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DESCRIPTION

The conversion of electrical signals to and from other physical quantities requires the use of a transducer device. Transducers are used for measuring physical quantities or transmitting and receiving information through a medium. Information may be transmitted by propagating energy waves or signals in the media. Numerous types and combinations of electrical conversion transducers, media and energy waves exist so it is proposed to select only a small number of them to illustrate this description. Some examples of media are: air, a vacuum, glass, water, tissue, metal. Examples of energy waves are mechanical vibrations, acoustic vibrations, sound, electromagnetic waves, light. An example of an electromagnetic wave transducer for the radio frequency spectrum is an antennae. An example of an acoustic transmitting transducer is a loudspeaker; a receiving transducer example is a microphone. Examples of light transducers include photo-diodes for receiving and laser diodes for transmitting.

Transducers are designed to provide the efficient generation and reception of the signals involved but invariably they are unable to do this without introducing non-linear distortion. Non-linear distortion limits the transmission and reception signal quality but signal processing can be used to compensate for the distortion. In order for this signal processing to work correctly it is necessary to measure this distortion accurately. Accurate measurement requires a transducer test signal that has a significantly lower non-linear distortion than the transducer under test.

State of the art measurement systems are limited in accuracy and linearity by the methods used for generating the transducer test signal. Signal processing methods have been applied to correct for transducer non-linear distortion but the degree of correction has been limited by the threshold of measurement precision. This Specification will describe a transducer test method that overcomes this limit and therefore facilitates precision correction of non-linearity in transducers. First, an audio system will be used to illustrate this problem in order to show the benefits of the method.

In an audio system the transducers that are responsible for non-linear distortion are the microphone and loudspeaker. Audio non-linear distortion is usually measured using a sine wave test signal and specified in terms of the total harmonic distortion (THD). In order to test the distortion of a loudspeaker it is first necessary to drive it with a pure sine wave test signal. In practise this is difficult to achieve at high power levels as the driving amplifier performance is generally then least linear and generates significant harmonics. This is an area where the known art is deficient.

A microphone is used to complete the loudspeaker measurement as it converts the acoustic signal from the loudspeaker back to an electrical signal. The amplitude of the harmonics present, relative to the amplitude of the fundamental, are measured and the result is the THD. In order for this figure to be an accurate representation of the non-linearity of the loudspeaker, several conditions must apply.

1. The harmonic distortion of thc microphone must be known at the sound pressure level in use.
2. The microphone, and all electronic amplifiers involved in the measurement must have much less distortion in total than the loudspeaker.

Electronic amplifier distortion can be measured and corrected using well-known methods but this correction is limited by the difficulty in producing a sufficiently pure electrical sine wave test signal. Conventionally, the accurate measurement of microphone distortion requires a variable frequency pure acoustic sine wave test signal. This is an area where the known art is particularly deficient.

One example of this is a system that uses a loudspeaker to produce a distorted sine wave that is band pass filtered using an acoustic resonator in an attempt to reduce the harmonic distortion to a low level. Acoustic filters are complex items so are manufactured for fixed frequency operation only: typically 500Hz. Published [1] information on the present state of the art indicates that the residual THD is close to 0.3%. As this figure is the sum of the THD of both the acoustic signal and the microphone it is impossible to measure the THD of each separately. One consequence is that there is at present no means to measure loudspeaker distortion that is less than the 0.3% measurement system limit. Frequency dependent non-linearity of a microphone is therefore not measurable with precision using the known art. A similar situation exists when applying transducers to other measurement systems.

The foregoing description of the state of the art indicates that there is a need for a new method for testing and measuring the performance of transducers. The present Specification will describe such a method, which is not limited by the non-linearity of the transducers or electronic circuits. Furthermore, as it makes use of a test signal that covers the complete bandwidth of the transducer system, the non-linearity performance of the transmitting and receiving transducers can be determined in one measurement. This overcomes the limits of the known art.

