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(54) **Active noise cancellation using frequency response control**

(57) An active noise cancellation system (20) includes using a frequency domain response of a secondary path (44) of the system. The frequency domain response information provides an indication of a desired magnitude and phase of a reference signal that is used for generating a cancellation signal that drives a speaker (28) to achieve the desired amount of noise cancellation. Using a frequency domain response greatly reduces the number of computations required and the amount of memory used within the system controller. In one example, a reference signal adjustment module (40) applies the desired magnitude and phase adjustments to a reference signal having a known frequency. In another example, the referenced signal tone generator (22, 40) incorporates the desired amplitude and phase in the reference signal.

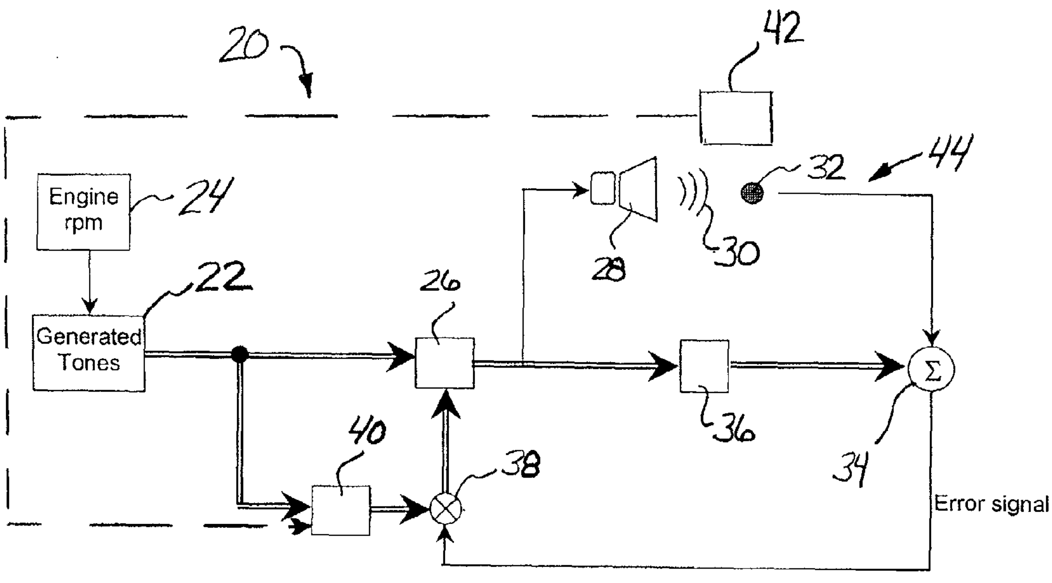

Fig 1

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Description

1. Technical Field

[0001] This invention generally relates to active noise cancellation systems. More particularly, this invention relates to frequency response control for generating reference signals in a noise cancellation system.

2. Description of the Prior Art

[0002] Noise cancellation systems have a variety of uses. One example use is on automotive vehicles for reducing noise propagation into the passenger compartment.

[0003] Modern day vehicles typically include an air induction system. One drawback of air induction systems is that engine noise frequently travels through the air induction system and emanates out of the mouth of the air intake such that the noises are noticeable in the passenger compartment. This is particularly true under wide open throttle conditions. Various efforts have been made to reduce the amount of engine noise traveling through the air induction system. Some arrangements include using passive devices such as expansion chambers and Helmholtz resonators. Other efforts include active methods such as anti-noise generators.

[0004] Other sources of noise may be associated with a vehicle exhaust or a supercharger, for example. Regardless of the particular application, various challenges exist when designing an effective and economical noise cancellation system.

[0005] Typical active systems include a speaker that generates a sound to attenuate the noise. The sound from the speaker typically is out of phase with the noise and combines with the noise such that the result is a reduced noise, which results in less noise transmission into the passenger compartment, for example. The speaker sound can be referred to as a noise cancellation signal.

[0006] Digital signal processors such as microprocessors typically generate cancellation signals for driving the speaker to achieve the noise cancellation. The microprocessor typically requires some input from the relevant environment to adequately address the need for noise cancellation. In some examples, computer modeling is used so that the microprocessor is able to provide a desired level of noise cancellation.

[0007] While such systems are useful, they do not address all difficulties associated with operating an effective noise cancellation system. Further, such systems often rely upon signal processing techniques that tend to require undesirably high amounts of multiplications or other signal processing techniques along with storing large amounts of data, which tends to place limitations on the microprocessor. In many situations it is desirable to minimize the amount of memory required in a microprocessor so that less-expensive electronics may be used or a faster system response is possible.

