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(54) Method for extending the spectral bandwidth of a speech signal

(57) The present invention relates to a method for extending the spectral bandwidth of an excitation signal of a speech signal, comprising the following steps:
- determining a bandwidth limited excitation signal of the speech signal,
- applying a nonlinear function to the excitation signal for generating a bandwidth extended excitation signal

wherein the nonlinear function is the following quadratic function:

$$\tilde{x}_{Anr,i}(n) = c_2(n)x^2{}_{p,i}(n) + c_1(n)x_{p,i}(n)$$

c1, and c2 being determined in such a way, that

$$c_1(n) = K_1 - x_{\max}(n)c_2(n) = K_1 - x_{\max}\left(\frac{K_1 - K_2}{x_{\max}(n) - x_{\min}(n) + \varepsilon}\right)$$

$$c_2(n) = \frac{K_1 - K_2}{x_{\max}(n) - x_{\min}(n) + \varepsilon}.$$

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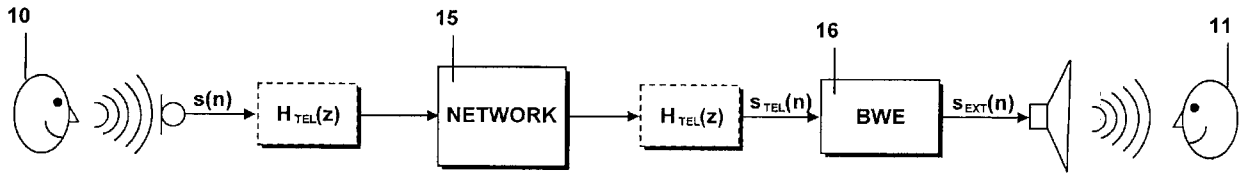
Fig. 1



Description

[0001] The invention relates to a method for extending the spectral bandwidth of an excitation signal of a speech signal, to a method for reconstructing noisy parts of a speech signal recorded in a noisy environment and relates to a method for enhancing the quality of a speech signal.

[0002] Speech is the most natural and convenient way of human communication. This is one reason for the great success of the telephone system since its invention in the 19th century. Today, subscribers are not always satisfied any more with the quality of the service provided by the telephone system especially when compared to other audio sources, such as radio, compact disk or DVD. The degradation of speech quality using analogue telephone systems is caused by the introduction of band limiting filters within amplifiers used to keep a certain signal level in long local loops. These filters have a passband from approximately 300 Hz up to 3400 Hz and are applied to reduce crosstalk between different channels. However, the application of such bandpass filters considerably attenuates different frequency parts of the human speech ranging from about 0 Hz up to 6000 Hz.

[0003] Great efforts have been made to increase the quality of telephone speech signals in recent years. One possibility to increase the quality of a telephone speech signal is to increase the bandwidth after transmission by means of bandwidth extension. The basic idea of these enhancements is to establish the speech signal components above 3400 Hz and below 300 Hz and to complement the signal in the idle frequency bands with this estimate. In this case the telephone networks can remain untouched.

[0004] Additionally, mobile communication systems such as cellular phones have been developed in recent years which are used in different environments. By way of example cellular phones are often used in vehicles or in other environments where a strong background noise exists. In vehicle applications a hands-free speaking system is often used in order to avoid that the driver is diverted from the traffic while using the cellular phone.

[0005] Additionally, speech recognition systems have been developed which are also often used inside vehicles. These systems are able to control different functions of the vehicle. In these systems the speech recognition system has to recognize the order of the driver, the recorded signal comprising speech components and noise components. The same is true for hands-free systems, in which the recorded speech signal from the driver also comprises noise components from the background noise inside the vehicles.

[0006] In both systems, when a telephone call is received via a telecommunication system having a limited bandwidth or when speech is recorded in a noisy environment there exists the problem that certain frequency ranges are either not present in the transmitted signal or are heavily distorted. A speech signal having an extended frequency range can be better understood.

Accordingly, the speech quality in the above-mentioned scenarios (e.g. in very high noise conditions) where traditional methods such as noise suppression systems do not work properly any more needs to be improved.

Accordingly, a need exists to provide a method for restoring a signal for which a certain frequency part is missing.

[0007] These needs are met by the features of the independent claims. In the dependent claims preferred embodiments of the invention are described.

[0008] According to one embodiment of the invention the latter relates to a method for extending the spectral bandwidth of an excitation signal of a speech signal comprising the steps of determining a bandwidth limited excitation signal of the speech signal. Once the bandwidth limited excitation signal is determined, a nonlinear function is applied to the excitation signal for generating a bandwidth extended excitation signal. According to the invention the nonlinear function is a quadratic function according to the following formula:

$$\tilde{x}_{Anr,i}(n) = c_2(n)x^2{}_{p,i}(n) + c_1(n)x_{p,i}(n)$$

[0009] The coefficients c_1 and c_2 of above-mentioned applications are determined in such a way that

$$c_1(n) = K_1 - x_{\max}(n)c_2(n) = K_1 - x_{\max}\left(\frac{K_1 - K_2}{x_{\max}(n) - x_{\min}(n) + \varepsilon}\right)$$

$$c_2(n) = \frac{K_1 - K_2}{x_{\max}(n) - x_{\min}(n) + \varepsilon}.$$

[0010] The parameters will be explained in detail later on.

[0011] By choosing the quadratic function as mentioned above and by selecting the coefficients c_1 and c_2 as described an extended excitation signal can be obtained for which the adaptive coefficients c_1 and c_2 allow to adjust whether the linear term or the quadratic term should be considered more than the other term. Tests have shown that, when the bandwidth of the excitation signal is extended using the above-defined function, the speech signal sounds more natural and the speech quality in general is increased as well.

By way of example the enhanced speech quality can be shown using comparison mean opinion score (CMOS) tests.

[0012] The basic idea of bandwidth extension algorithms is to extract information on the missing components from the available narrowband signal. For finding information that is suitable for this task most of the algorithms employ the so-called source-filter model of speech generation. This model is motivated by the anatomical analysis of the human speech apparatus. A flow of air coming from the lungs is pressed through the vocal cords. At this point two scenarios can be distinguished. A first scenario in which the vocal cords are loose causing a turbulent nose-like air flow. In a second scenario the vocal cords are tense and closed. The pressure of the air coming from the lungs increases until it causes the vocal cords to open. Now the pressure decreases rapidly and the vocal cords close once again. This scenario results in a periodic signal. The signal observed directly behind the vocal cords is called excitation signal.

[0013] This excitation signal has the property of being spectrally flat. After passing the vocal cords the air flow travels through several cavities of the human mouth. In all these cavities the air flow undergoes frequency dependent reflections and resonances depending on the geometry of the cavity. The source-filter model tries to rebuild these two scenarios that are responsible for the generation of the excitation signal by using two different signal generators: a noise generator for rebuilding unvoiced (noise-like) utterances and a pulse train generator for rebuilding voiced (periodic) utterances.

[0014] By applying the nonlinear quadratic function to the bandwidth limited excitation signal, the bandwidth of the excitation signal can be increased, an extended excitation signal is generated. The extended excitation signal can be used to generate an extended speech signal. The extended speech signal comprises frequency components which have either been suppressed by a transmission line such as a telecommunication line or the extended signal parts can replace parts of a speech signal recorded in a noisy environment, the recorded speech signal comprising noisy components in which the background noise is the dominant factor.

[0015] According to a preferred embodiment of the invention a bandwidth limited spectral envelope of the speech signal is determined for generating the excitation signal and removed from the speech signal by applying the inverse spectral envelope to the speech signal. This can be done either in the frequency domain or in the time domain of the signal. In the frequency domain of the signal the inverse spectral envelope is multiplied with the speech signal in order to remove the spectral envelope. In the time domain this multiplication corresponds to a convolution of the spectral envelopes and of the speech signal. By removing the spectral envelope the excitation signal can be obtained. The excitation signal itself is a spectrally flat signal. Before generating a bandwidth extended excitation signal the narrowband excitation signal has to be determined first.

[0016] According to a preferred embodiment of the invention the speech signal is divided into overlapping segments for carrying out the necessary calculations and for extending the bandwidth of the excitation signal. Each segment of the speech signal can be described by a vector, the vector describing one segment of the speech signal when the spectral envelope of the speech signal has been removed, i.e. when the inverse filter, the predictor error filter has been applied:

$$x_p(n) = \left[x_{p,0}(n), x_{p,1}(n), \ldots, x_{p,N-1}(n)\right]^T.$$

[0017] Additionally, the parameters x_{max} and x_{min}, describing the maximum or the minimum of the input vector x_p are defined as follows:

$$x_{\max}(n) = \max\left\{x_{p,0}(n), x_{p,1}(n), \ldots x_{p,N-1}(n)\right\},$$

$$x_{\min}(n) = \min\{x_{p,0}(n), x_{p,1}(n), \ldots, x_{p,N-1}(n)\}$$

[0018] The values $x_{max}(n)$, $x_{min}(n)$ are necessary for determining the coefficients c_1, c_2 mentioned above.

[0019] ε is a small number lager than zero in order to avoid a division through zero.

The two constant factors K_1 and K_2 determine the minimum and the maximum after applying the quadratic function to the speech signal. The following values have been found as being particularly useful for the above-mentioned excitation signal: N being the length of the input vector.

[0020] K_1 is a value in the range from 0.5 to 1.7, preferably in the range from 1.0 to 1.5, even more preferably K_1 is 1.2. K_2 is in the range from 0.0 to 0.5, preferably in the range from 0.1 to 0.3, more preferably K_2 is 0.2.

[0021] One property of these nonlinear characteristics used above for extending the bandwidth of the excitation signal is that these nonlinear characteristics produce strong components around 0 Hz which have to be removed. Accordingly, the extended excitation signal may be highpass filtered for removing the frequency components around 0 Hz.

[0022] Before the extended excitation signal can be calculated the bandwidth limited spectral envelope of the bandwidth limited speech signal has to be determined. This limited spectral envelope can be determined using a linear predictive coding (LPC) analysis known in the art. With about ten coefficients of the linear predictive coding analyis it is possible to estimate the spectral envelope of a speech signal in a reliable manner.