The invention will now be described by way of a particular example and will refer to: Figure 1.

In Figure 1, a harmonic line spectrum generator 1 produces a signal 2 at its output. Signal 2 drives a transmitting transducer 3. 3 may optionally include a power amplifier or this amplifier may be a separate unit. 3 produces an energy wave 4.

A harmonic line spectrum generator 5 produces a signal 6 having a substantially different base frequency to 2. Signal 6 drives transmitting transducer 7. 7 may optionally include a power amplifier or this amplifier may be a separate unit. 7 produces an energy wave 8. Energy waves 4 and 8 combine in the transmission medium 16. Receiving transducer 9 receives the sum of energy waves 4 and 8 and produces an electrical signal 10 at its output. Signal 10 represents the sum of energy waves 4 and 8. Correction unit 11 incorporates a signal processing circuit that provides a variable non-linear input-output characteristic. The parameter values are adjusted in 11 according to a control signal 12. Analyser 13 measures the value of the non-linearity present at output signal 14 using the comb-filtering arrangement described in the known art [2]. Analyser 13 provides control signal 12 to guide correction unit 11 to minimise the non-linearity present at 14. Output terminal 14 provides a corrected receiving transducer signal that has less non-linear distortion than transducer 9 provides at signal 10. Switch 15 enables the correction unit to adapt when it is closed. The correction unit 11 stores and holds its settings when switch 15 is open.

The operation of the system depicted in Figure 1 will now be described by way of a specific example: a block diagram of a microphone test and correction system. At least two loudspeakers 3 and 7 are required. An electronic signal 2, with a line spectrum test signal comprised of signals harmonically related to a common base frequency, is applied to 3. This spectrum may be likened to a 'comb' of frequencies where the teeth of the comb correspond to the harmonics. The test signal generator 1 is preferably a pseudo random binary sequence (PRBS) generator but other signals that also produce harmonic line spectra can be used such as a square or a triangle waveform [3]. Non-linearity in the loudspeaker 3 will therefore generate harmonic and intermodulation products that will fall only on frequencies that are already contained in the test signal. It is clear therefore that non-linearity in the electrical amplifier or loudspeaker will only add to the harmonics and intermodulation products at the same frequencies that are present in the test signal and will not fall between the teeth of the test signal. Non-linear distortion therefore does not alter the frequency content of the acoustic signal produced by each loudspeaker. Modification of the amplitudes at each harmonic does not alter the ability of the test method to measure distortion. If there existed an ideal amplifier and loudspeaker it would generate an acoustic signal that was the same as the electrical test signal, i.e. one consisting only of a harmonic line spectrum. Hence the frequency content in the acoustic signal 4 from loudspeaker 3 is equivalent to one produced by a test signal source that has no non-linear distortion.

Generator 5 preferably uses a PRBS to produce an electrical test signal 6 with a line spectrum test signal comprised of signals harmonically related to a common base frequency, but with a base frequency ideally not related to the base frequency of 2 by a simple ratio. Signal 6 is applied to loudspeaker 7. The acoustic signal 8 has a spectrum that is again equivalent to one that has no non-linear distortion as non-linearity does not introduce spectral components in the spectral gaps of the test signal.

The two or more acoustic signals arriving at the microphone under test 9, combine in (transmission medium 16) air and provides the required acoustic test signal free of loudspeaker generated non-linearity distortion components. Any non-linear distortion from this point on would generate spectral products that fall between the teeth of the test signal line spectra. This acoustic test signal now conforms to the known art for measurement of signal transmission circuits as described in [2].

The potential non-linearity of the transmission medium can be important in some applications. It is not a factor that limits this audio application as its effect on the fidelity of music reproduction is the same for both live and reproduced music.