[0008] This invention provides an enhancement to active noise cancellation that reduces the burden on the processor within the system and provides a more accurate and reliable method of canceling noise. One particular application for a system designed according to this invention is for canceling engine noise in a vehicle air intake assembly.

SUMMARY OF THE INVENTION

[0009] In general terms, this invention is a system for canceling noise that includes using a frequency domain response of a portion of the system and then modifying the amplitude and phase of a reference signal based upon the frequency domain response information.

[0010] A system designed according to this invention includes a speaker. A microphone is arranged to detect a combination of a sound from the speaker and noise in the system. A controller has a first module that provides a frequency domain response of the portion of the system associated with the speaker and microphone (i.e., the secondary path) for at least one known frequency. A second module provides a reference signal having an amplitude and phase that are set based upon the frequency domain response information. The reference signal is then used by another portion of the controller for generating a cancellation signal, which drives the speaker.

[0011] Applying the frequency domain response information to the reference signal in one example is accomplished by multiplying the amplitude of a reference signal and shifting the phase of the reference signal in amounts corresponding to the frequency domain response information. In another example, the reference signal is effectively broken down into sine and cosine components. An appropriate gain is then applied to each of the components to achieve the desired amplitude and phase adjustments based upon the frequency domain response information. Modulating the sine and cosine components provides the desired reference signal characteristics.

[0012] In one example system, the module of the controller that provides the frequency domain response first determines a time domain response of the portion of the system including the speaker and the microphone. The first module then applies a Fast Fourier Transform to the time domain response to determine the frequency domain response information.

[0013] A system designed according to this invention greatly reduces the amount of computation required within a controller of an active noise cancellation system. One significant benefit of this invention is that it requires less memory within a controller, which allows for a greater variety of electronics to be utilized. Another advantage is that the controller is able to provide a faster response during active noise cancellation.

[0014] A method according to this invention for generating a reference signal in a noise cancellation system having a path associated with a speaker and a microphone includes determining the frequency domain response of the path for a reference signal of a known frequency. The phase and amplitude of the reference signal are adjusted responsive to the determined frequency domain response.

[0015] The various features and advantages of this invention will become apparent to those skilled in the art from the following detailed description of the currently preferred embodiments. The drawings that accompany the detailed description can be briefly described as follows.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016]

Figure 1 schematically illustrates selected portions of an active noise cancellation system designed according to this invention.

Figure 2 schematically illustrates an alternative arrangement to the embodiment of Figure 1.

Figure 3 graphically illustrates a time domain response of a secondary path in an active noise cancellation system.

Figure 4 graphically illustrates an example amplitude adjustment based upon the frequency domain response of the system from which the information in Figure 3 was obtained.

Figure 5 graphically illustrates a phase adjustment based upon the frequency domain response of the system from which the time domain response of Figure 3 was achieved.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0017] Figure 1 schematically shows selected portions of an active noise cancellation system 20. This system may have a variety of uses where active noise cancellation is desired. For purposes of discussion, the system 20 will be assumed to be part of an active noise cancellation system for canceling noise in an air induction system on a vehicle that is useful for reducing the level of engine noise that propagates into a passenger compartment. The invention is not limited to such an environment.

[0018] A tone generator 22 generates a reference signal responsive to information from a sensor 24. In the illustrated example, the sensor 24 comprises a tachometer that provides information regarding the rotations per minute (RPM) of a vehicle engine. The tone generator 22 preferably includes programming to provide a plurality of discrete tones each having a known frequency, which tones are selected based upon the information regarding the engine RPM. The particular frequencies and the number of tones generated by the tone generator 22 preferably are selected to meet the needs of a particular situation. Those skilled in the art who have the benefit of this description can use known techniques for deciding how the tone generator 22 should respond to the different inputs available from the sensor 24.

[0019] A cancellation signal generating module 26 modifies the reference signal tones from the tone generator 22 and provides a cancellation signal for driving a speaker 28. A noise cancellation signal (i.e., sound) 30 emanates from the speaker 28 responding to the cancellation signal from the module 26.

[0020] The noise cancellation signal 30 preferably attenuates noise within the system to a desired level. A microphone 32 provides modeling and feedback information regarding the results of the noise cancellation signal 30. The microphone 32 detects the combination of noise within the system and the noise cancellation signal 30. Under ideal circumstances, the noise cancellation signal 30 has the effect of minimizing the noise to a desired level.