[0023] According to a preferred embodiment of the invention the extended parts of the excitation signal are used for replacing noisy parts of the bandwidth limited excitation signal, the bandwidth limited excitation signal corresponding to the speech signal recorded in a noisy environment for which the frequency components in which the noise is a dominant factor have been suppressed.

[0024] Furthermore, the extended parts of the excitation signal can also be used for replacing the corresponding parts of a bandwidth limited excitation signal corresponding to a bandwidth limited speech signal transmitted via a transmission unit of a telecommunication system, the spectral parts of the speech signal suppressed by the transmission line being generated on the basis of the extended spectral bandwidth parts of the excitation signal. As mentioned in the introductory part of the specification not all frequency components are transmitted in an analogue telephone system. According to the invention the spectral parts suppressed by the transmission system can be generated using the extended excitation signal as mentioned above.

[0025] The basic idea of bandwidth extension in order to extract information on missing components from the available narrowband signal is used in another embodiment of the invention in a method for reconstructing noisy parts of a speech signal recorded in a noisy environment.

[0026] The method comprises the steps of determining the noisy parts of the speech signal in which the noise components of the recorded signal dominate the speech components of the speech signal. By way of example the noisy parts could be the parts of the speech signal in which the signal to noise ratio is about 0 dB. In these very high noise conditions traditional methods such as noise suppression systems do not work properly any more.

[0027] According to another step of the method according to the invention a bandwidth limited spectral envelope of the speech signal is determined. Furthermore, on the basis of the speech signal a bandwidth limited excitation signal is determined, the noisy parts of the speech signal being suppressed when the excitation signal is determined. Additionally, a bandwidth extended excitation signal is generated by applying a nonlinear function to the excitation signal. Additionally, noisy parts of the speech signal, in which the noise is the dominant factor, are replaced on the basis of the extended parts of the bandwidth extended excitation signal for generating an enhanced speech signal. Especially in hands-free systems or in speech recognition systems used in vehicles the recorded speech signal often comprises a large noise component originating from the vehicle itself or from the wind when the vehicle is moving. For improving the recognition rate of the speech recognition system or for improving the speech quality noise reduction schemes are used in prior art systems. These systems can help to improve the signal to noise ratio and therefore to improve the speech quality. However, when the speech data are largely deteriorated by the noise, the noise reduction methods of the prior art deteriorate the quality of the signal recorded by the microphone.

[0028] According to this aspect of the invention the noisy parts of the speech signal are replaced by an extrapolated signal

[0029] Preferably the noisy parts of the speech signal are determined by first determining the parts of the recorded speech signal comprising speech components. For the part of the speech signal comprising speech components the part of the signal is determined in which the noise components are so dominant or powerful that noise suppression methods do not work any more.

[0030] Preferably the bandwidth limited envelope of the recorded speech signal is determined using a linear predictive coding analysis. It could be understood that any other method can be used for determining the envelope of the speech signal.

[0031] Once the bandwidth limited envelope of the speech signal is determined the bandwidth extended envelope

can be determined. Preferably the bandwidth extended envelope can be determined by comparing the bandwidth limited spectral envelope to predetermined envelopes stored in a lookup table or codebook and by selecting the envelope of the lookup table which best matches the bandwidth limited spectral envelope speech signal. This approach of determining the extended spectral envelope is also called codebook approach. A codebook contains a representative set of band limited and broadband vocal tract transfer functions. Typical codebook sizes range from 32 up to 1024 entries. The spectral bandwidth limited envelope of the current frame is computed, e.g. in terms of ten predictor coefficients by using the above-mentioned linear predictive coding analysis, the coefficients being compared to all entries of the codebook. In case of codebook pairs the band limited entry that is closest according to a distance measure to the current envelope is determined and its broadband counterpart is selected as extended bandwidth envelope. This extended envelope corresponds to the envelope of the speech signal which would be recorded if the signal were recorded in an environment having less or no background noise.

[0032] The best matching envelope can then be combined with the bandwidth extended excitation signal resulting in the enhanced bandwidth extended speech signal. The bandwidth extended excitation signal can be multiplied with the best matching envelope in the frequency domain, however a convolution of the two signals in the time domain is also possible.

[0033] Preferably the parts of the speech signal are not taken into account in which the noise is the dominant factor, when the bandwidth limited excitation signal is determined. This helps to prevent that very noisy parts of the signal deteriorate the finding of the right envelope. By suppressing these parts the speech signal for the bandwidth limited excitation signal is determined and the correct envelope can be determined more easily.

[0034] Preferably the enhanced speech signal is generated by replacing the noisy parts of the recorded speech signal by the corresponding parts of the extended speech signal while the other parts of the originally recorded speech signal remain unchanged. Even if the signal is not exactly the same as the original one the speech quality can be increased together with the recognition rate.

[0035] According to a preferred embodiment the speech signal is recorded at a sampling frequency higher than 8 kHz. Most of the fricatives have a frequency part which is higher than 3 kHz. If the frequency domain between 3 and 4 kHz is strongly deteriorated by noise components the estimation of the envelope may become difficult. If, however, signal components in the frequency range larger than 4 kHz can be used, the envelope can be determined more easily.

[0036] As discussed above the noisy parts of the speech signal are suppressed before the excitation signal is determined. Accordingly, the bandwidth of the excitation signal has to be extended to the suppressed frequency ranges which could not be used due to the strong noise. Preferably the extended excitation signal is calculated as described in the above-mentioned method for extending the spectral bandwidth of the excitation signal. By multiplying the bandwidth limited excitation signal to the quadratic function described in more detail above, the extended excitation signal can be calculated in a very effective way.

[0037] The invention further relates to a method for enhancing the quality of a speech signal in which the spectral envelope of the speech signal is determined based on a bandwidth limited speech signal. Furthermore, a bandwidth limited excitation signal is generated from the speech signal. Moreover, the spectral bandwidth of the excitation signal is extended, and the bandwidth extended excitation signal is applied to the envelope for generating the enhanced speech signal. According to a preferred embodiment of the invention the above-mentioned steps are used for extending the spectral bandwidth of the speech signal transmitted by a bandwidth limited transmission system. At the same time, however, the above-mentioned steps are also used for reconstructing noisy parts of a speech signal recorded in a noisy environment. As can be seen from the above said, the method for a spectral bandwidth extension of a speech signal transmitted by a limited bandwidth transmission system such as a telecommunication system and the method for reconstruction noisy parts of a speech signal recorded in a noisy environment comprise many steps in common. A joint scheme can be obtained to restore frequency parts of a speech signal. For bandwidth extension of telephone band limited signals the frequency range that needs to be restored is fixed (e.g. below 300 Hz and above approx. 3.5 kHz). For a signal reconstruction of a speech signal recorded in a noisy environment the frequency range to be restored is not specified in advance, but depends on the type of noise and on the individual speech frequencies. By means of the joint scheme the speech quality can be enhanced, especially in those scenarios where traditional methods such as noise suppression systems do not work properly any more.

[0038] Preferably the spectral envelope is removed from the bandwidth limited speech signal for generating the bandwidth limited excitation signal. The bandwidth limited excitation signal is then used for generating the bandwidth extended excitation signal as described above by multiplying it with the nonlinear function. However, if the bandwidth of the speech signal should be increased it is also necessary to increase the sampling frequency at the beginning of the process, i.e. before the spectral envelope is determined. According to one embodiment the part of the frequency domain to be replaced by the bandwidth extension is known in advance. This is the case when the speech signal is the signal transmitted via a transmission unit/line of a telecommunication system, the spectral parts of the speech signal suppressed by the transmission line being added by the spectral bandwidth extension.

[0039] Preferably the spectral envelope is determined on the basis of the bandwidth limited speech signal transmitted

by the bandwidth limited transmission system, the bandwidth extended envelope being determined by comparing the bandwidth limited spectral envelope to predetermined envelopes stored in the lookup table. The envelope in the lookup table which best matches the bandwidth limited spectral envelope of the voice signal is selected and the extended spectral envelope is applied to the extended excitation signal for generating the enhanced speech signal which has an extended bandwidth.

[0040] Preferably, the noisy parts of a speech signal recorded in a noisy environment are reconstructed according to a method as mentioned above.

[0041] The invention further relates to a system for extending the spectral bandwidth of the speech signal transmitted by a bandwidth limited transmission system and for a signal reconstruction of noisy parts of the speech signal recorded in a noisy environment. According to the invention one system can be used for both cases, for the receiving part of a telephone and for the transmitting part of a telephone used in a noisy environment. To this end a determination unit is provided for determining the spectral envelope of the speech signal based upon a bandwidth limited part of the speech signal. Additionally, a generating unit is provided for generating a bandwidth limited excitation signal. A calculation unit is provided for calculating the bandwidth extended excitation signal and for applying the spectral envelope to the bandwidth extended excitation signal for generating the enhanced speech signal.

[0042] These and other aspects of the invention will become apparent from the embodiments described hereinafter.

[0043] In the drawings

Fig. 1 shows a telecommunication system in which the bandwidth extension can be used,

Fig. 2 shows a hands-free communication system or a speech recognition system using the spectral bandwidth extension,

Fig. 3 shows a system for extending the bandwidth of a speech signal,

Fig. 4 shows the different signals for the bandwidth limited telephone signals and the bandwidth extended signal,

Fig. 5 shows a flowchart comprising the different steps for carrying out the bandwidth extension shown in Fig. 3,

Fig. 6 shows a system for reconstructing noisy parts of a speech signal recorded in a noisy environment,

Fig. 7 shows different graphs of the recorded speech signal and the enhanced speech signal,

Fig. 8 shows a flowchart comprising the different steps for replacing the noisy parts of a recorded speech signal,

Fig. 9 shows a flowchart comprising the common steps used for a bandwidth extension of a bandwidth limited telephone signal and for reconstructing noisy parts of a speech signal recorded in a noisy environment, and

Fig. 10 shows the nonlinear function which can be used for extending the spectral bandwidth of an excitation signal.