In the known art [2] , the analyser uses two or more comb filters aligned with the harmonic spectra of the test signal to remove the test signal leaving only a signal that represents the non-linear distortion of the microphone. If the known art of [2] were used to measure microphone distortion it would first require a perfectly linear loudspeaker and is therefore not applicable. This acoustic test signal now has no frequency components that can interfere with the measurement of non-linear distortion and the precise non-linearity of the microphone can be measured.

To compare with the state of the art, if the known art [2] were applied this would involve generating an electrical test signal with comb spectra combined in the electrical domain. This test signal would be applied to the loudspeaker to be tested and the electrical signal from the microphone would be analysed using comb filters as described in [2]. It is important to note that the measured distortion will also include that of the microphone. The ability of the known art to measure the distortion of the loudspeaker is again limited by the accuracy and non-linearity of the microphone. The new test method requires that the two comb spectra signals are combined in the non-electrical domain. This ensures that the final generation of the test signal is not limited by transducer non-linearity.

The algorithm used to adapt the correction in 11 makes use of the known art to correct for non-linearity over the range of amplitudes and frequencies present in the test signal. When adaptation is completed, correction unit 11 contains coefficients that represent the inverse non-linearity of the microphone. At this time the correction unit adaptive operation can be halted by opening switch 15 and the results stored for future use. The microphone 9 and correction unit 11 now represent a highly linear microphone and amplifier. This can be used as a reference transducer to measure the distortion of acoustic signals and hence enable other loudspeakers and microphones to be measured with much higher accuracy than previously possible.

By using the above described method and apparatus it can be seen that it is now possible to measure the true non-linearity of a receiving transducer or microphone without the restrictions imposed by the known art. This enables the application of well-known signal processing methods, for example, functional modelling, Volterra Series and electronic equivalent circuit modelling, to correct the non-linearity distortion of the receiving transducer with greater accuracy. This arrangement now provides a corrected reference receiving transducer. This enables the true non-linearity performance of the transmitting transducer to be measured and corrected with greater accuracy than the known art.

The use of the corrected receiving transducer to measure and correct the transmitting transducer will now be described by reference to Figure 2. Figure 2 depicts a system that makes use of the receiving transducer first corrected by the test system of Figure 1. Transducer correction unit 11 and transducer 9 have been previously used in the system of Figure 1 and the correction coefficients retained for the measurements to be made by the system in Figure 2.

Harmonic line spectrum generators 20 and 21 provide signals with similar specifications to 1 and 5 in Figure 1. Summing and filtering unit 22 provides a multi-level multi frequency band limited test signal 23 conforming to the known art [2]. Switch unit 33 enables test signal 23 to be applied to the signal input terminal 31 of Correction unit 24. The transfer function of 24 has a variable non-linear input-output transfer characteristic controlled by signal 30. Switch 32 connects control signal 30 when it is closed and enables the adaptation of unit 24. The adaptation of 24 halts when 32 is open. Transmitting transducer 25 is the unit to be tested and corrected. Correction unit 24 provides the test signal to drive 25 and 25 converts this signal into an energy wave 26. Energy wave 26 now contains non-linear distortion products introduced by 25 and propagates across medium 16 to receiving transducer 9. Transducer 9 converts this energy wave back to an electronic signal and this is processed by correction unit 11 to remove any non-linearity introduced by 9. Signal 28 therefore includes non-linear distortion products due only to the transducer 25 under test. Analyser 29 is substantially the same in operation as 13 in Figure 1 but may optionally have different gain and response time settings. 29 measures the amplitude of these non-linearity products as in Figure 1 and uses this to provide a control signal 30. Control signal 30 is used by correction unit 24 to adapt its non-linear transfer characteristic so that the amplitude of 30 is minimised.

The operation of the transmitting transducer correction system will now be described by referring to a specific example of Figure2: loudspeaker non-linearity correction.