[0021] The signals from the microphone 32 preferably are processed, using a summer 34 for example, to determine whether the desired noise cancellation effect is achieved. The desired level of noise cancellation in the illustrated example is provided to the summer 34 by a desired signal generator module 36. The results of the comparison between the desired signal and the information received by the microphone 32 provide an error signal that is input to a convergence module 38. The illustrated example utilizes any one of a variety of known convergence techniques such as an LMS algorithm so that repeated modifications to the noise cancellation signal eventually result in the desired noise reduction in the system.

[0022] A reference signal modifying module 40 provides modification to the reference signal from the tone generator 22. This allows continuously modifying the reference signal information using the convergence module 38 to repeatedly update the effects of a cancellation signal generated by the module 26 so that an ideal cancellation signal for a given input may be determined. Those skilled in the art who have the benefit of this description will realize that a variety of convergence techniques may be used as known to accomplish the results needed for this portion of a noise cancellation system designed according to this invention.

[0023] The reference signal modifying module 40 preferably operates based upon a frequency domain response of the portion of the system that includes the speaker 28 and the microphone 32 (i.e., the so-called secondary path). In the illustrated example, a frequency domain response modeling module 42 provides information regarding the frequency domain response of the secondary path 44 to the reference signal modifying module 40.

[0024] According to one example implementation of this invention, the reference signal modifying module 40 multiplies the amplitude of a reference signal from the tone generator 22 using an amplitude adjustment factor that is determined based upon the frequency domain response information. The reference signal modifying module 40 preferably also adjusts (i.e., shifts) the phase of the reference signal in an amount that corresponds to the frequency domain response of the secondary path 44.

[0025] There are a variety of ways to implement the adjustment of amplitude and phase in a system designed according to this invention. In one example, a multiplier is applied to the amplitude of the signal and a phase adjustment amount is applied to the phase to achieve the desired phase of the reference signal prior to that reference signal being fed to the cancellation signal generating module 26. According to the example of Figure 1, the tone generator 22 generates a plurality of reference tones having known frequencies with a unity amplitude and zero phase that is adjusted by the reference signal modifying module 40.

[0026] In the example of Figure 2, the tone generator 22 includes the reference signal modifying module 40 so that the reference tones are generated with the known frequencies and include the desired phase and amplitude, which were determined based upon the frequency domain response information.

[0027] The various modules discussed above and schematically illustrated in Figures 1 and 2 comprise software within a controller in some example systems designed according to this invention. The various modules may not necessarily require distinct or separate portions of software code to achieve the results accomplished by each of the modules. The module distinctions within this description are schematic and for illustration purposes only as those skilled in the art may realize that there are functions of one or more of the modules that may be accomplished within another module designed according to this invention. Additionally, while software modules are utilized in one preferred implementation of this invention, various microprocessors or dedicated portions of controllers may be used to perform the same functions. Additionally, custom designed circuitry may accomplish one or more of the functions of the modules described in this specification. Those skilled in the art who have the benefit of this description will be able to decide what combination of software and hardware will work best to meet the needs of their particular situation. Given this description, those skilled in the art will be able to develop the necessary software code to achieve the results provided by this invention.

[0028] Achieving the frequency domain response of the secondary path 44 in one example is accomplished by first obtaining a time domain response of the secondary path 44. Figure 3 graphically illustrates an example output 50 of a finite impulse response filter, which is obtained using known techniques. Finite impulse response (FIR) filters provide a time domain response of a secondary path and provide an output similar to that illustrated in Figure 3, depending on the particular configuration of a given system. In the illustrated example, the FIR filter has 126 taps, which provides the controller of the system with 126 numbers that would be used within the controller for filtering a reference signal, for example. In some prior systems, the FIR filter was used to filter the reference signal to achieve the desired reference signal needed to accomplish the noise cancellation for a given situation. Such filtering techniques require a relatively large amount of computation and memory. For example, each reference tone would be multiplied 126 times using the FIR filter.

[0029] This invention provides an improved system by operating based upon a frequency domain response of the secondary path rather than the time domain response. Figures 4 and 5 graphically illustrate a frequency domain response of the secondary path 44 that corresponds to the time domain response of Figure 3. Figure 4 graphically illustrates the amplitude 52 of the frequency domain response while Figure 5 graphically illustrates the phase 54 of the frequency domain response. According to this invention, the values from Figures 4 and 5 are preferably stored within memory in the system controller so that the desired amplitude and phase adjustments are accomplished. In this example, each reference tone is multiplied twice (rather than 126 times) to achieve the desired adaptation.