[0044] Fig. 1 shows a first embodiment in which the bandwidth extension according to the invention can be used. As shown in Fig. 1 a first subscriber 10 of a telecommunication system communicates with a second subscriber 11 of the telecommunication system. The speech signal from the first subscriber 10 s(n) is transmitted via a network 15. The dashed lines indicate the locations where the transmitted speech signal $s_{tel}(n)$ undergoes the band limitations which take place depending on the routing of the call. The degradation of the speech quality using analogue telephone systems is caused by the band limiting filters within amplifiers, these filters having a bandwidth from 300 Hz up to 3400 Hz. One possibility to increase the speech quality for the subscriber 11 receiving the speech signal is to increase the bandwidth after transmission by means of a bandwidth extension unit 16. The bandwidth extended speech signal $s_{ext}(n)$ is then transmitted to subscriber 11, extended sound signals sounding more natural and, as a variety of listening tests indicates, the speech quality in general is increased as well.

[0045] In Fig. 2 a system is shown, in which the present invention can be incorporated. The system can be a hands-free speaking system which may be incorporated into a vehicle. However, the system could also be a speech recognition system used, by way of example, in vehicles for controlling different functions of the vehicle with the use of speech commands. In the upper part of Fig. 2 the incoming speech signal x(n) is shown. In the case of a hands-free speaking system the received signal x(n) is the telephone signal. In the case of a speech recognition system the signal x(n) is the signal which is to be emitted from the speech recognition system. When the system "talks" to its user the received signal is input into a bandwidth extension unit 20,

where the bandwidth of the received signal is extended before it is emitted via the loudspeaker 21. In the case of a telecommunication signal the bandwidth extension unit adds the non-transmitted frequencies in the range from about 0 to 200 Hz and from about 3700 Hz to 6000 Hz. When the emitted signal as the extended bandwidth up to 6000 Hz the speech quality of the signal $\tilde{x}$ (n) can be increased.

[0046] In the case of a speech recognition system the spectral bandwidth extension has different advantages: the coding of the emitted promts can be done by using simpler coding and decoding methods when the bandwidth extension is done during the emitting process. Additionally, less space is needed for storing the bandwidth limited coded data than for storing the bandwidth extended coded data. The lower part of Fig. 2 shows the transmitting path of the system, i.e., when a telephone signal used in a hands-free system is transmitted to the other subscriber, or when the user uses a command for controlling a device with the help of a speech recognition system. A microphone 22 records the voice of the user. Furthermore, the background noise 23 present in the neighbourhood of the user is also recorded by the microphone 22. The background noise can be the background noise present in a moving vehicle, or the background noise can be any other noise present in the neighbourhood of a user of a hands-free speaking system.

[0047] In the prior art methods are known for reducing the background noise which can be used up to a certain signal to noise ratio. The system of Fig. 2, however, does not reduce the background noise, but replaces the noisy parts of a signal using a bandwidth extension method.

[0048] As will be described in detail later on, both parts of the system, the receiving part and the transmitting part use a common approach, depicted in Fig. 2 by the unit 24. The speech reconstruction unit 25, in which noise reduction schemes may also be used, and the bandwidth extension unit use a common approach for reconstructing the missing part of the signal, be it the missing part due to the bandwidth limited transmission system as in the upper part of Fig. 2 or be it the noisy parts of a recorded speech signal as in the lower part of Fig. 2.

[0049] In connection with Figs. 3 and 4 the bandwidth extension of a bandwidth limited signal is explained in more detail. In Fig. 3 the bandwidth limited telephone signal x(n) is input into a converting unit 31 which increases the sampling frequency of the received speech signal. If additional frequencies are to be generated, the sampling frequency has to be increased in advance. In unit 31 no additional frequency components are generated. In Fig. 4a typical parts of the spectrum of the signals are shown. The spectrum 41 shows the spectrum of a speech signal. When this speech signal 41 is transmitted using a commonly known telecommunication system, the receiving person receives the signal as shown by graph 42. As can be seen by comparing signals 41 to 42 the frequency components below 200 Hz and above around 3500 Hz attenuated by the transmission system. The received signal 42 should be transformed in a frequency expanded signal after the transmission again. To this end, as can be seen in Fig. 4b a bandwidth limited spectral envelope 43 of the bandwidth limited speech signal 42 is determined. The bandwidth limited envelope 43 can be determined using a linear predictive coding analysis. Additionally, it is known to use neuronal networks therefore.

[0050] When the linear predictive coding analysis is used it is possible to estimate the spectral envelope of a speech signal in a reliable manner when about 10 coefficients of the LPC analysis are known. Once the bandwidth limited spectral envelope 43 is determined the broadband envelope 44 can be calculated. This can be done by comparing the determined limited envelope 43 to a predetermined envelope stored in a lookup table or codebook and by selecting the envelope of the lookup table which best matches the bandwith limited spectral envelope of the speech signal. The codebook or lookup table comprises representative sets of broadband and band limited vocal tract transfer functions. When the spectral envelope of the current frame of the speech signal is computed, e.g. in terms of 10 predictor coefficients the latter are compared to the entries or the codebook. In case of codebook pairs the band limited entry that is closest according to a distance measured to the current enveloped is determined and its broadband counterpart 44 is selected as the estimated broadband spectral envelope. It is also possible that the codebook only comprises broadband envelopes. In this case the search is directly performed on the broadband entries.

[0051] In the next step the spectral envelope of the speech signal is removed, e.g. by applying the inverse filter (predictor error filter) on the speech signal in order to obtain the excitation signal itself. This can be done by multiplying the spectrum of the speech signal with the inverse spectral envelope, so that the signal 45 shown in Fig. 4c is obtained. The signal 45 is the band limited excitation signal. As mentioned in the introductory part of the description the excitation signal comes from the so-called source-filter model of speech generation, the excitation signal being the signal observed directly behind the vocal cords. This excitation signal has the property of being spectrally flat as can be seen in Fig. 4c. After passing the vocal cords the flowing air travels through different cavities resulting in a speech signal which is shown by graph 41. Once the bandwidth limited excitation signal 45 is obtained, the bandwidth extended excitation signal 46 has to be calculated.

[0052] The way of broadening the spectra of the excitation signal will be explained in detail later on. Once the spectral envelope in its broadband form is determined the broadband excitation signal 46 can be multiplied with the extended envelope 44 of Fig. 4b. This multiplication in the frequency domain corresponds to a convolution in the time domain. After this step the signal 47 is obtained as can be seen in Fig. 4d and the calculated signal 47 does not completely correspond to the originally speech signal 41, however, a remarkable improvement of the speech quality can be achieved.

[0053] Returning to Fig. 3, the received telephone signal x(n) bandpass-filtered by a bandpass 32, the bandpass

transmitting the frequencies of around 200 Hz to about 3700 Hz. This corresponds to the received limited signal 42 shown in Fig. 4a. In order to extend the spectral bandwith the signal is transmitted to a unit 33, where based on the bandwidth limited envelope the broadband envelope of the signal is determined. Additionally, the excitation signal may be determined in unit 34. The excitation signal ...(n) can be mixed with the broadband envelope in unit 35. The resulting signal then passes a band delimiting filter 36 which eliminates the frequency components which were passed by the bandpass 32, i.e. filter 36 eliminates the frequency components of around 200 to about 3700 Hz. The extended signal componens ... (n) are then combined with the original signal resulting in the enhanced speech signal ... (n) as shown in the right part of Fig. 3.

[0054] In Fig. 5 the different steps for carrying out the bandwidth extension of a bandwidth limited signal transmitted via a bandwidth limiting transmission system are shown. In step 51 a sampling frequency has to be increased to a higher frequency. By way of example in the telephone system the sampling frequency is about 8 kHz, so that signals up to 4 kHz can be transmitted as is also shown in Figs. 4a and 4b. However, if the bandwidth should be extended up to 6kHz the sampling frequency has to be increased to around 12 kHz.

[0055] In step 52 the bandwidth limited envelope has to be determined. Using the bandwidth limited envelope and the codebook approach the extended envelope can be determined in step 53. For determining the excitation signal the envelope is removed from the speech signal in step 54. In the next step 55 the extended excitation signal is generated which is combined in step 56 with the extended envelope in order to generate an enhanced speech signal.

[0056] In Fig. 6 the lower part of the system of Fig. 2 is shown in more detail. As was already discussed in connection with Fig. 2, the recorded speech signal is recorded in a noisy environment, so that the recorded signal comprises speech components and noise components. In order to improve the speech quality noise reduction methods are used. These noise reduction methods work fairly if the signal to noise ratio is not too bad. In the case of speech signals strongly influenced by noise the most noise reduction methods also deteriorate the recorded speech signal. As will be discussed in connection with Figs. 6 to 8 the noisy parts of the spectrum of the speech signal are replaced by a signal in which the noisy parts are replaced by an extrapolated signal.

[0057] At the beginning the recorded speech signal y(n) is investigated and the parts of the signal are determined which comprise speech, however in which the components are dominated by the noise components. In the embodiments shown in Fig. 6 this can be done by a unit 61. As shown in Fig. 7a the parts 71 of the signal are determined in which the recorded signal 72 is strongly influenced by the noise, so that the speech signal 73 cannot be correctly identified any more, as the speech signal 73 is lower than the noise signal 74.

[0058] As indicated in Fig. 7b the spectral envelope of the voice signal is determined. In Fig. 7b graph 75 depicts the estimated envelope of the speech signal which is not influenced by the noise, graph 76 indicating the envelope of the recorded speech signal comprising noise components. The spectral envelope can be determined using a linear predictive coding analysis as described above.

[0059] For comparing the coefficients to the coefficients stored in the codebook, the parts of the speech signal where the noise dominates the speech signal (parts 71 of Fig. 7a) are not taken into account. This means that a bandwidth limited signal is used for determining the envelope. Using the codebook pairs the broadband corresponding envelope can be determined. The determination of the broadband envelope can be done in unit 62 of Fig. 6.

[0060] The output signal of unit 61 is input to unit 63, in which the excitation signal is extracted form the speech signal. This can be done by multiplying the speech signal, which may be a noise-reduced speech signal with the inverse of the spectral envelope which was determined before. As a result of this whitening of the signal the bandwidth limited excitation signal is obtained as can be seen by signal 77 of Fig. 7c. In the excitation signal 77 the frequency parts of the noisy parts 71 of the signal are omitted. These parts have to be replaced by a newly generated signal. This signal will be obtained as will be discussed in detail later on. Once the bandwidth extended excitation signal 78 of Fig. 7c is obtained, the bandwidth extended excitation signal 78 can be multiplied with the extended envelope 75. As a result the enhanced speech signal 79 is obtained which is, as can be seen in Fig. 7d quite close to the original speech signal 73. The enhanced speech signal 79 corresponds more precisely to the original speech signal 73 than the recorded noisy speech signal 72. The resulting enhanced speech signal 79 can be obtained by using the original speech signal in the non-replaced parts or by using a noise-reduced signal, wherein in the noisy part 71 the recorded speech signal is replaced by the extended parts of the excitation signal multiplied with the extended envelope calculated before.