The method of operation is as follows. First the microphone 9 non-linearity correction coefficients are measured using the system of Figure 1 and stored in correction unit 11. Signal generators 20 and 21 are preferably PRBS sources with base frequencies not related by a simple ratio. Filtering and summing unit 22 restricts the bandwidth of the test signal to that of the loudspeaker 25 under test. Audio bandwidth test signal 23 now conforms to the known art [2].
The audio signal normally used to drive loudspeaker 25 is disconnected from input terminal 31 and switch 33 is closed to connect the test signal to loudspeaker non-linear correction unit 24. Non-linearity in Loudspeaker 25 produces an acoustic signal 26 that contains frequency components in the spectral gaps of the test signal. This acoustic signal propagates in the air 16 between the loudspeaker and non-linearity corrected microphone unit 9 and 11. The signal 28 now represents the test signal with the added non-linearity of the loudspeaker. Analyser 29 uses comb filters aligned with the teeth of the test signal to extract the non-linearity signal present between the teeth. The analyser produces a control signal 30 used to control the adaptation of non-linearity Correction unit 24. 24 is instructed to start adapting by closing 32. The algorithms used in 24 can, for example, use well-known signal processing methods, such as Volterra Series and electronic equivalent circuit modelling to correct for the non-linearity distortion of the loudspeaker. When adaptation is complete the distortion signal present at 30 is minimised. The loudspeaker correction coefficients are then stored and held in 24 when 32 is opened. Test signal 23 is removed from input 31 when switch 33 is opened. Input 31 is then used for the normal audio input signal and the combination of 24 and 25 provides a linearity corrected loudspeaker. The adaptive correction can be made periodically, for example when the unit is turned on, or on

command, in order to ensure that any changes in the non-linearity over time are compensated for.

By the means described above it can be seen that the use of the system depicted in Figure 1 to correct for the non-linear distortion of a receiving transducer also enables the non-linear distortion in a transmitting transducer of Figure 2 to be corrected without being limited by the fundamental problem of generating low distortion acoustic test signals. This approach can be applied to measuring and correcting the non-linearity of transducers for other physical quantities and transmission media.

The attenuation of energy waves through a medium over a range of positions can be used to calculate an image of the contents of the medium using the known art. Examples of this are ultrasonic and computer aided tomography for medical imaging. However, the resolution of the image is limited by non-linear distortion due to the attenuation of the medium changing with the amplitude of the applied energy wave. An example of this is in ultrasonic imaging. The ultrasonic measurement system is first calibrated using a water or similar medium as this is substantially linear. When the ultrasonic system is then used to measure the attenuation in tissue the medium has a non-linear attenuation response. If this non-linearity of attenuation can be characterised over the different imaging positions of the transducer then in principle an image with greater clarity can be obtained by calculation. The degree of linearity correction for the medium possible using the known art is limited by the degree of transducer non-linearity correction possible using the known art. These limitations have previously been described in the context of other applications. There is therefore a need to be able to measure more accurately the non-linearity of a transmission medium and the following method that makes use of the forgoing Specification will be described.

The system depicted in Figure 2 can be modified to measure the non-linearity of different transmission media that use the same energy wave and transducers. This new configuration is depicted in Figure 3 which will now be described by comparison with Figure 2. In Figure 3 the transmitter non-linearity corrector 24 has stored correction coefficients obtained when used with a linear medium 16. The additional unit 35 is a non-linearity correction unit substantially the same as 24 and is controlled by analyser unit 29. The operation of the medium measurement method is now described.
Non-linearity corrected transmitting (units 9 and 24) and receiving (units 25 and 24) transducers are first corrected using the previously described methods using a transmission medium 16 that has low non-linear distortion. The medium 16 is next replaced by non-linear version one that can propagate the same energy wave. The output signal 32 of Analyser 29 now represents the non-linearity of the transmission medium. When the switches 33 and 34 are closed adaptation is enabled and on completion correction unit 35 contains coefficients that represent the non-linearity of the transmission medium. Optionally, correction unit 35 can be placed instead at the output of 11 and this configuration is depicted in Figure 4. The method operation of Figure 4 is the same as Figure 3.