[0030] In one example, the time domain response of Figure 3 preferably is converted into the frequency domain response of Figures 4 and 5 using a Fast Fourier Transform. This provides the value by which the amplitude of the reference signal preferably is multiplied and the amount by which the phase of the reference signal preferably is shifted. According to one example, the complex frequency domain response equation $A'_n = |\tilde{C}(\omega)| \times A_n$ is used where $\tilde{C}(\omega)$ is the complex frequency response of the secondary path. The following equation: $\phi'_n = \phi_n + \angle\tilde{C}(\omega)$ represents an example phase adjustment technique used in one example system designed according to this invention.

[0031] In another example system designed according to this invention, a quadrature method is applied for achieving the desired modification to a reference signal. In this example, the reference signal preferably is broken down into sine and cosine components. An appropriate gain is applied to each of the reference signal components to get the effect of amplitude multiplication and phase shifting according to the determined frequency domain response of the secondary path. Known modulation techniques also may be used on the sine and cosine components to yield the desired reference signal.

[0032] Whether a quadrature method or phase shifting and multiplication method are applied, they may be used in a module 40 that is separate from (i.e., downstream) the tone generator 22, which generates a reference signal having a unity amplitude and zero phase. Alternatively, as shown in Figure 2, for example, the adjustment to the phase and amplitude of the reference signal may occur in the tone generator, itself, so that a separate computation need not be applied once the reference tone is generated.

[0033] In a system designed according to this invention, the modeling that provides the frequency domain response preferably is accomplished with the system controller operating in a modeling mode. A separate control mode preferably is used for generating the noise cancellation signal from the speaker 30 during active noise control. The controller preferably operates in these two different modes at different times so that the available memory and processing time is not compromised.

[0034] In one example system designed according to this invention, the modeling mode includes using an FIR filter to obtain a time domain response of the secondary path using known techniques such as an LMS algorithm. In this example, there preferably is a delay between the modeling mode and the control mode. During this delay, the inventive system applies a Fast Fourier Transform to the model of the time domain response. This provides the amplitude and phase adjustment information that can be stored in the controller for later use during the control mode.

[0035] In another example system designed according to this invention, during the modeling mode, the controller makes a direct measurement of the frequency response of the secondary path using a known technique. The frequency domain response information can then be applied to the reference signal similar to the examples described above.

[0036] The preceding description is exemplary rather than limiting in nature. Variations and modifications to the disclosed examples may become apparent to those skilled in the art that do not necessarily depart from the essence of this invention. The scope of legal protection given to this invention can only be determined by studying the following claims.

Claims

1. A method of generating a reference signal in a noise cancellation system having a path between a generator of a noise cancellation signal and a sound detector that detects the effect of the noise cancellation signal, comprising the steps of:

determining a frequency domain response of the path for at least one signal of a known frequency; and
adjusting the phase and amplitude of the reference signal responsive to the determined frequency domain response.

2. The method of claim 1, including generating a plurality of reference signal tones each having a known frequency and adjusting the amplitude and phase of each tone, individually.

3. The method of claim 1, including using the adjusted reference signal to generate a noise cancellation signal.

4. The method of claim 1, including determining an amplitude adjustment value and applying the determined value to the reference signal amplitude and determining a phase shift amount and shifting the phase of the reference signal by the determined amount.

5. The method of claim 1, including applying a gain factor to each of a plurality of components of the reference signal comprising a sine component and a cosine component to achieve the adjusted phase and amplitude of the reference signal.

6. The method of claim 1, wherein the system includes a tone generator that generates the reference signal and wherein the adjusting occurs in the tone generator.

7. The method of claim 1, wherein the system includes a tone generator that generates the reference signal with a consistent phase and amplitude and wherein the adjusting occurs subsequent to the tone generator generating the reference signal.

8. The method of claim 1, wherein the system includes a tachometer that provides information regarding an RPM value of a vehicle engine and wherein the reference signal frequency corresponds to the RPM value.

9. The method of claim 1, including determining a time domain response of the path and determining the frequency domain response by applying a Fast Fourier Transform to the time domain response.

10. The method of claim 1, including operating in a first mode for determining the frequency domain response and operating in a second mode while adjusting the phase and amplitude of the reference signal and including a delay between the first and second modes.