[0061] Coming back to Fig. 6 the unit 65 indicates the unit where the broadband envelope is applied to the bandwidth extended excitation signal, the bandwidth extension of the excitation signal taking place in unit 63. Additionally, two frequency-selective filters 65, 69 are provided which are controlled by a control unit 66. The control unit 66 determines which part of the spectrum of the original signal is used for the enhanced speech signal by controlling the lower filter 69 indicated in Fig. 6. Moreover, the control unit controls the upper filter 65 of Fig. 6 in such a way that the noisy parts in which the noise dominates the speech signal cannot pass the lower filter 69, but these parts being replaced by the newly generated signal. These newly generated parts pass the upper filter 65 and are combined with the original speech signal in the adder 67. When the extended speech signal comprises higher frequency components a conversion of the sampling frequency is necessary and can be done in a converting unit 68.

[0062] In Fig. 8 the steps for carrying out the method for reconstructing noisy parts of a speech signal recorded in a noisy environment are summarized. First of all, the speech signal is recorded in step 81. Within the recorded speech signal the parts of the speech signal have to be determined in which speech is present (step 82). Within these parts the parts of the signal are determined in which the noise signal dominates the speech signal, as can be shown by graphs 73 and 72 (step 83). Additionally, the envelope is determined in step 84 based on the bandwidth limited speech signal, in which the noisy parts of the speech signal are suppressed. Once the bandwidth limited envelope is determined the bandwidth extended envelope can be determined in step 85 by using the corresponding codebook pair. The extended envelope is then removed from the speech signal (step 86), so that the excitation signal is obtained. In step 87 the extended excitation signal is generated by extending the bandwidth of the bandwidth limited excitation signal (signal 77 of Fig. 7c). Last but not least the extended excitation signal is combined with the extended envelope in order to generate the enhanced speech signal (step 88).

[0063] When comparing Figs. 5 and 8 or when comparing Figs. 4 and 7 it can be seen that the method for reconstructing noisy parts of a speech signal recorded in a noisy environment and the method for extending the spectral bandwidth of a speech signal transmitted via a bandwidth limited transmission system use a common approach. The common steps used in both cases are mainly the generation of the spectral envelope on the basis of the bandwidth limited speech signal. The next main step which is common to both approaches is the generation of the extended excitation signal on the basis of the bandwidth limited excitation signal.

[0064] As was discussed above, an excitation signal having a larger bandwidth than the bandwidth limited excitation signal has to be generated. In the following the generation of the extended excitation signal is discussed in detail. The basic idea of the bandwidth extension algorithm is to extract information on the missing components from the available narrowband signals x(n) and y(n). One way for expanding the bandwidth of the signal is the application of nonlinear characteristics to periodic signals. By applying a nonlinear characteristic to such a periodic speech signal harmonics are produced which can be used for increasing the bandwidth. The task of bandwidth extension can be mainly divided into two subtasks, namely the generation of a broadband excitation signal and the estimation of the broadband spectral envelope. The broadband spectral envelope can be obtained by using the codebook approach as mentioned above. The other task can be solved by applying a nonlinear characteristic, in the present case a special quadratic characteristic.

[0065] For calculating the extended excitation, the signal is divided into several segments, and the calculation is done for each segment of the signal.

[0066] By way of example the signal can be represented by the following vector:

$$x_p(n) = \left[x_{p,0}(n), x_{p,1}(n), \ldots, x_{p,N-1}(n)\right]^T. \qquad \text{(I)}$$

[0067] The parameter N designates the length of the segment.

[0068] In the following the newly defined quadratic nonlinear function is used for extending the bandwidth:

$$\tilde{x}_{Anr,i}(n) = c_2(n)x^2{}_{p,i}(n) + c_1(n)x_{p,i}(n) \qquad \text{(II)}$$

[0069] The two coefficients c_1 and c_2 are defined as follows.

$$c_1(n) = K_1 - x_{\max}(n)c_2(n) = K_1 - x_{\max}\left(\frac{K_1 - K_2}{x_{\max}(n) - x_{\min}(n) + \varepsilon}\right) \qquad \text{(III)}$$

$$c_2(n) = \frac{K_1 - K_2}{x_{\max}(n) - x_{\min}(n) + \varepsilon}. \qquad \text{(IV)}$$

[0070] The terms $x_{max}(n)$ and $x_{min}(n)$ represent the maximum and the minimum of the input vector x_p.

$$x_{\max}(n) = \max\{x_{p,0}(n), x_{p,1}(n), \ldots x_{p,N-1}(n)\}, \quad \text{(V)}$$

$$x_{\min}(n) = \min\{x_{p,0}(n), x_{p,1}(n), \ldots, x_{p,N-1}(n)\}. \quad \text{(VI)}$$

[0071] ε is a small positive number in order to avoid a division by zero. The two constants K_1 and $-K_2$ are the maximum and the minimum value after applying the above equation I to the speech signal. The following values of K_1 and K_2 have been found as being suitable for the present case: K_1=1.2 and K_2=0.2. It should be understood that the present invention is not limited to these two values. It is also possible to use any other value of K_1 and K_2.

[0072] In Fig. 10 the nonlinear quadratic function as applied to the bandwidth limited excitation signal in order to generate the bandwidth extended excitation signal is shown by graph 110. Additionally, the graph of a halfwave rectifier 120 is also shown for comparison.

[0073] As can be seen from equation III and IV the coefficients c_1 and c_2 also depend on n, i.e. on the time. Due to this it is possible to put more weight either on the linear factor or on the quadratic factor of equation II depending on the input signal, i.e the speech signal.

[0074] The enhanced speech signals which were generated based on a quadratic bandwidth extension scheme as mentioned above were investigated by listening tests. The tests have shown that, when the above-defined quadratic function is used, the speech quality can be considerably improved. When the steps carried out during the method for reconstructing noisy parts of the speech signal are compared to the methods for the bandwidth extension of a speech signal transmitted via a telecommunication line, it follows that the same steps are used. In Fig. 9 the common steps used in both approaches are shown. When the Figs. 4 and 7 are compared it can be seen that the first common step is to determine a bandwidth limited envelope based on a bandwidth limited speech signal (step 91). Based on the envelope determined in step 91 the extended envelope is determined in step 92 (the envelopes 44 and 75 in Figs. 4 and 7, respectively). In the next step 93 the extended envelope is removed from the speech signal in order to generate the excitation signal. In the next step 94 the extended excitation signal is generated by applying the above-defined quadratic function to the bandwidth limited excitation signal. Finally, the extended envelope is combined with the extended excitation signal in order to generate the enhanced speech signal (step 94).

[0075] When the bandwidth is extended for the bandwidth limited speech signal of the telephone signal (upper branch of Fig. 2) the missing frequency components are known in advance (the components from 0 to 200 Hz and the components above 3500 Hz).

[0076] In the lower branch of Fig. 2, when the noisy parts of a speech signal recorded in a noisy environment are reconstructed, the frequency components which have to be replaced are not known at the beginning, they have to be determined for each signal component. Nevertheless, the same steps are carried out as shown in Fig. 9.

[0077] Coming back to Fig. 2 this means that unit 24 carries out the steps which are common to both approaches and which are shown in Fig. 9. By way of example and as shown in Fig. 2 the coefficients of the linear predictive coding analysis are extracted by unit 20, are transmitted to unit 24, and the coefficients of the broadband envelope $c\tilde{x}$ are returned to unit 20. In the same way the coefficients cy(n) are transmitted to unit 24, and the coefficients of the broadband envelope $c\tilde{y}$(n) are fed back to the speech recognition unit 25, as a common codebook can be used in unit 24.

[0078] Summarizing, the present invention provides a joint scheme for restoring a signal in a certain frequency part, either the heavily distorted frequency part of the recorded speech signal or the frequency part not transmitted via the transmission medium. Additionally, the restored frequency parts are extracted from the residual frequency range. By means of the joint scheme the speech quality can be considerably enhanced, especially in those scenarios where traditional methods such as noise suppression systems do not work properly anymore.

Claims

1. Method for extending the spectral bandwidth of an excitation signal of a speech signal, comprising the following steps:

   - determining a bandwidth limited excitation signal of the speech signal,
   - applying a nonlinear function to the excitation signal for generating a bandwidth extended excitation signal

wherein the nonlinear function is the following quadratic function:

$$\tilde{x}_{Anr,i}(n) = c_2(n)x^2{}_{p,i}(n) + c_1(n)x_{p,i}(n)$$

c1, and c2 being determined in such a way, that

$$c_1(n) = K_1 - x_{\max}(n)c_2(n) = K_1 - x_{\max}\left(\frac{K_1 - K_2}{x_{\max}(n) - x_{\min}(n) + \varepsilon}\right)$$

$$c_2(n) = \frac{K_1 - K_2}{x_{\max}(n) - x_{\min}(n) + \varepsilon}.$$

2. Method for extending the spectral bandwidth of an excitation signal according to claim 1, **characterized in that** a bandwidth limited spectral envelope of the speech signal is determined and removed from the speech signal by applying the inverse spectral envelope to the speech signal.

3. Method for extending the spectral bandwidth of an excitation signal according to claim 1 or 2, **characterized in that** the speech signal is divided into overlapping segments, each segment being described by the following vector, with the spectral envelope of the speech signal being removed:

$$x_p(n) = \left[x_{p,0}(n), x_{p,1}(n), \ldots, x_{p,N-1}(n)\right]^T.$$

4. Method for extending the spectral bandwidth of an excitation signal according to any of the preceding claims, **characterized in that** x_{max} and x_{min} are determined in such a way that

$$x_{\max}(n) = \max\left\{x_{p,0}(n), x_{p,1}(n), \ldots x_{p,N-1}(n)\right\}$$

$$x_{\min}(n) = \min\left\{x_{p,0}(n), x_{p,1}(n), \ldots, x_{p,N-1}(n)\right\}$$

K_1=1.2
K_2=0.2
ε being a small number >0.