REFERENCES

[1] Erling Frederiksen, "System for Measurement of Microphone Distortion and Linearity from Medium to Very High Level", Brüel&Kjær Technical Review no1 2002.

[2] R A Belcher, "Measurement of non-linear distortion in signal transmission circuits", GB 1 529 472 .

[3] R A Belcher et al, "Band separation and the noise power ratio test", IEE ADDA99 Conference Publication 466

CLAIMS

We claim:

1. A non-linearity measurement and correction system for transducers comprising: a physical test signal generator which comprises a plurality of electrical to physical transducers for providing a physical test signal comprising a plurality of harmonic spectra;
a physical to electrical transducer for receiving the physical test signal;
a signal processing means for using the resulting electrical signal to derive and store correction coefficients for eliminating or reducing non-linear distortion in the physical to electrical transducer;
a signal processing means for subsequently deriving and storing correction coefficients for eliminating or reducing non-linear distortion in the electrical to physical transducer(s);

2. A physical test signal generator according to claim 1 where the physical signals are acoustic signals.

3. A physical test signal generator according to claim 1 where the physical signals are mechanical signals.

4. A physical test signal generator according to claim 1 where the physical signals are light signals.

5. A physical test signal generator according to claim 1 where the physical signals are electromagnetic signals.

6. A physical to electrical transducer according to claim 1 where the physical signals are acoustic signals.

7. A physical to electrical transducer according to claim 1 where the physical signals are mechanical signals.

8. A physical to electrical transducer according to claim 1 where the physical signals are light signals.

9. A physical to electrical transducer according to claim 1 where the physical signals are electromagnetic signals.

10. A means of deriving and storing correction coefficients for eliminating or reducing non-linear distortion in the physical to electrical transducer according to claim 1 where this is achieved by using non-linear signal processing methods such as Volterra series or electronic equivalent circuit modelling.

11. A means of deriving and storing correction coefficients for eliminating or reducing non-linear distortion in the electrical to physical transducer according to claim 1 where this is achieved by using non-linear signal processing methods such as Volterra series or electronic equivalent circuit modelling.

12. An electrical to physical transducer correction system according to claim 10 where the correction parameters are determined adaptively and periodically updated to compensate for changes in non-linearity over time.

13. A physical to electrical transducer correction system according to claim 11 where the correction parameters are determined adaptively and periodically updated to compensate for changes in non-linearity over time.

14. A transducer non-linearity measurement and correction system that uses all of the previous claims where the transmission medium is non-linear and the corrected transducers are used to measure and correct for the non-linearity of the medium.

15. A transducer non-linearity measurement and correction system substantially as herein described above and in the accompanying drawing.