11. An active noise cancellation system, comprising:

a speaker;
a microphone that detects a combination of a sound from the speaker and noise in the system;
a controller having a first module that provides a frequency domain response of the portion of the system associated with the speaker and microphone, a tone generator that generates at

least one reference signal having a selected frequency and a second module that adjusts the phase and amplitude of the reference signal responsive to the frequency domain response information.

12. The system of claim 11, wherein the tone generator generates a reference signal having unity amplitude and zero phase and wherein the second module adjusts the amplitude and phase of the reference signal subsequent to the reference signal being generated by the tone generator.

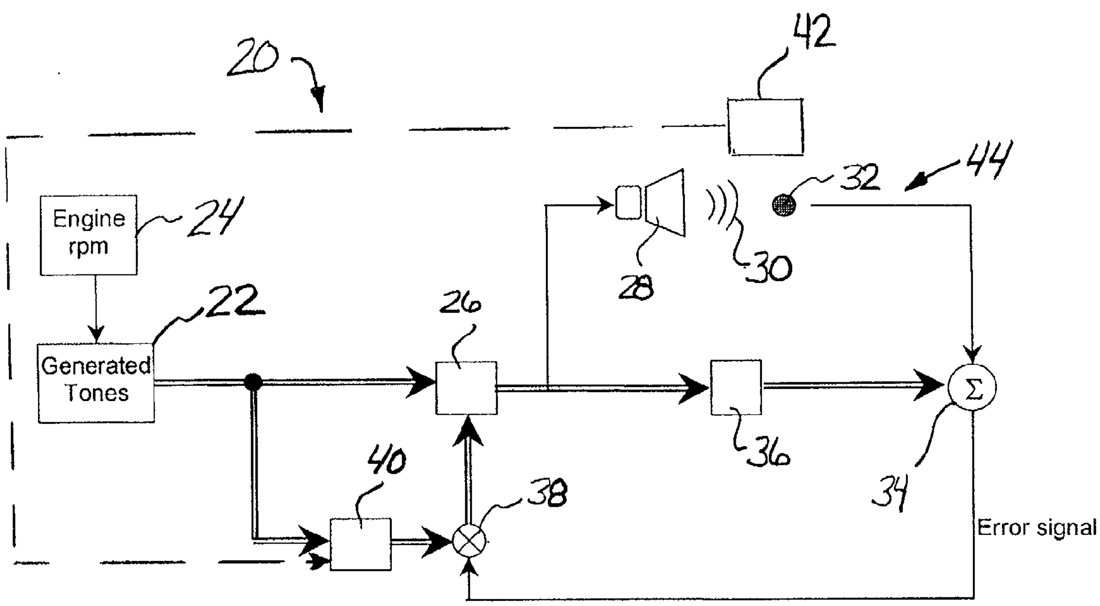
13. The system of claim 11, wherein the tone generator includes the second module such that the reference signal provided by the tone generator includes the desired amplitude and phase.

14. The system of claim 11, including a cancellation signal generating module that utilizes the reference signal to provide a cancellation signal for driving the speaker.

15. The system of claim 11, including a Finite impulse response filter that provides a time domain response of the portion of the system associated with the speaker and the microphone and wherein the first module applies a Fast Fourier Transform to the time domain response to provide the frequency domain response.

16. The system of claim 11, wherein the controller operates in a first mode for determining the frequency domain response and operates in a second mode at a different time for applying the phase and amplitude adjustments to the reference signal.