5. Method for extending the spectral bandwidth of an excitation signal according to any of the preceding claims, **characterized by** further comprising the step of high pass filtering the extended excitation signal for removing the frequency components around 0 Hz.

6. Method for extending the spectral bandwidth of an excitation signal according to any of claims 2 to 6, **characterized in that** the bandwidth limited spectral envelope of the speech signal is determined using a linear predictive coding

analysis.

7. Method for extending the spectral bandwidth of an excitation signal according to any of the preceding claims, **characterized in that** the extended parts of the excitation signal are used for replacing noisy parts of the bandwidth limited excitation signal, the bandwidth limited excitation signal corresponding to a speech signal recorded in a noisy environment.

8. Method for extending the spectral bandwidth of an excitation signal according to any of the preceding claims, **characterized in that** the extended parts of the excitation signal are used for replacing the corresponding parts of an bandwidth limited excitation signal corresponding to a bandwidth limited speech signal transmitted via a transmission unit of a telecommunication system, the spectral parts of the speech signal suppressed by the transmission line being generated on the basis of the extended spectral bandwidth parts of the excitation signal.

9. Method for extending the spectral bandwidth of an excitation signal according to any of the preceding claims, **characterized in that** the spectral envelope is removed from the speech signal by multiplying the inverse spectral envelope with the speech signal in the frequency domain of the speech signal or by convolving the inverse spectral envelope with the speech signal in the time domain of the speech signal.

10. Method for reconstructing noisy parts of a speech signal recorded in a noisy environment, comprising the following steps:

- determining the noisy parts of the speech signal in which the noise components of the recorded signal dominate the speech components of the speech signal,
- determining a bandwidth limited spectral envelope of the speech signal,
- determine an bandwidth limited excitation signal on the basis of the speech signal, the noisy parts of the speech signal being suppressed,
- generating a bandwidth extended excitation signal by applying a non-linear function to the excitation signal, and
- replacing the noisy parts of the speech signal on the basis of the extended parts of the bandwidth extended excitation signal for generating an enhanced speech signal.

11. Method for reconstructing noisy parts of a speech signal according to claim 10, **characterized in that** the noisy parts of the speech signal are determined by first determining the parts of the recorded speech signal comprising speech components and that for the speech signal comprising speech components the part of the signal is determined in which the noise components dominate the speech components.

12. Method for reconstructing noisy parts of a speech signal according to claim 11 or 12, **characterized in that** the bandwidth limited envelope of the recorded speech signal is determined using a Linear Predictive Coding analysis.

13. Method for reconstructing noisy parts of a speech signal according to claim 12, **characterized in that** the bandwidth extended spectral envelope of the speech signal is determined by comparing the bandwidth limited spectral envelope to predetermined envelops stored in a look up table and by selecting the envelope of the look up table which best matches the bandwidth limited spectral envelope of the speech signal.

14. Method for reconstructing noisy parts of a speech signal according to claim 13, **characterized in that**, when the bandwidth limited envelope is compared to the predetermined envelops, the noisy parts of the speech signal are not taken into account.

15. Method for reconstructing noisy parts of a speech signal according to any of claims 11 to 14, **characterized in that** noisy parts of the speech signal are suppressed before the bandwidth limited excitation signal is determined.

16. Method for reconstructing noisy parts of a speech signal according to any of claims 10 to 15, **characterized by** further comprising the step of combining the bandwidth extended excitation signal with the best matching envelope in order to generate the enhanced bandwidth extended speech signal.

17. Method for reconstructing noisy parts of a speech signal according to any of claims 10 to 16, **characterized in that** the enhanced speech signal is generated by replacing the noisy parts of the speech signal by the corresponding parts of the extended speech signal, the other parts of the speech signal remaining unchanged.

18. Method for reconstructing noisy parts of a speech signal according to any of claims 10 to 17, **characterized in that** the speech signal is recorded at a sampling frequency higher than 8 kHz.

19. Method for reconstructing noisy parts of a speech signal according to any of claims 10 to 18, **characterized in that** the extended excitation signal is calculated as described in any of claims 1 to 9.

20. Method for reconstructing noisy parts of a speech signal according to any of claims 10 to 18, **characterized in that** the recoded voice signal is recorded in a hands free speaking system or a speech recognition system inside a vehicle.

21. Method for enhancing the quality of a speech signal comprising the following steps:

- determining an spectral envelope of the speech signal based on the speech signal having a limited spectral bandwidth,
- generating a bandwidth limited excitation signal of the speech signal
- extending the spectral bandwidth of the generated excitation signal,
- applying the bandwidth extended excitation signal to the spectral envelope for generating the enhanced speech signal,

wherein the above mentioned steps are used for extending the spectral bandwidth of the speech signal transmitted by a bandwidth limited transmission system and are used for a signal reconstruction of noisy parts of the speech signal recorded in a noisy environment.

22. Method for enhancing the quality of a speech signal according to claim 21, **characterized in that** the determined spectral envelope is removed from the bandwidth limited speech signal for generating the bandwidth limited excitation signal.

23. Method for enhancing the quality of a speech signal according to claim 21 or 22, **characterized in that** the extended excitation signal is multiplied with the spectral envelope in the frequency domain of the speech signal for generating the enhanced speech signal.

24. Method for enhancing the quality of a speech signal according to any of claims 21 to 23, **characterized in that** the sampling frequency is increased before determining the spectral envelope.

25. Method for enhancing the quality of a speech signal according to any of claims 21 to 24, **characterized in that** the speech signal is a signal transmitted via a transmission unit of a telecommunication system, the spectral parts of the speech signal suppressed by the transmission unit being added by the spectral bandwidth extension.

26. Method for enhancing the quality of a speech signal according to any of claims 21 to 25, **characterized in that** spectral bandwidth of the excitation signal is extended according to a method as mentioned in any of claims 1 to 9.

27. Method for enhancing the quality of a speech signal according to any of claims 25 to 26, **characterized in that** for extending the spectral bandwidth the spectral envelope is determined on the basis of the bandwidth limited speech signal transmitted by the bandwidth limited transmission system, a bandwidth extended spectral envelope being determined by comparing the bandwidth limited spectral envelope to predetermined envelopes stored in a look up table and by selecting the envelope in the look up table which best matches the bandwidth limited spectral envelope of the voice signal, the extended spectral envelope being applied to the extended excitation signal for generating the enhanced bandwidth extended speech signal.

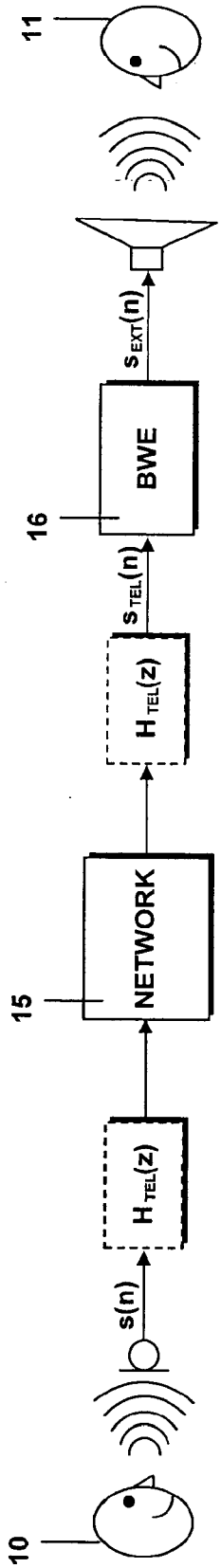
28. Method for enhancing the quality of a speech signal according to any of claims 25 to 27, **characterized in that** the frequency components suppressed by the transmission unit of the telecommunication system are the frequency components of the speech signal between 0 and approximately 200 Hz and frequency components larger than approximately 3700 Hz.

29. Method for enhancing the quality of a speech signal according to any of claims 21 to 28, **characterized in that** the noisy parts of the speech signal are reconstructed according to a method as described in any one of claims 10 to 20.

30. System for extending the spectral bandwidth of the speech signal transmitted by a bandwidth limited transmission system and for signal reconstruction for noisy parts of the speech signal recorded in a noisy environment, comprising

- determination unit for determining a spectral envelope based, upon a bandwidth limited part of the speech signal,
- a generating unit for generating an bandwidth limited excitation signal,
- a calculation unit for calculating an bandwidth extended excitation signal and for applying the spectral envelope to the bandwidth extended excitation signal for generating an enhanced speech signal.