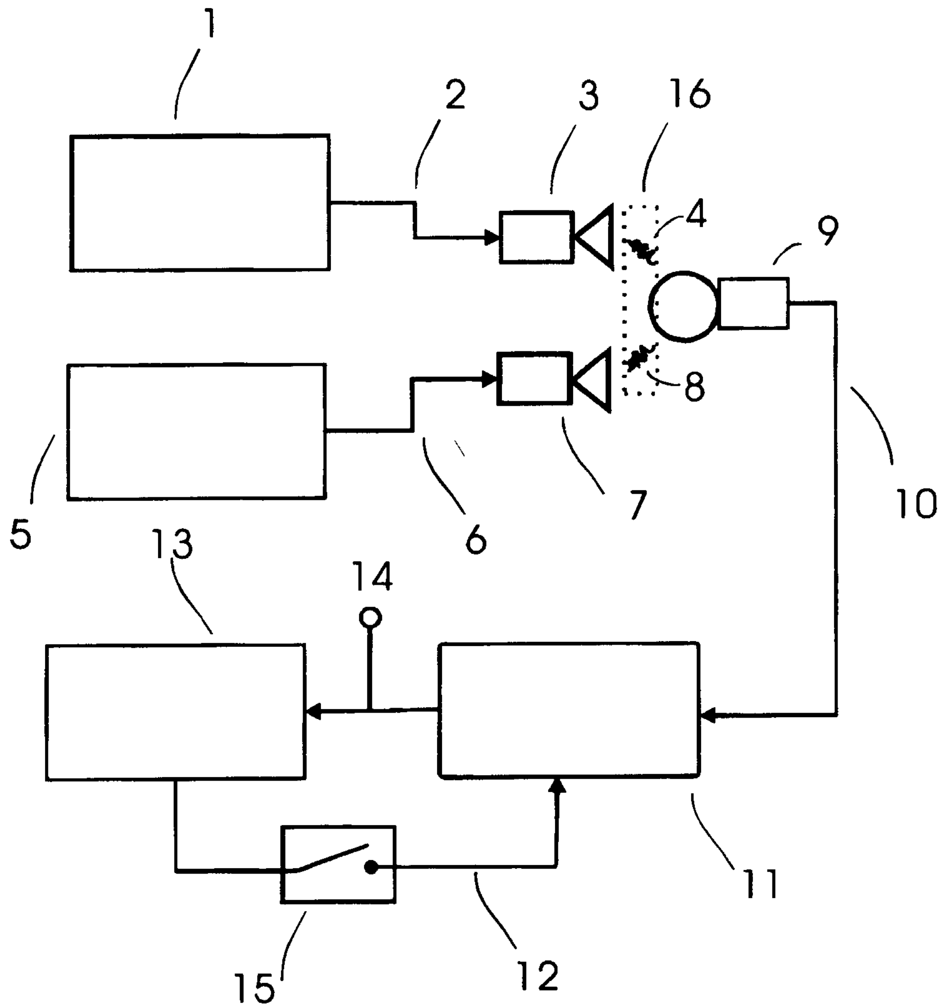

Figure 1

