program of claim 22, wherein the computer readable program code for filtering at least one of the signals comprises:

computer readable program code for anti-alias low pass filtering the input signal;

computer readable program code for anti-alias low pass filtering the reference signal;

computer readable program code for band pass filtering the decimated input signal to produce the first audio signal; and

computer readable program code for band pass filtering the decimated reference signal to produce the second audio signal.

24. The computer program of claim 18, further comprising computer readable program code for detecting a voice in the input signal;

wherein the computer readable program code for generating the indicator comprises computer readable program code for generating the indicator after detecting the voice in the input signal.

25. The computer program of claim 18, wherein:

each of the first and second audio signals comprises a plurality of frames; and

the computer readable program code for cross-correlating the first and second audio signals comprises computer readable program code for cross-correlating one frame from the first audio signal and multiple frames from the second audio signal to produce the cross-correlated signal.

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