Fig. 1



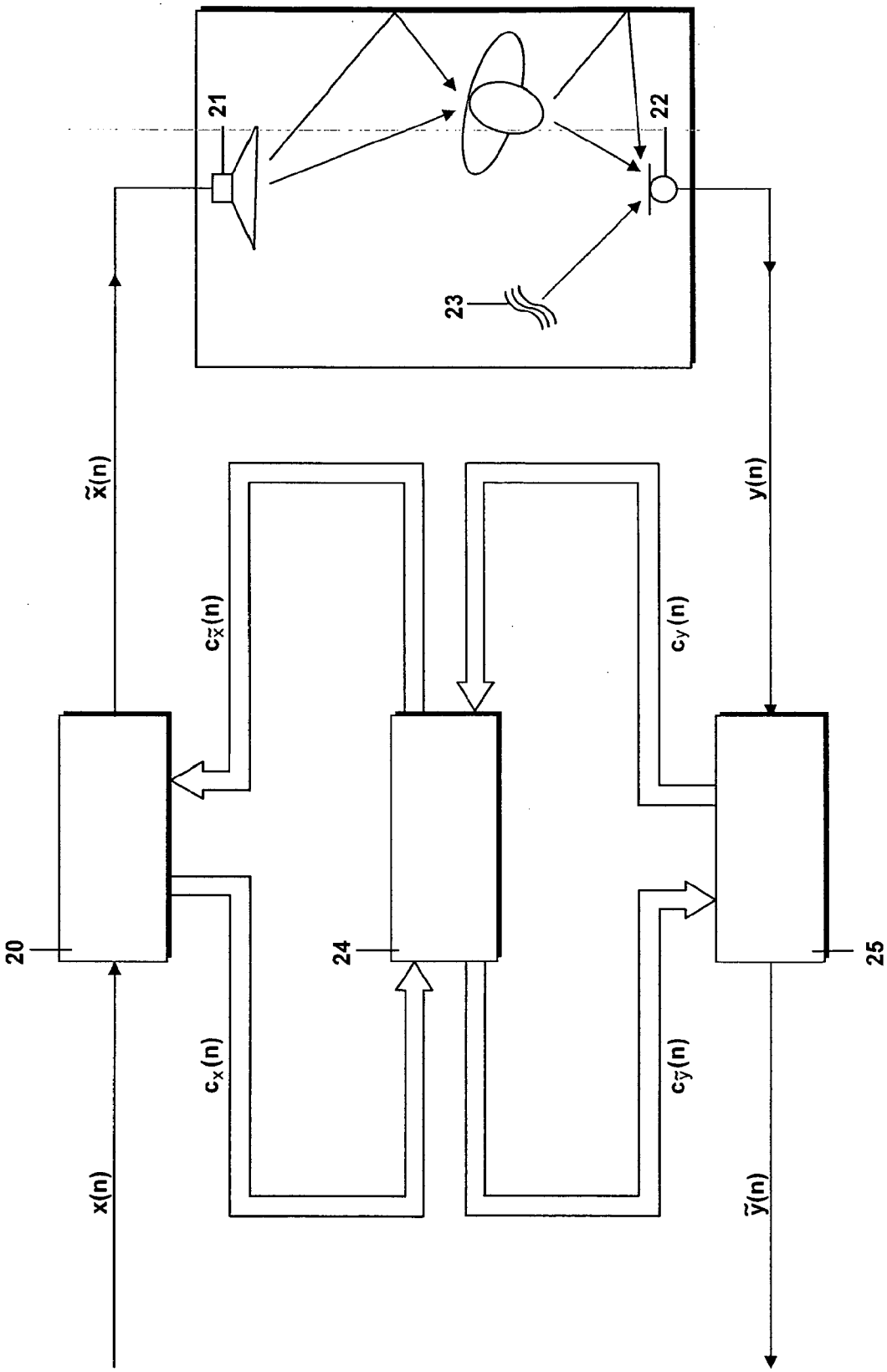

21
22
23
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Fig. 2

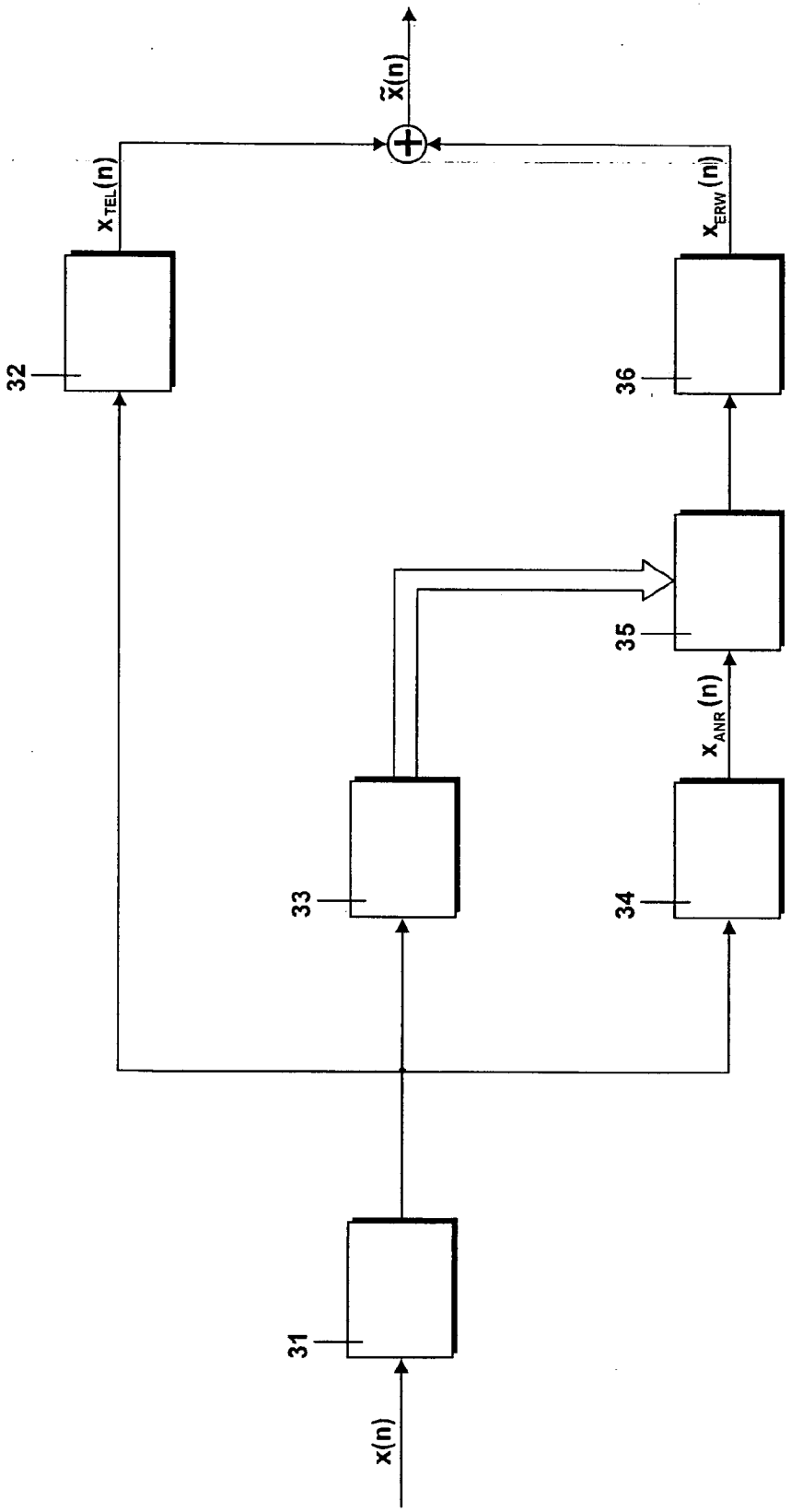
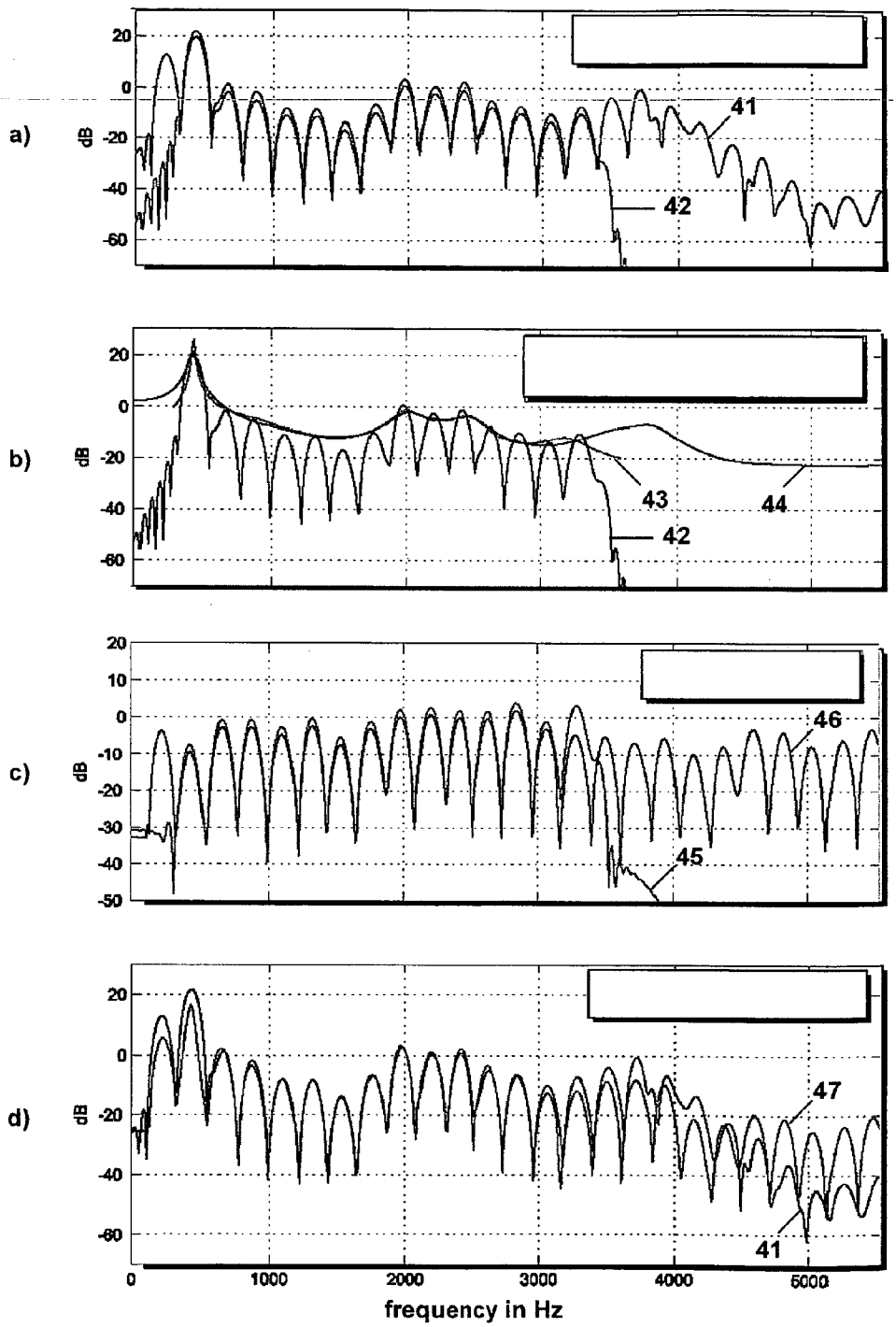