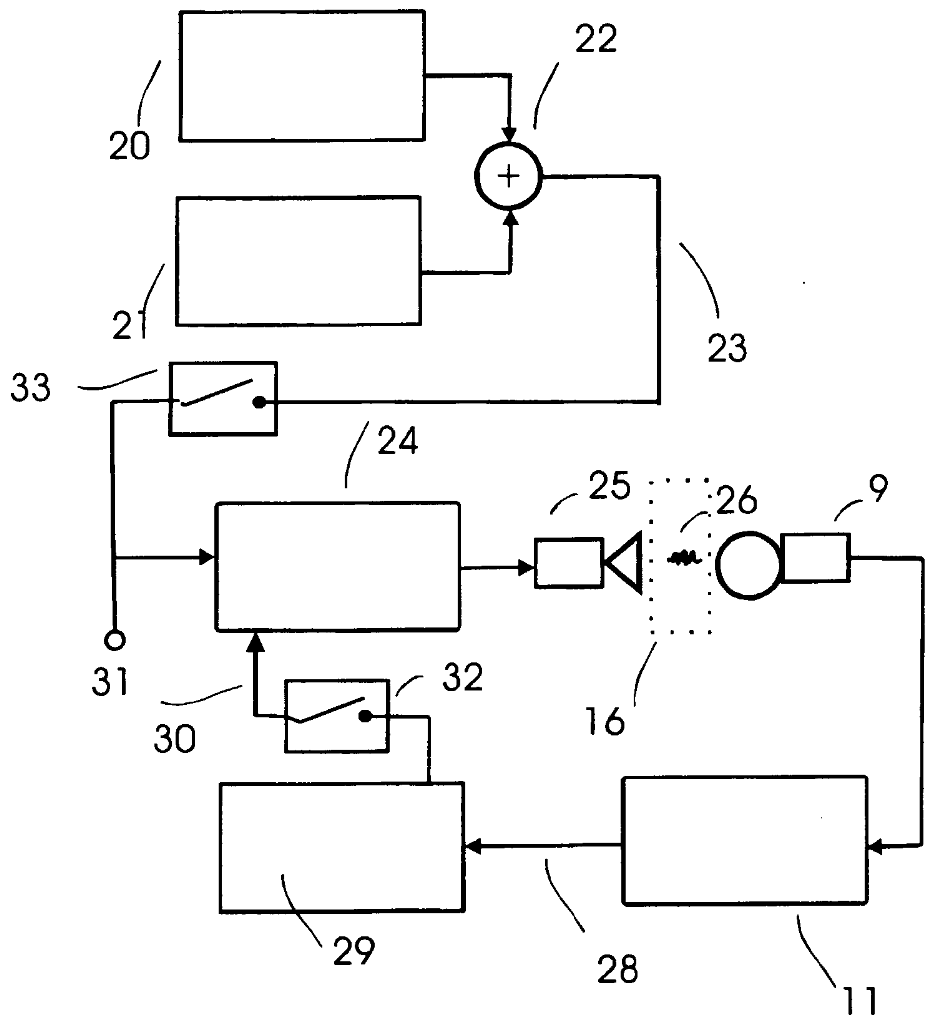

Figure 2

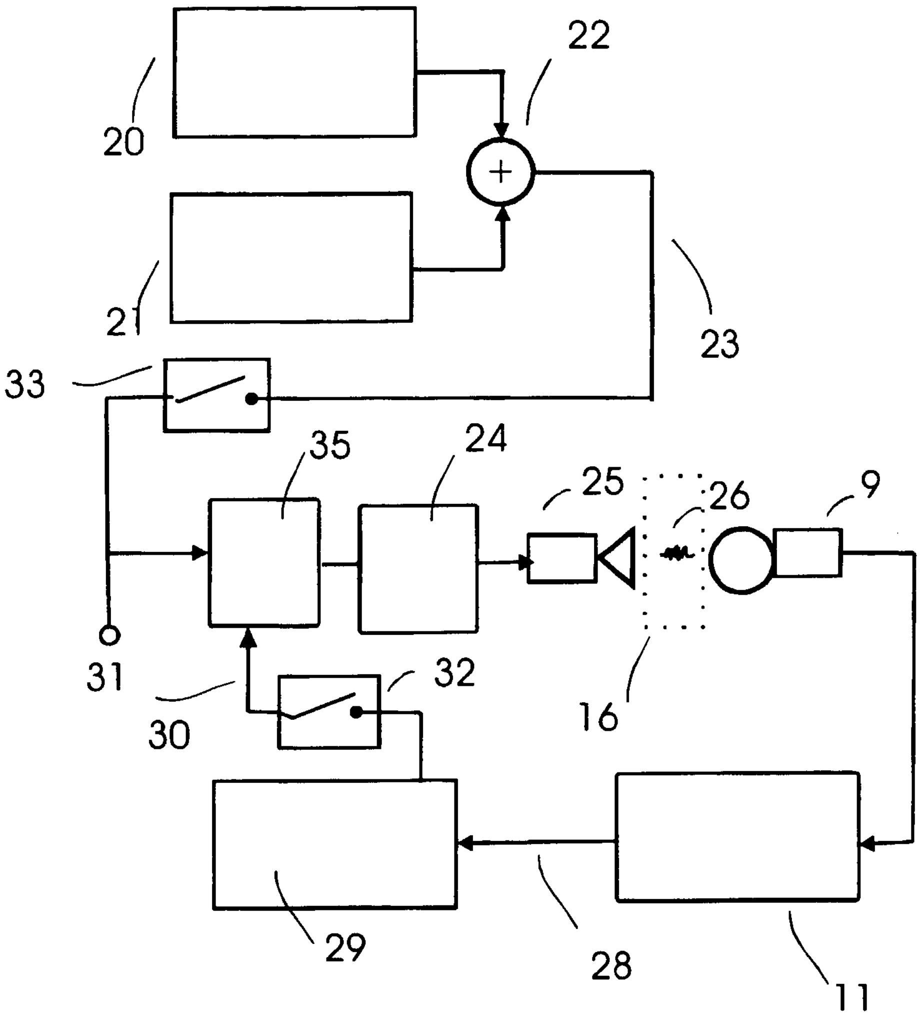