17. The system of claim 15, including a delay between the controller operating in the first mode and the second mode and, wherein the controller converts between a determined time domain response of the portion of the system associated with the speaker and the microphone and the frequency domain response during the delay.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42
44
32
Engine
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22
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Tones
Σ
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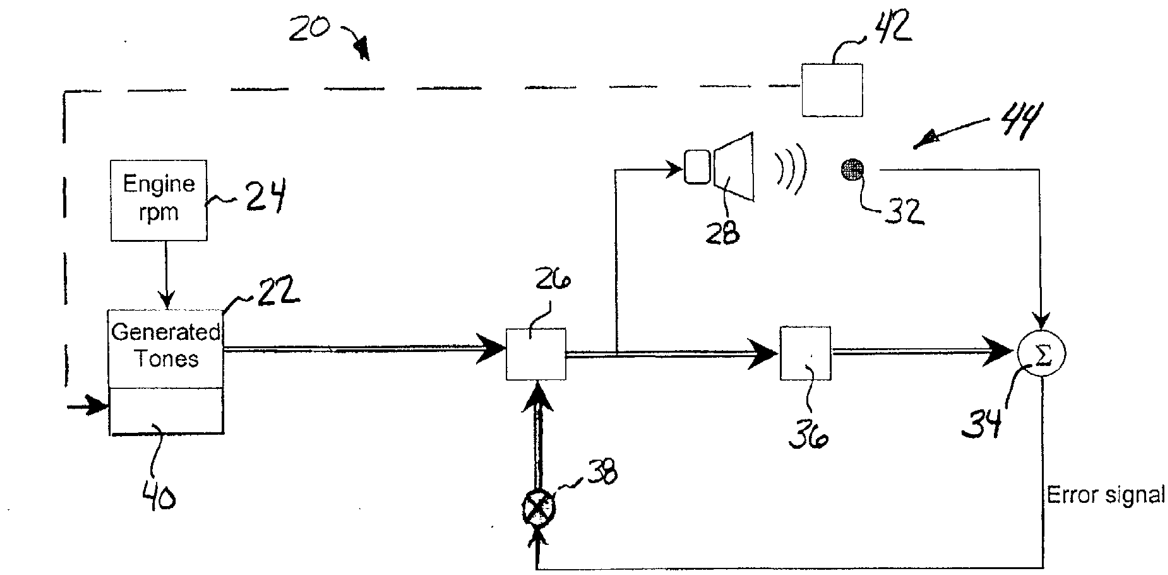
34
Error signal

Fig 1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Error signal

Fig 2

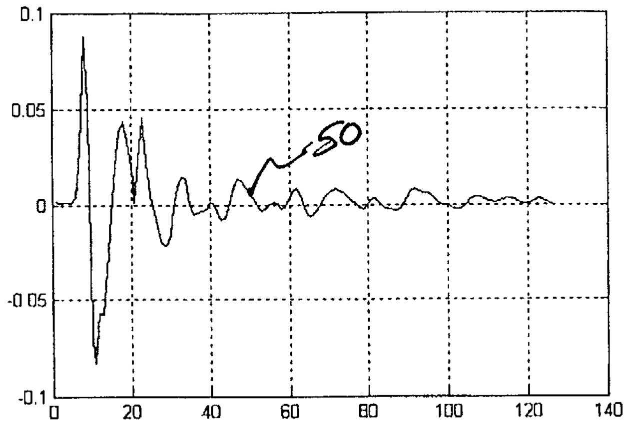

Fig 3

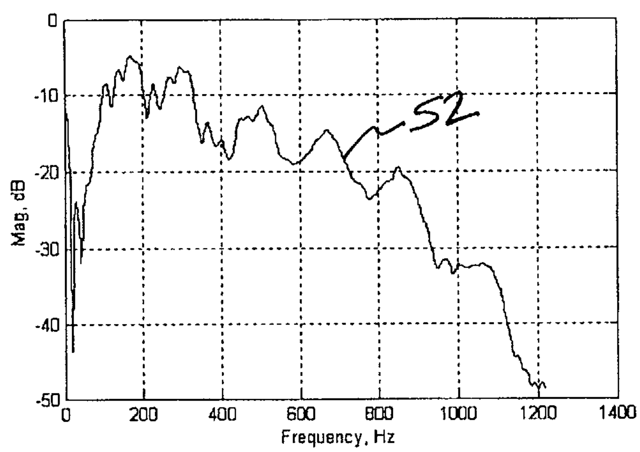

Fig 4

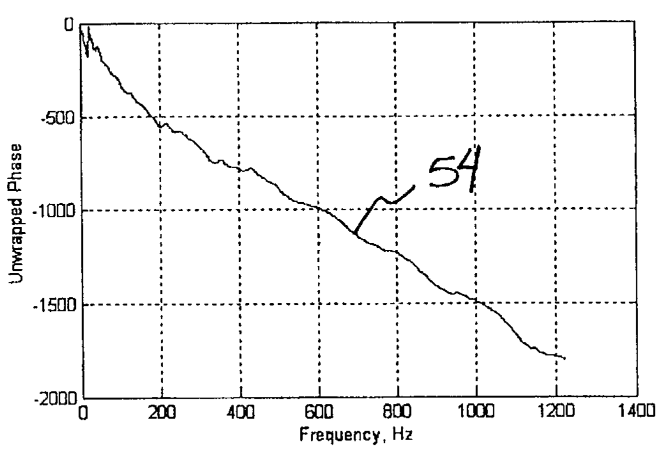

Fig 5