Fig. 3


a)
b)
c)
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dB
frequency in Hz
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42
43
44
45
46
47
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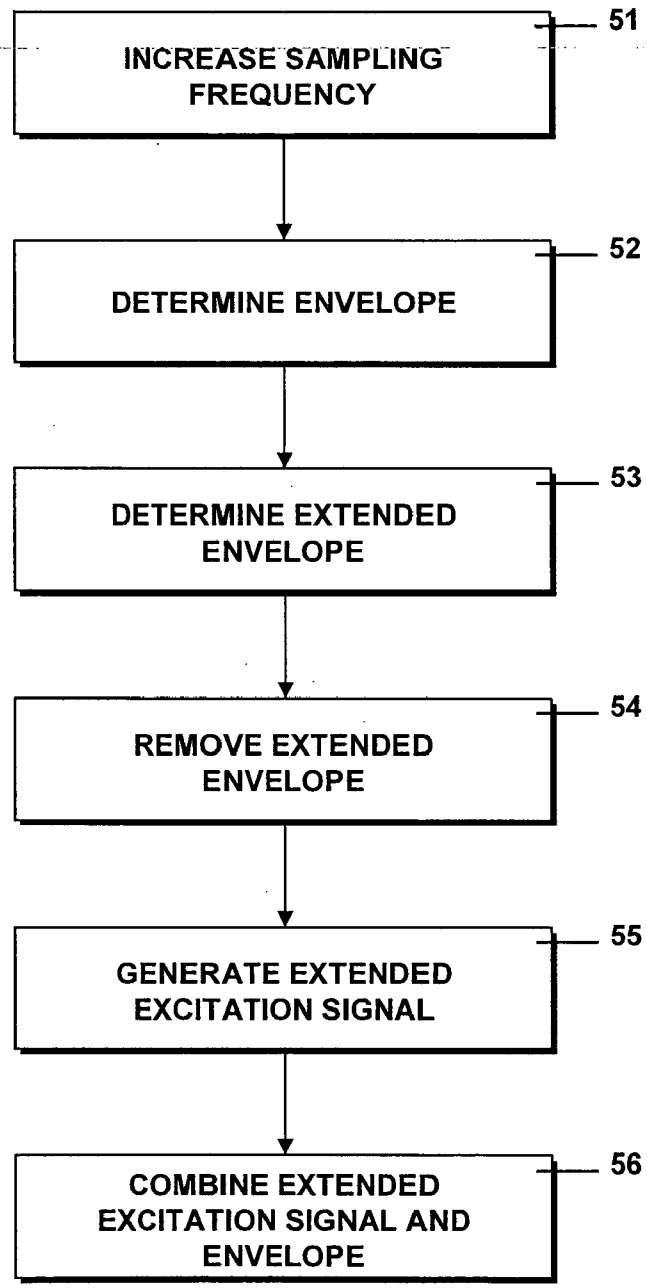
2000
3000
4000
5000

Fig. 4


INCREASE SAMPLING FREQUENCY
51
DETERMINE ENVELOPE
52
DETERMINE EXTENDED ENVELOPE
53
REMOVE EXTENDED ENVELOPE
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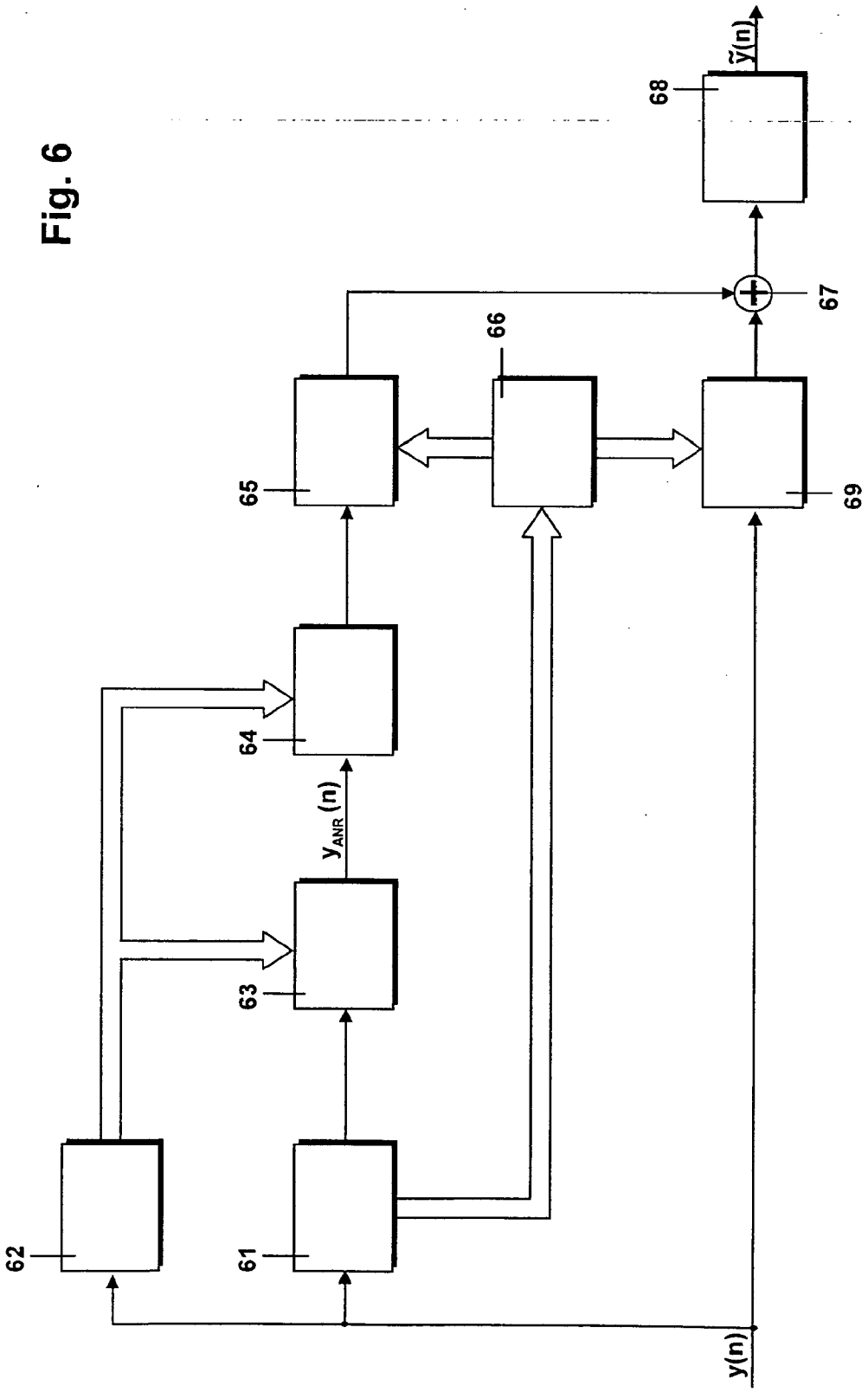
GENERATE EXTENDED EXCITATION SIGNAL
55
COMBINE EXTENDED EXCITATION SIGNAL AND ENVELOPE
56