Figure 3

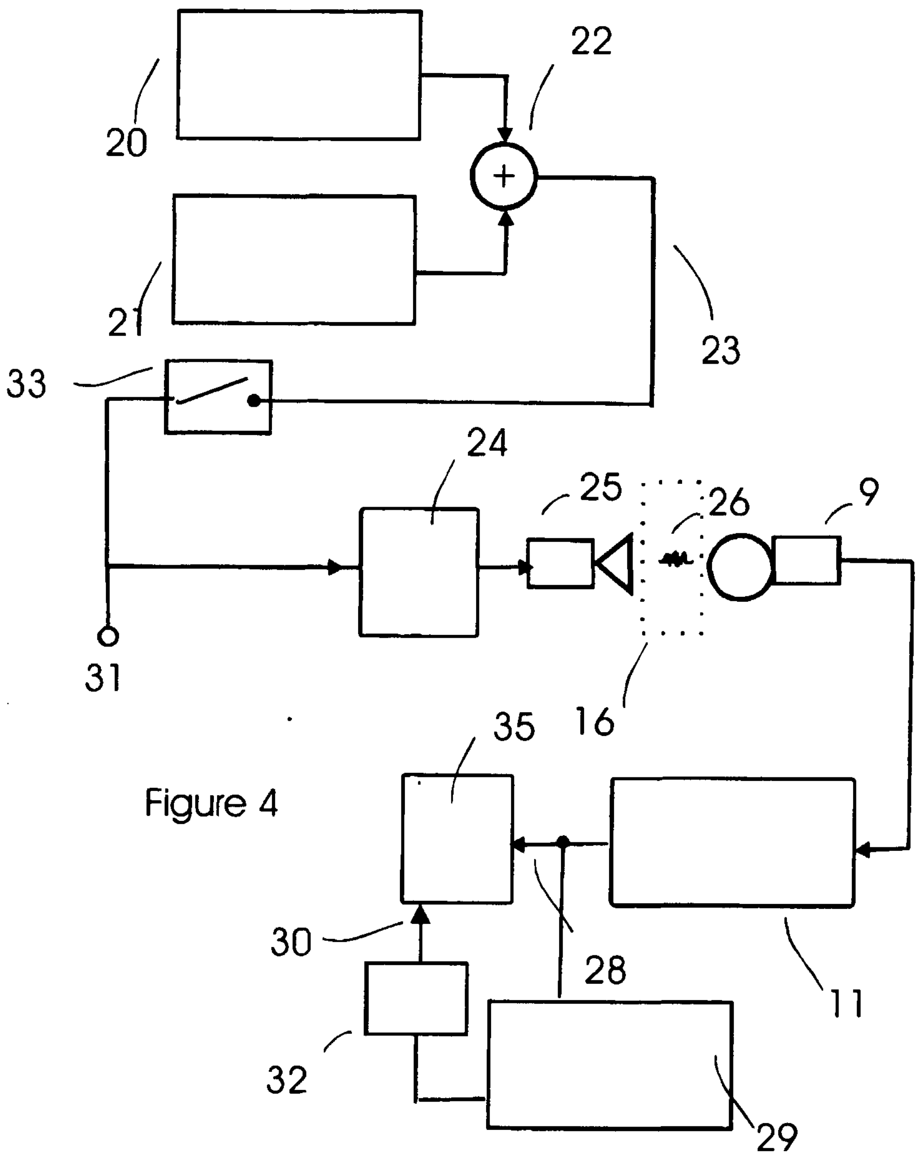

Figure 4