Fig. 5

Fig. 6



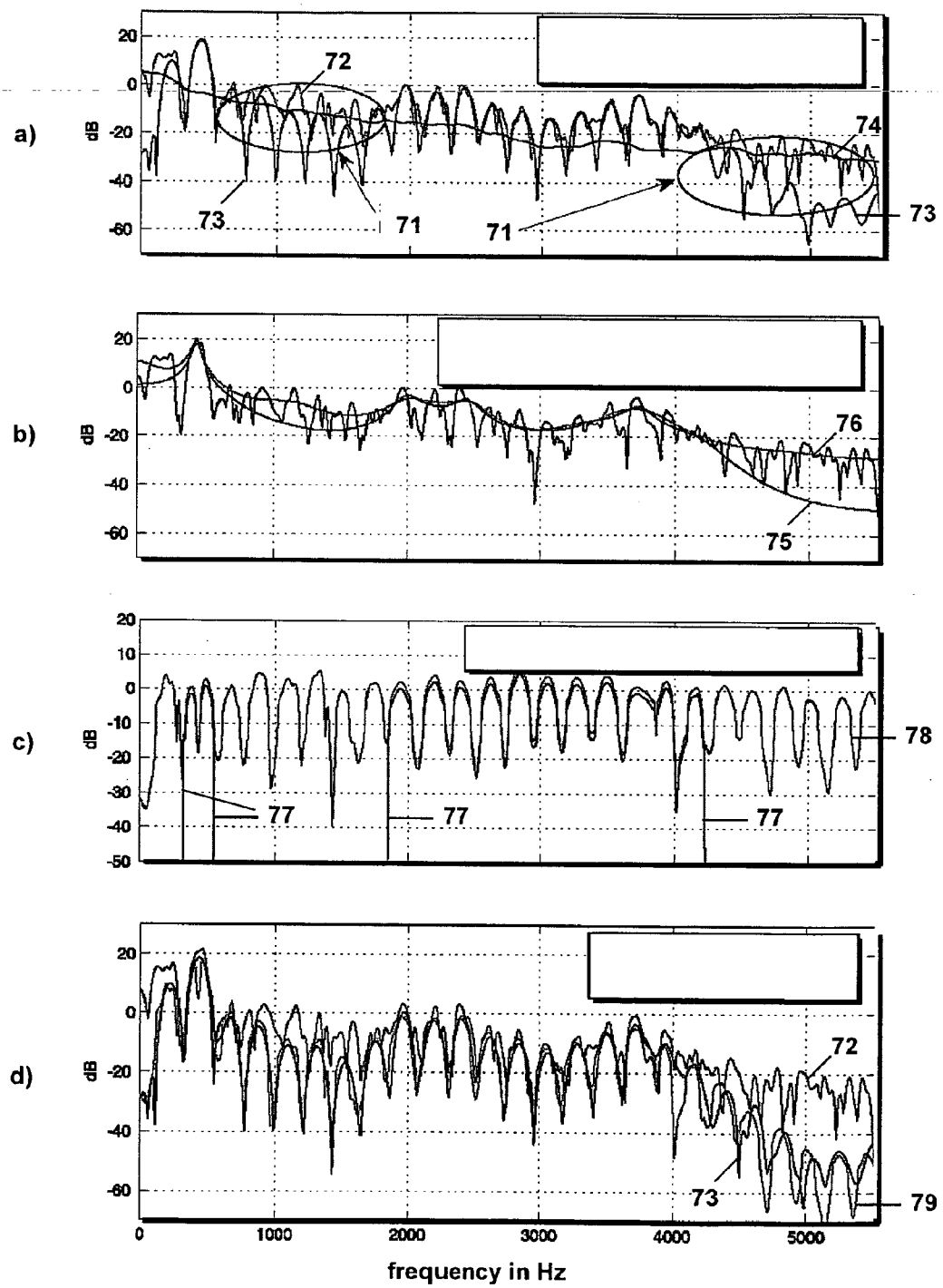

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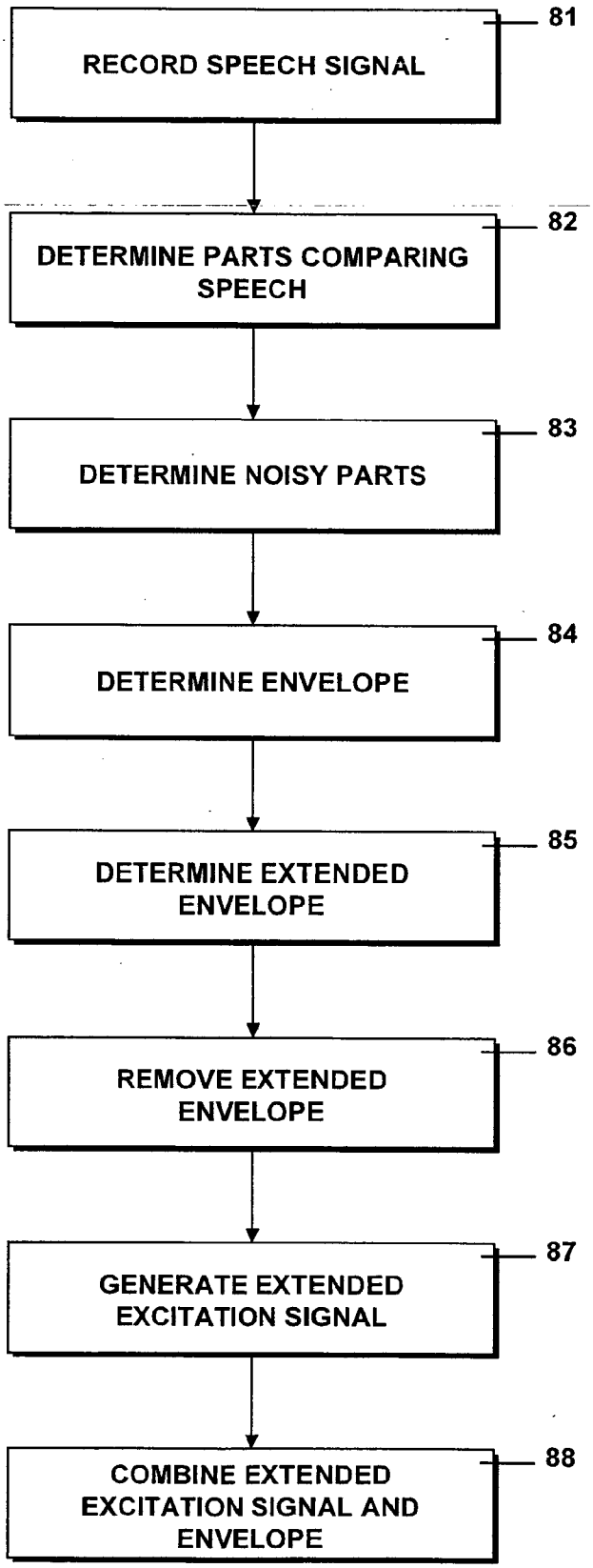
Fig. 7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REMOVE EXTENDED ENVELOPE
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GENERATE EXTENDED EXCITATION SIGNAL
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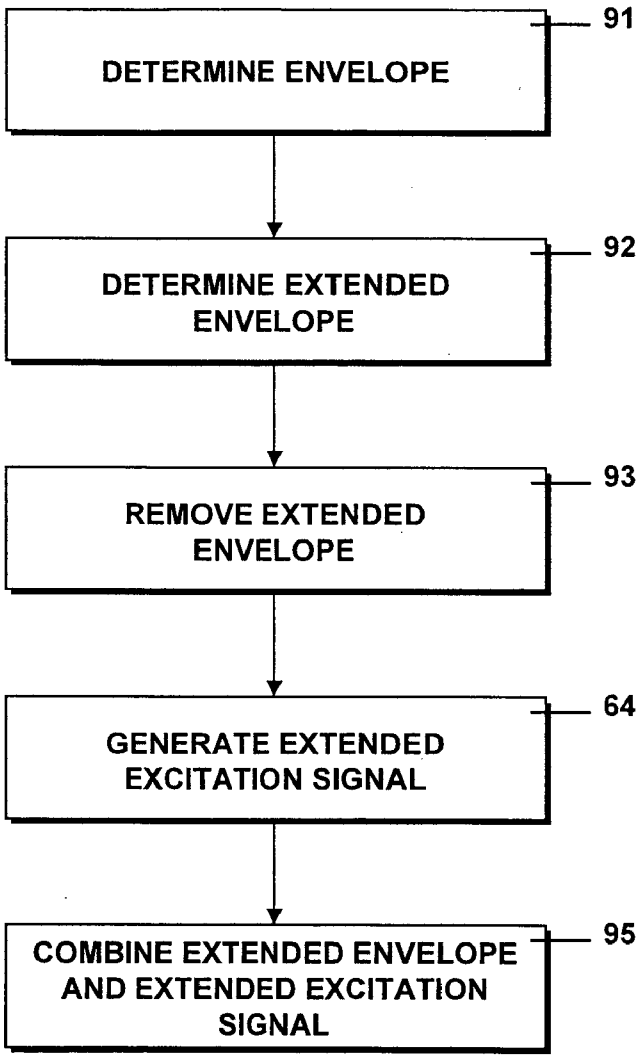
COMBINE EXTENDED EXCITATION SIGNAL AND ENVELOPE
88

Fig. 8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COMBINE EXTENDED ENVELOPE AND EXTENDED EXCITATION SIGNAL
95

Fig. 9

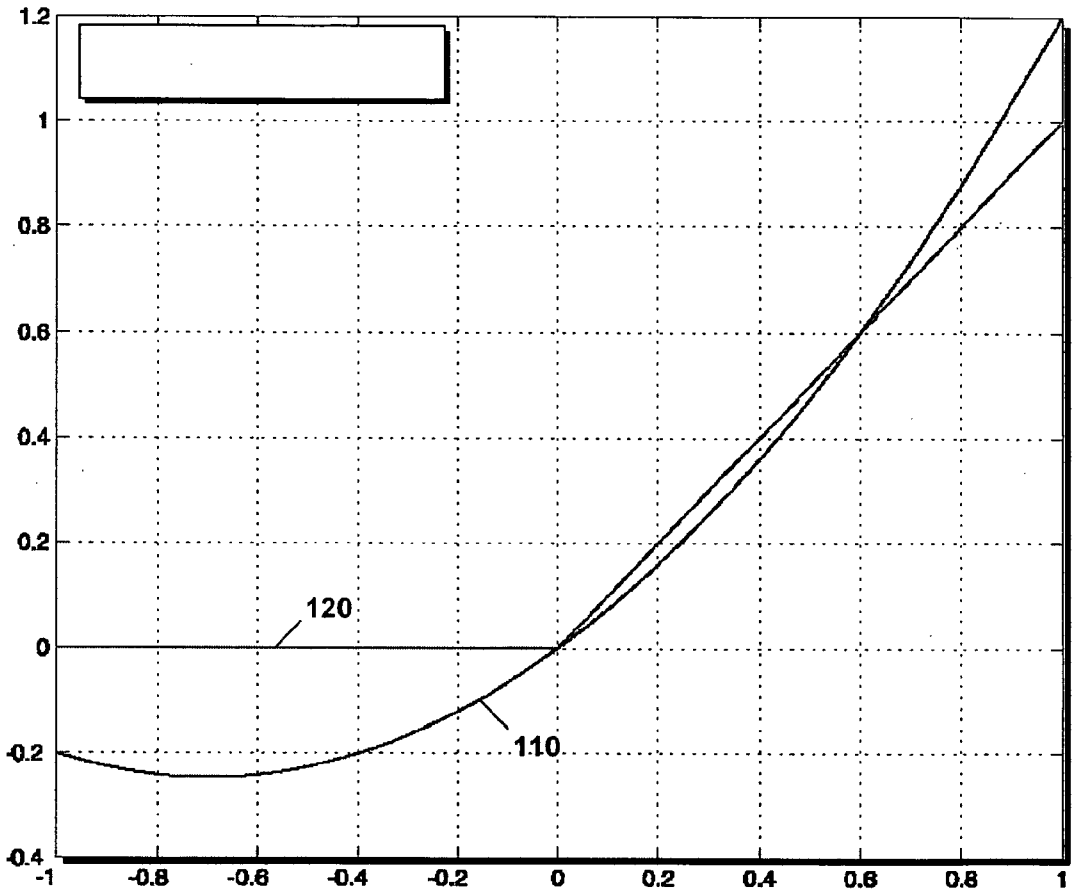

Fig. 10

European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 05 02 1934

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	B. ISER, G. SCHMIDT: "BANDWIDTH EXTENSION OF TELEPHONY SPEECH" EURASIP NEWSLETTER, [Online] vol. 16, no. 2, June 2005 (2005-06), pages 1-148, XP002372006 Retrieved from the Internet: URL:http://www.eurasip-newsletter.org/newsletter-16-2.pdf> [retrieved on 2006-03-13]	1-4,8, 10, 21-25,30	G10L21/02
Y	* paragraphs [0003], [03.2], [04.1], [4.1.2] *	7,9	
Y	US 2003/050786 A1 (JAX PETER ET AL) 13 March 2003 (2003-03-13) * abstract *	7,9	

TECHNICAL FIELDS SEARCHED (IPC)

G10L

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
The Hague	14 March 2006	Van Doremalen, J

CATEGORY OF CITED DOCUMENTS

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14-03-2006

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US 2003050786 A1	13-03-2003	DE 10041512 A1	14-03-2002
		WO 0217303 A1	28-02-2002

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82